Continental Scientific Drilling Workshop Series

Report 2013

A compilation of five individual workshop reports outlining the needs of the continental scientific drilling community.

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Cover photo: Hominin Sites and Paleolakes Drilling Project (HSPDP) drill site (June 2013) in the central Kenya Rift Valley (Tugen Hills). Drilling at this site retrieved a core record spanning the time period from ~3.45-2.5 Ma.

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Cover background photo: basalt core, Twin Falls, Idaho.

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Purpose of the Continental Scientific Drilling Workshop Series

Continental Scientific Drilling (CSD) is at a critical stage of growth in the United States. Opportunities to apply CSD technologies are rapidly expanding into disciplines and initiatives (e.g. Critical Zone Observatories) where there was little or no interest in drilling as recently as a decade ago. The need for CSD to address a wide array of earth and environmental science questions has been well documented through several recent workshop and NRC reports (Walton et al, 2009, 2010; Brigham-Grette et al., 2011; NRC, 2011). As a result of recent meetings (2011, 2012) of the Science Planning and Education and Outreach Committees of DOSECC a plan was put into place to provide NSF with broad community input concerning specific CSD science objectives in five broad areas:

Scientific Drilling and the Evolution of the Earth System: Climate, Biota, Biogeochemistry, and Extreme Systems (Conveners: Lynn Soreghan and Andrew Cohen)

Drilling active tectonics and magmatism (Volcanics, Geoprisms, and Fault Zones Post-SAFOD). (Conveners: John Shervais, Jim Evans, Virginia Toy, James Kirkpatrick, John C. Eichelberger and Amanda Clarke)

Drilling into High-enthalpy Geothermal Systems: A Collaborative Initiative to Promote Scientific Opportunities. (Conveners: Wilfred Elders, Joseph Moore, Alex Schriener, and Lucien Bartnicki)

Cyberinformatics for Paleogeoscience (Conveners: Anders Noren, Jack Williams, Kerstin Lehnert, Shanan Peters, Eric Grimm, Julie Brigham-Grette, Emi Ito, Dave Anderson, Lisa Boush)

Drilling, sampling, and imaging the depths of the critical zone. (Conveners: Clifford Riebe, Jon Chorover)

In a circular to the US Earth Science community (NSF “Dear Colleague” Letter 12-111), the National Science Foundation indicated its desire to “facilitate planning activities that are necessary to support earth science proposals requiring continental scientific drilling” and that such activities might include both workshop support and community planning activities. The workshops were held throughout 2013 at various U.S. locations. The “community planning” element which NSF identified was greatly enhanced by a concerted effort to coordinate both the execution and outcomes of those workshops.

This summary document compiles the five individual workshop reports and synthesizes the findings of all of these meetings vis-à-vis the needs of the continental scientific drilling community. Collectively, these five reports illustrate the vibrancy of CSD in the US community today, the wealth of new ideas and new directions where CSD could move in the coming decade, and the need for enhanced NSF investment in supporting the innovative use of drilling technologies to address important new questions in the earth sciences. Coordination of these workshops and the preparation of this final, comprehensive report was supported by NSF-EAR 1265197.

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Scientific Rationale

Over the past decade, numerous workshops and study groups within sedimentary geology, paleoclimatology, and paleobiology have repeatedly highlighted the importance of continental scientific drilling to address important science questions in climate and linked Earth systems (e.g., the U.S. National Science Foundation (NSF)-supported GeoSystems, DETELON, and Transitions workshops, and the U.S. National Research Council (NRC) reports on Deep-Time Climate and Climate and Human Evolution (Soreghan et al., 2003, 2005; Montañez and Soreghan, 2006; Bottjer and Erwin, 2010; NRC, 2010, 2011; Parrish, 2012).

In recognition of this sustained surge of interest, a workshop was held on May 17-19, 2013 at the University of Oklahoma to identify high-priority targets for scientific drilling aimed at assessing critical questions related to paleoclimate, paleobiology, and extreme events in Earth’s history.

The objectives of the workshop were to:

1. develop a community of researchers interested in using scientific drilling for stratigraphic targets to answer questions about Earth System evolution,
2. identify topics and drilling targets of broad scientific interest, and
3. offer researchers direction on how to develop compelling drilling proposals, how to evaluate and plan logistical issues related to drilling, and how to strategically develop a funding plan for drilling.

The ultimate intent is to galvanize research teams to move forward with future proposals involving continental drilling.

Workshop Format and Proceedings

All interested researchers were invited to submit a brief pre-proposal identifying a viable continental scientific drilling target to examine questions of scientific importance in the areas of paleoclimate, earth history, stratigraphy, paleoecology and/or paleobiology from any interval of Earth History. The 41 participants submitted 30 pre-proposals (White Papers; Appendix A) that articulated scientific themes in earth, evolutionary and ecological history spanning geologic time. Participants discussed the role of drill core studies in Earth/life history and identified locations where critical questions can best be approached.

The workshop included plenary sessions in which invited speakers addressed topics of overarching interest in scientific drilling. Additionally, principal investigators for each submitted pre-proposal presented a 5-minute talk outlining the science drivers, significance, and rationale to enable all par-
Participants to grasp the vast breadth of proposed projects, which span the geological record from the oldest sedimentary rocks to modern lakes, and range geographically from pole to pole (Figure 1).

Through the rest of the 2.5-day workshop, breakout groups identified critical science questions in Earth History that can be assessed with drill core data, and evaluated discipline-specific drilling problems. Themes were chosen to explore Earth history processes across time scales, and to consider how drilling can inform our understanding of those events.

**Glacial-Interglacial and Icehouse-Greenhouse Transitions and Biotic Consequences**

Earth’s atmosphere reached an historic threshold in May 2013, when sustained atmospheric CO$_2$ levels exceeded 400 ppmv for the first time in human history, and the first time in approximately 3 My (Beerling and Royer, 2011). Passing this threshold offers the opportunity to engage the public on climate transitions in Earth history, and the Earth System linkages accompanying these transitions, such as changes in biodiversity and ecosystems during glacial-interglacial transitions.

To this end, much research has focused on, in particular, the transition from the Last Glacial Maximum (LGM) to our current interglacial, as well as other transitions within the Pleistocene (e.g., Fawcett et al., 2011; Ivory et al., 2011; Brigham-Grette et al., 2013). These studies provide important insights into Earth’s climate behavior at a very high-resolution (millennial to annual) scale that are critical for grasping Earth’s recent climate behavior and informing deep-time studies of glacial-interglacial transitions. It is equally important, however, to understand the potential diversity of glacial-interglacial behavior throughout Earth’s record. What insights can we gain about climate behavior by examining Paleozoic and Neoproterozoic glacial-interglacial and --at a broader scale--so-called “icehouse-greenhouse” transitions (e.g., Bao et al., 2008; Fike et al., 2006; Kennedy et al., 2008; Mills et al., 2011; Barham et al., 2012).

Research over the past decade has highlighted the occurrence of major biological turnovers in Earth history accompanied by changes in greenhouse forcing, ocean acidification and climate change (e.g., Jiang et al., 2009; Johnston et al., 2012; Katz et al., 2008). Continental drilling can provide high-resolution records of these climate and life transitions. Looking back into the period of the Cenozoic when atmospheric CO$_2$ levels differed from today provides estimates of future climate change and ecological response. The deep past also highlights abrupt change, the information necessary to test how well climate models will predict abrupt changes in the next centuries (Valdes, 2011). The Paleozoic and Neoproterozoic icehouse-greenhouse transitions provide particularly extreme examples that, albeit poorly constrained, span evolutionary events such as the origin of animals and terrestrial ecosystems central to our existence.

**Records of Long-Term Evolution Events and Extinctions**

Developing reliable records of evolution and extinction requires access to high-resolution geochronologic control, and also unambiguous superposition, which is a great benefit of drill core over purely outcrop studies. Furthermore, both micro- and macrofossil records are critical for assessments of life transitions, so linked outcrop and coring studies are critical for questions targeting these issues. In addition, core provides access to unweathered material critical for geochemical analyses, including organic (e.g., biomarker) and potentially fossil DNA studies, which can shed light on ecological (including catastrophic) events and evolutionary history (e.g., Clyde et al., 2013).

Effective strategies for obtaining sufficient sampling across critical intervals include planning for
Figure 1: Geologic timescale (above) and global map (below) listing the (enumerated) thirty drilling project pre-proposals submitted to this workshop. The gray to black bars show the various timescales of the projects proposed. Note that the upper timescale is an enlarged version of the Holocene through Neogene interval, to portray projects proposed for this “near-time” slice. See below for the titles of the proposed projects (keyed to the numbers in the bars on this figure).

KEY TO PROPOSED DRILL SITES MAP (below). Detailed descriptions of each of these sites and proponent lists can be found at http://csdworkshops.geo.arizona.edu/Norman_OK.html

1. Stoneman Lake, Arizona Paleoenvironments Drilling Project
2. Trans-Amazon Drilling Project: History of the Neotropical Rain Forest
3. African Late Pleistocene Biotic and Environmental Revolution
4. Drilling the Late Miocene Höwenegg Lagerstätte, Hegau, Southern Germany
5. The Lago de Tota Drilling Project
6. Kings River Alluvial Fan Terrestrial Drilling
7. Drilling to Elucidate Causes of Extinction During the Oceanic Anoxic Event at the Cenomanian/Turonian Boundary
8. The Arctic in a Greenhouse World: Drilling within a Cretaceous Deep Time Observatory
9. The Terrestrial Greenhouse to Icehouse Transition (Eocene-Oligocene) of the Northern Great Plains
10. Pennsylvanian Cyclothsems of the Paradox Basin
11. Project EOCore
12. ANDRILL Coulman High Project: \( \text{CO}_2 \) Thresholds of Past and Future Ice Sheet Behavior
13. Argentina Loess Sequences
14. Eoarchaean Tidal Signatures in the >3.7 Ga Isua Greenstone Belt, Greenland
15. Cretaceous Microfossil Lagerstätte from Coastal Sections in Tanzania
16. Drilling the Ediacaran-Cambrian Transition in South China
17. Observing the Neoproterozoic Snowball Earth Transition
18. Return to Mochras: A New Global Standard for Early Jurassic Earth History
19. “Blue Sky” Geology- Core Drilling in the Unstudied Grove Center Late Paleozoic Outlier in Western Kentucky
20. Colorado Plateau Coring Project
21. Environments of Tropical East Africa since the Late Miocene: Continental Drilling in Lake Tanganyika
22. Recovering a 3 to 5 Million Year Paleolimnologic Record from Butte Valley, California
23. Documenting Tropical Climate During Earth’s Last Icehouse Collapse: The Permian of Western Equatorial Pangaea
24. Drilling Through Holocene Fossil Reefs on the Caribbean coasts of Panama and Columbia
25. Potentially Extensive Plio-Pleistocene Earth System Records at Yardi Lake
26. Post-eruptive maar sediments from the Giraffe Kimberlite: Potential for a World-Class Continental Record of Middle Eocene Paleoclimate from Northern Canada
27. Building a high-resolution history of Mono Lake from yesterday to 760 kyr BP (and beyond?)
28. Records of Glacial Advance, Retreat, and Large-Scale Glacial Flooding in Central North America
29. The Early Eocene Lacustrine Green River Formation
30. Outpacing the Anthropocene: The case for a rapid release of carbon at the Paleocene Eocene Thermal Maximum
multiple, shallow cores across a series of dipping strata, or targeted coring of key intervals defined by nearby outcrop studies. Drill cores eliminate the human bias of outcrop-based studies by taking an essentially random sample of local sedimentary facies through time and providing a continuous (albeit not necessarily complete) stratigraphic record across biotic transitions.

**Records of Major Biogeochemical Events in the Oceans**

The first oxygenation of the atmosphere and ocean is a critical biogeochemical event in Earth history. This transition was a prerequisite to the appearance of eukaryotic organisms and ultimately to emergence of animals and their major radiation—the Cambrian explosion. Many evolution and extinction events, especially those in Earth’s Precambrian record, are tied either directly or indirectly to oxygen availability. Research on Precambrian Earth systems has experienced a resurgence of interest as new geochemical tools have come online to assess these events, especially, various redox-sensitive metal tracers and their isotope systematics (Buick, 2007; Scott et al., 2008; Partin et al., 2013; Reinhard et al., 2013) and basin-scale reconstructions of redox state (Sperling et al., 2013) that enable tracking of oceanic oxygen levels.

Collectively, this work demonstrates that the view of a single large oxygenation event is yielding to a model of dynamic rises and falls in oxygen levels. This requires that the precision of our proxies increase and/or expand to meet the constraints placed by physiology (microbial and metazoan) in order to understand Earth’s major biological transitions (Sperling et al., 2013).

Improved understanding of Precambrian oxygenation events is also informing views of the global ocean redox landscape during Phanerozoic anoxic events (Lyons et al., 2009). Drill-core records provide a unique and fundamental opportunity to assess timing, duration, and possible drivers of these events, owing to their capacity to provide both continuous and, critically, unweathered (unoxidized) material. Beyond the ocean, coring of paleosols sheds light on the spread of oxygenation to continental systems and a direct measure of atmospheric oxygen. Further, refined data on ancient oxygen conditions are informing our view of ocean de-oxygenation scenarios under recent human influences, such as lower oxygen solubility in warmer surface waters and elevated riverine nutrient delivery (e.g., Falkowski et al., 2011).

Although atmospheric and oceanic oxygenation tie directly or indirectly to many of the most fundamental biogeochemical events in Earth history, other events best accessible through continuous and unweathered cores include ocean-acidification events (e.g., the Permian-Triassic and Paleocene-Eocene Thermal Maximum, as potential analogs for Earth’s near-term future (e.g., Zachos et al., 2005), the C3-C4 vegetation transition, and the effect on global carbon cycling linked to the radiation of diatoms and calcareous nannoplankton more recently (Katz et al., 2005). Drill cores can also provide links between oceanic and continental records to assess the role of continental processes such as nutrient recycling during times of oceanic anoxia, for example, and to evaluate the ‘buffering’ capacity of the oceans at times of high pCO₂.
1. chemical composition, such as the presence and proportions of \( \text{O}_2, \text{CO}_2, \text{SO}_2 \) (e.g., Kump, 2008),

2. aerosol composition, including the presence and proportions of mineral dust and black carbon, and --speculatively-- dimethylsulfide and \( \text{O}_3 \) (Wolff et al., 2010; Diessel, 2010; Bisiaux et al., 2012), and

3. circulation, such as the position of the Inter-Tropical Convergence Zone (ITCZ), presence and strength of monsoons, and storm intensity (e.g., Ito et al., 2001; Frappier et al., 2007).

Key events in atmospheric reorganization include both Precambrian and Phanerozoic shifts in

1. \( \text{O}_2 \) in response to evolutionary radiations of photosynthesizers (Canfield et al., 2007),

2. \( \text{CO}_2 \) in response to biological, tectonic, and weathering drivers (Bergman et al., 2004; Berner, 2006), and

3. atmospheric circulation, e.g., shifts from zonal to monsoonal circulations associated with continental positions and mountain elevations (e.g., Parrish, 1993; Clio et al., 2008).

Proxies and indicators useful to reconstructing atmospheric composition include various approaches to measuring, e.g., atmospheric \( \text{CO}_2 \) such as paleosol carbonate isotopes, leaf stomatal densities, and bryophyte photosynthetic fractionation (e.g., Royer et al., 2001; Fletcher et al., 2008). Proxies and indicators exist for temperature, moisture, and transport, such as various isotopes, biomarkers, and eolian provenance indicators (e.g., Soreghan et al., 2002; Eglington et al., 2008; Severman, 2009; Pullen et al., 2011; Woltering et al., 2011; Zambito et al., 2013), all of which benefit from pristine material offered by drill cores. Target records include loess deposits, paleosols, lacustrine and epeiric marine strata, and facies conducive to preservation of leaf waxes and associated biomarkers (e.g., Brigham-Grette et al., 2013). Drilling of continental records is particularly needed to assess the range of responses on the continents to global change. The integration of proxy results to constrain climate models offers the potential to refine predictions for future sea level and agricultural productivity under higher levels of greenhouse gases.

**Lagerstätten and Exceptional Fossil Biota in Cores**

Some continental cores preserve fossil Lagerstätten (exceptionally preserved fossil biota) of microfossils or very small macrofossils (Pearson et al., 2006; Wendler et al., 2011; Wolfe et al., 2006). Microfossil Lagerstätten in core are especially useful for yielding estimates of true diversity (Jiménez Berrocoso et al., 2010). Cores can also provide critical sedimentary and geochemical context for Lagerstätten of larger fossils or extraordinarily-preserved sedimentary deposits (e.g., varves or tidalites) that give detailed records of environmental conditions. Access to such deposits via core recovery facilitates high-resolution geochronological correlation and provides well-preserved samples with no weathering overprint. Analyses of Lagerstätten in the context of continuous core can reveal biotic sensitivities to environmental change and shed light on kill mechanisms during extinction events. As such, cores containing fossil Lagerstätten or exceptional sedimentary deposits offer key insights on the evolution of Earth’s system states over time.

**Drill Core Records of Vegetation and Landscape Change through Time**

Landscapes reflect the combined effects of physical, biological, and (since humans evolved) anthropogenic influences occurring at Earth’s surface over time, and thus preserve a 4D record of processes affecting a sedimentary basin (Driese and Nordt, 2013). Vegetation and landscape changes are identified through composition of and changes in, e.g., fossil flora (e.g., leaves, wood, seeds, flowers, root traces, phytoliths, palynomorphs, charcoal, etc.), trace fossils, paleosols, thermochronological signatures, and various isotopic records. The geologic record of landscapes
is best addressed by an approach that combines outcrop studies (where feasible) with drilling -- the former to access records such as megaflores, and the latter to enable geochemical analyses of pristine material (e.g., Retallack and Dilcher, 2011).

Outstanding issues in landscape analysis that could benefit from systematic inclusion of drill core records include 1) linking sediment sources to sinks, 2) characterizing extinct soil types and ecosystems, 3) determining spatial variability in fossil landscapes, and 4) determining uplift histories (potentially rates and reliefs and even paleoelevation through time now accessible by detrital thermochronology). Ultimately, core analyses could enable systematic analysis of the evolution of Earth’s Critical Zone through time. With regard to landscape analysis, even the surfaces encountered in cores -- the hiatus events -- provide key data for landscape reconstruction (e.g., Nordt et al., 2013; Sauer et al., 2013).

Beyond the deep-time geological record of landscape change, the recent anthropogenic record offers insights to landscape changes wrought by pre-industrial human transformations, especially the commonly recognized but poorly characterized history of anthropogenic deforestation and fire use (Ruddiman, 2013). Cores may allow us to distinguish the onset timing and magnitude of human-induced fire, for example in the fire-adapted ecosystems of the African miombo or Australian woodlands.

**Paleobiology**

Recovery of adequate macrofossil assemblages and fragile or flat biota in core is possible, and could be maximized in novel ways not available to paleobiologists relying on a single core. For example, multiple cores taken along a transect, or through recovery of long lateral sections via horizontal drilling of fossiliferous units, and inclusion of outcrop studies can best account for assemblage characteristics. The usefulness of paleobiologic records, especially if biogeochemical analyses are envisioned, can be compromised by potential contamination, so logistical issues are critical, including choice of lubricants, drilling fluids, and core recovery techniques (e.g., use of liners, etc.), as well as post-drilling core handling and curation (curing, sieving). Processing technique should be planned so as to avoid inadvertent destruction of macro remains. Use of analytical methods such as X-rays and CT scans can be extremely helpful for imaging macrofossils as well as traces in 3D and in situ, to reveal the occurrence of thin or small specimens that might be enigmatic in 2D slab cuts. Much as-yet unexplored potential exists in the integration of paleobiology with genomics/molecular genetics/protemics in unweathered drill core samples (Cohen, 2011).

**Stratigraphy/Sedimentology**

All stratigraphic/sedimentary studies benefit from recovery of pristine, continuous records, uniquely offered by drilling. In addition, core provides critical tie points that link outcrop with seismic imaging datasets. This is essential for building robust, basin-wide chronostratigraphic frameworks that ensure reproducible correlations. The spatial perspective, coupled with linkages to paleoecological research in complex terrestrial environments, suggests that multiple drill cores or core transects may be required to address interdisciplinary research objectives in some basins. Key subject areas for science questions that can be addressed in the realm of stratigraphy and sedimentology include large-scale basin geodynamics and source-to-sink issues (e.g., sediment budgets, long-term erosion rates, subsidence analysis, fault evolution), including biogeomorphological feedbacks, such as source-sink systems at major Earth-life and climatic transitions. For example, fluvial records show a fundamental shift in stratigraphic architecture associated with major phytogeographic changes (Ward et al., 2000; Davies and Gibling, 2009) -- an important set of transitions in the Phanerozoic Earth system (atmosphere-biosphere).
At finer time scales, cyclostratigraphy applied to continental drill core holds promise for casting new light on the dynamics of Earth’s orbit (e.g., Olsen and Kent, 1999). Cyclostratigraphic insights span timescales beyond the well-known application to Milankovitch periodicities, including diurnal records that reveal profound changes in Earth’s speed of revolution and interactions among the Earth-Sun-Moon system. Drill core stratigraphic records likewise hold strong potential for preserving sedimentary evidence of catastrophic “events” important to the evolution of the Earth system, including ancient storms, earthquakes, and volcanism. Drill core studies applied to such issues can be greatly augmented through the collection of ancillary geophysical logs for color spectra, neutron, formation imaging and geochemical element logging.

**Geochemistry and Geochronology**

Best practices for maximizing recovery of geochemical and geochronological information from drill cores include 1) obtaining core orientation for paleomagnetic and fabric studies, 2) minimizing variation in core description by involving a minimal number of observers, 3) routine XRF and UV scanning (highlighting occurrences of, e.g., tephras), and measurement of downhole temperatures (which can shed light on incipient diagene- sis, and augment auxiliary databases relating to, e.g., trends in climate warming and heat flow).

The importance of special handling to maximize recovery of geochemical and geochronological data merits creation of a study committee to create a best-practices document to detail contingency preparation (long term core sample storage for analyses using future technologies), and how to strategize recovery of information with cost effectiveness. From the initial drilling, to core handling and curation, care should be taken to record all “metadata” associated with core capture and subsequent treatment—any action that could potentially impact future analyses, such as

1. characterization of all drill site fluids and lubricants used,
2. sampling of pore fluids, and
3. subsequent storage conditions of the core (e.g., dry at ambient temperature, dry at 4°C, frozen, or stored in an N₂ (anoxic) atmosphere).

Such “best practices” are applicable to many datasets beyond geochemistry and geochronology.

Potential geochronological approaches useful for sedimentary core material includes U-Pb (tephras, detrital zircons), Ar-Ar (feldspars from tephra), Re-Os (organic-rich shales), Lu-Hf (phosphorites), Pb-Pb (carbonates, primary and secondary), and Sr isotopes. Other useful methods include low to moderate temperature thermochronology using U-Th-He, and Ar-Ar, and thermochronology/geochronology (e.g., C-14, U-series disequilibrium, thermo-luminescence, cosmogenic nuclides, etc.).

Exciting novel geochemical proxies include redox metal and isotopic approaches to assess productivity, methods to assess paleo-redox conditions, temperature, pH and pCO₂, weathering and hydrothermal fluxes (e.g., Anbar and Rouxel, 2007; Severmann and Anbar, 2009; Frank, 2011; Pufahl and Hiatt, 2012). Many of these techniques depend on the acquisition of pristine materials best be obtained from core samples.

**Science Drivers**

Closing discussions at the workshop focused on the over-arching science drivers for which drill core can make a difference in our understanding of the evolution of the Earth system. The key theme, holding the most impact in terms of societal relevance, is that of climate change and biotic evolution. More specifically, how do transitions in climate drive biotic change, and what role can unweathered, stratigraphically continuous scientific drill cores play in advancing our understanding of this linkage, and the relevant processes (e.g., Jaramillo et al., 2010)? In the face of growing con-
cerns over the current pace and possible future impacts of climate change, we must understand how climate changes archived in Earth’s past have affected life, i.e., to assess the biotic tolerances of environmental changes, at all time scales. This is best done by focusing on times in the geologic past that capture transitions in climate states (e.g., Parrish et al., 2012). Tied to this theme, albeit at longer time scales, is research on climatic-tectonic feedbacks, to understand the full range of how climate has varied on Earth.

Other areas that could be addressed by drilling include research on the function and history of the geodynamo, and long-term solar-system dynamics—topics that arose from consideration of the centrality of geochronology to all other endeavors relating to scientific drilling of stratigraphic targets. Pursuit of these areas could ultimately lead to a fully calibrated astrochronology through the Paleozoic.

The Unique Role for Continental Drilling

Scientific drilling, and particularly drilling applied to continental targets, provides truly unique opportunities in Earth Science research. Perhaps the key opportunities are the abilities to 1) obtain pristine material suitable for geochemical and (potentially) paleogenomic analyses, 2) obtain continuous stratigraphic record with minimal sampling gaps, especially in depocenters poorly exposed in outcrops, 3) tap Earth’s entire geologic record (extending through the Archean), and 4) tap the full depth of the dynamic range of climate change (see below).

Outcrop-based studies are and will continue to be fundamental for research on Earth System evolution. However, as our abilities to extract climatic and biotic data from the past have grown, most notably from a plethora of novel geochemical approaches, the need for pristine sedimentary samples has become paramount. Indeed, the very “shelf-life” of cores may be more limited than previously recognized, owing to the emergence and growth of analyses utilizing organic biomarkers, redox-sensitive transition metals, and DNA analyses, all of which rely on availability of fresh, unoxidized material. The potential utility of core for such analyses becomes compromised the moment the core is exposed to the atmosphere. Addressing this issue, and especially the possibility of archiving material for use in perpetuity, may require future workshops on novel approaches to core archival. These could include the storage of sample splits in anoxic conditions.

In addition to providing pristine sample material, drill core has long been recognized as the primary means to obtain a continuously sampled section, and --where the drilling site is chosen to maximize it-- obtaining a stratigraphically continuous section. The latter is particularly critical in the case of basin depocenters in tectonically stable regions lacking outcrop. The value of such archives is only increasing as new tools for continuous core analysis become routine, including, e.g., whole-core CT scans, XRF scans, etc.

The rich potential offered by drilling the continental record remains vastly underutilized. Ocean drilling has provided paradigm-shifting insights into our understanding of the Earth system (e.g. deMenocal, 1995; Haug et al., 2001; Zachos et al., 2005; Sluijs et al., 2006), but is limited by subduction to (primarily) the Cretaceous and younger record. Continental drilling lays open Earth’s archive extending to the far depths of deep time preserved on the planet -- the Archean. Vast stores of undeformed sedimentary sections dating from throughout the Phanerozoic and into the Precambrian lay preserved across the stable cratons of the world.

Perhaps most critically, albeit a great treasure of climatic data, the ocean record exhibits a limited dynamic range of response to climate change in

The continental record exhibits an extremely broad range of environmental and climate states...the full dynamic range of climate change. Documenting the global changes in continental regions is critical to documenting the biotic responses to climate change.
that the effects are buffered by the vastness of the ocean system. In contrast, the continental record exhibits an extremely broad range of environmental and climate states, capturing local, regional, and global conditions tied to the history of life on land, in freshwater, and in marginal seas: the full dynamic range of climate change. In light of the land-based existence of our species, documenting the regional and even local responses to global changes in continental (and epeiric sea) regions is critical to documenting the biotic responses to climate change.

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References


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Drilling active tectonics and magmatism: Volcanics, Geoprisms, and Fault Zones Post-SAFOD

I. INTRODUCTION

 Forces originating deep within the active Earth are expressed on Earth’s surface, where they have a profound effect on human societies. On a global scale, these effects include the development of mountain ranges and subduction zones. On a local scale, they are expressed as active faults (with slip ranging from a few meters to hundreds of kilometers) and volcanoes (ranging from individual volcanoes to large volcanic chains or fields).

The significance of these tectonic processes for human societies is well known, from the cataclysmic eruption of the super-volcano Santorini in 1650 BCE, to more recent plate boundary earthquakes and tsunamis in Indonesia and Japan, and the strike-slip earthquake in Haiti that killed hundreds of thousands of people. Even less massive events can have a profound effect on local populations. Active faults and volcanoes are common in the western United States, but recent destructive earthquakes in Virginia and Oklahoma, along with the compilation of active faults in the US (USGS, 2012) show that few parts of the country are immune. Further, much of the world’s population live near fault zones or volcanoes.

Understanding how fault systems and volcanoes operate is crucial to mitigating these hazards. Unfortunately, studying young active systems is difficult because earthquake nucleation and propagation, as well as crucial magmatic processes, take place hundreds to thousands of meters below the surface, obscured from direct or simple observation techniques. Although deeper parts of faults and volcanic plumbing systems may be exposed by erosion in older terranes, information on active processes can only be inferred. In young active terranes, critical relationships are still hidden beneath the Earth, and require deep scientific drilling to be studied.

The Workshop

In order establish how continental scientific drilling can be used to address these critical societal issues, a workshop was held in Park City, Utah, in May 2013, sponsored by the National Science Foundation, and attended by 41 investigators in active tectonics and geodynamics. This workshop explored how continental scientific drilling can be used to better understand active tectonic processes expressed by faults, volcanoes, and volcanic provinces. Although emphasis was placed on our goal of helping to define a U.S-based program of continental scientific drilling, participants included representatives from Canada, Japan, India, Italy, Great Britain, and New Zealand, who are actively engaged in international research efforts in cooperation with U.S.-based investigators. A list of participants with their affiliations is found in Table 1, and a list of presentations from the meeting is in Table 2.
Workshop Goals

Participants were asked to define significant scientific justifications for examining the active tectonics and magmatic processes related to faults and volcanoes that can be addressed by a coordinated program of continental scientific drilling and related site investigations. Workshop participants were also asked to prioritize these processes, and to propose the types of faults and volcanoes that would be targeted by these efforts. Our goal for this workshop was to provide a roadmap of specific science objectives and projects that address the most pressing issues in active tectonics drilling.

In addition to exploring the scientific issues that drive a need for continental scientific drilling, potential projects were discussed and evaluated within the context of these drivers. Workshop participants addressed the scientific motivations for these proposed projects and their corresponding target sites, and attempted to prioritize them based on the strength of the science drivers, and on their readiness for formal review. Many of these proposed efforts are interdisciplinary and are directly related to ongoing NSF initiatives (e.g., Geoprisms; IRIS; Earthscope), and apply to a range of scales, from localized fault systems to plate boundary faults, and from small monogenetic vents to super-volcanoes. Other projects are being supported in part by other agencies, e.g., USGS and Department of Energy, or internationally (e.g., drilling in the Deccan traps). The members of this workshop team examined these issues in detail and the product is a roadmap of specific projects to address the most pressing issues in drilling active fault and volcanic systems.

Workshop Organization

Workshop participants were asked to provide, prior to the meeting, White Papers on specific drilling targets, more generalized focus areas, or on techniques that can be applied to a range of projects. These White Papers were distributed digitally to all participants before the workshop, and White Paper authors were allowed to update and revise their White Papers after the workshop in order to reflect what they learned during the meeting. These White Papers are included in Appendix B of this report and are available online: (http://digital-commons.usu.edu/geology_facpub/386/).

The workshop spanned two full days of meetings. On Day One, keynote speakers presented talks on “Trends and Topics” in scientific drilling of faults and volcanoes (see Table 2). This was followed in the afternoon and on the morning of Day Two by short talks (5-10 minutes) by the workshop participants highlighting their White Papers; a complete list of these presentations is in Table 2. The remainder of Day Two was devoted to breakout groups on faults, fault processes, active volcanism, and the geodynamics of volcanic terranes. At the end of Day Two, scribes from each breakout group presented summaries of their findings. Finally, the Steering Committee met on Day Three to prepare a draft report.

Building on Past Success

The concept of using deep continental drilling to address long-standing problems in active tectonics is not new, and some of continental drilling’s most successful projects have grown out of issues related to active processes in faults and volcanoes, and those related to chemical geodynamics of the Earth. The success of these projects demonstrates the effectiveness of continental scientific drilling, and these projects formed the basis for the new projects proposed and discussed at this workshop.

Drilling projects that have addressed the mechanics of fault zone processes include SAFOD (Zoback et al., 2010), the Chelungpu fault (Taiwan) Drilling project (Ma et al., 2006), the Alpine (New Zealand) fault project (Towend et al., 2009), the Nojima fault drilling project, the Wenchuan, China project (Ma et al., 2006), and (within the oceanic...
realm) the NanTroSeize plate boundary project to drill faults within an accretionary prism (Tobin et al., 2006, 2009).

Drilling projects that addressed the origin, evolution, or eruptive mechanisms of volcanoes or young active volcanic terranes include the Mt. Unzen scientific drilling project (Nakada et al., 2005) and the Iceland Deep Drilling Project (IDDP: Friðleifsson and Elders, 2005; Elders and Friðleifsson, 2009). Projects focusing on chemical geodynamics include the Hawai‘i Scientific Drilling Project (DePaolo et al 1996, 2007; Stolper et al 2009) and Hotspot: the Snake River Drilling Project (Shervais, et al., 2006, 2012).

II. THE BROADER CONTEXT

Continental Scientific Drilling is not an end in itself; it is a tool for studying processes that cannot be accessed through normal surface-based investigations. As such, it complements existing NSF programs such as GeoPrisms, Earthscope, Frontiers in Earth System Dynamics (FESD), Integrated Earth Systems (IES), Critical Zone Observatories (CZO), Petrology and Geochemistry, Tectonics, and Paleo Perspectives on Climate Change (P2C2). Scientific drilling is also an important component of other agency programs, such as the U.S. Geological Survey (USGS), the Department of Energy (DOE: geothermal energy, CO₂ sequestration) and the Department of Defense (DOD: geothermal energy). As a result, the science drivers for Continental Scientific Drilling overlap with the science objectives in these programs.

**Science Drivers for USA Continental Drilling**

The goals addressed by participants at this workshop reflect priorities for Earth science research that have been proposed to NSF in a series of recent NRC reports (NRC 2008, 2011, 2012). For example, in regards to faults and fault zone mechanics, the 2012 NRC report “New Research Opportunities in the Earth Sciences” recommends

> “EAR should pursue integrated interdisciplinary quantification of the spectrum of fault slip behavior and its relation to fluxes of sediments, fluids, and volatiles in the fault zone. The successful approach of fault zone and subduction zone observatories should be sustained, because these provide an integrative geosystems framework for understanding faulting and associated deformation processes.”

Similar observations and goals are proposed for volcanic systems and mantle geodynamics:

> “Volcanoes and their associated hydrothermal systems provide the primary means by which the mantle passes material to the oceans, atmosphere, and crust. Volcanoes probably created Earth’s early atmosphere and oceans, and they continue to resupply these regions with water, CO₂, and other constituents that keep Earth’s surface habitable” (NRC, 2008), and “Evidence of this small-scale convection is provided by hot spots—large clusters of volcanoes, the most active of which are in Hawaii, Iceland, the Galapagos Islands, Yellowstone, and Reunion (Indian Ocean). Hot spots are usually explained as the surface outpourings of magma formed in mantle plumes, which are cylindrical upwellings of hot (and hence low viscosity) rock that are thought to form near the base of the mantle and rise to the surface at rates much faster than plate velocities. Mantle plumes should form as a consequence of heat entering the bottom of the mantle from the much hotter outer core” (NRC, 2008).
installation of observatories at depth in fault zones and volcanic terranes.

**Integration with other drilling programs**

It is important to remember that Continental Scientific Drilling funded by NSF does not exist in a vacuum: there are other programs and agencies that support CSD projects both domestically and internationally. Domestic agencies that fund drilling science include the Department of Energy, the Department of Defense, and the U.S. Geological Survey. International programs include the International Ocean Drilling Program, the International Continental Drilling Program, and the domestic funding agencies of many foreign governments.

As also noted in a recent NRC report:

> "EAR can enhance the impact of its research portfolio by encouraging and supporting interagency and international coordination of facilities, community consortia, and individual investigations." (NRC NROES, 2012).

Many of these programs have goals and objectives that coincide with those fostered by NSF, or which complement NSF’s programs. In some cases, these agencies will fund drilling projects that address science objectives similar to those supported by NSF (e.g. IODP, ICDP, USGS). In others, these agencies may fund drilling project that have more practical objectives, but which have collateral benefits for pure science investigations (e.g., DOE, DOD). In both cases, support of PI’s by NSF can be crucial for U.S. investigators to take advantage of these opportunities.

**Learning from IODP**

Continental Drilling can be improved by adapting the approaches and procedures developed by IODP to CSD projects. These include database implementations, logging and sampling protocols, initial reports, and follow-up studies. These have proven to be extremely efficient in disseminating data and advertising the availability of samples and data for follow-up studies. Adapting these to CSD will be important for bringing new people and communities to the program.

Workshop participants strongly endorsed the following viewpoints:

- **Funding from other Agencies** (e.g., DOE, DOD, USGS) and International Partners (e.g., ICDP, IODP) can be critical for many drilling projects, and may comprise the main or only funding for some projects. These projects represent significant opportunities for U.S. scientists by removing the need for NSF support of drilling operations, resulting in what the workshop participants referred to as “free core”.

- **There is a strong need for NSF support** for science investigations to leverage these resources, even though the drilling was not paid for by NSF. Funding U.S.-based scientists to work on samples (or on down hole studies) obtained by non-NSF funded drilling projects will allow NSF to focus more of its resources on science investigations, and significantly lowers the demand for logistical support (drilling). These opportunities fall into two broad groups:

  1. Science support for US-based investigators in international collaborations. Many international projects (supported by ICDP and foreign agencies) welcome the participation of U.S. PI’s, but participation is contingent on support of those PI’s by NSF. In many cases only science-related funding is needed; in others, some logistical or drilling support is also required (but much less than the full cost).

    An example related to this workshop is the Koyna Drilling Project in India, which is funded by ICDP and the Indian government to core several sections through the Deccan traps; the Indian research focus is on reservoir-induced seismicity, but there is a significant opportunity to carry out petrologic and geochemical studies on the core.

  2. Science Support for U.S.-based investigators with non-NSF drilling support. Domestic U.S. agencies that support scientific drilling, such as DOE, DOD, and the USGS, often have a more
programmatic approach to drilling projects, with goals that complement but do not match NSF science objectives. These agencies may not provide funding to address science objectives that do not align with their programmatic goals. Nonetheless, the core samples produced (or the hole itself) may present major opportunities to address NSF-supported science objectives.

An example related to this workshop is the Snake River Geothermal Drilling project, funded by DOE and DOD, which has produced ~5.3 km of core; agency funded science focuses on physical properties of the core and hydrology. There is a major opportunity here for petrologic and geochemical studies as well. Another example is the “PTA” drilling project on Mauna Kea, funded by the U.S. Army.

There needs to be better integration between the U.S. Continental Scientific Drilling program and IODP. While there is a range of existing projects in fault-zone processes that already address this (e.g., J-FAST, NantroSEIZE, Alpine Fault-DFDP, proposed Hikurangi margin drilling), there is little coordination between IODP and continental drilling projects that address active magmatism or geodynamics. For example, workshop participants see opportunities to study hotspot-related continental breakup with onshore studies of continental LIPS and off-shore studies of the resulting plume track.

III. FAULT ZONE PROCESSES AND GEOMECHANICS

Workshop participants interested in active faulting recognized that the key scientific questions and hypotheses proposed in the white papers submitted to the workshop, and most topical among this research community at present could be summarized in two major topics and associated set of subquestions: Topic 1: Understanding the seismic cycle and Topic 2: 4D mechanics and architecture of fault zones. These concepts are expanded in below. We also identify white papers (Appendix B) that provide further detail of each of the sub-questions.

**Topic 1: Understanding the seismic cycle**

1. How and why do earthquakes initiate? (White Papers by Carpenter, Savage)
2. What physico-chemical mechanisms control earthquake triggering and interaction? (White Papers by Carpenter, Omura, Savage, Singh)
3. What controls the spectrum and style of fault zone slip rates? (White Papers by Carpenter, Hadizadeh, Reinen & Toy, Lee)
4. Are there clear textural and mineralogical records that are diagnostic of the spectrum and style of fault zone slip rates? (White Papers by Carpenter, Hadizadeh, Reinen & Toy, Schleicher)
5. What are the controls on, and records of, the evolution over the seismic cycle of permeability, fluid pressure and flow, the stress field, strength, and temperature? (White Papers by Carpenter, Christie-Blick, Kale, Kampman, Omura, Savage, Fulton, Lee)

**Topic 2: 4D mechanics and architecture of fault zones**

1. How do faults act as barriers and conduits for fluids? How does this influence mineralization, heat flow and generation of fractures, and migration and storage of multi-phase fluids (H$_2$O, CO$_2$, CH$_4$, H$_2$, He and magma)? (White Papers by Ball, Kampman)
2. How do the mantle, the lower crust, and upper crust interact? What are the avenues and rates of mass, heat and fluid transport? (White Papers by Ball, Kampman, Martel, Miller & Lee)
3. On tectonic timescales, how do geometry, composition, stress, processes, and mechanical properties of fault zones evolve? (White Pa-
Why is scientific drilling necessary to study faults and fault zones?

Scientific drilling provides unique access to dynamic geologic environments and samples. As a scientific community, we are interested in examining active processes at in situ conditions (P, T, fluid conditions) at depth before they are overprinted or altered during exhumation. The following advantages to drilling active tectonic targets were emphasized by the workshop participants:

• Drilling allows us to explore the full range of conditions and scales observed at depth in nature, which cannot be replicated in the laboratory.
• Installation of observatories in the subsurface allows measuring the environmental conditions at depth over timescales comparable to the seismic cycle (e.g. coseismic, afterslip or aftershock sequence durations).
• By drilling we can collect in situ samples of rocks, fluids, gasses, microbes from depth and over time.
• By drilling we can measure in situ geophysical, geochemical, mechanical, physical and hydrological conditions and their evolution over time.
• In particular, borehole techniques provide the only conventional methods for measuring stress.
• Borehole seismometer installations dramatically increase the signal:noise ratio and accuracy of our seismic records.
• By drilling we can obtain fairly continuous records of how fault and host rocks and physical conditions vary in three dimensions around fault zones. These records expand incomplete surficial records.
• Understanding active magmatic interactions in the deeper crust is only possible through drilling.
• We may be able to sample rock that is actively deforming at conditions not found in the near surface (e.g. those with a temperature-dependent rheology).
• Drilling into active tectonic or magmatic environments stimulates new technology development and testing.

Specific Projects/Sites Recommended By The Workshop

The active faulting group prioritized several future drilling projects that will address the key topics outlined in the scientific questions section above. The first two of these fall into the ‘Understanding the seismic cycle’ topic and the last three are closely aligned with the ‘4D mechanics and architecture of fault zones’ topic. However, we emphasize that there are significant potential overlaps between all of the projects outlined below.

A. Understanding the seismic cycle

1. Reoccupying and extending the SAFOD site. (White Paper by Carpenter et al.)

This project proposes to drill an additional multi-lateral borehole off the existing SAFOD main hole, to penetrate a repeating earthquake patch (the Hawaii, HI, patch). There has already been significant investment in the San Andreas Fault Observatory at Depth (SAFOD). Established infrastructure includes two boreholes and downhole instruments. Microstructure and physical properties of fault rocks from the active fault zone, fluids and gases, and physical conditions at depth have already been characterized and there is an extensive suite of geophysical data, including high resolution seismological records. New observations from recovered material, downhole measurements and monitoring can be directly compared to the results of these previous studies.

2. Triggering earthquakes for science. (white paper by Savage et al.)

The physical mechanisms driving earthquake nucleation, propagation and arrest, and the triggering of earthquakes by both distant earthquakes and anthropogenic perturbations to the subsurface are unknown. This project proposes to design and in-
stall an observatory consisting of terrestrial and borehole seismometers and down-hole strain and pore pressure sensors to make in-situ measurements of the stresses and strains at the source of nucleation. An earthquake occurring within the observatory is critical to the success of the project. The probability of capturing a natural earthquake in the exact fault patch that has been drilled is minuscule. To overcome this problem, the project will draw on the recent advances in unconventional energy extraction and trigger an earthquake within the observatory by pumping water into the fault at depth.

B. 4-dimensional mechanics and architecture of fault zones

3. Mechanics of the Sevier detachment. (white paper by Christie-Blick et al.)

The Sevier Desert detachment initiated at, and accommodated normal slip of <47 km, at a dip of ~11°, as recently as the Holocene (< 8 ka), implying it has very low effective frictional strength. Drilling aims to elucidate the mechanism(s) or physical conditions that result in such weakness, and more broadly to characterize fault zone geometry. Magneto-telluric studies demonstrate fluids interact with the structure at depth so this project also addresses fault-fluid interactions. An ICDP workshop has already been held to define both scientific objectives and a preliminary drilling plan, and the workshop group considers that pursuing the project further will address the aims of Topic 2.

4. Tectonic evolution and mechanics of the Rio Grande rift. (white paper by Ball et al.)

The Sangre de Cristo fault system accommodated late Quaternary extension in the northern Rio Grande rift. However, surficial geology and a wealth of geophysical data show the structure is complex and has a long tectonic history. Scientific drilling through multiple and representative elements of the SCF presents opportunities to better understand the processes of fault system evolution within an intracontinental rift and provide an analog to other extensional terranes. In-situ fault zone characterization, rock sample collection, hydraulic and thermal experimentation, and in-situ stress determination would provide the subsurface...
ground truth and monitoring necessary to evaluate hypotheses on tectonic evolution, modern strain accommodation, and the heterogeneity created by faults. Significantly, this project will develop results that address seismic hazard and groundwater resource exploitation in the wider Rio Grande rift region.

5. **Fluid flow and supercritical fluid-rock interactions in the Little Grand Wash fault.** (white paper by Kampman et al.)

Carbon dioxide degassing normal faults at Green River, Utah are important analogues to engineered geological CO$_2$ storage. Surface studies have provided important constraints on the CO$_2$ source and the Quaternary degassing history of the faults, which imply large temporal variations in fault hydraulic behavior. Recent drilling at the site provided core and fluid samples that constrain fluid flow and fluid-rock reaction in the shallow subsurface (~300 m). Deep drilling at depths >800 m, where the CO$_2$ is supercritical, presents an opportunity to investigate how these mantle-derived volatiles react both within a fault damage zone and with the surrounding reservoir rocks and impermeable seals. Instrumental observations of in-situ stress, fracture permeability and fluid flux, combined with acoustic measurements of two-phase flow and geochronological studies of carbonate mineralization would provide invaluable information on fault damage zone fracture flow and the relative importance of tectonic, climatic and geochemical controls on fault hydraulic behavior.

**C. Active Tectonics: Other Potential Targets**

The following target sites and project ideas were also agreed to have significant scientific merit by the workshop participants. However, these proposals were considered less mature than those discussed above, and will require more development before they can be considered for funding.

- **Dixie Valley** (White Paper by Wannamaker): An active Basin & Range fault with hydrothermal/magmatic interactions; possibly also induced seismicity. The fault is already being drilled by DOE, and it makes sense to take advantage of this campaign. However, we assign slightly lower priority to this site because the same scientific questions are able to be addressed through drilling at the Rio Grande Rift.

- **The Snake Range Detachment fault zone** (White Paper by Miller and Lee) provides the opportunity to investigate the coupling between brittle and ductile crust; in particular we can consider if the footwall was rigid or experienced a form of channel flow/stretching. A major question is "how do the thermal structure of crust and/or rates of extension control the formation and evolution of this and similar faults?".

- **Mono Basin** (White Paper by Jayko et al): Drilling the tectonically and volcanically active Mono Basin to measure the stress field and evaluate the role of the Eastern Sierran frontal fault system on controlling the timing, location and rates of magmatism and volcanism. These issues are crucial for defining the tectonics of the Walker Lane, assessing the role of faults as conduits for magmatism and for evaluating the geothermal energy potential in the area.

- **The San Andreas fault near Little Rock**: It is proposed the asymmetric damage zone characterized from surface outcrops, was generated co-seismically, perhaps due to preferential rupture propagation direction or because of differences in mechanical properties of the wall rocks. Drilling to quantify the spatial distribution of fault damage in the subsurface could validate whether the surficial structure was indeed generated coseismically at depth by coring across the fault zone.

- **The San Andreas fault at San Juan Bautista** (White Paper by Hadizadeh et al.): Geodetic

As a scientific community, we are interested in examining active processes at in situ conditions (P, T, fluid conditions) at depth before they are overprinted or altered during exhumation.
records clearly document that this site, at the northern end of the creeping section of the San Andreas Fault, accommodated some slip during a ‘slow earthquake’ at ~2-4 km depth in 1998. Drilling and coring the rupture area of the slow earthquake could access fault rocks and conditions surrounding faults that accommodated slip at the full spectrum of rates (from slow creep to earthquake rates).

- The Puysegur Subduction Zone (White Paper by Reinen and Toy): The young (<11 Ma) incoming Australian Plate crust at this seismically active (e.g. it accommodated an Mw 7.9 event in 2011) subduction zone has morphology indicating it may have peridotite at or very near the surface. Thus it is possible the subduction thrust interface is within ultramafic rock or serpentine. The latter mineral has peculiar mechanical properties that mean it may slip seismically, or creep aseismically depending on the imposed slip rate (e.g. Reinen et al., 1994; Reinen 2000). The subduction zone is fairly well-instrumented so slip distribution models can be constructed, there are a diverse range of ground shaking proxies on land in the Fiordland area (e.g. landslide records), and the area is subject to a proposal to collect a large transect of geophysical data under the Geo-Prisms initiative. This site therefore represents a good future opportunity to investigate how serpentine in particular plays a role in slip rate behavior of faults.

IV. ACTIVE MAGMATIC SYSTEMS

Active volcanic systems are important both to science and society – hazards to human populations associated with volcanic eruptions are significant in many parts of the world and have in the past resulted in tens to hundreds of thousands of deaths.

Understanding these risk factors is critical to the prediction and monitoring of hazardous eruptions.

Active magmatic systems also drive hydrothermal circulation, which has been linked to exhalative and epithermal mineral deposits (e.g., Au, Ag, Cu, Mo, Pb, Zn), and to high-enthalpy geothermal energy resources (Elders and Sass 1988; Fournier 1999; Eichelberger and Uto, 2007). These linkages provide the opportunity for multi-disciplinary studies that combine hazards analysis with both green energy and mineral resource research. Such linkages are critical to obtaining funding from a range of sources, thereby spreading the both the risk and cost associated with drilling across several agencies or interest groups.

One critical way to constrain the hazards posed by a particular volcano is to document its eruptive history.

Active volcanoes also provide information about mantle and crustal chemistry and dynamics. All active volcanoes carry information about their source regions and the processes that drive melting in their setting. Depending upon the location (i.e., oceanic or continental crust) magma composition will yield information on the source region and/or contamination processes, as well as crystallization kinetics and sequences. Examples include Hawaiian volcanoes, which provide information on deep-seated mantle processes and geochemical fractionation within the Earth, and arc volcanoes, which are driven by complex processes that include decompression melting, fluid flux from the subducting slab, and partial melting of subducted sediments and altered basalts.

There are also practical questions, e.g., are associated mineral deposits generated by the composition of the source region or through post-magmatic contamination? These issues have strong societal relevance and demonstrate the importance investigating through drilling active magmatic systems.
Active magmatic systems (volcanoes) are extremely challenging environments for drilling. They are characterized by high temperatures, corrosive gasses and fluids, and wide variations in physical rock properties. None the less, they are also extremely rewarding when drilling is successful. The motivations for scientific drilling into active volcanic systems include:

- Volcano eruption cycle: What is the spatial and temporal evolution of magma migration and storage? What is the temporal evolution of eruption style? What are the systematic and asystematic aspects of eruption cycles?
- Sustainability, stress, and recovery: How do eruption cycles integrate with ecological and local societal systems? (interdisciplinary – stress and recovery following eruptions for Bio and Eco systems).
- Eruption hazards: How can we improve short- and long-term eruption prediction? To what extent can we reduce the risk of volcanic eruptions?

Scientific questions in active magmatic systems: Outstanding questions related to active magmatic systems revolve around the fundamental issues of understanding how volcanoes work and constraining what hazards they may pose in the future. The detailed questions and problems that fall under these headings can be summarized in five main categories:

Scientific and Technical Rationale for Drilling Active Magmatic Systems

Schematic diagram of Nigorikawa Caldera, where both the geothermal system and the structure of a young volcanic vent have been revealed through commercial geothermal drilling (from Eichelberger and Uto, 2007, after Hanano 2005).
extent can we forecast near-field (e.g., lava flows, pyroclastic flows) and regional to global hazards (e.g., ash plumes)? (interdisciplinary beyond Geo. Societal impacts)

- Verification of Geophysical Models: How reliable are estimates and uncertainties for internal processes and structures of volcanoes, determined from surface observations? (seismic tomography, reflection, and anisotropy; gravity; magma plumbing systems –geometry and strength; stress/thermal regimes– also time dependence)
- Interactions with other Earth systems: What are the potential climate impacts of volcanic eruptions? To what extent can volcanic systems help us understand tectonic and geodynamic processes?

One critical way to constrain the hazards posed by a particular volcano is to document its eruptive history. Drilling and extracting core can contribute to this goal by probing a volcano’s deep geologic history that is not accessible from surface outcrop. Such drilling can help to 1) quantify magmatic flux through time, 2) characterize temporal evolution of eruption style through time, including documenting detailed eruptive stratigraphy in order to identify precursory eruptive patterns, and 3) document the temporal evolution of erupted magma composition (magmatic chemistry and volatile content). These temporal sequences also contribute to answering geodynamic questions related to using volcanic products to understand the evolution of the chemistry and dynamics of melt source regions and magma migration pathways as they relate to tectonic conditions.

Another way to reduce volcanic hazards is real-time monitoring. Borehole instrument packages have proven to be successful (e.g., at the Soufrière Hills Volcano, Montserrat) because of their very high sensitivity to changes deep in the volcanic system. Monitoring packages should measure (1) state of local stress and strain, which may provide eruption warning by detecting subsurface magma migration, (2) seismic data which may also provide clues about rock fracture and fluid migration, (3) temperature, and (4) pore pressure.

Drilling also can serve to constrain geophysical properties of the edifice. Geophysical imaging and interpretation of geodetic data hinge on several critical physical parameters, and improved constraints of these parameters will serve to improve both monitoring and development of conceptual models of the subsurface plumbing system.

Syn-drilling measurements should include resistivity, moduli (in situ & laboratory measurements), material strength, thermal conductivity, country rock porosity and permeability, seismic velocities, and rock density.

A more ambitious investigation of active magmatic systems involves drilling the magmatic plumbing system at depth (e.g., Unzen drilling project: Nakada et al. 2005). The motivations behind drilling magma at depth include characterization of the plumbing system geometry (e.g., conduit or dike width, lateral and vertical variations in magma properties within a dike or conduit), testing models of magma chamber structure and melt distribution (what is the structure of a magma chamber?), analysis of detailed chemistry, mineralogy of chamber boundary zone (what does the transition from hydrothermal circulation to melt zones look like?), constraining the moduli/strength of chamber boundary zone, and obtaining quenched samples at depth to better-constrain original magmatic volatile abundances.

"Volcanic eruptions provide spectacular and frequent (more than 70 different volcanoes erupt every year) reminders that Earth is a dynamic and evolving planet. Lava flows, pyroclastic flows, and ash fall are proximal hazards; gases and dust lofted into the atmosphere have global effects on climate, life, and air traffic. Volcanic hazard does not end with the eruption—lahars and landslides create hazards long after an eruption ends. Despite a long history of investigation, numerical models of volcanic processes, laboratory characterization of the properties of magmas, and real-time monitoring of active volcanoes are only now beginning to show their promise to both predict eruptions and quantitatively interpret volcanic deposits" (NRC NROES, 2012).
Specific Projects/Sites Recommended By The Workshop

Workshop participants discussed a wide range of proposed scientific drilling projects in all areas of Active Magmatic Systems. Discussions focused primarily on projects presented in the attached White Papers and by workshop participants. Some of these project proposals were deemed to be mature enough to proceed through the formal proposal process. Others proposals were judged to need more development before moving forward as formal proposals. The following assessment discusses both mature proposals and those deemed worthy of consideration but which require more development to move forward. More details on all of these projects can be found in the attached White Papers.

Although certainly not an exhaustive list, several sites have been suggested as possibly fruitful drilling targets. Each of these sites is represented by at least one White Paper in Appendix B. Several of these represent mature proposals for which much of the preliminary site survey work is either in progress or has already been largely completed. See section V for projects involving active Hawaiian volcanoes.

1. Okmok Volcano, Alaska, USA (White Paper by Masterlink et al)

Okmok Volcano has produced two caldera-forming eruptions in the last 10,000 years, along with frequent smaller eruptions. Okmok could serve as an interdisciplinary natural laboratory to address several relevant problems which are transferrable to other volcanic systems. These include improving methods for identifying eruption history (timing, magnitude, and style) and constraining the rheological structure of shallow caldera regions and the influence on magma migration and storage.

Key goals of the drilling project would include identifying eruptive materials comprising the shallow caldera, determining the rheologic structure of the shallow caldera, verifying seismic tomography and magma migration models and quantifying related uncertainties, and characterizing, in space and time, stress and thermal regimes associated with the subsurface plumbing system.

Okmok project components and activities include pre-drilling geophysical surveys (geodetic, seismic, gravity, EM) to refine hypotheses and preliminary numerical models. Syn-drilling activities would obtain materials, thermal, and geophysical measurements to a few kilometers. Post-drilling activities fall into three main categories: laboratory analyses and experiments (petrology, geochemistry, rheology), borehole geophysics (thermal, fluid characteristics, stress and strain), and numerical modeling in order to verify seismic tomography and magma migration patterns, and characterize loading/stress and thermal regimes (in space and time). The broader context of studying Okmok volcano includes Integration of the USGS with NSF and other initiatives and interests:

- Knowledge gained is potentially transferable to any actively deforming system (volcanoes and fault systems alike). This has huge implications for geophysical data initiatives, e.g., Earthscope and remote sensing missions such as NASA DESDynI, Japan ALOS, ESA Sentinel, $100M+ missions.
- Goals dovetail nicely with those of other scientific programs and agencies, including several cross-disciplinary programs, e.g., the Aleutians Science Corridor of Geoprisms, and the USGS Volcano Hazards program, which combines geophysics and geoinformatics. Okmok is an existing USGS research target, with a focus on volcano hazards for Aleutians and societal impacts (such as the North America-Asia air corridor). There is the potential to develop applications for other active volcanoes, and the Okmok project could be a catalyst for new interdisciplinary initiatives (for example, field/Lab/Space-borne data + numerical methods = STEM showcase).
- DOE/Geothermal Energy industry: Dike propagation results from pressure-induced hydrofracturing, which can be used to model enhanced geothermal systems (EGS), which are a major focus of the DOE Geothermal Programs office.
2. Aso Caldera, Japan (white paper by Nakada)

Aso Caldera is a large caldera, which may be overdue for eruption. The scientific goals of drilling Aso Caldera include gaining a better understanding of:
- Structural evolution of the last caldera eruption (ring-fault zone)
- Temporal and spatial relationships of caldera-collapse and climactic eruptions
- Precursory phenomena of climactic eruption events
- Environmental impact of eruptions on life and recovery
- Most effective monitoring and subsequent prediction techniques for its hazardous volcanic events

3. Mount St. Helens, Washington, USA

Mt. St. Helens is a natural target because it erupts frequently and has the potential to affect large populations in the continental US, especially if ash-fall is significant. The Mount St. Helens system is well-characterized because it has been and continues to be extensively monitored. Furthermore, there is an upcoming Geoprisms-sponsored geophysical imaging project, paving the way for all the preliminary work required to support an ambitious drilling project.

4. Newberry Volcanic Monument, Oregon, USA (White Paper by Frone)

Newberry Volcano is one of the largest Quaternary Volcanoes in the conterminous US; it covers ~1600 km² and has a volume of ~450 km³ (MacLeod & Sherrod, 1988). It has experienced at least two caldera forming eruptions (~300 ka and 83±5 ka), and has had several other recent eruptions, including the 7 ka (post-Mazama) sequence of dominantly basaltic andesite, and Intra-caldera rhyolites, the youngest of which is 1.3 ka. Its magmatic system is apparently bi-modal, resides in the backarc and could put a large population at risk (ranked very dangerous by the USGS). Scientists are particularly interested in the depth, volume (estimated to be 1-8 km³), composition, and melt fraction of the proposed magma chamber at 3–6 km depth. Significant geophysical data has been collected to support drilling efforts at Newberry, including lidar, gravity, magnetotellurics, areomagnetics, and seismic tomography. In addition at least two holes have been drilled already (to 932 m and 424 m depth), from which useful data may be extracted without additional drilling operations.

V. GEODYNAMIC AND GEOCHEMICAL EVOLUTION OF EARTH

The geodynamic and geochemical evolution of the Earth are intimately linked to two dominant processes of heat transfer: plate tectonics (driven by the sinking of cold lithospheric plates in subduction zones, and the rise of hot asthenospheric mantle below midocean ridges to form oceanic crust) and the rise of thermally (and possibly compositionally) buoyant mantle to form hotspots with their associated ocean island basalts and flood basalts. Together these dominant processes are responsible for the Wilson cycle, in which continents continually grow by collision and amalgamation with other continents, rupture to form new continental fragments, and then collide again. Continents also grow over time through the addition of new continental crust formed in island arcs by the subduction of oceanic crust.

Plumes and Large Igneous Provinces (LIPS)

The connection between deep-seated mantle plumes, ocean island basalts, and large igneous provinces (LIPS) is becoming relatively robust as new techniques in mantle tomography establish visible connections between hotspot volcanoes and deep thermal anomalies (DePaolo and Weiss 2007). What does the time-integrated development of LIPS tell us about mantle reservoirs involved in their formation? Are any of these reservoirs located in the deep mantle, or at the core-mantle boundary? Do these reservoirs change over time, or with location? How do deep-seated magmatic sources affect crustal architecture and evolution? LIPS may also have significant implications for short-term climate change that can affect biotic evolution and extinctions, and some may be tied to Ocean Anoxic Events (Elements LIP issue).
Research into Plumes and LIPs can be divided into three focus areas that can be addressed by Continental Scientific Drilling:

1. Large Igneous Provinces exposed on land, largely continental flood basalts but also including emergent portions of oceanic LIPs. The current paradigm suggests that these represent catastrophic melting of an engorged “plume-head” at relatively shallow depths, but other non-plume models have also been proposed;

2. Ocean island chains that are thought to represent the active conduits of deep-seated mantle plumes erupted through oceanic lithosphere as it moves continuously over the relatively fixed thermal anomaly;

3. Continental hot-spot tracks, which are thought to represent the intra-continental equivalent of ocean island chains that form as continental lithosphere moves continuously over the relatively fixed thermal anomaly. As with LIPs, non-plume models have also been proposed for both ocean island chains and continental hot-spot tracks.

Each of these focus areas engages a series of significant scientific questions which overlap in part, but also address some distinct issues. For example, continental flood basalts erupt over geologically short time spans and may have significant environmental impacts. But because they erupt through continental crust, their compositions are affected to various extents by interactions by subcontinental mantle lithosphere or continental crust. In contrast, ocean island chains erupt over prolonged time spans, but are erupt through thin oceanic lithosphere, which has only minimal impact on their chemical and isotopic composition. Continental hotspot tracks erupt magmas that may be strongly affected by continental interaction, and their chemical and isotopic compositions may be decoupled.

Scientific Issues addressed by CSD on Large Igneous Provinces include:

• What are the mode(s) of eruption during LIP formation?
• What is the duration of LIP volcanism?
• How does the LIP source vary over time?
• What is the mode of LIP origin – -- is it through deep-seated plumes or from the upper mantle only, or can it be a combination of both?
• What are the environmental impacts of LIP volcanism – Is LIP emplacement responsible for mass extinctions, Oceanic Anoxic Events, etc.?
• What is the nature of the melting anomaly that produces LIPs (thermal, chemical)?
• How does the flood basalt magma source evolve over time?
• Does one model fit all LIPs?
• What are the environmental impacts of LIP volcanism?
• Is LIP emplacement responsible for mass extinctions, Oceanic Anoxic Events, etc.?
• What is the nature of the melting anomaly that produces LIPs (thermal, chemical)?
• How does the magma source(s) evolve over time?

Scientific Issues addressed by CSD on Ocean Island chains include:

• What is the scale of mantle heterogeneity and variation in partial melting for oceanic volcanoes?
• What are the magma production and lava accumulation rates for oceanic volcanoes and do these rates vary over time?
• How do oceanic island volcanoes grow (internal vs. external growth)?
• What is the heat flow within an oceanic volcano?
• Are there significant gaps in the volcanic section during the volcanoes magmatic history?

Scientific Issues addressed by CSD on Continental Hotspot Tracks:

• How do the variations in magma chemistry, isotopic composition, and age of eruption con-
strain the mantle dynamics of hotspot-continental lithosphere interaction?
• What do variations in magma chemistry and isotopic composition tell us about processes in the crust and mantle? To what extent is magma chemistry controlled by melting, fractionation, or assimilation of crustal components, and where do these processes occur?
• Is the source region predominately lithosphere, asthenosphere, or plume? What are the proportions of each? Are there changes in the magma source/proportions at any one location along the plume track through time relative to the position of the hotspot?
• How does a heterogeneous lithosphere affect plume-derived mafic magma? Effect of crust-lithosphere age, structure, composition, and thickness on basalt and rhyolite chemistry, from variations in lava chemistry along the plume track.
• What is the time-integrated flux of magma of continental plume-track volcanic system? Is it consistent with models of plume-derived volcanism, or is this flux more consistent with other, non-plume models of formation?
• Can we establish geochemical and isotopic links between the “plume head” volcanic province, and the “plume tail” province?

Workshop participants also endorsed the concept of integrated onshore-offshore studies that combine CSD projects on continental LIPS with IODP or Special Platform studies of ocean islands related to that LIP.

LIPS, and the Continental Flood Basalt-LIP connection: Integration with IODP

The close genetic relationship among continental flood basalts (CFBs), LIPs, and ocean island chains presents a unique opportunity for linkages between continental scientific drilling (CSD) and the Integrated Ocean Drilling Program (IODP) and its successor, the International Ocean Discovery Program. These linkages were highlighted at an NSF-IODP workshop held in Colraine, Northern Ireland, in 2007 (Neal et al, 2008). They include onshore-offshore linkages between CFB’s and their related “plume-tail” oceanic tracks, and the onset of continental rifting, syn-LIP sedimentation (which preserves the onset of LIP eruptions). A key target for ICDP drilling should be the sill complexes presumed to underlie most LIPs. These complexes, relatively inaccessible in ocean basins, are important for four reasons: (1) they are an important element in the magmatic plumbing of each LIP, (2) volatile-release at sill-sediment contacts contributes greatly to climate impact, (3) valuable deposits of Ni, Cu, and Pt-group elements are located in these sills, and (4) intrusions in sedimentary basins influence the maturation of petroleum deposits and complicate exploration for such deposits. An understanding of the sill complexes, therefore, has important economic implications, in both continental and oceanic settings.

Subduction Systems and Geoprisms

“Reconciling geochemical evidence favoring isolated mantle reservoirs, seismic evidence for down-welling slab material in the lower mantle, and geodynamic models that tend to favor extensive, although possibly intermittent, circulation remains at the heart of this long-standing controversy. With rapid growth of human population, society faces increasing exposure to catastrophic effects of earthquake faulting, tsunamis, and volcanic eruptions.” (NRC NROES, 2012).

The large-scale evolution of subduction zones and volcanic arcs is fundamental to understanding how continental crust form. What magmatic processes create intermediate magmas? What roles do lateral accretion and magmatic intrusion play in the growth of arc crust? Is the lower mafic crust of the arc recycled back into the mantle and, if it is, how
is this accomplished? How much of the magma at a convergent margin is new juvenile addition to the crust and how much is recycled older crust? What causes the intrinsically high water and oxygen fugacities of arc magmas? These large-scale questions have not been addressed by continental drilling but some have been addressed by ocean drilling projects that sample the non-emergent parts of these systems. But there are many questions about how arcs form and evolve that can only be addressed by drilling projects that look at the long-term life cycle of magmatic arcs whose older roots are buried by younger activity.

Most drilling activity related to subduction systems, or to Geoprisms, will be carried out by IODP, because for the most part active subduction systems are found below sea level. However, these are portions of some active systems, as well as many fossil systems, that are found on land; these areas are the subject of the ExTerra initiative of Geoprisms. The ExTerra initiative seeks to understand subduction dynamics by investigating exposed portions of active systems or a few well-preserved fossil systems.

For example, drilling an exposed supra-subduction zone mantle wedge can provide continuous core through this system, which would be impossible to obtain from an active fore-arc. Further, drilling projects can be combined with surface mapping and geophysics to build a detailed 3D model of mantle wedge architecture. Rock properties can be studied in situ at the outcrop scale or larger, providing more realistic constrains than lab experiments on hand samples (for example, vertical seismic profiles, or cross-hole experiments between two or more drill holes). Finally, if core can be oriented relative to earth’s magnetic field, intrinsic properties such as rock magnetism and lattice preferred orientation fabrics can be measured and compared to experimental results and observed subduction systems.

“Concerted community efforts to study subduction zones such as GeoPRISMs bring together diverse research communities that can address the volatile budget and flux problem, and large-scale studies of uppermantle structure such as those conducted under the Continental Dynamics and EarthScope programs now regularly cast interpretations of seismic models in terms of coupled thermal, volatile, and chemical heterogeneities rather than solely thermal models.” (NRC NROES, 2012).

Specific Projects/Sites Recommended By The Workshop

Workshop participants discussed a wide range of proposed scientific drilling projects in all areas of geodynamics. Discussions focused primarily on projects presented in the attached White Papers and by workshop participants. Some of these project proposals were deemed to be mature enough to proceed through the formal proposal process. Others proposals were judged to need more development before moving forward as formal proposals. The following assessment discusses both mature proposals and those deemed worthy of consideration but which require more development to move forward. More details on all of these projects can be found in the attached White Papers.

Geodynamic and Geochemical evolution of Earth: Potential targets

LIPS, and the Continental Flood Basalt-LIP connection: Integration with IODP

One of the most significant and poorly-understood geologic processes is the movement of deep-seated mantle material, possibly from the core-mantle boundary, to the base of the lithosphere, where it melts adiabatically to form massive volcanic provinces. Continental flood basalts, LIPs, and ocean island chains are all related to this process, and any attempt to understand this process requires progress in all three settings.

Several high-priority projects were identified by the workshop participants, representing all three areas of interest. These include projects that are currently being drilled, and holes that were recently drilled, with non-NSF funding (ICDP, DOD, DOE, and international partners). Also included are new projects that will require funds for drilling as well as science and curation.


At the Park City workshop an update was given with regard to the Indian initiative to drill through the Deccan Traps flood basalt pile. The discussion that followed showed that there is a unique opportunity to build upon this unique drilling target with further continental and ocean drilling. Plume theory posits that once the magmatism initiated by the surfacing plume head is exhausted there is a transition to plume tail magmatism that is lower in magnitude and compositionally distinct (e.g., Hill, 1991). The continental drilling conducted on the Deccan Traps has currently drilled through the lava pile and into the underlying Precambrian gneiss. Therefore, the first large Deccan Traps lava flow has been sampled and there are plans to drill two more holes through the lava pile in different locations.

As can be seen from the figure, the Reunion Island-Deccan Traps trace extends southward from the western edge of the Deccan Traps, is bifurcated by the Central Indian Ridge, and terminates at Reunion Island. By combining continental drilling on the western edge of the Deccan Traps with that offshore along the hotspot trace, the plume hypothesis would be tested by evaluating the timing and extent of the change from plume head to plume tail magmatism, as well as investigating the heterogeneity of the two magma systems.

2. Snake River Plain Continental Plume Track

(White Papers by Christiansen, Shervais, Hanan, Potter, Schmitt and Lee)

The Snake River volcanic province represents the world-class example of time-transgressive intracontinental plume volcanism. The SRP is unique because it is young and relatively undisturbed tectonically, and because it contains a complete record of volcanic activity associated with passage of the hotspot which can only be sampled by drilling. The central questions addressed by drilling the SRP are: (1) how do mantle hotspots interact with continental lithosphere, and (2) how does this interaction affect the geochemical evolution of mantle-derived magmas and continental lithosphere? At this time, three new deep drill holes have been completed, with funding from the International Continental Drilling Program, the Department of Energy, and the Department of De-
3. Other Potential LIP-Flood Basalt Targets

Participants identified additional potential targets for scientific drilling of LIPS and flood basalts, along with their related hotspot tracks. These include:

a. Etendeka-Walvis Ridge: This is a Plume Head – Plume Tail couplet in the South Atlantic ocean that formed with the opening of the South Atlantic.

b. CAMP: On-shore and Off-shore: The Central Atlantic Magmatic Province (CAMP) formed during the early opening of the central Atlantic – the first segment of the Atlantic ocean to form, and a type locality for a “volcanic rifted margin.” CAMP magmatism began with the intrusion of Triassic dikes and sills, and continued with volcanic eruptions into the Jurassic.

c. Ethiopian Traps: The Ethiopian traps represent the onset of LIP volcanism in a continental setting. They form our best modern example of LIP volcanism, and can be related to rift zone volcanism to the south, and ocean basin formation to the north.

Ocean Islands: The Oceanic Record of Plume Tail Volcanism

In order to evaluate geochemical and isotopic components in the mantle geodynamic framework, it is necessary to avoid contamination from continental crust – which has extreme compositional and isotopic compositions that can mask more subtle mantle signatures. This is traditionally approached by sampling “plume tail” hotspot tracks that formed on oceanic crust. Because the oceanic crust is thin and compositionally similar to plume-derived basalts, this minimizes contamination and allows detailed evaluation of the mantle component.

An unprecedented opportunity is available to gain a more detailed record of a Hawaiian volcano. The U.S. Army has funded (~$6 M) the drilling of two, ~2,000 m deep boreholes in search for water on the upper flank of Mauna Kea Volcano on the Island of Hawaii (PTA project). The first hole, located ~10 km from the volcano’s summit, was completed to ~1760 m deep with a high rate of recovery (>90%). Operations are scheduled to start the second hole before the end of 2013. These two holes provide a rare prospect for detailed examination of the volcanic history of a Hawaiian volcano and will allow many important issues to be examined including:

Mantle plumes, such as the one that formed the Hawaiian Islands, have strongly influenced our views of Earth’s deep mantle. Lavas from these areas are the principal geochemical probes into the mantle, and testing grounds for understanding Earth’s mantle convection, plate tectonics, volcanism, and changing magnetic field (Stolper et al., 2009). Study of the petrology and geochemistry of oceanic volcanoes has contributed immensely to our present understanding of Earth processes (e.g., Weis et al., 2011). Drilling is essential to evaluation the temporal evolution and structure of mantle plumes because surface exposures typically reveal only a small fraction of a volcano’s stratigraphy (e.g., ~3% of the 10- to 15-km height of Hawaiian volcanoes).

The Snake River Plain project represents a prime example of the opportunities presented by intra-agency cooperation and joint support of projects, especially those where all of the drilling costs are borne by other agencies.
• What are the magma production and lava accumulation rates for Hawaiian volcanoes? Lava accumulation rate estimates based on dating HSDP2 core are minimum values because of the location of the drill site 50 km from the volcano’s summit and the problems encountered in dating the core, which was mostly deposited submarine sea level where rapid quenching and secondary minerals are common. The PTA section will be entirely subaerial. Thus, the lavas will be easier to date using Ar-Ar methods allowing us to better constrain magma production rates.

• What is the scale of heterogeneity and variation in partial melting within the Hawaiian plume? The PTA site location allows finer resolution of the volcano’s geochemical variation and assessment of the structure of the Hawaiian mantle plume than the HSDP2 core. Work on historical lavas of Kilauea volcano has shown fine-scale source variations that are cyclic on scales of decades to centuries (Greene et al., 2013).

• What is the nature of the transition from shield to post-shield volcanism? The PTA core will provide an exceptional record of the timing and duration this transition as the volcano moves off the hotspot causing lower degrees of melting and change in source components (e.g., Hanano et al., 2012).

• How do Hawaiian and other volcanoes grow (internal vs. external growth)? Francis et al. (1993) proposed 2/3 of the growth of Hawaiian shield volcanoes is by endogenous (intrusive) growth. A new gravity study (Flinders et al., 2013) suggested that intrusions represent <30% of the mass of Hawaiian volcanoes. The close proximity of the drill site to the volcano’s summit will allow us to evaluate this new interpretation.

• What is the heat flow within an oceanic volcano? Unlike the HSDP sites, the PTA site should not be affected by circulation of cold seawater. Thus, its temperature profile will be more representative of the heat flow above the Hawaiian mantle plume, which is poorly known.

• What is the extent of explosive volcanism for Hawaiian volcanoes? Kilauea’s Holocene deposits record numerous major violent events and suggest its explosive frequency is on par with Mt. St. Helens (Swanson et al., 2011). Adjacent Mauna Loa is thought to have had a large explosion associated with a major debris avalanche (Lipman, 1980). Careful examination of the fragmental material in the core will provide insight into the frequency of explosive eruptions for this, and the other, major shield volcanoes on Hawaii Island, which will have implications for hazard mitigation and planning.

There is much we still do not know about how Hawaiian and other volcanoes grow, which has natural hazards implications. The new Mauna Kea Volcano drilling provides an exceptional opportunity to gain a detailed understanding of crustal and mantle processes within plume-related and other volcanoes at no cost to NSF for drilling.

2. Mauna Loa Project (White paper by Rhodes)

The most important recent result of Hawaiian studies is the resurrection of the concept of an asymmetrical mantle plume in which volcanoes along two en-echelon trends, the Loa and Kea trends, exhibit distinct major element and isotopic compositions (Abouchami et al., 2005; Weis et al., 2011). This asymmetry in plume source components is attributed to asymmetry in the lowermost mantle preserved in the melting zone within the plume (Weis et al., 2011; Farnetani et al., 2012). Loa trend magmas are thought to contain a greater contribution of recycled crustal material than those of Kea trend volcanoes. An unresolved and contentious problem is whether Loa magmas result from melting discrete lithological domains (pyroxenite/eclogite) of this crustal material within the plume, or whether they reflect melting of peridotite fertilized by pyroxenite/eclogite melts (Jackson et al., 2012). In order to understand Hawaiian volcano growth, melt production and the identity, composition and lithology of plume components it is necessary to drill a Loa-trend volcano to obtain comparable information to that obtained by the HSDP for Mauna Kea, a Kea trend volcano (Stolper et al., 2009).
Mauna Loa, the world’s largest active volcano (~100,000 km³), is the obvious candidate because a great deal more is known of its recent sub-aerial history (< 120 ka) and also of its earlier (> 400 ka) submarine growth than other Loa trend volcanoes (Rhodes, accepted for publication). Consequently, more informed questions and problems can be raised and solved through drilling. These include:-

- Submarine lavas are significantly older (Jicha et al., 2012) than predicted by Hawaiian volcano growth models (Depaolo and Stolper, 1996; DePaolo et al., 2001). Clearly, Hawaiian volcano growth models need revisiting.
- Current Mauna Loa sampling is bi-modal (sub-aerial < 120 ka; submarine > 400 ka). What was happening on Mauna Loa in the intervening 300 ka? Has shield-stage volcanism waxed and waned?
- Was the decline in eruption rates on the submarine southwest rift zone around 300 - 400 ka (Jicha et al., 2012) volcano-wide, or did eruptive activity shift to other parts of the edifice?
- Is there evidence for cyclical periods of explosive and effusive activity on Mauna Loa, as recently documented for Kilauea (Swanson, 2011)?
- Drilling on Mauna Loa’s western flank could intersect the disconformity between lavas erupted before and after the giant Kona landslide, providing a possible opportunity to date this prodigious event.

Subduction Systems, Geoprisms: Potential targets

1. Drilling the Josephine Ophiolite – Direct Observation of a Subduction Zone Mantle Wedge (White paper by Shervais and Dick).

VI. TECHNOLOGY ISSUES

There are a number of technology issues which should be addressed by NSF, or the proposed CSD Coordination Office, that are critical for many of the drilling initiatives proposed here. Many of these are specific to certain environments (e.g., high-temperatures in active magmatic systems) while others affect a range of drilling environments and project types. These include:

- Down hole Observatories. Permanent or semi-permanent downhole observatories for temperature, strain, or microearthquakes may provide a significant added bonus to many drilling projects. For many of these observatories, drilling the hole to place them into is often the most expensive part of the system. Installation of permanent or semi-permanent downhole observatories can be an extremely cost effective way to maximize the return on investment of drilling dollars. Identify and develop robust sensor and deployment systems for long-term monitoring of strain, seismic waves, temperature, fluid pressure and fluid chemistry in active faults at temperatures of >1200°C and under chemically hostile conditions.
• Oriented Core for paleosecular variations and fabric studies. Paleosecular variation in the Earth’s magnetic field is a powerful tool for unraveling volcanic stratigraphy on a decadal or centennial time scale – far shorter than the uncertainties in Ar-Ar dates on young volcanic rocks. Without oriented core, only the inclination of remnant magnetism can be used. With oriented core, both the inclination and declination can be used, effectively doubling the resolving power of the technique.

• High temperature down hole logging tools (>1500°C) for slim hole projects (<15 cm diameter). Current tools max out at 700°C or 1400°C, which is insufficient for studies of active magmatic systems, high-heat flow regimes, or geothermal settings.

• Improved gas and fluid sampling tools (down hole) for slim drill holes. Obtaining gas-saturated water samples from slim holes (<15 cm diameter) is a delicate operation that takes considerable rig time (e.g., 12 hours per run) and is often unsuccessful. Because water and gas chemistry is critical in many studies, more reliable tools are critical.

• Develop or modify drilling/coring techniques, mud systems, directional control, downhole measurements and casing/cementation to maximize success in highly deformed and unstable fault zone environments.

VII. SUMMARY AND RECOMMENDATIONS

Summary

Workshop participants discussed both the significant science issues addressed by a targeted program of continental scientific drilling of faults, fault zones, volcanoes, and volcanic terranes, and specific targets that can best answer these questions. The scientific questions and targets discussed here align with the priorities specified in the recent National Research Council report “New Research Opportunities in the Earth Sciences” (NRC, 2012), as well as previous NRC reports (NRC 2008, 2011).

Linkages with other Federal agencies (e.g., USGS, Department of Energy, Department of Defense), International Ocean Drilling Program (IODP), and international partners are critical to a successful U.S. scientific drilling program because resources can be leveraged across programs to maximize return on investment for all participants. Recent examples of intra-agency efforts include the Chesapeake Bay drilling project (USGS, ICDP), the Snake River Drilling project (DOE, ICDP, USAF), and the “PTA” drilling project on Mauna Kea (U.S. Army, NSF). Additional linkages should be sought with industries that rely on drilling (Oil-Gas, Geothermal).

Participants working on faults and fault zone processes highlighted two overarching topics: Understanding the seismic cycle (topic 1), and 4-dimensional mechanics and architecture of fault zones (topic 2). Five projects were recommended for consideration at this time, with several others recommended for consideration in the future after their concepts are more fully developed. The five recommended projects are:

1. Reoccupying and extending the SAFOD site (white paper by Carpenter et al.)
2. Triggering earthquakes for science (white paper by Savage et al.)
3. Mechanics of the Sevier detachment (white paper by Christie-Blick et al.)
4. Tectonic evolution and mechanics of the Rio Grande rift (white paper by Ball et al.)
5. Fluid flow and supercritical fluid-rock interactions in the Little Grand Wash fault (white paper by Kampman et al.)

The first two projects listed above address Topic 1 “Understanding the Seismic Cycle;” the next three projects focus on Topic 2: “4-dimensional mechanics and architecture of fault zones”. Other projects considered include two that focus on the San Andreas system, two that focus on extensional faulting in the basin and range, and one that examines linkages between faulting and volcanism in a pull-apart basin. Two projects (Rio Grande Rift and Mono Basin), are led by scientists from the
USGS, and are part of larger efforts that have produced significant background data. Another (Dixie Valley) has linkages with DOE geothermal efforts.

Participants working on tectonics and magmatic activity defined three dominant themes: Active Volcanism, Geodynamics/Chemical Evolution of the Earth, and Geoprisms. In active volcanism, four projects were recommended for consideration at this time. The recommended projects are:

1. Okmok Volcano, Alaska, USA (White Paper by Masterlink et al)
2. Aso Caldera, Japan (white paper by Nakada)
3. Mount St. Helens, Washington, USA
4. Newberry Volcanic Monument, Oregon, USA (White Paper by Frone)

The first two projects listed above are backed by mature, well-developed proposals. The Okmok Volcano project is led by scientists from the USGS as part of their volcano hazards program. The Aso Caldera project, in Japan, would represent significant international effort, with much of the funding coming from international partners. Newberry volcano is the subject of current geothermal studies and has potential industry partners.

Participants working on Geodynamics and Geoprisms highlighted five projects for consideration at this time. The five recommended projects are:

2. Snake River Plain Continental Plume Track (White Papers by Christiansen, Shervais, Hanan, Potter, Schmitt and Lee)
3. Mauna Kea PTA Project (White paper by Garcia)
4. Mauna Loa Project (White paper by Rhodes)
5. Drilling the Josephine Ophiolite – Direct Observation of a Subduction Zone Mantle Wedge (Shervais and Dick white paper).

The Deccan project would focus on U.S. participation in a drilling project underway in India at this time, plus a IODP companion proposal to follow the hotspot lavas back to their place of origin. The Snake River and Mauna Kea projects have already been drilled, or are in progress, with funding from the Departments of Energy and Defense; both represent opportunities to leverage intra-agency drilling funds to carry out important science investigations. The Mauna Loa project complements previous work on Mauna Kea, while the Josephine project addresses the geodynamics of subduction zones.

**Broader Impacts**

A primary goal of this workshop was to provide community input to NSF Program Managers that will assist them in setting programmatic goals and allocating resources. Another goal was to formulate a specific plan to apply continental scientific drilling to a range of significant and timely problems in faults, fault zone mechanics, active volcanism, and volcanic geodynamics.

Additional impacts will come through the workshop’s cultivation of early career faculty, who will be the ones to initiate and carry out the research programs defined at the workshop. Involvement of early career faculty and, if possible, graduate students who are near completion of their PhD programs, will have an enormous impact on their future research success, as well as on the success of the continental scientific drilling program. They will also bring new ideas to the table that will impact current projects, and those already in process. The preparation and education of the geoscience workforce has a high priority in industry and academia, and the implementation of strong scientific drilling projects will enhance these goals.

> “Addressing these and other earth science issues requires a well-educated and trained workforce. The Bureau of Labor Statistics projects that job growth will increase by 21 percent for geoscientists (geologists and geophysicists) and by 18 percent for hydrologists from 2010 to 2020, compared to 14 percent for all occupations. Despite high projected demand for earth scientists, however, the number of graduates in earth science fields has not fully recovered from a sharp decline in the early 1980s…”
> (NRC, 2013).
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</table>

Table 1: List of Participants
### Table 2: List of Presentations

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<td>The CSD Proposal Process</td>
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<tr>
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<td>D. Schmitt</td>
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<td>Kerstin Lehnert</td>
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<tr>
<td>Dennis Neilson</td>
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<td>Drilling Technology: Review of tools, techniques, challenges</td>
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<td><strong>Faults</strong></td>
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<tr>
<td>Jim Evans</td>
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<td>Fault Rock Characterization</td>
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<tr>
<td>Virginia Toy</td>
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<td>Fault mechanics in active systems</td>
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<tr>
<td>Jamie Kirkpatrick</td>
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<td>Rapid response drilling</td>
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<td>Lyndsay Ball</td>
<td>J. Caine, T. Grauch, C. Ruleman</td>
<td>Evolution of Fault Zone Geology in an Active Continental Rift: Scientific Drilling Opportunities along the Sangre de Cristo Fault System, Northern Rio Grande Rift, Colorado</td>
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<td>Brett Carpenter</td>
<td>J. Chester, S. Hickman</td>
<td>Capturing the Seismic Cycle: Sampling and Instrumenting an Earthquake Nucleation Patch at SAFOD</td>
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<td>Jafar Hadizadeh</td>
<td>Thibault Candela, Joseph C. White, Francois Renard</td>
<td>Coring and studying clay gouges from mature active fault zones</td>
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<td>Vivek Kale</td>
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<td>Koyna - Warna Seismic Zone, Western India : A unique intraplate setting for drilling for an active fault zone underlying a basaltic pile</td>
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<td>Stephen Martel</td>
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<td>Mechanics of Normal Fault Systems</td>
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<td>Elizabeth Miller and Jeff Lee</td>
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<td>Societal and economic importance of normal faults</td>
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<td>Kentaro Omura</td>
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<td>Drilling Investigations on the Mechanics of Faults; Downhole measurements to detect time variation of in-situ stress (20 Years after Fault Drilling)</td>
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<td>Linda Reinen and Virginia Toy</td>
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<td>The Puysegur Subduction Zone: Investigating the complex role of peridotite and serpentinite in the seismicity of the subduction zone interface</td>
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<td>Heather Savage</td>
<td>N. van der Elst, J. Kirkpatrick</td>
<td>Earthquake Triggering and Fault Zone Drilling</td>
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<td>Patrick Fulton</td>
<td>E. Brodsky, Y. Kano, J. Mori, M. Kyo, F. Chester, Y. Namba, H. Muraki, N. Eguchi, S. Toczko, Y. Ito, T. Kasaya</td>
<td>The JFAST Observatory: Monitoring the frictional heat from the 2011 Tohoku Earthquake</td>
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<td>Wade Johnson</td>
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<td>A Brief overview of SAFOD Round 4 core solicitation</td>
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<td>Liberty Lee</td>
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<td>Active fault/volcanic terrane imaging borehole measurements for slip rates, physical property measurements, and improved surface imaging</td>
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<td>Anja Schleicher</td>
<td>B. van der Pluijm</td>
<td>Clay growth in active fault zones</td>
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<td>Ramesh Singh</td>
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<td>Deep Drilling to Understand Tectonic Settings of Intraplate Earthquakes in US</td>
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<td>John Eichelberger</td>
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<td>Thoughts on the future of research drilling in volcanic systems</td>
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<td>Michael Garcia</td>
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<td>Mantle Plumes in Oceanic Crust: Insights from Deep Drilling</td>
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<td>Clive Neal</td>
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<td>Large Igneous Provinces (LIPs) and the IODP Connection</td>
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<td>John Shervais</td>
<td>B. Hanan</td>
<td>Hotspots, Plumes, and Continental Lithosphere</td>
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<td>Barry Hanan</td>
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<td>Radiogenic isotope models for Snake River Plain basalt mantle source</td>
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<td>Angela Jayko</td>
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<td>Do Mono Basin and Long Valley overlie an incipient mantle plume? Or, are the late Holocene melts localized by transtensive block rotation within a regional releasing bend within the Walker Lane?</td>
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<td>Michael Rhodes</td>
<td>F. Trusdell</td>
<td>Mauna Loa: Drilling the Other Side of the Hawaiian Plume</td>
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<tr>
<td>Loic Vandervklyusen</td>
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<td>Emplacement of large igneous provinces</td>
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<tr>
<td>Amanda Clarke</td>
<td></td>
<td>San Francisco Volcanic Field (or similar monogenetic basalt fields)</td>
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<td>Zachary Frone</td>
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<td>Setsuya Nakada</td>
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<tr>
<td>Katherine Potter</td>
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<td>an investigation of the kimama drill core: A Multi-Log Approach</td>
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Continental Scientific Drilling Workshop Series  
Drilling active tectonics and magmatism: 37
Investigating ultra high-enthalpy geothermal systems: a collaborative initiative to Promote Scientific Opportunities

Report of an NSF-Sponsored Workshop held October 13-16, 2013, Lake Arrowhead, CA

W. A. Elders¹, D. Nielson², P. Schiffman³, and A. Schriener Jr⁴

Abstract

Scientists, engineers, and policy makers gathered at a workshop in the San Bernardino Mountains of southern California in October 2013 to discuss the science and technology involved in developing high-enthalpy geothermal fields. A typical geothermal well between 2,000-3,000 meters deep produces a mixture of hot water and steam at 200-300°C that can be used to generate about 5-10 MWe of electric power. The theme of the workshop was to explore the feasibility and economic potential of increasing the power output of geothermal wells by an order of magnitude by drilling deeper to reach much higher pressures and temperatures. Development of higher enthalpy geothermal systems for power production has obvious advantages; specifically higher temperatures yield higher power outputs per well so that fewer wells are needed, leading to smaller environmental footprints for a given size of power plant. Plans for resource assessment and drilling in such higher enthalpy areas are already underway in Iceland, New Zealand, and Japan. There is considerable potential for similar developments in other countries that already have a large production of electricity from geothermal steam, such as Mexico, the Philippines, Indonesia, Italy, and the USA.

However drilling deeper involves technical and economic challenges. One approach to mitigating the cost issue is to form a consortium of industry, government and academia to share the costs and broaden the scope an investigation. An excellent example of such collaboration is the Iceland Deep Drilling Project (IDDP) which is investigating the economic feasibility of producing electricity from supercritical geothermal reservoirs, and this approach could serve as model for future developments elsewhere. A planning committee was formed to explore creating a similar initiative in the USA.

1 Introduction

This workshop was under the aegis of DOSECC, a consortium of United States universities where investigators are interested in research involving subsurface sampling, measurement and observation. DOSECC is actively seeking to engage a wider earth science community by sponsoring five workshops on different topics where the science being investigated requires drilling (see www.dosecc.org). This initiative is designed to foster a more integrated Continental Scientific Drilling Program that will strengthen scientific drilling in the USA and interact in more fruitful ways with the International Continental Scientific Drilling Program (see www.icdp.org).

The workshop had two objectives, firstly to discuss scientific studies of active very high-enthalpy hydrothermal systems, and secondly to stimulate

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collaboration between academic scientists, government agencies, and industry. Such collaboration is highly desirable because the scientific study of active hydrothermal systems requires drilling and sampling boreholes whose costs far exceed budgets normally available to academic scientists; it is industry that drills wells to access geothermal resources. Although drilling into these deep unconventional geothermal reservoirs is more expensive, the higher productivity per well should offset this by reducing the number of wells needed for a given power output (Friðleifsson and Elders, 2005). Developing these resources would make available new large and environmentally benign sources of alternative energy. In addition, such developments would make important scientific contributions. It would permit major advances in our understanding of active hydrothermal processes that are important on a global scale but are not otherwise available for direct investigation, (Elders, and Friðleifsson, 2010). These include the coupling of magmatic and hydrothermal systems and their mass and energy transfer, hydrothermal ore formation in magma ambient conditions, the transition from low to higher grade metamorphism, and aspects of volcanic hazards.

The theme of the workshop was to explore the feasibility and economic potential of increasing the power output of geothermal wells by an order of magnitude by drilling deeper to reach much higher pressures and temperatures.

The participant list and program of the workshop appear in Table 1, the workshop program is Table 2, and White Papers are included in Appendix C. The talks presented at the workshop are available on the workshop website: http://csdworkshops.geo.arizona.edu/Lake Arrowhead CA.html. Two scientists from New Zealand, two from Mexico, and one from each of Iceland, Italy, Philippines, and Russia participated in the workshop. This led to discussions of programs in various countries that are currently investigating, or planning to investigate, “ultra high-enthalpy” geothermal systems.

Plans for deep drilling to explore for deeper, much higher enthalpy, geothermal resources are already underway in Iceland (Iceland Deep Drilling Project), in the Taupo Volcanic Zone of New Zealand (Project HADES), and in northeast Japan the “Beyond Brittle Project” (JBBP), is an ambitious program attempting to create an Enhanced Geothermal Systems (EGS) reservoir in ~500°C rocks. Although there is a significant undeveloped potential for developing high-enthalpy geothermal systems in the western USA, Hawaii and Alaska, there is no comparable national program to develop such resources. The main difficulty in implementing such programs is the very high cost in drilling deep into hostile environments.

2 The Iceland Deep Drilling Project

One approach to mitigating the cost issue is to form a consortium of industry, government and academia to share the costs and broaden the scope of investigation. An excellent example of such collaboration is the Iceland Deep Drilling Project (IDDP). The aim of IDDP is to produce geothermal energy from magma-hydrothermal systems at supercritical conditions, similar to environments found at depth on mid-ocean ridges. It is funded by an industry-government consortium (Friðleifsson, Elders and Albertsson, 2014). The drilling and well completion was funded by an industry-government consortium and the science sampling program by the ICDP and the US National Science Foundation (Friðleifsson, Elders and Albertsson, 2014).

In 2009 this industry-government consortium drilled a well in the volcanic caldera of Krafla in NE Iceland (Figure 1). Continuing the search for supercritical geothermal resources in Iceland in 2014-2015 the IDDP will drill a new deep well on the Reykjanes Peninsula in SW Iceland that is the continuation of the Mid-Atlantic Ridge on land (Figure 1; Friðleifsson, Elders, and Bignall, 2013). In the future, a third deep well will be drilled at Hengill, another high-temperature system.
The critical point for pure water occurs at 220 bar and 374°C. Exceeding such pressure-temperature conditions, for likely pressure-temperature gradients, requires drilling to depths of 4 to 5 km (Fournier, 1999). Supercritical fluids have higher enthalpy and greatly enhanced rates of mass transfer relative to conventional lower-temperature geothermal resources (Dunn and Hardee, 1981; Hashida et al., 2001). Figure 2 shows that water at supercritical conditions with a temperature of 400°C and a pressure of 250 bar has more than five times the power producing potential than that of liquid water at 225°C (Tester, 2006).

Geothermal wells in Iceland typically range up to 3.0 km in depth and produce steam at <300°C, at a rate sufficient to generate about 4 to 10 megawatts (MWe) of electricity. Modeling suggests that producing superheated steam from a supercritical reservoir could potentially increase the power output of geothermal wells by an order of magnitude relative to the output of lower enthalpy wells (Friðleifsson and Elders, 2005). A conventional dry-steam well with a down hole temperature of 235°C and pressure of 30 bar with a volumetric flow rate of 0.67 m³/s can generate ~5 MWe, whereas we estimate that a supercritical well at the same volumetric flow rate, but with a down hole temperature of 430-550°C and pressure of >200 bar could generate ~50 MWe. The IDDP aims to produce supercritical fluid to the surface such that it transitions directly to superheated steam.

2.1 The IDDP-1 well

The first IDDP well was drilled in the Krafla geothermal field within a volcanic caldera in the central active rift zone of NE Iceland (Figure 1). At Krafla production wells drilled since 1971 supply steam to a 60 MWe geothermal power plant. During 1975-1984, a rifting episode occurred at the Krafla volcano, involving 9 volcanic eruptions. A large magma chamber, believed to be the heat source of the active geothermal system, was detected by S-wave attenuation at 3-7 km depth within the center of the caldera and this was confirmed by a recent MT-survey. The well IDDP-1 was sited to reach 4.5 km depth close to the margin of this magma chamber (Friðleifsson, Elders and Albertsson, 2014). However, in 2009, at only 2104 m depth a >900°C rhyolitic magma filled the bottom 9 m of the drill hole (Pálsson et al. 2014). Our studies indicate that this magma formed by partial melting of hydrothermally altered basalts within the Krafla caldera (Elders et al., 2011; Zierenberg et al., 2013). The decision was made to terminate drilling, cement production casing, allow the well to heat, and to flow test the well.

Figure 1. The location of rift-ting (shaded) in the neovolcanic zone of Iceland, an extension of the Mid-Atlantic Ridge. The map shows the location of three high-enthalpy magma-hydrothermal systems, Krafla, Hengill, and Reykjanes that are sites that were chosen for deep drilling by the Iceland Deep Drilling Project (IDDP). The irregular ellipses are active central volcanoes.
The resultant well had very high enthalpy and produced superheated steam from the contact zone above the intrusion (Hauksson et al., 2014). With a well-head temperature of ~450°C and a well-head pressure of up to 138 bar, it became the hottest producing geothermal well in the world and, with a flow rate of 45/kg/s of dry superheated steam, it was estimated to be capable of generating >35 MWe (Figure 3). In July 2012, after ten months of full scale flow, the well was shutdown to recondition some of the surface equipment.

The future utilization of this magmatic resource at Krafla is still being discussed. It may be possible to recondition the IDDP-1, or several new wells could be drilled towards the contact zone of the magma. Ideally building completely new high-enthalpy turbines would be preferable, as the existing turbines at Krafla have an inlet pressure of only 7 bar. In the future it may even be possible to produce energy directly from the magma, either utilizing a downhole heat exchanger or by creating the world’s first EGS production and injection wells in magma.

3 Wider Applications

The IDDP-1 well engendered considerable international scientific and engineering interest. A special issue of the journal Geothermics was published in January 2014 reporting some of this work. In contrast to the fresh water system at Krafla, the Reykjanes geothermal system, which lies directly on the landward extension of the mid-Atlantic...
Ridge, produces hydrothermally modified seawater. Processes at depth at Reykjanes should be quite similar to those responsible for black smokers on oceanic rift systems (Elders and Friðleifsson, 2010; Friðleifsson, Elders and Bignall, 2013). If new IDDP wells at Reykjanes and Hengill prove successful, this could trigger similar activities elsewhere. In the future such very high enthalpy geothermal systems could become significant resources worldwide, wherever suitable young volcanic geothermal systems occur (Figure 4).

3.1 Developing ULTRA Geothermal Resources:

Developing such ultra high-enthalpy supercritical geothermal resources at drillable depths is most credible:

- At young volcanic rocks along plate boundaries and at hot spots
- Near shallow, still hot (or partially molten) igneous intrusions
- At well-established high-enthalpy geothermal fields for example in:
  - Iceland – Reykjanes, Hengill, Krafla
  - Northeast Japan (JBBP)
  - New Zealand in the Taupo Volcanic Zone (HADES)
  - Philippines, Indonesia, Italy, Mexico (Cerro Prieto, Los Humeros)
  - USA – Hawaii, California, the Cascade Volcanic Chain, the Basin & Ranges, Alaska, etc.

In fact, projects comparable but differing in approach to the IDDP are already underway in both Japan and New Zealand. The plan in Japan is to drill beyond the brittle ductile transition in a 500°C or hotter neo-granite and to thermally fracture the...
rocks to form permeability in the ductile zone and thus create a contained EGS system (Figure 5). The expectation is that a combination of government and industry funding will permit drilling to begin in two or three years (See http://www-icdp.icdp-online.org/front_content.php?idcat=1741).

A similarly ambitious project is underway in New Zealand, although possibly not so far advanced as the IDDP or the JBBP. “Hotter and Deeper Exploration Science” (HADES) is a long-term program of exploration and assessment in the Taupo Volcanic Zone in the North Island of New Zealand that aims to use geological, geochemical and geophysical data to assess the resource potential of deep geothermal systems in the Taupo Volcanic Zone (Figure 6).

Preliminary indications of this “Hotter and Deeper” project suggest that by 2025, New Zealand’s deep geothermal resources (3-7km) could supply at least 20% of New Zealand’s electricity requirement. Conservative estimates point to the total potential of accessible deep geothermal resource in the Taupo Volcanic Zone (TVZ) exceeding 10,000 MWe. (See www.gns.cri.nz/Home/Our-Science/Energy-Resources/Geothermal-Energy/Research/Hotter-and-Deeper).

For more than a decade the US Department of Energy had a “Magma Energy Program” aimed at extracting high-enthalpy energy directly from magma, using a downhole heat exchanger. A special...
issue of the Bulletin of the Geothermal Resources Council in 1990 was devoted to discussing that concept (Eichelberger and Dunn, 1990). After a nation-wide study (Finger and Eichelberger, 1990), the Long Valley Caldera in California was chosen as the optimum site in the USA to drill into magma. A drilling rig began drilling a well designed to reach a depth of almost 7 km to reach a magma chamber believed to exist below the caldera. However, due to funding problems, it was abandoned far short of its target, at less than 3 km depth where the temperature was only 120°C (Bender-Lamb, 1991).

A more recent assessment of geothermal resource base to 10 km depth in the USA is shown in Table 1.1 for different categories of geological environment as reported in Tester, (ed.), 2006. The major thrust of that report was to assess the potential of Enhanced (or Engineered) Geothermal Systems (EGS) in the USA, and it greatly increased the assessment of the EGS resource base of the USA in crystalline basement rocks over the estimate made in 1975. The overall conclusion of that comprehensive assessment was clearly that the largest part of the EGS geothermal resource base resides in the form of thermal energy contained in sedimentary and basement rocks that are heated by radiogenic heat sources and conductive heat transfer. The size of its resource base is orders of magnitude greater than the resource base of "conventional" geothermal systems in permeable rocks that are associated with volcanic-related hydrothermal temperature anomalies. However, as Table 1.1 from Tester (ed.), 2006 shows, supercritical volcanic EGS also has a large potential in the USA.

Although field experiments to create EGS in crystalline rocks began in the USA in the 1970’s, at present all of the 3400 MWe of geothermal power currently generated in the USA comes from conventional hydrothermal systems. Since the early experiments in the USA, development of EGS resources has been attempted in the UK, France, Japan, Australia, Sweden, Germany, and Switzerland. However today the total world installed generating capacity from EGS is less than about 10 MWe, and in each case its development has required large government subsidies. These EGS experiments have largely focused on systems with temperatures less than 300°C (and in some cases only 200°C as deep as 5 km). This slow development is a function of both some of the inherent technological difficulties and economic limitations of low to moderate enthalpy EGS.

3.3 Developing a Project to Develop “ULTRA” Geothermal Systems

One outcome of the workshop was the formation of a planning committee (consisting of the authors of this report) to develop a project similar to the IDDP in the USA. Implementation of such a plan will require formation of a consortium with participation from industry, government agencies, and universities. The planning committee is tasked with the creation and implementation an “ULTRA Geothermal Development Project in the USA”. Ultra geothermal resources are magma ambient and/or supercritical geothermal systems that have much higher enthalpy and pressures than the geothermal systems that are currently utilized to generate electricity today.

Unlike the situation in the UK, France, Australia, Germany and Switzerland, as Table 1.1 shows, there is a large potential to develop supercritical volcanic EGS in the USA. In addition supercritical hydrothermal geothermal systems not requiring EGS technology could be developed where convective heat transfer operates due to the existence of appropriate combinations of pressure, temperature and lithology. In basaltic terrains, such as in Iceland, the brittle ductile transition occurs at much higher temperatures than in the granitic terrains such as those being investigated by the JBBP. Today there is revived and growing interest

Table 1.1 (from Tester, ed., 2006, p.12)
in investigating high-enthalpy geothermal systems in the USA (Elders, 2013; Elders, Friðleifsson, and Albertsson, 2014).

3.4 The aims of ULTRA Geothermal Development Projects

- Improve the economics and efficiency of base load electrical power production from sustainable geothermal resources without increasing their environmental footprint.
- Explore and demonstrate the feasibility of increasing geothermal electrical power production by approximately an order of magnitude through production of ULTRA high-enthalpy geothermal fluids.
- Create projects in for developing ULTRA high enthalpy resources that builds upon those already underway in Iceland (IDDP), Japan (JBBP), and New Zealand (HADES).
- Promote and enhance collaboration amongst governmental agencies, industry, and academia in the USA and internationally, to advance the capitalization, study, and development of ULTRA high-enthalpy as sustainable geothermal resources.
- Through such collaboration, to develop multidisciplinary approaches and best practices for site selection in the exploration for ULTRA high-enthalpy geothermal resources in the USA.
- Identify candidate sites where a drilling project targeting ULTRA high-enthalpy fluids has the greatest potential for transforming the ability of geothermal energy to contribute to sustainable, electrical power production.
- Explore the potential of using EGS technology to optimize electrical power production from ULTRA high-enthalpy geothermal resources.
- Develop the science and technology for ULTRA high-enthalpy exploration and development that is transferable to other Earth and Material Science applications.
- Enhance our understanding of fundamental problems in the Earth Sciences including: ore genesis, very high-temperature fluid-rock interactions, and magmatic/hydrothermal transitions.
- Educate and train the future work force and create new employment opportunities in this field of green sustainable energy.

3.5 The criteria for site selection for the UGDP include:

- The site must contain ULTRA-high enthalpy resources at depths attainable by current drilling technology on the basis of existing surface and subsurface data.
- The site must have substantial infrastructure, access, and permitting, as well as availability to power and testing facilities.
- The site must have an existing operator willing to be an active partner in this project.
- The site should maximize the scientific and technological benefits and transferability for a given capital investment.
- The initial site must be one in which this project could readily demonstrate the proof of concept that the development of ULTRA high-enthalpy resources is viable.

3.6 Some advantages and potential barriers to creating an UGDP:

The principal barrier to creating programs to develop magma ambient and supercritical geothermal resources are their high costs. The obvious solution therefore is to share the costs between industry and government, with involvement of national laboratories and university scientists and engineers participating and providing scientific and technical input.

Among the potential advantages of such collaboration with strong industrial involvement is that industry can furnish access to:

- “Holes of Opportunity” i.e. boreholes sited and drilled by industry for its own purposes;
- large and flexible funding sources;
- industry data bases relevant to site selection;
- industry leasing and permitting;
- industry technical expertise, equipment, and infrastructure;

Among the reasons why such collaborations have previously not been more common are:

- industry’s concern with protecting propriety data and leaseholds in competitive situations;
- it is complicated and time consuming;
Continental Scientific Drilling Workshop Series

Investigating ultra high-enthalpy geothermal systems:

- the long lead time for return on investment for the industry partner;
- it requires coordination of multiple funding sources and timetables.

To overcome these disadvantages requires good faith by all parties, patience, flexibility, mutual understanding, back-up plans, and an optimism that continued progress will overcome obstacles with collaboration. This requires having clearly enunciated and understandable scientific and technical goals, seizing opportunities, building working relationships based on trust, stressing benefits to both parties, being flexible, and educating funding agencies about timetable constraints and drilling contingencies. This can be done, as was demonstrated by the IDDP.

4 Conclusions

Amongst approaches to improve the economics of the geothermal industry development of Ultra Geothermal Resources could reduce the number of wells needed and increase the power output of each well, by producing supercritical fluid and/or high-enthalpy dry superheated steam. The potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. Not only would this call for re-evaluation of the geothermal energy resource base on a local scale, but also on a global scale. Accessing supercritical fluids within drillable depths could yield a significant enlargement of the accessible geothermal resource base.

The scientific significance of investigating ULTRA Geothermal Systems is that it allows direct study of active:
- supercritical phenomena
- coupling of hydrothermal & magmatic systems
- hydrothermal alteration and ore formation
- fluid circulation at continental rift systems and at mid-ocean ridges and black smokers
- related volcanic hazards

Supercritical zones are most important for the practical goals of the ULTRA Geothermal Development Project. It is predominantly there that mobile fluids are heated and interact chemically with their host rocks, where most of the geologically important heat flow, chemical alteration, and hydrothermal ore formation take place. Supercritical fluid-rock interactions are important in the overall heat and fluid budgets of mid-ocean ridges. Studying analogous systems on land is much more practical than drilling from a ship in 3 km of water. And finally supercritical fluid and/or superheated steam represent an attractive source for electric power generation.

Acknowledgements

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Hauksson, T., Marksson, K., Einarsson, S.N., Karlsdóttir, A., Einarsson Á., Möller, A. and Sigmarsson, P., Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland, 49, 76-82, 2014


Author

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Table 1: List of Attendees

Dennis L. Nielson, DOSECC Exploration Services, USA
Edward Bertrand, GNS Science, New Zealand
Hiroshi Asanuma, GSJ/AIST, Japan
Peter Schiffman, University of California, Davis, USA
Flavio Poletto, OGS (Istituto Nazionale di Oceanografia e di Geofisicaientale), Italy
Viacheslav Spichak, Geoelectromagnetic Research Centre IPE RAS, Russia
Andrew Fowler, University of California, Davis, USA
William L. Osborn, Geothermal Resource Group Inc, USA
Phil Wannamaker, University of Utah/EGI, USA
Mark H. Reed, University of Oregon, USA
Sabodh K. Garg, LEIDOS, San Diego, USA
Georgina Izquierdo M., Instituto de Investigaciones Electricas, Mexico
Rosalind Archer, University of Auckland, New Zealand
Lilja Magnusdottir, ISOR (Iceland Geosurvey) Iceland, (visiting LBL)
Heber Didier Diez L., Comision Federal de Electricidad (CFE), Mexico
Marie Jackson, University of California, Berkeley, USA
Alexander Schriener Jr., CalEnergy Operating Corp, USA
Louis Capuano Jr., Capuano Engineering Company, USA
Mitchel Stark, Chevron / Philippine Geothermal, Philippines
William Rickard, Geothermal Resource Group, USA
Michelle Sulera, Geothermal Resource Group, USA
John W. Shervais, Utah State University, USA
Paul von Hirtz, Thermochem, Santa Rosa, USA
Randy Norman, Permaworks, USA
Robert A. Zierenberg, University of California, Davis, USA
Elizabeth Easley, Thermochem, Santa Rosa, USA
Jonathan Hernandez, Geothermal Resource Group, USA
Osinachi Ajou (Student), University of California, Riverside, USA
Rainer Luptowitz (Student), University of California, Riverside, USA
Wilfred A Elders (Convenor), University of California, Riverside, USA
### Table 2: Program of the Workshop

#### Session 1: Introduction to high-enthalpy and supercritical geothermal resources
1. Wilfred Elders (UCR) "The concept of the Iceland Deep Drilling Project".
2. Hiroshi Asanuma (AIST, Japan) - "The Japan Beyond the Brittle Project (JBBP)."
3. Ted Bertrand (GNS,NZ) "Hotter and Deeper Exploration Science in New Zealand (HAD ME)."
4. Rosalind Archer (U of A, NZ) - "Fluid flow models at a grand scale".
5. Falvio Poletto (OGS, Italy) - "Use of seismic exploration methods while drilling."
6. Heber Diez (CFE, Mexico) "Development of high-enthalpy geothermal resources in Mexico."
7. Georgina Izquierdo (IIE, Mexico) "Los Humeros geothermal field, Mexico."
8. Viascheslav Spichak (Moscow, Russia) "Electromagnetic sounding for geothermal exploration."
9. Alex Schriener (CalEnergy, USA) "Drilling to 500 C: Thoughts from a development geologist."
10. Mark Reed (U. of Oregon) "Potential sources of high-enthalpy geothermal fluids."
11. Dennis Nielson (DOSECC drilling) - "Higher enthalpy geothermal systems."
12. Lilja Magnusdottir (Iceland/LBL) "Modeling the deep roots of geothermal systems."
13. Sabodh Garg (Leidos) - "Modeling of high-enthalpy geothermal systems."

#### Session 2: Related scientific studies
15. Peter Schiffman (UCD) "Studies of the contact zone of the intrusion in well IDDP-2. Iceland."
16. Robert Zierenberg (UCD) "Geochemistry of sulfur in high-enthalpy geothermal systems."

#### Session 3: Technical challenges to drilling, completing and sampling high-enthalpy wells
17. William Rickard (Geothermal Resources Group) "High Temperature Well Drilling and Completion Challenges."
18. Louis Capuano (GRC & Capuano Drilling) - "The challenge of drilling deep and hot."
19. Paul von Hirtz (ThermoChem) "Downhole fluid sampling."
20. Paul von Hirtz (ThermoChem) "Corrosive Superheated steam."
21. Randy Norman (Permaworks) "New approaches to high temperature logging."

#### Session 4: Studies of Specific High-enthalpy Systems
22. Phil Wannamaker (UU/EGI) - "Magmatic-hydrothermal transitions in extensional regimes of USA."
23. Mitch Stark (Chevron) "The Geysers high-temperature zone."
24. Marie Jackson (UCB) "Mineralogical analyses of altered tephras."

#### Session 5: Break Out Panels leading to writing a white paper
Breakout Panel 1 – "Scientific Goals and Site Selection."
Breakout Panel 2 – "Technical challenges."
Breakout Panel 3 – "Strategies for organization and funding."

#### Session 6: Plenary Session – Reports from the Breakout Panels
- Discussions of the way forward.
Introduction

Forty-five participants gathered in Minneapolis to assess the current state and trajectory of the paleoceanography domain, here defined as the community of scientists working to establish and synthesize paleorecords of Earth environment and biosphere. The defining characteristics of this broad domain are: 1) its focus on past earth and life processes; and 2) all scientific inferences in this domain are ultimately based on the collection of physical samples in the field, from which many kinds of geochemical, geobiological, and geophysical measurements are extracted. This domain includes (but is not limited to) scientists working on paleorecords from: cores drilled in the seafloor, lakebeds, peatlands, continental crust, glaciers or ice sheets, or trees; rock samples hammered from outcrops; fossil remains retrieved from various depositional environments; speleothems; corals; boreholes; packrat middens, etc. Participants’ expertise spanned most of these disciplines, with heavy emphasis on the many subfields of paleoclimate and paleobiology. Outreach to the small proportion of communities not represented was accomplished during the four months of workshop preparation, through postings to relevant listservs, direct communications to community representatives, town hall gatherings at the GSA and AGU national meetings, and an online survey tailored to the community.

The main themes from workshop discussions are summarized below. A list of workshop participants is included in Table 1. Included in Appendix D are full notes from all workshop breakout sessions, an inventory of current community cyberinfrastructure resources and the results from the online community survey.

SCIENCE ISSUES AND CHALLENGES

1 Important science drivers and challenges:
Participants identified several high-priority science questions that will be the focus of interdisciplinary efforts during the next 5-15 years. Some of those common themes are described below.

Overarching theme: The History and Future of Life and Environment Interactions on Earth

- Establishment of a 4D framework for life and its environment on Earth. All other community priorities emerge from this primary objective. This framework will integrate across all time...
scales, regions, taxa, physical/geochemical properties, etc., and enable the ability to extract system state and rate of change at any spatiotemporal moment of interest.

- Determine climate/ocean/biosphere interactions during times of great change in climate and environment, including extinction events, periods of extreme warmth, and changes over decades to millions of years, including the present geologic transition. Develop detailed characterizations of these past events to inform predictions of future changes.

- Advance the capability to model the coupled carbon-climate Earth system, deriving the feedbacks, tipping points, and other processes from the paleo record, which is especially critical for deciphering the high magnitude/slow feedback mechanisms (e.g. ice sheet loss, deep ocean circulation) that climate models do not yet fully incorporate.

- Assimilate paleo observations into process-based Earth System Models to reconstruct Earth history (lat, long, elev, and time), developing a suite of products that facilitate research, inform policy and decision-making (carbon cycle, sustainability, hazards), and deepen the public understanding of environmental vulnerability.

The participants recognized the value of recent efforts in characterizing many of the critical science drivers and challenges, including:

TRANSITIONS:  http://www.sepm.org/CM_Files/ConfSumRpts/TRANSITIONSFinal.pdf
NROES:  http://www.nap.edu/openbook.php?record_id=13236
DETELON:  http://detelon.org
NRC 2011 Report:  www.nap.edu/catalog/13111.html (added by steering committee)

Advanced cyberinfrastructure can enable the paleo community to reach these goals by 1) integrating small pieces of information scattered across the long tail (many small science projects), 2) refining sample ages and age uncertainty requisite to meet above challenges, and 3) facilitating a new era of vigorous collaboration across the many subdisciplines within and outside the paleogeosciences (e.g., hazards, paleomagnetics, tectonics, climate impacts, resource management, STEM education).

2 Current challenges to high-impact, interdisciplinary science:

Several themes emerged as consistent challenges faced within/across the paleorecord community. Data/IT issues:
- Difficulty of discovery and vetting legacy data and dark data and their associated metadata; lack of funds for digitizing legacy data
- Unstructured data
- Unawareness and/or underutilization of standards for data/metadata
- Inconsistent data formats
- Difficulty of importing/exporting data from databases
- Expense of IT development and maintenance
- Multiple databases for certain data types increases difficulty of finding data of interest

Social issues:
- Some disciplines do not have organized databases or sample repositories
- Barriers to data contribution (time, unease dealing with data formats and portal interfaces, perceived lack of incentive to contribute data, lack of citation for reused data)
- Perceptions of data ownership, personal investment in data and reluctance to share
- Lack of community organization

TECHNICAL INFORMATION / ISSUES / CHALLENGES

1 Desired tools, databases, etc. needed for pursuing key science questions with brief elaboration:
Breakout session 4 addressed the needs of the community in satisfying the science and educational objectives. The following summary attempts to represent the themes identified independently by two or more of the groups, organized roughly according to group reports. These items represent the minimum requirements needed to reach the overarching community goal stated above. NB: “existing resources” here means databases, museum digital and specimen holdings, models/model results, and data analysis tools/methods.

- Intuitive 4D access to all existing knowledge products and underlying data/metadata and methods used to generate those knowledge products
- Intuitive 4D mapping and visualization capability across data resources/model outputs
- Better access to and discovery of tools and methods to manipulate and analyze data of different common types (e.g., time series, stratigraphic position)
- Improved agreement upon standards and semantics for basic, widely-used data/methods, particularly for age/time representation
- System for determining and dynamically updating age models (and uncertainties) within and between existing resources and model results
- Improved user workflow and explicit reward system for data generators (e.g., acquisition and submission to databases/repositories)
- Coupled earth-life system models that have good two-way, “live” integration with distributed data resources
- Increased awareness/utilization of existing resources within and outside of the paleo community and funding to sustain and improve these resources
- Improved metrics to evaluate success and contributions of existing efforts on a community and individual level; metrics to evaluate successes of new efforts
- System to identify gaps in existing data sets and prioritize/incentivize verification of contradictory information, as well as filling gaps with new records
- New educational capability that is built upon data and results drawn “live” from existing resources
- Support for long-term archiving and retrieval of digital data/tools and physical samples
- Need 4D visualization(s) for researchers (easy data comparison, discovery of gaps, etc.), scientists outside the paleo community, educators, policy-makers, and the public
- Legacy and dark data incorporation – noisy signal processing (sort out bad data, dropped data, sparse matrix data (missing images, geochem, geomorph; this type of tool is also fairly standard but it needs to be incorporated)

**COMMUNITY NEXT STEPS**

1. List of what your community needs to do next to move forward how it can use EarthCube to achieve those goals:

   Develop an EarthCube RCN proposal with the goal of building an EarthCube community in Paleogeoscience.

   - Working groups representing subdomains such as paleobiology, paleoclimatology, paleoceanography, curation, and cyberinfrastructure were established with initial membership to contribute to the content of the proposal

   - Proposed activities will:
     - generate awareness of EarthCube and broaden participation within the paleo community, especially engaging early career scientists; consider iDigBio model of building working groups that focus on specific topics to increase participation
     - explore ways to advance the integration of the paleo community; reach out to other communities that have successfully transitioned from dispersed to integrated, and learn from them; develop incentives for participation
     - create a comprehensive inventory of existing data resources, models, and tools, and assess and evaluate them with support from computer and informatics scientists to determine optimal means of creating virtual connections between the resources
     - review existing data/metadata standards and coordinate with established interdisciplinary standards and publication/citation organizations to develop relevant community-specific standards, including ontologies and vocabularies (with particular emphasis
on the urgent need to develop standards for time/age representation), and best practices for data citation and data publication

- establish a broad initiative across EarthCube to describe and assess current methods of age representation in the geosciences and plan for a Building Block proposal to address this topic

- Community engagement will continue through contact on the EarthCube website, posting to listservs, webconferences, and AGU and GSA EarthCube sessions and town halls.

**USE CASE EXAMPLES**

1. **Big Science Use Case: Earth-Life Transitions**

We want to be able to fuse all forms of paleo evidence into a common 4D spatiotemporal framework, establishing what we empirically know about the past transitions in the Earth’s system and its biota. This system makes it easy to find, search, and compare paleodata and to fuse these data with process-based models of the Earth-Life system. We move from incomplete and disconnected domains of knowledge into comprehensive and interlinked characterizations of the past Earth System and its biota. There is a seamless chain from primary observations to high-level data products and all information can be linked back to the original investigators. Data-derived products (e.g. past sea level, global temperature fields, species distributions, and rates of extinction) are dynamically updated as new information is generated, assimilated with earth system models.

Utility of Scenario: Such a framework would highlight data hotspots as well as baldspots for future data collection effort. A comprehensive framework would allow comparative studies that are the basis for testing causal hypotheses in historical science. The critical societal need is a model that can forecast Earth-Life system response at multiple spatiotemporal scales into the future. This model forecast is constrained by the data and knowledge collected by the entire paleo community over the past decades and the data-model fusion is advanced by state-of-the-art analytical and visualization tools.

2. **Use Case: Empowering Individual Geoscientists**

Now we take the prior example and invert it, to represent the perspective of an individual geoscientist.

Zoe is a paleolimnologist specializing in the reconstructions of salinity and temperature from fossil diatom assemblages extracted from lake sediments. She works with small research teams of other paleolimnologists, paleoecologists, geochemists, paleoclimatologists, each of whom specializes in the measurement and analysis of a particular kind of ‘proxy’, from various physical, geochemical, and biological sources (e.g. diatoms, ostracodes, stable isotopes, organic geochemical biomarkers). These data are of great interest to Earth System modelers seeking empirical constraints on their simulations of past transitions in the Earth-Life system (e.g. the Paleocene-Eocene Thermal Maximum, the Younger Dryas), and also to other paleolimnologists seeking to discern larger patterns from their individual time series. EarthCube has the potential to smooth every step in this scientific workflow.

Project Planning: During the initial planning stage, EarthCube allows Zoe to determine an optimal site, by confidently identifying ‘bald spots’ (places where no cores have been taken, the measurements from earlier work are no longer adequate to answer current questions, and/or the original core samples have been lost or destroyed). EarthCube also lets Zoe access archives of paleoclimatic model simulations and identify times or places of model ambiguity that would benefit from new observations.

Field Work: While Zoe is in the field, she tags each core collected with a unique digital object identifier and is able to digitally upload and link geospatial coordinates, field photos, and other field observations to relevant EarthCube repositories as they are collected in the field and in the lab. Zoe can easily share the data with colleagues and has the
option to embargo sensitive portions of her data until they are published.

Lab Work and Project Management: Zoe’s identifications of diatoms are checked against online reference libraries consisting of images of diatom species that are community-curated and synchronized with taxonomic databases. Visualization software makes it easy for Zoe to jointly plot and share her data with her team members during monthly teleconferences and for the entire team to set Zoe’s data in the context of existing paleo-records.

Analysis: Next-generation software allows Zoe to use state-of-the-art statistical methods, e.g. to 1) build age models (needed to infer the time dimension) and 2) reconstruct past salinity and water temperature based on the environmental tolerances of the assemblages. Often these statistical methods will borrow strength from other previously collected datasets. Age models would use the most up-to-date timescales and standards and advanced estimates of uncertainty. This allows times-slices to be rapidly created using standardized data.

Synthesis: Once Zoe has finished her analyses, she can easily compare her data to other time series data stored in online public repositories and to the output from Earth System models that have been run previously for similar time periods.

Sharing: Upon publication, her diatom observations are made publicly available through Earth-Cube-affiliated federated repositories as are her age models and paleoenvironmental reconstructions. Her data are automatically incorporated in on-going larger-scale syntheses of paleoclimatic data and made available for subsequent data-model assimilations.

3. Key Concepts
- Seamless movement between data and models.
- Integrated Earth Systems models (interlinked atmosphere, ocean, biosphere) that are built iteratively to fit available data that is assimilated continuously from multiple data networks.

4. Key Needs:
- Global Access to Global Collections: establish repositories for all physical samples and the biological, geochemical and physical measurements made from those samples.
- Automated tools for finding ‘dark data’ and adding this data to repositories.
- Targeted Data Rescue campaigns for legacy data not in digital format or in obsolete, or difficult-to-use formats.
- Database linking: Improve connectivity among existing databases through adoption of common standards, establishment of standard and shared digital object identifiers, and/or shared semantic/ontology frameworks for linking between databases.
- Creation, enhancement, and sharing of workflow and data-management software designed for research teams ranging from a few scientists to large drilling campaigns.
- Formalization of “Level 0/Level 1/Level 2/Level 3” data products (i.e. ranging from the raw field and lab measurements to interpretations, global reconstructions, and other products; higher the level, more processed) and developing expert-guided workflow software that can dynamically update higher-level products.

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Table 1: List of Attendees

David Anderson, NOAA
Nicole Anest, Columbia University/LDEO
Franco Biondi, University of Nevada, Reno
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Marjory Chan, University of Utah
Mark Chandler, Columbia University
Emilie Dassie, Columbia University/LDEO
Edward Davis, University of Oregon
Josh Feinberg, University of Minnesota/IRM
Doug Fils, Ocean Leadership
Russ Graham, Penn State University
Eric Grimm, Illinois State Museum
Ben Hardt, USGS
Sonja Hausmann, University of Arkansas
Sean Higgins, Columbia University/LDEO
Brian Huber, Smithsonian
Virginia Iglesias, Montana State University
Randall Irmis, University of Utah
Emi Ito, University of Minnesota
Chris Jenkins, University of Colorado/INSTAAR
Jim Klaus, University of Miami
Kerstin Lehner, Columbia University/LDEO
Xiaoming Liu, Carnegie Institution of Washington
Amy Myrbo, University of Minnesota/LacCore
Charles Nguyen, University of Minnesota
Anders Noren, University of Minnesota/LacCore
Ryan O’Grady, University of Minnesota/LacCore
Thomas Olszewski, Texas A&M University
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Anne Thessen, Data Conservancy
Michael Tuite, Marine Biol. Lab/Data Conservancy
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Lisa Park-Boush, NSF
Executive Summary

This report summarizes outcomes of an NSF-supported workshop, entitled Drilling, Sampling, and Imaging the Depths of the Critical Zone, which was conducted on October 24–26, 2013, in the days preceding the annual meeting of the Geological Society of America, in Denver Colorado. The workshop hosted 49 participants from 35 institutions scattered over 2 continents. Participants represented diverse disciplines, including geophysics, geochemistry, geomorphology, soil science, hydrology, and drilling technologies. Participants were also diverse in career level, ranging from second-year graduate students to directors of national and international facilities and programs. Over the course of two days of presentations, breakout groups, and plenary discussions, the following 10 outcomes, recommendations, and conclusions were reached: (1) There is strong interest and sense of excitement around advancing deep critical zone (CZ) research through a program of drilling, sampling, and geophysical imaging; (2) The CZ research community has now embarked on a long-term effort to unveil the deep critical zone at a scale appropriate to enhanced understanding of processes vital to the evolution of the CZ and to the prediction of CZ response to change in the future; (3) Shallow drilling and geophysical imaging projects do not have a funding source of their own, yet there is a need expressed across the community, including multiple disciplines, to support both drilling and geophysical studies of the deep CZ; (4) Overcoming limitations imposed by disciplinary silos will require new connections between CZ scientists, near-surface geophysicists, and experts in drilling technologies (some promising connections were made at the workshop); (5) Funding mechanisms must accept that proposals to study the CZ could (and often should) have strong geophysics and drilling components; funding of such work could alternatively be structured around a service model (similar to NCALM for LiDAR imaging) over the long-term; (6) Drilling and geophysics need to go hand in hand to capitalize on potentially powerful synergies and to understand the great compositional and spatial variability of the CZO; (7) The observations that are made using drilling and geophysical imaging should be driven from a hypothesis-testing framework; (8) The CZOs have already made many of the measurements needed to simultaneously test and demonstrate the value of geophysics and drilling with abundant existing data to fuel hypotheses; (9) A program of cross-disciplinary education is recommended to grow a new breed of CZ scientists who are educated in deep CZ investigation methods including drilling and geophysics; a good way to start may be to follow the REU model already established at NSF; (10) A panel of experts should be formed to serve in an advisory role for the growing community of scientists interested in deep CZ research using drilling and geophysical imaging.

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What is the “Critical Zone”?

The “critical zone” (or just the “CZ”) has been defined as the near-surface environment where water, rock, air, and life meet in a dynamic interplay that generates soils, sustains ecosystems, and shapes landscapes (Brantley et al., 2007; Chorover et al., 2011). Understanding the chemical, physical, and biological processes that influence the CZ and the life it supports is important across a diverse range of problems, from assessing soil sustainability over timescales of human observation, to quantifying feedbacks between climate, weathering, and tectonics over millions of years (Brantley et al., 2006; National Resource Council, 2010). Increasingly, these problems are being tackled in exciting studies that are bridging a broad range of disciplines, from geophysics to geochemistry and from hydrology to soil science.

Motivation for a workshop on drilling and imaging the “deep CZ”

The CZ extends from the outer periphery of vegetation to the lowest limits of freely circulating groundwater (Brantley et al., 2006). Yet, thus far, subsurface CZ research has focused mostly on just the upper 1-2 m or so of weathered rock and soil (Riebe et al.). Although this work has greatly advanced understanding of soil production (Heimsath et al., 1997), erosion (Blanckenburg, 2005), weathering (Anderson et al., 2002), and biogeochemical cycling (Chorover et al., 2007), it is now increasingly recognized that the top 1-2 m, and indeed life as we know it at Earth’s surface, is often profoundly influenced by processes that occur beneath it, in saprolite and fractured rock that collectively extend to depths of 100 m or more in many landscapes (Holbrook et al., 2014; Goodfellow et al., 2013; Rivé et al., 2013; Wald et al., 2013; Anderson et al., 2013; Leopold et al., 2013; Befus et al., 2011; Buss et al., 2013; Buss et al., 2010; Fletcher et al., 2006; Anderson et al., 1995; Graham et al., 2010; West, 2012). This deeper layer, referred to here as the “deep CZ”, lies below the limits of most CZ studies to date. Hence it is an “unmeasured zone”, despite its widely recognized importance in surface-subsurface interactions and the feedbacks that are inherent in the development and maintenance of weathering profiles and the ecosystems that they support.

With the establishment of a diverse network of Critical Zone Observatories (CZO), both in the United States (Anderson et al., 2008) and elsewhere (Banwart et al., 2011), our understanding of the CZ has deepened markedly. So too has recognition that the community must investigate processes at greater depths within the CZ to understand its evolution to the present, its trajectory into the future, and its influence on the sustainability of vital ecosystem services (Riebe et al.). The deep CZ is crucial theater of processes and interactions relevant to geobiology, geochemistry, geomorphology, and soil science. For example, there are clear indications that the chemistry and hydrologic response of streams at the surface may often depend crucially on CZ processes in complex fractured bedrock systems at depth (Anderson et al., 2002; Onda et al., 2004; Langston et al., 2011; Kuntz et al., 2011; Salve et al., 2012). This implies that characterization of the deep subsurface is crucial to predicting how the CZ will evolve in a changing climate. In addition, it has been shown that the degree of weathering in saprolite may be a key regulator of soil production (Burke et al., 2007; Dixon et al., 2009), making quantitative understanding of the deep CZ crucial to addressing topics ranging from soil sustainability to landscape evolution. Surface processes affect – as well as depend on – deep weathering (Frazier and Graham, 2000; Clarke and Burbank, 2011), raising the prospect of exciting, yet-to-be explored feedbacks among landscape evolution, regolith formation, biogeochemical cycling, and hydrologic processes (Brantley et al., 2011). Hence it’s evident that deep CZ research is a key 21st Century frontier for a number of subdisciplines within the broad field of Earth-systems science, including watershed hy-
hydrology, geobiology, geomorphology, soil science, and low-temperature geochemistry (National Resource Council, 2010).

One of the great hurdles in understanding and quantifying processes in the deep CZ is depth itself; regolith and subsurface biota, the objects of study, are difficult to characterize in situ because they are mostly buried at difficult-to-access depths (Montgomery and Dietrich, 2002; Heilweil et al., 2006; Winter et al., 2008; Sherriff et al., 2009; Befus et al., 2011). Near-surface geophysical techniques can be employed to help image the subsurface over broad scales (Robinson et al., 2008; Samouëlian and Cornu, 2008), but interpretation of such images is problematic in the absence of direct observations of physical and chemical properties of material at depth. Such direct observations are usually possible through drilling and coring, for spot sampling of solid-phase geochemistry, microbiology, pore-water solutions, and other material properties (Begonha and Braga, 2002; Olona et al., 2010). Boreholes from drilling have the added advantage of providing access for pump tests and installation of long-term hydrologic and geochemical monitoring equipment (Day-Lewis et al., 2006). Yet the logistics and technical difficulties of coring make minimally perturbed, representative samples difficult to obtain, especially from deep boreholes that would be ideal for long-term monitoring installations.

Coring and borehole installations are time-consuming and expensive, placing practical limits on the number of holes that can be drilled in the characterization of the deep CZ. Hence it is crucial to make each drilling effort as effective as possible at addressing key questions about the deep CZ in different landscapes. To achieve this goal, studies of the deep CZ need to be able to optimize locations of boreholes, to provide a high yield of data per unit cost invested in drilling and instrumentation. The traditional approach to identifying prime borehole locations involves geophysical imaging of the subsurface during preliminary site investigations (Kieft et al., 2007). In deep CZ research, geophysical imaging of the subsurface takes on added importance, in the aftermath of coring, as a way to extrapolate the spatial extent of subsurface heterogeneities (Robinson et al., 2008; Befus et al., 2011) observed in individual cores. Such heterogeneities are typically both extensive and often also key targets of study for hydrologists, soil scientists, geobiologists, biogeochemists and geomorphologists alike (Banfield et al., 1999; Hubbard and Rubin, 2000; Massoud et al., 2009; Graham et al., 2010).

In a synergistic development for deep CZ research, the field of near-surface geophysics is in the midst of a renaissance, with its own recently established focus group within the American Geophysical Union and a recently established journal, entitled Near Surface Geophysics. This represents tangible evidence of a growing community of geophysicists who are actively studying what we refer to here as the deep CZ. This surge in interest in near-surface geophysics dovetails nicely with the recent surge in interest from Earth scientists who are advancing towards research goals in understanding Earth’s deeper records via a renewed commitment to continental scientific drilling in the US. Hence, the time is right for a community-wide consensus on how to best advance CZ science on a vital mutual research frontier for a diverse array of disciplines.

**Workshop objectives**

The goal of this workshop was to develop a community-wide, cross-disciplinary consensus on how to overcome the traditional difficulties of deep CZ research. The target disciplinary backgrounds of participants included CZ researchers and near-surface geophysicists, as well as engineers with experience in drilling, coring and borehole instrumentation. The workshop was designed to exploit the chance alignment of: (i) an increasing need for advances in deep CZ research, voiced in a recent consensus of CZ scientists from around the world (e.g., see Riebe et al., in review); (ii) recent advances in near-surface geophysics, includ-
ing improved techniques for imaging the deep CZ and interpreting geophysical properties in terms of CZ architecture; and (iii) recently renewed momentum behind establishing a formal program of continental scientific drilling in the US. It was recognized that the workshop would need to bridge disciplinary gaps and foster productive new collaborations among scientists and engineers from diverse backgrounds, in order to be successful. As indicated next, the expertise and backgrounds of actual participants was indeed very diverse. Moreover, over the course of a series of presentations and breakout meetings during the workshop, there was lively discussion that converged on a series of concise recommendations. We hope these recommendations will serve as a foundation for advancing study of the deep CZ through a coordinated program of targeted drilling and geophysical imaging.

**Workshop participants**

The workshop was advertised through a number of e-mail list serves, including “gilbertclub”, “GEO-MORPH-L”, “CZEN”, and “GEOPHYSICS”. The workshop was also advertised to CZO co-PIs, students, collaborators, and affiliates directly via the lead PI, who were apprised of the workshop by the workshop PIs. Our advertisements included a clear call for applications from researchers from diverse disciplines at all career levels. An example advertisement is included in Appendix E. Prospective participants submitted a total of 53 applications using an online application form available at [http://csdworkshops.geo.arizona.edu/Denver_CO.html](http://csdworkshops.geo.arizona.edu/Denver_CO.html). All applications were accepted, but four of the successful applicants (including three from NSF and one from the US Forest Service) were unable to attend due to complications related to the government shutdown. Hence, there were 49 attendees representing 35 different institutions (Table 1) scattered across North America and Europe (Figure 1). On their registration forms, which applicants completed online, participants self-identified themselves as follows (with corresponding numbers of participants in parentheses): “Graduate students” (12); “Professors” (27); “Post-docs” or “Research scientists” (8); and “Other” (2) (see Table 1). Although the official award announcement for the four new CZOs had not yet been made at the time of the workshop, all ten of the current Critical Zone Observatories sent representatives numbering 25 in total. In addition, there were representatives from the US Geological Survey, ANDRILL (the Antarctic Geologic Drilling program), LacCore (the National Lacustrine Core Facility), WyCEHG (the Wyoming Center for Environmental Hydrology and Geophysics), and SoilTrec (the European CZO group) numbering 10 in total. Disciplines represented by participants were diverse, including geophysics, geochemistry, geomorphology, soil science, hydrology, engineering, and drilling technologies. The expertise and interests of participants are captured in this report in a list of self-reported summaries gathered from workshop registration forms (Table 2). In addition to filling out surveys, participants also contributed 10 white papers, collected here in appendices, and 10 posters, which were on display throughout the workshop.

Fig. 1 – Google Earth images showing distribution (push-pins) of institutions represented by participants at workshop convened in Denver (star).
**A brief account of what happened at the workshop**

The workshop was held in conference rooms at the Hilton Garden Inn in downtown Denver, Colorado from October 24–26, 2013. A copy of the schedule for the workshop is included in Appendix E. Some modifications were made as the workshop progressed in response to feedback from participants. This section provides highlights of what actually happened during the workshop.

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**First order questions include:** Where is the bottom of the CZ and how should it be defined? How does the base of the CZ relate to the surface? What factors control the thickness of the CZ and the variability of CZ thickness?

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**Plenary keynote presentations**

On Thursday, October 24th, participants gathered for an icebreaker dinner at the Hilton Garden Inn in downtown Denver. (Many of the participants stayed in this hotel during the workshop and thus capitalized on the low lodging rates secured as part of a block deal by the conveners.) Following the dinner, there were two excellent keynote talks about needs and prospects in deep CZ research. The first was given by Professor Bill Dietrich (UC Berkeley and lead PI on the new, Eel R. CZO) and the second was given by Professor Sue Brantley (Penn State and lead PI on the Shale Hills CZO). These talks provided motivation and context for the workshop activities that followed.

Topics that Dietrich stressed included: (i) the fundamental importance of understanding the topography of unweathered bedrock at depth (in particular it is a crucial boundary condition for all processes in the critical zone); (ii) the merits of studying “characteristic” hillslopes at each site that might reflect, in a general way, how the surface and subsurface interact during deep weathering; (iii) the general observation that regolith thickness increases from the channel bottom to the drainage divide; (iv) the need to focus some effort on the ridge, where weathering can be conceptualized as a 1 D process; (v) the hypothesis that the position of the water table is a regulator of bedrock weathering in some landscapes (i.e., if bedrock can’t be drained, it can’t be weathered); and (vi) the need for multiple theories about bedrock weathering to motivate the drilling campaign.

Topics that Brantley stressed included: (i) the control of weathering at depth by acid-base reactions and redox titrations; (ii) the weathering front is an undulating surface where O2 and CO2 in circulating waters are depleted (i.e., electron rich rock has neutralized the water as it moved down through the subsurface); (iii) case study: oxidation of biotite in granite drives fracturing and produces a thick (10 m) profile of regolith, whereas regolith on diabase, which is iron-rich, is thinner (2 m), due to downward propagation of CO2 front before O2, (iv) when weathered minerals are observed at the surface in landscapes, it implies that erosion is fast compared to weathering (or, rather that residence time is too short to completely deplete soil of mineral); and (v) saprolite may be thickest at ridges because fluctuations are largest there.

**Plenary talks on drilling and sampling the deep CZ**

On Friday, October 25th, the workshop reconvened at 7 am over breakfast, which was followed by the first session of talks on drilling and sampling of the deep CZ. The first speaker was Dennis Nielson (DOSECC) on the basics of drilling in the CZ. There were several important messages conveyed in this talk: (i) there are challenges to drilling at remote, off-road sites in steep country that might be preferred by CZ scientists; (ii) there are technical challenges to recovering core from incoherent weathered material, which may often be desirable sample material in a deep CZ drilling project; and (iii) DOSECC is available to help with

**Hypothesis:** The depth of the weathering zone is controlled by tectonics, erosion, climate and climatic history.
these technical challenges. Some of the possibly useful technologies discussed included freeze coring to extract unconsolidated materials, and a number of in-situ tests (blow counts, standard penetration tests, cone penetration tests) to quantify properties of subsurface in zones that yield limited core materials for laboratory tests.

The next two talks included results and discussion about recent successful applications of drilling to CZ science. Brian Clarke was first with a presentation about drilling at the Shale Hills CZO; his topic was geologic preconditioning (i.e., lithology and fracture distribution) and its influence on deep-CZ processes. As the title suggests, Clarke’s talk focused on the role of lithology in influencing subsurface properties, including fractures. He showed how borehole geophysics can help in measuring fracture spacing and orientation in wells. This was followed by a talk by Heather Buss, who highlighted results from drilling at both the Luquillo CZO, and a CZO in the Czech Republic. Buss’s talk highlighted results from each site, including the finding of repeated zones of highly weathered and fresh rock, which made core recovery difficult at the Luquillo CZO. She ended with a sobering warning about not underestimating the difficulty of sampling the deep CZ by drilling. In particular she stressed the reality that most of the local drilling companies that CZ scientists might use will not know how to drill/core through unconsolidated materials, particularly when they are very variable in coherence as a function of depth.

This was followed by an introduction to the posters, which were on display in an adjoining room throughout the workshop; these introductions consisted of brief two-minute “pop-up” talks with one or two slides featuring overview images and graphs of poster content. Many of the graduate students and some of the other participants presented introductions to their posters during this time. Topics spanned a diverse range, from isotope fractionation during basalt weathering to the use of geophysics to quantify the depth to bedrock along an elevation transect. One of the pop-ups was delivered by Anders Noren, who highlighted core research facilities available at LacCore. This session was followed by a brief coffee break and a period of time where people could gather and talk about the posters in the next room.

Next, participants gathered in the plenary room for talks by Olivier Bour (Geosciences Rennes), Bob Graham (UC Riverside), and Suzanne Anderson (University of Colorado, Boulder). Like the first set of morning talks, this set was topical, featuring specific examples of deep CZ research, with an emphasis on aspects of sampling. Bour discussed tracer studies to image flow pathways and fracture geometry with GPR and time lapse imagery; an important take-home message was that in-situ
experiments (a form of sampling) can be used to determine properties of the subsurface empirically, and thus have an important place at the table along with geophysical imaging and coring. Next, Graham gave an overview talk of the deep CZ from the perspective of a soil scientist, with an emphasis on the nomenclature and properties of “saprock” and “saprolite”. Graham also stressed the importance of biological processes that generate these layers (e.g., penetration of mycorrhizal hyphae to depths much greater than roots, and the role of roots themselves in the breakdown of rock at depth). Then Anderson discussed drilling work at the Boulder Creek CZO and the Coos Bay site of her PhD dissertation, showing how drillholes could be used to map subsurface 3-D structure. Anderson also discussed response of wells to the fall 2013 storm that pummeled the Front Range, where the Boulder Creek CZO is situated.

**Breakout Session 1**

After a break for lunch, which was provided by the workshop, participants returned for breakout group discussions. There were three breakout groups. This culminated in a plenary synthesis, wherein each breakout group presented outcomes. This was followed by group discussion. Summaries provided by breakout group leaders are provided next.

Group 1 discussed the first order questions that remain unresolved: Where is the bottom of the CZ and how does one define it? How does the base of the CZ relate to the surface? In particular, what factors control the thickness of the CZ, and the variability of CZ thickness? Group members recognized that, to address these questions, the community will need to determine subsurface architecture (spatial distribution of material properties) within a broad tectonic and geologic framework. It may be possible to accomplish this using geophysics to extend 1D view from cores to 3 dimensions (across slopes). The point was raised that describing fractures in boreholes will not be a panacea for hydrologic modeling of subsurface flow. In addition it was stressed that most hydrologic models are based on physical observations and not on geochemistry, which reflects fluid flow. Roadcuts may work well for calibrating geophysical techniques (shallow seismic refraction and GPR).

Group 2 discussed an overarching strategy to tackle deep CZ unknowns in a community wide project. Step 1 is to establish context: topography, surficial geology, soil maps, and geophysics, including a synthesis of existing site data. This is a good time to look at proxy locations (roadcuts, quarries, etc.). Step 2 would be to formulate multiple hypotheses, based on current theory. At this stage one could target observations and measurements at sites where competing hypotheses disagree, based on simulations and back-of-envelope estimates that put bounds on what one should expect to see according to different models. Step 3 would be to “saw” or trench the ridge as deeply as possible. This would provide horizontal context, at least near the surface (as far down as you could get with the trenching). It would, in particular, allow 2-D observations and measurements of soil, saprolite, and the near-surface bedrock zone. Step 4 would be to drill the ridge with multiple holes for multiple purposes. It will be crucial at this stage to understand tradeoffs of how many holes to drill. The idea came up to make a matrix of which types of samples needed from each hole are compatible with others and which are not, and why. It was stressed that in context, the drilling will be relatively cheap, compared to the personnel costs of sampling, analysis, and interpretation, which will always be the bulk of the budget.

Group 3 discussed competing model-driven hypotheses that leverage existing well instrumented sites and informative datasets, such as those from the CZOs. They discussed the idea of beginning the testing with inexpensive observations including push tests and small (Winkie-type) drills, ground-based geophysics, and geoprobing. This would in-
form future drilling of more expensive boreholes. One recommendation was to develop a proposal vetted by community for drilling plan for a more expensive drilling program with core extraction. They discussed post-drilling infrastructure development. They also discussed the need for expertise to help inform and execute drilling, reflecting on themes introduced earlier by Buss and Neilson.

**Plenary Synthesis**

In the plenary synthesis of Day 1, implementation strategies were a continuing theme. It was argued that one might drill a specific lithology across topographic and climatic gradients to develop a theory to explain observations. One possibly testable hypothesis that was suggested was that the depth of the weathering zone is controlled by tectonics, erosion, climate and climatic history. A series of theoretical models, developed from competing conceptual frameworks, would provide specific predictions of measurable CZ properties across the sites.

It was suggested that the community might coordinate the drilling activities and science questions so that they could be integrated and explored at all 10 CZO locations. This would bring the CZOs together as a network, as originally envisioned by NSF. An unresolved question that came up (especially from coPIs of the Intensively Managed Landscapes CZO) was what fresh bedrock is, and where its boundary might be when the landscape is underlain by 1000s of m of unconsolidated materials.

Specific outcomes of the workshop were discussed. It was recognized that the workshop would need to culminate in a set of specific recommendations. A debate arose over whether the community should focus on a very specific research question or a series of general questions that might be addressed through combinations of subsurface techniques. It was noted for example, that the community might suggest a program in which its researchers developed the skill sets, methodologies, and technologies on the way to the initiation of a program that explores variations across controlling factors of the deep CZ. The framework for such a program was discussed and it was recognized that such an effort would need to have both theoretical and pragmatic aspects. It was recommended that the community might suggest a three-year study proposal to illustrate how the field work might be implemented, with the goal of bringing together the technical skills and to articulate the problems. Plenary talks on geophysical imaging of the near surface

On Saturday, October 26th, participants reconvened after breakfast (provided by the workshop) for a session on geophysical imaging that started with a talk by Lee Slater (Rutgers) and ended with a talk by Steve Holbrook (WyCEHG). These talks were somewhat longer and involved than the talks of the previous day, and Slater and Holbrook used the time to give broad overviews of what can be done in the near surface with geophysics, including case studies for illustration.
Slater has been particularly interested in methane release from peat lands, and he featured that work in his talk. He also featured work on groundwater-surface water interactions at sites on the Columbia River in Washington. Slater highlighted several tools: fiber-optic distributed temperature sensors; resistivity; and ground penetrating radar. Slater focused on the challenges of geophysical imaging of the deep critical zone. The limited resolution of the imaging was discussed, and it was stressed that a parameter of interest must be identified. Slater also stressed the power of joint inversions of multiple types of geophysical data and or investigations that include measurements of both geophysics and hydrologic data.

Slater discussed at length some of key aspects of resistivity. In particular he stressed that resistivity is a complex function of many things CZ scientists care about, including moisture content, surface area, porosity, temperature, and groundwater composition. In general, petrophysical relationships are used to interpret results. Induced polarization is a type of resistivity measurement. It reflects how energy is stored and is affected by surface area. Slater also discussed the use of towed arrays and cross-borehole resistivity to do tomography. Resistivity can also be measured over time, both from continuous monitoring and using tracers.

Slater clarified that GPR does not work in conductive materials. Hence it is crucial to know the conductivity of the material. GPR is sharper than resistivity. It can be used to measure moisture content using a petrophysical model. Measurements can be made down boreholes. Permittivity of soil, water, and air may need to be known. Slater stressed the challenge of imaging fractures, which are planar features; geophysics is better at resolving change across a continuum.

Slater stressed the importance of driving the geophysics with hypothesis-based science. He likened geophysical imaging to “eye-candy” if it is not accompanied by a physical framework for interpreting it. However, it was recognized that it should be easy to find the depth to bedrock and how it varies, thus solving a major 1st order challenge of deep CZ research. Ground-truthing, via drilling, is needed to interpret layering observed in geophysical images.

Steve Holbrook followed Slater with a talk in which he suggested that geophysical interrogations of the CZ might start with airborne geophysical surveys, for a broad overview, and progress to ground-based investigations at sites identified in part from the airborne data. He motivated the talk by saying that geophysics can help researchers test CZ hypothesis and that it can both add value to and benefit from drilling. Holbrook focused for some time on seismic refraction as a tool for identifying the bottom of saprolite and for quantifying porosity. Porosity is of course important in hydrology but also in understanding weathering in the deep CZ. It may also be possible to measure the subsurface structure with high resolution (10 m scale) using full waveform inversion techniques applied to seismic refraction.

EM induction and electrical resistivity were also discussed. Holbrook indicated that 4 to 5 people could get 1 km/day of resistivity data. He also highlighted the possible usefulness of time-lapse resistivity to show differences in conductivity over time, with particular reference to tracer studies. Holbrook discussed Ground Penetrating Radar next, indicating that it may be useful in imaging fractures and other reflectors in weathered granodiorite. He stressed the need for direct observations to confirm patterns inferred from the GPR. Holbrook then talked about a series of tools including magnetics, sub-bottom profilers, complex resistivity, and magnetic resonance sounding. He finished his discussion of techniques on airborne geophysics, highlighting the possible benefits of making measurements quickly over broad scales.

Next Holbrook shifted to a discussion of how geophysics could be used to answer questions about
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the deep CZ. Examples included: quantifying aspect-related differences in weathering profiles; climatic and topographic effects on weathering; and the thickness of regolith. Some of the key challenges to making advances are: overcoming current limits on horizontal and vertical resolution to quantify heterogeneity; parameterizing petrophysical relationships, so that geophysics can be used to measure flow and water holding capacity; using passive source (ambient-field) seismic approaches to maximize use of information and thus resolve more detail in the subsurface. He stressed the importance of not overly relying on a single technique (i.e., GPR, or seismic, or resistivity) but rather should always seek to use the strengths of each method to overcome the weaknesses of the others. Holbrook stressed that geophysics should insofar as possible always be accompanied drilling and that drilling should be informed by geophysics. Downhole geophysical logging is something to consider at any significant deep CZ drilling effort.

Finally, Holbrook set the group up for the breakout session by asking whether the community can come to a consensus on “baseline” geophysical data that should be acquired at CZ sites. He also suggested that the CZO’s would be well served by acquiring airborne geophysical data as a baseline subsurface dataset (akin to LiDAR for the surface).

**Breakout Session 2**

The morning talks were followed by a coffee break, provided by the workshop, and then a set of morning breakout group discussions about geophysical imaging. Summaries discussed in a plenary synthesis are given below:

Group 1 raised the compelling concept of calibrating geophysical images using direct observations from a site where it is easy to collect data. This could lead to measurements in areas that are more difficult. They identified several questions that could be answered with geophysics, including: What is the total amount of stored water in porous rock? What are the lower and upper boundaries of porosity? They also noted the importance of quantifying petrophysical parameters; it was suggested that the CZOs could become an initial database of geophysical parameters. There was recognition that airborne geophysics would be a great tool. It was argued that we should construct a matrix of geophysical methods and what they can do, what they cannot do, and the limitations of each. There was discussion of distributed temperature sensing, EMI, and both surface-based and downhole ERT, downhole temperature monitoring, and downhole Nuclear Magnetic Resonance (NMR). The value of airborne geophysics for at least some of the CZOs was discussed.

Group 2 discussed the importance of measuring depth to bedrock, depth to clay-rich illuvial horizons, depth to original soil surface, the location and size of corestones and fractures, and spatially distributed hydraulic conductivity. They introduced the term “depth to critical interfaces” to refer to these measurements. There was also discussion of the spatial distribution of properties both on the surface and at depth. They wondered how these properties vary across the CZOs. They recognized the importance of multiple methods at each site and wondered if it was suggested that the full data-set of properties would help geophysicists develop petrophysical models. They also asked whether gravity, not discussed at length in the morning talks, could yield information about weathering at depth.

Group 3 discussed the importance of bringing geophysicists together with hydrologists, geomorphologists, and geochemists. They recognized the tradeoffs between high resolution borehole data and lower resolution surface surveys. The CZOs provide rich opportunities to validate coupled observations from drilling and geophysical imaging with existing datasets.
idea that airborne surveys may be the best way to integrate this data was discussed. The strength of looking at surfaces, interfaces, and changes in time using geophysics was discussed. It was recognized that quantifying surface area as a function of depth is a different way of quantifying depth to bedrock. Questions came up about how to identify the depth of weathered bedrock using geophysical imaging. The group made a list of questions and issues that might be addressed with geophysics: (i) quantifying spatial variations in subsurface properties in a way that we cannot be done via direct measurements from a single borehole; (ii) drilling probably should never be done without geophysics; (iii) geophysics might be trained using hydrology, including pump tests and tracers; and (iv) use wells to extrapolate data and ground truth geophysics. As a way forward, the group suggested that the community should request support for cross-site work between CZO sites. The goal would be to solve a common problem across the CZO sites using geophysics.

**Grand Synthesis**

After lunch, provided by the workshop, there was a plenary grand synthesis of what was learned during the workshop, culminating in a discussion of study design and recommendations for future actions. Participants started by restating the importance of deep CZ research. It was recognized that the evolution of the deep critical zone changes how earth’s surface interacts with everything, affecting land-atmosphere-biota interactions, influencing its own evolution, and governing the conveyance of water, energy, and Earth materials across the surface as well as at depth. Understanding precisely how is essential to an integrated understanding of the critical zone.

The base of the critical zone is a critical boundary condition for a vast array of surface process-
observations are needed to drive hypotheses. The tension inherent in these needs is further enhanced by the fact that hypotheses are needed for the foundation of viable proposals to fund the work.

A consensus was reached to build on the CZOs, at least at first, and then populate study sites along state-factor gradients (i.e., sites spanning gradients in lithology, climate, and tectonics). This would bring in a much wider community with new types of expertise that add to the whole. It was deemed wise to start by making measurements in CZOs that are already well developed. The concept of establishing a panel of experts, to help guide the effort, was raised. It was recognized that this would help build a community of scientists to enable cross-site comparisons and leverage a quickly evolving knowledge base on methodology and data interpretations.

Outcomes, Recommendations, and Conclusions

The Drilling, Sampling, and Imaging the Depths of the Critical Zone workshop brought together 49 scientists from diverse disciplines for two days of community-building discussion on how to overcome outstanding challenges of deep CZ research. Specifically, the focus was on the part of the CZ concealed at depths that are difficult to directly access without major excavations or intensive drilling campaigns. Based on discussions that arose after 10 oral presentations, around 10 posters, in two breakout session (consisting of three breakout groups each), and during three plenary discussion sessions, we offer the following summary of outcomes, recommendations, and conclusions:

1. There is strong interest in advancing deep CZ research through a program of drilling, sampling, and geophysical imaging. This is a consensus that represents opinions from a broad community of geochemists, geophysicists, geomorphologists, soil scientists, and drilling engineers. The strong attendance at the workshop, with representation from each of these disciplines underscores the excitement that people have been expressing recently around this research objective.

2. Workshop participants agreed that the community is at the beginning of a long-term effort to unveil for the first time the deep critical zone at a scale that is appropriate to understanding of processes that are vital to the evolution of the Earth’s terrestrial surface to its current state and to understanding the sustainability of critical zone services into the future.

3A. Shallow drilling projects do not have a funding source of their own, separate from disciplinary programs at NSF and other agencies. In addition, drilling projects are not currently part of the funded CZ proposals to the extent that the workshop participants feel drilling should be, given the importance of the deep CZ in the coupled biological, chemical, and physical processes that shape Earth’s surface, modify its soils, and drive its biogeochemical cycles.

3B. Shallow geophysics does not have a funding source of its own, separate from disciplinary programs at NSF and other agencies. In addition, shallow geophysics projects are not currently part of the funded CZ proposals to the extent that the workshop participants feel that it should be.

3C. All agreed that the time is right to support wide campaigns of coordinated drilling and geophysical studies of the deep critical zone.

4. A key challenge will be to overcome limitations imposed by disciplinary silos. Near-surface geophysicists will need to understand the significance of their trade with respect to advancing critical zone science. This will require new thinking and new studies involving geophysical sensors, instrumentation, and petrophysical interpretation. Leadership by programs like WyCEHG at the University of Wyoming may be key to overcoming these challenges, but the entire community needs to get behind the effort in support. Meanwhile, CZ scientists need to be made aware of the great advances geophysical imaging might help bring to understanding CZ evolution and processes.

5. We suggest that proposals to study the CZ could (and often should) have strong geophysics and drilling components. Funding of this work could be structured around a service model (similar to
NCALM for LiDAR imaging) over the long-term. LacCore, which has already claimed a role as a facilitator for continental scientific drilling (though this was not known at the time of the workshop), could aid in making petrophyics (measurements on core material) accessible to the geophysicists for calibrations.

6. There was a consensus that drilling and geophysics go hand in hand. One can be (and has been) done without the other, but this overlooks potentially powerful synergies (Figure 2). Moreover, it can be argued that the great compositional and spatial variability of the CZO demand use of both techniques together. The corollary is that there is no single method that will solve all problems in the CZ. Some sites and questions will require different tools.

7. The observation that we make using drilling and geophysical imaging should be driven from a hypothesis-testing framework.

8. The CZOs have already made many of the measurements needed to simultaneously test and demonstrate the value of geophysics and drilling. Here “test” refers to validation of techniques. Value comes from proving that the drilling and geophysics can help us overcome gaps in understanding of CZ processes and evolution. A consensus was reached that the community could overcome the limitation inherent in the need to calibrate and demonstrate the value of geophysics by building an initial program around the CZOs. It is important to stress, however, that it would be crucial to follow up initial work by expanding along state-factor gradients. This would bring in a much wider community of people who know their study locations and have new types of value-added expertise.

9. A program of cross-disciplinary education is recommended to grow a new breed of CZ scientists who are educated in deep CZ methods including drilling and geophysics. For example, there could be an REU in near-surface geophysics. Another way to foster education would be through field camps (for both graduate and undergraduate students) at institutions with strong programs in near-surface geophysics.

10. A panel of experts should be formed to serve in an advisory role for the growing community of scientists interested in deep CZ research using drilling and geophysical imaging.

References


Continental Scientific Drilling Workshop Series


Going deep to quantify limits on weathering in the Critical Zone (in review): Earth Surface Processes and Landforms.


Rain, rock moisture dynamics, and the rapid response of perched groundwater in weathered, fractured argillite underlying a steep hillslope: Water Resources Research, v. 48, no. 11, p. n/a–n/a, doi: 10.1029/2012WR012583.


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Table 2. Self-reported interests of workshop participants

- My main interest lies in physical and geochemical development of the weathering profile in fine-grained, glaciogenic materials
- I am a groundwater hydrologist who is mainly interested in the characterization of groundwater systems, especially in heterogeneous crystalline rocks. My main research activities focus on the understanding of groundwater systems at watershed scales and on the development of new methods for characterizing and imaging the flow and transport properties of deep heterogeneous critical zones.
- PI of Susquehanna Shale Hills CZO
- I am interested in understanding the coupled mechanisms that create the critical zone and develop its characteristics including its resilience. In particular, I study the relationships between chemical, physical and biological weathering of rocks in the deep critical zone.
- I am applying Ground Penetrating Radar and Electromagnetic Induction to study the variability of soil depth across Providence watershed in CZO Southern Sierra.
- The Jemez-Catalina CZO seeks to understand the role of deep subsurface flow paths in biogeochemical weathering reactions and surface water dynamics.
- Developing methods of imaging, exploring, and sampling the deep CZO and quantifying material properties - understanding how the deep CZO influences geomorphic, hydrologic, weathering processes.
- Coming to the workshop as representative of the Luquillo CZO
- My interest is the depth of the regolith and its role in groundwater movement in catchments. Specifically, I am interested in estimates of regolith volume, temporal scales for water movement in the regolith and its connection to montane stream and meadow systems.
- I am interested in developing methods to identify crucial information before drilling in order to make drilling as efficient as possible. I am also interested in combining direct sampling and geophysical methods.
- I am interested in the process of granitic weathering and using geophysics to help answer hydrological and botanical questions.
- Collaborator in the proposed Reynolds Creek CZO; interested in linkages between plant water use, groundwater, and stream networks.
- Ecological processes in our research area in the Prairie Potholes Region of the northern Great Plains is controlled by deep critical zone processes that have occurred over the last 10K years. We seek to characterize these processes over large areas using core and geophysical data.
- Geomorphology/chemical weathering - Processes that control critical zone thicknesses and the spatial distribution of chemical weathering.
- The formation, distribution, and role of weathered bedrock in landscapes, ecosystems, and hydrology.
- Interested in how lithologic (and hence geochemical/mineralogical) differences affect rates of weathering and the distribution and thickness of the weathered zone. Also interested in feedbacks between regolith and plants.
- The primary interest focuses on remotely sensing and sampling the CZ, not only from a geological and landscape evolution focus, but also with respect to hydrogeologic and geochemical standpoint. Coming from a strong background in near-surface coastal plain studies, I want to better serve additional purposes with colleagues and students in my department who focus on geochemical and hydrological issues and to strengthen undergraduate and graduate training and research in CZ science.
- I am working on the Southern Sierra CZO trying to coordinate Geoprobe sampling of deep regolith and pairing that with Geophysics. I am very interested in cross-CZO and experiments to investigate...
water holding capacity of the deeper regolith and the potentially buffering capacity of this water reservoir.

• My interest is to use geophysics, particularly seismology, to help inform deep Critical Zone science. I am more specifically interested in quantifying the spatial distribution and frequency of heterogeneity at the scale of seismic resolution.

• I have been working on near-surface geophysical characterizations of the deep (10’s of m) critical zone for the past couple of years, including several field surveys at the Southern Sierra CZO. I am also Co-Director of the new Wyoming Center for Environmental Hydrology and Geophysics, which aims to promote cross-disciplinary work in the CZ, with an emphasis on hydrogeophysics.

• I am interested in chemical weathering and solute export (chemical erosion), particularly in subsurface environments. Recent work includes grain discrete geochemical microanalysis of minerals, and the elemental and isotopic chemistry of surface and subsurface waters to constrain weathering reactions. Currently, I am focused on using transient atmospheric tracers to constrain residence times of groundwater and estimate groundwater weathering and subsurface solute export rates.

• Use of geophysical (in particular ground penetrating radar) and associated subsurface drilling tools (vibracoring, geoprobe, diamond drilling) to map the subsurface in 2D and 3D perspectives.

• I am interested in soil development feedbacks between vegetation and bedrock and wish to better understand methods for measuring the deep critical zone.

• Together with Riebe and others, I developed the method of inferring long-term weathering rates from cosmogenic nuclides and geochemical mass balance. To do this right, one needs to know the unweathered bedrock composition, and thus one needs to sample well below the nominal “bedrock boundary”. I have also championed the importance of deep “residual” storage in catchment hydrology, which also requires understanding the deep CZ.

• I am interested in using non-traditional stable isotopes to trace processes in deep Critical Zone. In addition, I am interested in drilling and sampling the DCZ.

• To better understand the subsurface dimension affecting surface processes and degradation that I have been investigating with terrestrial LiDAR on hillslope surfaces and to gain insight into regional differences, such as temperate and polar climates. I am interested in knowing about the techniques that will be developed for studying the deep critical zone and whether it will be a field of research I would want and be able to pursue further through collaborations when I complete my PhD.

• 1. The legacy of sub-surface frost cracking in temperate non-glaciated soil-mantled landscapes on critical zone architecture and present-day processes 2. Feedbacks between surface topography (curvature) and deep Critical Zone topographically generated fractures.

• New Calhoun CZO and general interest in watershed hydrology and interactions of deep and shallow flow systems.

• Development of tools and techniques to effectively drill and sample the CZ.

• Understanding linkages between surface and deep subsurface. Scaling approaches from point measurements to landscape. Pedogenic transformations in weathered bedrock.

• I am interested in drilling into the critical zone with a focus on water and rock chemistry.

• Sensors and Measurements

• Currently, I am a PhD student in the Department of Geography and Environmental Engineering at Johns Hopkins. My research broadly falls within the category of landscape hydrology though I am most interested in understanding flow and transport processes in the thick saprolite of the eastern Piedmont. I am eager to discuss methods of mapping, conceptualizing, and generally understanding the processes which are at work within the deep Critical Zone, especially those that may affect flow mechanisms.

• I’ve submitted a proposal to NSF for the Continental Scientific Drilling (CSD) Coordination Office and we are currently waiting to hear their decision about this matter. I would like to participate in the CZO
Workshop to better understand the needs of the CZO community with respect to continental drilling and also take the opportunity to meet the people involved in CZ science.

- Coupling geophysical techniques and deep CZ imaging with digital soil mapping techniques.
- Controls on the spatial pattern of fresh bedrock topography under ridge and valley topography; near-surface geophysics; fractured rock hydrology.
- Lower boundary issues in pedology and CZ science
- I've been a PI on the Shale Hills CZO, and am now actively working at the Boulder Creek CZO. I'm interested primarily in groundwater flow at both.
- Advancement of geophysical characterization and monitoring technologies for provided spatiotemporal information that can better constrain understanding of deep critical zone processes.
- The deep Critical Zone science is the topic of my research on chemical weathering and the generation of mineral surface area.
- I am interested in deep critical zone science from the point of view of understanding weathering processes at the scale of watersheds, and how they regulate long-term global climate and supply of nutrients to ecosystems. I published a paper in 2012 that used a global inversion to consider the problem of where weathering takes place and identified deep weathering as being particularly important in upland settings, which complements prior and ongoing work on hydrochemical perspectives.
Appendices - PreProposal Documents (White Papers) and Notes

Appendix A: White Papers - Scientific Drilling and the Evolution of the Earth System
Appendix B: White Papers - Drilling active tectonics and magmatism
Appendix C: White Papers - Investigating ultra high-enthalpy geothermal systems
Appendix D: Workshop Notes - Cyberinfrastructure for Paleogeoscience
   (including workshop breakout sessions, an inventory of current community cyberinfrastructure resources and
   the results from the online community survey)
Appendix E: White Papers - Drilling, Sampling and Imaging of the Depths of the Critical Zone
Appendix A: PreProposal Documents (White Papers)

SCIENTIFIC DRILLING AND THE EVOLUTION OF THE EARTH SYSTEM: CLIMATE, BIOTA, BIOGEOCHEMISTRY, AND EXTREME EVENTS

May 17-19, 2013
Norman, Oklahoma
Conveners: Lynn Soreghan and Andrew Cohen
Anderson_Stoneman Lake
Baker-Fritz_Amazon
Bernor_ALBER
Bernor_LakeHoewenegg
Bird_LagodeTota
Brady_KingsCynFan
Chin_Arctic
Curry_Glacial
Dyer_Paradox
Fluegeman_EOCore
Harwood_ANDRILL
Heil_Loess
Hinnov_Isua
Huber_Tanzania
Kaufman_Ediacaran
MacDonald_Snowball
Malka_GreenRiver
Miller_Mochras
Nelson_Kentucky
Russell_Tanganyika
Sageman_OAEs
Smith_ButteValley
Soreghan_Permian
Terry_GreatPlainsCZO
Toscano_Caribbean
WoldeGabriel_YardiLake
Wolfe_GiraffeKimberlite
Zimmerman_MonoLake
Stoneman Lake, Arizona, Paleoenvironments (SLAP) Drilling Project

Project Members:

R. Scott Anderson (Northern Arizona University)
Peter Fawcett (University of New Mexico)
Erik Brown (University of Minnesota, Duluth)
Joe Werne (University of Pittsburgh)
Darrell Kaufman (Northern Arizona University)
Gonzalo Jiménez-Moreno (University of Granada)
John Geissman (University of Texas, Dallas)
Michael Ort (Northern Arizona University)

Long continuous sediment cores from lakes provide enormous potential for interpreting paleoenvironmental histories. An increasing number of these records (examples) are revolutionizing our understanding of changing terrestrial conditions on glacial – interglacial timescales. We have assembled a core of researchers interested in obtaining a sediment core from Stoneman Lake, Arizona, in order to expand our knowledge of paleoenvironmental history of the arid Southwest. The following is a brief summary of issues pertaining to the science and logistics of obtaining sediment cores from Stoneman Lake for the purposes of paleoenvironmental reconstruction of a sensitive region in the American Southwest.

Science

Location and age of target deposits. Stoneman Lake is located at 34° 47’ N, 111° 31’ W, in the Mormon Lake volcanic field, on the southern edge of the Colorado Plateau (the Mogollon Rim). The lake, situated at 2047 m elevation, is spring fed and currently alternates between a marsh and a lake, with water levels having fluctuated by 3+ meters over the last 25 years (Hasbargen 1994). This is probably due to its small closed drainage basin (ca. 2.5 km²).

The Stoneman Lake basin is a circular depression formed by a collapse in the mid-Miocene to late Pliocene volcanics (Dohm 1995), based on analogy with volcanic units of Mormon Lake area (Holm 1994; Holm and Shafiqullah 1994). It is likely a collapse above a breccia pipe in Paleozoic rocks (Kaibab Fm, Redwall Ls, Martin Fm; Beus et al. 1966; Holm et al. 1989).

A well drilled sometime prior to the 1960s penetrated ca. 100 m of sediment without hitting bedrock (McCabe 1971). Unfortunately, the drill log cannot be located. McCabe (1971) used a SAR from the top 1.3 m and volumetric calculations to estimate ca. 100-200m of sediment would have accumulated in ca. 300-600k years.
Compelling science issue(s) / hypotheses to be addressed by drilling, focusing on topics in paleoclimate, paleoenvironments, paleobiology, and/or extreme events. Several reasons compel us to propose this record for analysis:

(1) Stoneman Lake potentially has a long record covering several glacial cycles in a region poorly known for the middle to late Pleistocene, many of which contain evidence of millennial-scale change.

(2) It is one of a series of basins with long records in the West across both temporal and geographic gradients, allowing us to temporal / spatial patterns through time. Important southern basins and records include Santa Barbara Basin, CA (MIS 1-6; Heusser 1992), Baldwin Lake, CA (MIS 2-4; Kirby et al. 2006), Owens Lake, CA (MIS 1-6+; Woolfenden 2003; Bischoff et al. 1997; Litwin et al. 1997), Snowmastodon site, CO (MIS 4-6; Johnson et al. 2001), Valles Caldera, NM (MIS 10-14; Fawcett et al. 2011). A more northerly transect of basins includes Carp Lake, WA (MIS 1-5; Whitlock et al. 2000), Clear Lake, CA (MIS 1-5; Adam et al. 1981; Adam and West 1983), Bear Lake, UT/ID (MIS 1-7+; Jiménez Moreno et al. 2007); Great Salt Lake, UT (MIS 1-13+; Davis 1998; Davis and Moutoux 1998).

(3) Stoneman Lake presently, and likely did during previous interglacials, exists as sensitive vegetation (ponderosa pine / piñon – juniper) and climatic ecotone with a small drainage basin. This suggests that sediments will record short-term as well as long-term environmental change.

(4) It is in an area directly impacted by summer monsoonal precipitation, with the potential for determining the long-term relationship between summer and winter precipitation for the Southwest. In addition, occurring in an arid region periodically impacted by severe drought, sediments here have the potential for long records of drought, and can provide a link between hydroclimate and temperature, as Fawcett et al. (2011) did for the Valles Caldera, NM, record.

Stratigraphic completeness, continuity and resolution. Unfortunately, well logs from previous drilling cannot be located. However, comparison with other nearby lake records suggests potential for excellent pollen preservation for both interglacials and glacials in Stoneman Lake. For example, Hasbargen (1994) found excellent pollen and organic preservation (< 5% deteriorated) in a Holocene section of Stoneman Lake. Anderson (1993) & Anderson et al. (2000) found excellent pollen preservation in ca. 40k yr core from nearby Potato Lake – MIS 2 and 3 sediments were complete, but a gap did exist in the Holocene. Hevly et al. (1985) and Anderson et al. (2000) documented good preservation in ca. 50k Walker Lake, located north of Flagstaff in San Francisco Peaks.

Age of the deposit. Mid to late Pleistocene - Please see above section.

Existence of baseline stratigraphic, and paleontologic data. Presently the only stratigraphic and paleontologic data for Stoneman Lake sediments come from
Hasbargen (1994) for the Holocene, a study encompassing pollen, diatoms and macrofossils.

Existence of or/potential to collect supporting data from correlative outcrops, geophysics or prior drilling. Although well logs do not exist, or cannot be located, we assume we can get geophysical information prior to drilling, using one or more techniques.

Existence of or potential to collect a robust age model through the target interval. We anticipate being able to develop a chronology for these sediments by:

(1) We assume that using one or more techniques we will be able to obtain a paleomagnetic profile, and identify younger geomagnetic excursions.

(2) There exists the likelihood of tephra occurrence in Stoneman Lake sediments. A tephra was identified in a Dry Lake, Arizona, sediment core (NW of Stoneman Lake) at ca. 486-491 cm depth. One potential source of this tephra is Sugarloaf Mountain (ca. originally thought to be 200+ka BP, but now 92ka [Ort, pers. comm.] to the east in the San Francisco Peaks.

(3) An Amino Acid Racemization dating curve might be able to be constructed. Shells of the shallow aquatic snail Gyraulus were found in the Holocene section of the Hasbargen (1994) Stoneman Lake record.

(4) Identification of short-lived, globally recognized magnetic field polarity events in the sediments, such as the Blake, Albuquerque, and Jamaica (Lund et al., 2006).

Logistics

Challenges to drilling the site and obtaining subsurface information (e.g., suitable terrain for site-survey geophysics). Although the configuration of the basin and the lack of permanent water may make it difficult, one possibility would be to use a technique like CHIRP as a potential for mapping sediments. If this does not work, we might try other passive or active seismic techniques.

Access for drilling equipment. Access to Stoneman Lake is excellent. The site is ca. 12.8 km NW of Interstate-17. The first 8km is paved while the last 4.8km is improved dirt road. A second access from the east is an entirely improved dirt. A small residential community occurs around the lake, providing year-round access to the lake. In recent years, the lake has dried so that the surface is essentially a marsh. In the winter, it is unusual, but not unheard of, for the surface to freeze in years when the lake fills. A well-maintained boat ramp exists at the lake for times when it contains water. Otherwise, access to the sediments would be through driving a drill rig out onto the marsh surface.

Permitting issues. Permits for sediment drilling would have to be obtained from the
US Forest Service. We could obtain a special use permit for scientific research. There is a Home Owners Association for the residents, but it does not own any property into the lake. We would want to work with the HOA to keep the residents informed.

*Complexity of operations, local impact/cooperation (community and environmental).* There are several year-round and many part-time residents with properties bordering Stoneman Lake. We would want to hold an informational meeting about this project to inform residents of the merit of the study. At least one resident has registered serious interest in assisting us with a place to store equipment.

Stoneman Lake, 17 August 2008

**References**


Trans-Amazon Drilling Project: History of the Neotropical Rain Forest

US Investigators
Lead PI, Paul Baker (Professor, Duke University: paleoclimate, geochemistry)
Lead PI, Sherilyn Fritz (Professor, University of Nebraska: micropaleontology, paleoclimate)
Co-PI, David Battisti (Professor, University of Washington: climate dynamics)
Co-PI, Brian Horton (Associate Professor, University of Texas: tectonics)

Introduction and Motivation: The origin of the great biodiversity observed in tropical South America has spurred debate for well over a hundred years (Darwin 1859, Agassiz and Agassiz 1868, Wallace 1878) and remains one of the foundational problems in modern science. We propose to undertake an ambitious drilling project that will continuously sample sediment from late-Cretaceous to modern age in four different ancient sedimentary basins that transect the equatorial Amazon region of Brazil, from the Andean foreland to the Atlantic Ocean (we also plan to submit a related IODP proposal with the goal of extending the transect to sites on the Amazon Fan offshore in order to take advantage of marine biostratigraphic age dating). The overarching goals of this project are (1) to document the evolution of biodiversity of the Amazon forest across most of its entire reach throughout its entire history, and (2) to determine how the evolution of the physical environment (e.g. tectonics, climate, geomorphology) has shaped the generation, distribution, and preservation of neotropical biodiversity.

The Need for Drilling: Long sedimentary records distributed across the continent are needed to characterize the evolution of the physical environment, forests, and biodiversity of the Amazon -- in most of the region, these sedimentary records are only available by drilling. In general, the Cenozoic geology of the westernmost and easternmost parts of the Amazon region is much better known than is that of the central Brazilian Amazon, the focus of our proposed study. Many geological studies have been undertaken in the Peruvian, Ecuadorean, and Colombian Andean foreland basins of the far western Amazon, where the uplift of foreland basin sequences provides outcrops of Cenozoic sediments that are relatively easily accessed and observed. Yet even here, complete and continuous sections are non-existent. At the far eastern margin of the Amazon region, on the Ceara Rise far offshore of the mouth of the Amazon, drilling on ODP Leg 154 recovered long sequences of sediment with some Amazonian provenance. Even longer stratigraphic records were recovered in industry exploration wells on the Amazon slope and shelf – these were well dated using marine microfossils. In the Brazilian central Amazon basin, however, Cenozoic outcrops are scarce, vegetation-covered, and deeply weathered - the critical sedimentary sequences are only available in the subsurface. Despite extensive hydrocarbon exploration undertaken in the Amazon region, including many deep drill cores and thousands of kilometers of seismic lines, little is known about the non-petroleum-bearing shallow (Cenozoic age) part of the sedimentary record, the part of the record that holds the key information about evolution of the modern rain forest and establishment of the Amazon River drainage system. Most samples that still exist are decades old, composed only of cuttings, undated, and relatively difficult to access even by Brazilian scientists. Without a doubt, the proposed study can only be accomplished by collecting continuous, fresh drill cores from the central Amazon region.

Geological Background: South America is a continent, more so than any other, whose land surface is dominated by large rivers. Many of these modern rivers flow along the major axes of old and long-lived sedimentary basins – in Brazil, the Solimões, Amazonas, Araguaia, Tocantins, Parnaiba, and Paraná rivers all are hosted by eponymous ancient sedimentary basins. This is significant for our proposed work, because it means that the modern rivers provide a convenient means to access the seismic stratigraphy and geology of the underlying deep sedimentary basins. The Brazilian Amazon region is largely comprised of a series of east-west trending, Paleozoic-age sedimentary basins, overlying and bounded by Precambrian continental basement rocks to the north and south. From west to east these basins are the Acre, Solimões, Amazonas, Marajó, and the Foz do Amazonas (which includes the Amazon deep-sea fan); all of these
basins have several km of sediment fill. The basins are separated from each other by structural highs that displace basement rocks, have been reactivated many times in the Phanerozoic, and, at least in some cases, remain active to the present day. From west to east these structural features are the Iquitos Arch, Purus Arch, Gurupá Arch, and an unnamed structural high offshore of the mouth of the Amazon that separates the Marajó graben from the Foz do Amazonas basin. These features have previously been posited as topographic highs that played a role in the development of Amazon trans-continental drainage and the origins of Amazon biodiversity. Understanding the Cenozoic evolution of this region is critical to developing a clearer picture of the changing biodiversity of the rain forest and the changes in the surface environment (e.g., climate, tectonic, geomorphic change) that may have contributed to diversification or extinction. The proposed project will be the first to sample the entire late Cretaceous to modern record across the entire Amazon with the main purpose of determining pollen and spore diversity through time as a record of the evolution of rain forest biota, climate, and paleo-environment.

Research Questions to be Addressed with Drilling:

(1) What is the history of biotic diversity across the Amazon basin? Is the Amazon a "museum", steadily accumulating diversity through time? Or does diversity co-vary with global temperature, perhaps as a result of areal expansion of the tropics? Does diversity respond to specific environmental drivers, such as Andean uplift? Are there any clear extinction events throughout the Amazon forest? Contemporary α-diversity of trees is highest in western Amazonia, where precipitation is higher and soils are more fertile than farther east (ter Steege et al. 2003). Did this west-to-east gradient persist throughout the Cenozoic? Is diversity in some parts of the Amazon more stable through time than in others?

(2) What is the history of tropical South American climate from the late Cretaceous to today? How did the Paleocene-Eocene Thermal Maximum impact rain forest taxa? Does the thermal history of the Amazon mirror the global history surmised from the deep-sea oxygen isotopic record? Were thermal optima relatively wet or dry periods? The Held and Soden (2006) paradigm predicts a wetter Amazon in past thermal maxima and a drier Amazon in past cold periods. Was this in fact the case?

(3) What is the history of Andean uplift and erosion? Andean uplift and erosion is recorded in Andean foreland basins. The Acre foreland basin may be ideal for this purpose in being close enough to the Andes to receive detrital input, yet distal enough from the Andes to have a relatively slow and continuous rate of accumulation of finer-grained sediment (more tractable for paleoecological study). A related pair of questions is whether or not the transition from under-filled to over-filled foreland sedimentary basins controlled the history of Amazon drainage and how development of trans-continental Amazon drainage was connected to Andean uplift.

(4) When did west-to-east continuity develop between Amazon basins? This can be directly tested using U/Pb in detrital zircons from the equivalent time interval of each drill core. Did the Purus Arch act as an ancient hydrologic divide between eastward and westward drainage? Was the breaching of the Purus Arch related to the origin of the Amazon Fan, as previously proposed? Did the Gurupá Arch, the Marajó Basin, and the Pre-Cambrian "Shelf Arch" have similar roles (to the Purus) in controlling ancient Amazon drainage history and sedimentation on the Fan?

(5) If we encounter the K/T boundary, how is it expressed (clear extinction signal, iridium anomaly, black carbon, etc.) in the Amazon?

(6) Did the global Miocene onset of C₄ grasslands impact Amazon biodiversity? We predict that this transition will be imprinted on the carbon and hydrogen isotopic record of organic matter and perhaps be evident in enriched biogenic silica, such as opal phytoliths.

(7) What is the spatial extent of various geomorphic features, including marine incursions (Räsänen et al. 1995; Hovikoski et al. 2010), "mega-lakes" or "mega-wetlands" (Hoorn and Wesselingh 2010), and structural arches (e.g. the Fitzcarrald, Iquitos, Purus, Michicola, and Vaupes, Patton et al. 2000) that have been posited to have caused vicariance and subsequent biological diversification?

Proposed Site Survey, Selection of Drill Sites, Permits: We expect that the proposed drilling can be undertaken for relatively modest costs and that access to the drilling sites and the drilling itself will be
quite straightforward. We anticipate requesting four drill holes, one in each of four basins, which will penetrate to the upper Cretaceous at a typical depth of 500 to 1000 meters. We can access each of these sites by boat. We suggest that drilling can be undertaken by truck-mounted drill rigs, which are shipped to drill sites located exactly on the river margin. Before we undertake drilling, additional information on the optimal locations for siting the drill holes is needed. Much of this information can be gleaned from Petrobras reports and generalized stratigraphic columns that are available in the region around each of our proposed drill sites. The final selection of sites and the placement of these sites in the context of known sub-surface stratigraphic architecture will be aided by a site-survey cruise. We have limited funding from the Brazilian government for some preliminary fieldwork (CNPq Grant #402575/2012-1) and also will submit a proposal to US NSF for additional site-survey funding. The proposed research will involve senior personnel from several US, Brazilian, and German universities or research centers. Project PI Baker is an Adjunct Professor at Universidade Federal Fluminense in Niteroi, Brazil and will work with Brazilian collaborators to obtain the required permits for sampling in Brazil.

Work Plan: 

(1) **Downhole logging:** We expect to deploy a standard suite of slim-hole logging tools, including electrical resistivity, sonic velocity, natural gamma, and magnetic susceptibility. In addition, we would likely deploy a borehole televiewer to aid in textural analysis of sedimentary and deformational structures and will explore applicability of the Delft paleomagnetic logging sonde to these low-latitude drill sites.

(2) **Core description, sedimentology, and inorganic geochemistry:** We will analyze cores for sedimentary structures, grain size, mineralogy, bulk geochemistry, organic and inorganic carbon, sulfur, and biogenic silica. We will use the full suite of logging tools, including high-resolution digital photography, whole- and split-core magnetic susceptibility, acoustic velocity, gamma density, electrical resistivity, natural gamma, color spectrophotometry, and scanning XRF. Where present (expected in Marajo Basin), we will undertake marine microfossil biostratigraphy. We plan stable C and O isotopic analysis on any ostracode or other shell materials and paleosols that we expect to encounter in the drill cores. If we encounter the K/T boundary, we will undertake high-resolution analysis for Ir and other extra-terrestrial markers, as well as black carbon.

(3) **Palynology, plant macrofossils, palynostratigraphy, and charcoal:** The key analysis that we will undertake at high resolution on all drill cores is the quantitative determination of pollen and spore "morphospecies" and plant macrofossil remains (Jaramillo et al. 2006, 2010). These analyses will yield the data of forest biodiversity. Palynostratigraphic studies will also be undertaken as a method of age control in all basins, and palynostratigraphic zonations will be refined if we can develop a marine biostratigraphy in the Marajo basin. Charcoal analyses will yield information about fire history.

(4) **Paleomagnetic stratigraphy and absolute age dating:** We expect to be able to develop a paleomagnetic stratigraphy, and these largely terrestrial sequences should be ideal for retaining a stable paleomagnetic signature. Independent age control may be possible in some cases, as well-developed lateritic horizons in the central Amazon have been utilized for stratigraphic correlation (Truckenbrodt et al. 1982) and may contain phases (e.g., cryptomelane) suitable for Ar-Ar dating (Vasconcelos et al. 1994).

(5) **Provenance studies:** Several of the questions concerning evolution of Amazon drainage can be addressed by provenance studies of well-dated sediments from all of the drill cores. Mapes (2009) established the utility of U/Pb ratios for determining the provenance of detrital zircons in the Amazon basin – his results bear directly on the timing of the breaching of the Purus Arch and the eastward transport of Andean-derived sediments. Despite some caveats (e.g. Lawrence et al. 2011, Hietpas et al. 2011), the U/Pb method is considered reliable for determination of provenance.

(6) **Organic geochemistry:** We plan to analyze δ¹³C and δ²H of n-alkanes with the goals of reconstructing paleohydrology and deducing C₃/C₄ ratios. We will analyze chain-length distributions that contain information about vegetation type. We will determine CPI as a measure of preservation of organic matter against diagenetic alteration. We plan GDGT analyses to provide information on continental soil/air temperatures and soil pH (related to amount of rainfall).
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High Latitude Drilling for the Plio-Pleistocene ALBER Initiative

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The ALBER Initiative

The ALBER, or African Late Pliocene Biotic & Environmental Revolution, Initiative is tailored to forge a deeper global understanding of biotic changes associated with the ~2.6 Ma climatic excursion (recognized by many geoscientists to mark the beginning of the Quaternary and commencement of the Pleistocene; Palombo, 2007), and more broadly the 4-1 Ma interval. This prominent earth-life transition was marked by major faunal changes in Europe (the Villafranchian; Azzaroli, 1983; Rook and Martínez-Navarro, 2010), Asia (the Nihewanian; Qiu, 2006) and Africa (Werdelin and Sanders, 2010; Bibi et al., 2013). The ALBER Initiative includes some 60 internationally based scientists committed to producing crucial new specimen-level data from intensive field efforts, and to integrating their research results in this single initiative.

ALBER will engage in combined, coordinated, basic field research and intensive laboratory analytical work intended to yield detailed new data for the poorly-known African late Pliocene time period (~3.0 to ~2.4 Ma). This corresponds to “Interval C” of the East Africa Drilling Initiative (HSPDP Cohen et al., EAR1123000 and BCS1241859 funded projects). ALBER collaborators will, as part of their studies of mammalian and human evolution, extend this specific interval to 4-1 Ma (HSPDP intervals B-D). ALBER will make direct comparisons of geology, paleoclimate, paleoenvironments and mammalian evolution to the southern European Villafranchian and Chinese Nihewanian. A recent National Research Council report (C.E.S.C.H.E., 2010) on the relationship between human evolution and climate was ably summarized by deMenocal (2011): “The grand challenge will be to develop coordinated sets of observations to test proposed links between African climate and faunal change. The foremost task will be to improve the fossil and paleoclimate records, especially for those intervals where available evidence is most suggestive of climatic forcing of adaptive evolutionary change.”

ALBER broadens this scientific inquiry to augment East African terrestrial records and extend acquisition of these same records to higher, Eurasian, latitudes. If funded, the ALBER Initiative will provide a great range of testable hypotheses concerned with Old World intercontinental climate change and biotic response.

Nihowan Basin (NB), China

The Nihowan Basin is in the eastern end of the Loess Plateau in northern China, approximately 150 km northwest of Beijing. The NB includes a total thickness of 150 m. of fluvial-lacustrine and overbank deposits. The “classic Nihowan fauna” includes more than 40 mammal species (Teilhard de Chardin and Piveteau, 1930) that have been used as one of the standards of the early Pleistocene in East Asia, the Nihewanian land mammal age (Qiu et al., 2013). Field work during the last 50 years has revealed rich stone tool artifacts from several sites within the Nihowan Basin, such as Xiaochangliang, Donggutuo, and others (You et al., 1980; Huang, 1985; Wei, 1985; Wei et al., 1985), and several key sections have since been magnetically dated to be the earliest lithic site of Homo erectus in Asia, with a bracketed age range of 1.66-1.32 Ma for stone tool layers (Zhu et al., 2001; Zhu et al., 2004). Recent research on small mammal faunas has established a dense mammalian biostratigraphic sampling that spans from ~3.5 to 0.7 Ma (Cai et al., 2013). Nihewan large mammals share broad similarities with southern European Villafranchian faunas, especially that of Olivola (Val d’Arno). For example, of 20 genera shared with Olivola, more than half are of comparable stage of evolution, such as Canis, Megantereon, Pachycoelus, Chasmavorothetes, Elephas, Equus, Bos and Eucladoceros and others (Qiu, 2000; 2006). The prospects for drilling the Nihowan Formation are:

- Location and age of target deposits: North China (N40°05' E114°10'), Plio-Pleistocene
• Compelling science issues: continental climate change across Plio-Pleistocene boundary, hominin and mammalian evolution in response to environmental change
• Stratigraphic completeness, continuity and resolution: 150 m stratigraphic section spanning 3.5 to 0.7 Ma, ~50 mm/1000 years (HSPDP Intervals B-D correlative and younger)
• Existence of baseline stratigraphy and paleontologic data: multiple paleomagnetic sections, a rich and diverse mammalian fauna, and Paleolithic stone tool collections available
• Supporting data from correlative outcrops: multiple measured sections, exposures can be visually correlated within short distances, no prior drilling has been undertaken
• Existence or potential to collect robust age model: Chinese Loess Plateau has many high-resolution magnetostratigraphic sections that offer excellent age models
• Challenges to drilling the site and obtaining subsurface information: selection of sites to maximize stratigraphic continuity
• Access for drilling equipment: Chinese drilling companies available for contract
• Permitting issues: The Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) has cultivated excellent relationships with local cultural authorities in Hebei Province which will facilitate the issuing of permits
• Complexity of operations, local impact/cooperation: co-funding from Chinese sources is expected

Upper Valdarno Basin, Tuscany – the Type Villafranchian Mammal Stage of Europe.

The Upper Valdarno Basin (UVB) Villafranchian mammal sequence includes the historical reference sections for the European Plio-Pleistocene and forms an important basis for correlating penecontemporaneous deposits in Europe, Asia, South Asia and Africa. These deposits are rich in fossil vertebrate material and have been collected since Renaissance times and served as inspiration to Nicholas Steno in formulating the basic principles of modern stratigraphy (Ghinassi and Sagri, 2013; Rook et al., 2013). The Scottish palaeontologist Charles I. Forsyth Major initiated accurate stratigraphic records of fossil mammal collections in the late 19th century accompanying his extensive collections across the Valdarno Basin (Forsyth Major, 1877). Fossil remains from the Valdarno Fm. are extensive with collections housed by natural history museums in Basel, Florence and Rome housing the bulk of type Villafranchian mammals (Pareto, 1865) spanning from 3.5 to 1 Ma (HSPDP Intervals B-D correlative, and slightly younger). Azzaroli (1983) and Azzaroli et al. (1988) integrated century-long stratigraphic and paleontologic work on these deposits providing a mature and well sustained biochronologic subdivision of the European Villafranchian. The chronological subdivision of the Villafranchian was defined finally in the 1970s-1980s into successive “Faunal Units” assembled into Early, Middle and Late Villafranchian (Azzaroli, 1977, 1983; Gliozzi et al., 1997; Torre et al., 2001; Rook et al., 2013). Chronostratigraphic subdivision of the Villafranchian is currently understood to be: Early Villafranchian, Late Pliocene (~3.5 to ~2.6 Ma); Middle Villafranchian early Quaternary (~2.6 to ~2.0 Ma); Late Villafranchian, Early Pleistocene (~2.0 to ~1.0 Ma) (Rook et al., 2013). Since the 1990’s detailed UVB palynological investigations have provided an important archive of Plio-Pleistocene climate change (Albianelli et al., 1995; 1997; Bertini and Roiron, 1997; Mazza et al., 2006; Bertini et al., 2010; Ghinassi and Sagri, 2013). A comprehensive summary of the UVB stratigraphy and sedimentology (Fiolini et al., 2013; Ghinassi et al., 2013), structural geology (Bonini et al., 2013; Brogi et al., 2013), fossil mammals and their stratigraphy (Rook and Angelone, 2013; Rook et al., 2013), invertebrate assemblages (Esu and Ghinassi, 2013), palynological and paleoclimatic reconstructions (Bertini, 2013) and paleopedological characterizations (Fidolini and Andreotta, 2013) provide important, current data on the Valdarno Basin. The prospect for drilling the UVB Villafranchian sequence is:

• Location and age of target deposits: Tuscany, Italy, Plio-Pleistocene
• Compelling science issue(s): continental climate change across Plio-Pleistocene boundary, mammalian evolution in response to environmental change
• Stratigraphic completeness, continuity and resolution: over 400 m strata spanning 3.5 to 0.7 Ma including both the “traditional” (1.8 Ma) and new (2.58 Ma) Plio-Pleistocene boundaries
• Existence of baseline stratigraphic, and paleontologic data: multiple paleomagnetic sections and rich mammalian collections available for study
• Existence of, or potential to collect, supporting data from correlative outcrops, geophysics or prior drilling: numerous measured sections, exposures can be visually correlated within short distances, prior drilling available in the lower portion of the succession (an area that was exploited for lignite mining)
• Existence of, or potential to collect, a robust age model through the target interval: volcanic layer intercalated in the succession; high resolution palynological stratigraphy. Focusing on the 2.6 Ma event:
  o i) Within the Upper Valdarno Basin, depositional systems record this event with the accumulation of deposits in arid (eolic/fluvial) context of sedimentation (the only documented event of such a kind along the Apennine mountain chain)
  o ii) These arid deposits are calibrated by paleomagnetism and by tephra dated to 2.2 Ma, that constrain the succession
• Challenges to drilling the site and obtaining subsurface information (e.g., suitable terrain for site-survey geophysics): available seismic/magnetic survey; possible selection of sites to maximize stratigraphic continuity
• Access for drilling equipment: Access is not an issue. Italian drilling companies are available for contract
• Permitting issues: The Earth Science Departments of the University of Florence and Padua have cultivated excellent relationships with local authorities
• Complexity of operations, local impact/cooperation (community and environmental): as above

Databasing

The ALBER Initiative will utilize the mature, New and Old World (NOW; Helsinki, Finland) Database directed by Prof. Mikael Fortelius. The NOW database will initially assemble all mammalian systematic, chronologic and ecometric data for fossil mammals in the 3.0-2.4 Ma interval, and further target the 4.0-1 Ma interval for Ethiopia, Italy and China as part of the ALBER Initiative. Fortelius is likewise assembling data for this chronologic interval as part of the Turkana Basin Institute’s (TBI) research program. This database will provide rich opportunities for the community to integrate and analyze diverse biotic and paleoclimatic datasets.

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Drilling the Late Miocene Höwenegg Lagerstaette, Hegau, Southern Germany

Ray Bernor (Howard University) and Alan J. Kaufman (University of Maryland)

Introduction –

Höwenegg is a late Miocene locality (~10.3 Ma) exceptional for its remarkable lagerstaette of articulated fossil mammals and associated fossil animal and plant remains entombed in ancient lake sediments. The distribution and preservation of these fossils at several stratigraphic levels suggest episodic mass kill events. Insofar as the lake may have developed within the confines of a volcanic caldera or maar, we hypothesize that the animals died en-masse by asphyxiation due to rapid overturn of the lake and expulsion of massive amounts of carbon dioxide gas, similar to a recorded event in 1986 at Lake Nyos in the Cameroons that killed ~1700 humans and countless livestock.

The age of the Höwenegg lagerstaette is radiometrically constrained by single crystal argon age technique on volcanic rocks trenched from the deposit by Bernor and scientists at the Staatliches Museum für Naturkunde in Karlsruhe (SMNK; Swisher, 1996; Woodburne et al., 1996). Initial excavations, which led to the discovery of the articulated fossil mammals, were undertaken by Tobien and Jörg in the 1950s and 1960s (Tobien, 1986). Our current excavations – led by W. Munk and H.W. Mittmann at the SMNK – commenced in 2001 and continue to the present. We have identified four main fossiliferous horizons and have increased the number of articulated skeletons by our own excavations from 29 to 47, with hundreds of additional isolated vertebrate specimens (Munk et al., in preparation). Of paramount importance are the skeletons of *Hippotherium primigenium* (n = 16; Bernor et al., 1997) and *Miotragocerus pannoniae* (n = 24; Wolf, in prep.). The Höwenegg *Hippotherium* is a basal, primitive species of an extensive clade of Eurasian and African hipparionine horses that evolved between 11 and 0.5 Ma. The *Miotragocerus* species is uncommonly abundant at Höwenegg and is a primitive Old World bovid with apparent evolutionary relationships to living *Boselaphus* (South Asia), *Tetracerus* and possibly *Tragelaphus* (equatorial Africa). Characterization of mammalian skeletal morphology, functional anatomy, dental mesowear and microwear (Wolf et al., 2012) as well as carbon and oxygen isotopic studies are providing new insights into these taxa’s systematics and paleobiology, that are paramount to understanding their adaptations and evolutionary trajectories. These studies have consequences that transcend the lagerstaette and have relevance for Neogene Eurasian and African vertebrate evolution and paleoenvironmental reconstruction.

The Höwenegg project has archived all biotic elements for the 60 years duration of excavations. All vertebrate skeletons have been collected with 3D coordinates and precise stratigraphic provenance. Our research team has integrated the current and past collections from Höwenegg (Munk et al., 2007; in prep.; Mittmann et al., in prep.) providing an outstanding paleontological archive, which includes diverse mammalian, reptilian, amphibian and fish taxa, as well as limnic and terrestrial gastropods, pollen, seeds, fruits and whole leaves (Munk et al., 2007; in prep.).

Lake Höwenegg sediments accumulated when Central and Western Europe was experiencing subtropical to tropical climatic conditions. At the same time, conditions in the rest of Eurasia and Africa were characterized by warm temperate to tropical open country “savanna-like” woodlands (Bernor, 1983, 2007; Bernor et al., 1996; Eronen et al., 2009). At this time, the diversity and biogeographic extent of Eurasian and African large bodied great apes reached their acme, including members of the great ape-human clade (Bernor, 2007) and intercontinental
faunal exchanges occurred (Bernor, 1983, 1996, 2007; Bernor et al., 2009). Strategically acquiring correlative Old World lake drilling cores such as from Höwenegg will provide an important new context for understanding this interval’s paleoclimatic and environmental record for comparison with key Eurasian and African paleontological localities.

**Compelling science issues and hypotheses to be addressed by drilling –**

Drilling ancient Lake Höwenegg will provide us with new insights into the origin of lake and its sediments, as well as episodic environmental perturbations that led to the mass kill events. Our tiered agenda includes 1) site characterization using magnetic and seismic surveys, to evaluate the spatial extent and depth of the paleo-lake and identify appropriate locations for scientific drilling, 2) search for volcanic horizons that may be conducive to geochronological studies, and 3) high-resolution time-series micro-palaeontology, as well as mineralogy, elemental, and isotopic measurements (cf. Kaufman et al., 2007), to test our working hypothesis about the kill mechanism resulting in this spectacular lagerstaette.

Assuming the lake developed in a volcanic caldera or a maar, which are abundant in southern Germany, it is conceivable that there was a continuous or episodic flux of carbon dioxide (and perhaps hydrogen sulfide) to ancient Lake Höwenegg that resulted in the buildup of the gas its deeper reaches. Predictable consequences of this scenario include lower pH and Eh conditions in the water column that would dictate the types of clay and carbonate minerals that would be stable (Tosca et al., 2010). To this end, our time-series geochemical analyses will focus on the search for smectitic clays and iron-bearing carbonates associated with the lagerstaette horizons. Currently, iron carbonate (siderite) is found in Lake Nyos (Bernard and Symons, 1989), and significantly around volcanic inputs to several German lakes (Bahrig, 1988). The proposed kill mechanism for Höwenegg has similarly been proposed for the lagerstaette in the Eocene Messel Shale.

Through our time-series micro-paleontologic studies we additionally aim to characterize the paleoclimate of the Höwenegg lagerstaette. We will test the hypothesis that the Höwenegg locality represents a very stable regional ecosystem for its entire duration. These studies will provide baseline data for intra-provincial and inter-continental scale comparisons. Developing core data for Höwenegg will provide baseline data for the late Miocene Central European province (Bernor, 1983, 2007) for comparisons with other provincial (Rudabanya, Hungary) and extra-provincial great ape bearing localities in Spain (Can Llobateres), Turkey (Sinap), the Siwaliks (early Nagri) and Ethiopia (Chorora).

**Existence of Baseline Stratigraphic and Paleontologic Data:** The Höwenegg lagerstaette has been excavated since 1952 and important stratigraphic, sedimentologic and paleontologic data has been summarized by Tobien (1986), Jörg and Rothausen (1991), Heizmann et al. (2003), Munk et al. (2007, in prep.) and Mittmann et al. (in prep). A detailed monographic study of the fossil equid *Hippotherium primigenium* was published by Bernor et al. (1997) and the antelope *Miotragocerus* is currently undergoing study by Wolf. Other vertebrate taxa have been published by Giersch et al. (2010, *Trogontherium minutum*), Hünermann (1989, *Aceratherium incisivum*), Zapfe (1989, *Chalicotherium goldfussi*), Beaumont (1986, carnivores), Schleich (1986, Testudinata). The age of the deposit is known through a single crystal argon date of ~10.3 Ma, which has been corroborated by magnetostratigraphic (Berkeley Geochronology Center, Swisher, 1996) and biochronologic correlations (Woodburne et al., 1996).
Existence of, or Potential to Collect, Supporting Data from Correlative Outcrops, Geophysics or Prior Drilling –

The Höwenegg project undertook drilling on the western edge of the fossiliferous quarry in 2007 in cooperation with the Geological Survey Baden-Württemberg who agreed to drill this core solely for the purpose of further radioisotopic dating at the University of Heidelberg. To date no results have been reported, and no paleoenvironmental or other geochemical data were retrieved from that core. What the core did establish, however, is that the underlying earlier Miocene Upper Freshwater Molasse sediments lie two meters below the Höwenegg beds at the western edge of the quarry. Correlative outcrops do exist in the immediate vicinity of the Hegau volcanic district and there is a need to undertake magnetic and seismic studies to identify similar lacustrine sediments prior to undertaking additional local drilling. If funded, we intend to undertake an initial magnetic survey to find the lateral extent and deepest part of the Höwenegg lake beds in the valley to which the site is connected. We have good reason to believe that Lake Höwenegg had an approximately three km diameter (Jörg and Rothausen, 1991). Once the magnetic survey identifies the lake’s existing boundaries, we propose to undertake seismic studies to target the best places to drill two to three additional sites. The SMNK museum geologist is engaged in this research and the Geological Survey of Baden-Württemberg has undertaken previous geophysical research in the Hegau, but nothing has been published to date. Kaufman will be engaged in the geological and geophysical work and will identify additional scientists to undertake seismic studies. We intend to collect samples of all paleobotanical, as well as fossil invertebrate and vertebrate specimens, for study by our colleagues at the natural history museums of Karlsruhe, Stuttgart, Darmstadt, the Senckenberg Institute and Howard University. The University of Maryland (Kaufman) will undertake geochemical and isotopic analyses. As follow through, project members will survey the Hegau district beyond Lake Höwenegg for additional late Miocene lacustrine sediments.

Robust Age Model: As cited earlier, a robust age model for the Höwenegg lake sediments exists (Swisher, 1996). Drilling two to three additional cores will allow us to access volcanic materials from additional stratigraphic levels for new geochronologic determinations using single crystal argon and magnetostratigraphic methods.

Challenges to Drilling the Site and Obtaining Subsurface Information: The local terrain is suitable with a wide dirt road leading up to the site. The site of Höwenegg itself is protected by the Baden-Württemberg forest service and Town of Immendingen.

Access for Drilling Permit: This will be handled by the SMNK, which has supervisory responsibilities for the site and is supported by the Town of Immendingen.

Permitting Issues: There are no obstacles for permitting. We anticipate continued (since 2001) full support and assistance from the SMNK, Town of Immendingen, the Geological Survey and Regional Forestry service of Baden-Württemberg.
Bibliography:


Dr. Andrew Cohen (cohen@email.arizona.edu) and Dr. Lynn Soreghan (lsoreg@ou.edu ).
APPENDIX: Hegau Volcanic District, Hoewenegg Quarry and Skeletons of Hippotherium primigenium (lower left) and Miotragocerus pannoniae (lower right) both with fetuses in situs utero
Dr. Andrew Cohen  
Department of Geosciences  
University of Arizona  
Tuscon, AZ 85721

Dear Dr. Cohen,

Below you will find our pre-proposal for the NSF sponsored workshop: Scientific Drilling and the Evolution of the Earth System. If accepted, I would request support for two project team members to attend the workshop in Norman, OK, from May 17 to 19.

Thank you and I look forward to hearing the workshop committee’s decision.

Sincerely,

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The Lago de Tota Drilling Project

Principal Investigators: Broxton W. Bird (USA), Jaime Escobar (Colombia), Pratigya Pollisar (USA), Maria Isabel Velez (Colombia/Canada)

1.0 Science

1.1 Location and age of target deposits

Lago de Tota is located in Boyaca, Colombia, near the town of Aquitania in the Eastern Cordillera of the Colombian Andes at 3000 m above sea level (N5.544610, W72.928339; Fig. 1a). Lago de Tota (hereafter Tota) is the largest lake in Colombia with an area of 55 km², a length of 12 km and a width of 7.2 km. The lake has a maximum water depth of 60 m in the central basin and water depths of 40 m or more across much of rest of this basin (Fig. 1b). Sediment cores have never been retrieved from Tota and little is know about its sediment archive or limnology. Given that the lake is tectonic in origin, it is likely that there are thick sequences of sediments within the Tota basin that span at least the late Pleistocene. Some sources also suggest that the lake is stratified.

Fig. 1 (a) Map of South America showing the location of paleoclimate records from lakes and bogs (black circles), ice cores (triangles), caves (diamonds) and the target lakes, including Lago de Tota, that will be cores in July, 2011 (red circles). Also shown with the white dashed lines is the position of the ITCZ during the Southern Hemisphere winter (July) and summer (January). (b) Batymetric map of Lago de Tota (depths in meters). Red circles indicate planned core locations.

1.2 Lago de Tota Reconnaissance: Summer 2013

With funding from IUPUI, Dr. Bird and Dr. Escobar will lead a team of international scientists this summer with the goal of establishing a basic understanding of Lago de Tota’s potential as a target for deep drilling. Single drive 3.5 m-long percussion hammer cores will be collected from the deepest part of Lago de Tota and Livingstone cores from shallower littoral regions (Fig. 1b). The water column will be
characterized with profile measurements of pH, conductivity, redox potential, turbidity, temperature and dissolved oxygen. Water samples will be collected at 1 to 5 meter depth intervals for analysis of major, minor and trace elements, cations and anions. Vegetation, soil and bedrock samples will be collected from around the watershed. Funds are being sought to conduct a seismic survey of the lake.

Once cores are collected and returned to IUPUI, we will assess the potential to establish robust chronologies with $^{210}\text{Pb}$, $^{137}\text{Cs}$, $^{14}\text{C}$, and U/Th. We will also determine the sediment composition and which proxies will be suitable for paleoenvironmental reconstruction (e.g., carbonate $\delta^{18}\text{O}$, leaf wax $\delta^{D}$, diatoms, grain size, pollen).

1.3 Motivation, Questions and Hypotheses

Despite the ability of the South American Summer Monsoon (SASM) to significantly impact human and natural systems by rapidly shifting between pluvial and drought states (e.g., Lewis et al., 2011), relatively little is known about past variability in this system at timescales that are relevant to human society (10 to 100 year intervals). This is especially true in the Northern Hemisphere tropics because there are no published terrestrial paleoclimate records that are resolved at decadal timescales or better. Our understanding sub-millennial SASM variability is therefore largely based on the few high-resolution SASM records that have been produced from Southern Hemisphere South America (Moy et al., 2002; Cruz et al., 2005; van Breukelen et al., 2008; Cruz et al., 2009; Bird et al., 2011) and the Caribbean (Haug et al., 2001; Mora and Martinez, 2005). Obtaining new high-resolution paleoclimate records from the Northern Hemisphere South American tropics is therefore critical in order to improve our understanding of the SASM’s mean state and its natural variability. This information will allow us to test hypotheses regarding SASM variability under different mean climate states and during rapid transitions in climate boundary conditions (e.g., glacial terminations).

The Lago de Tota region is also home to several well-studied archeological sites, including the El Abra rock shelters. These shelters have evidence for human occupation starting at 14,500 yr B.P., making them one of the oldest known sites of human habitation in the Americas (Hurt et al., 1972). Climate records from this region therefore offer the opportunity to investigate relationships and interactions between human cultures and climate through comparison with the archeological record.

With long sediment core from Lago de Tota, this work will address the following hypotheses and questions:

1) The combined response of the SASM to insolation forcing on orbital timescales is meridionally uniform across the Andes, but zonally anti-phased across tropical South America.
2) Northern Hemisphere surface temperatures and North Atlantic sea surface temperatures are critical in driving Northern Hemisphere SASM variability.
3) Is SASM variability in the Northern Hemisphere in-phase or anti-phased with other climatological processes?
Northern Hemisphere monsoon systems on orbital, millennial and centennial timescales?
4) Climate changes in the tropical Andes have been associated with cultural changes such that periods of aridity coincided with cultural declines and pluvials helped cultures to flourish.

In addition to the questions and hypotheses listed above, long sediment cores from Lago de Tota will allow for comparison with paleoclimate records from other critical monsoon centers including Africa and Asia. Ultimately, this will improve our understanding of regional and interhemispheric monsoon dynamics and tropical hydrology.

2.0 Logistics

2.1 Access

The area immediately surrounding Lago de Tota is highly populated and a popular tourist destination. The town of Aquitania is located in close proximity to the lake and would be a logical base for drilling operations as it contains numerous hotels and other amenities. Tota can be accessed easily from multiple points along a ring-road that circles the lake. Roads to the lake and in the area are well-maintained paved and/or dirt roads. This will allow for drilling and geophysical equipment to be deployed on the lake with minimal difficulty.

2.2 Permits

Permits will be requested through La Universidad del Norte with the help of its research office and Dr. Jaime Escobar, co-investigator of this proposal and Director of the Institute for Sustainable Development. The Ministry of Environment and the Regional Autonomous Environmental Corporation will grant these permits. Sediment exportation permits will be requested from the Colombian Geological Survey.

2.3 Complexity of operations, local impact/cooperation (community and environmental)

This research will involve the local community while at the same time minimizing negative impacts to the environment. Specifically, we will seek the cooperation of the Regional Autonomous Environmental Corporation for the drilling operation. During the drilling operation, we will have students from nearby universities (Bogota, the Capital of Colombia is three hours away by car) and people from the community visiting us. We plan to have several Colombian graduate students under this project. The environmental impacts of the drilling operation will be minimal because the area around Laga de Tota is already highly developed and there are established access points to the lake.
3.0 References


Kings River Alluvial Fan Terrestrial Drilling (KRAFTD)
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Location and age of target deposits: upper Cenozoic Kings River Alluvial Fan, Central Valley, California. The estimated time span of the sedimentary record of the fan itself spans ~1Myr (Lee et al., 2010), with drilling expected to provide better resolved age-constraints on the fan and basin fill history and meter-scale resolution of the spatial and vertical distribution of depositional facies within the alluvial fan system. A better resolved age-model and understanding of stratigraphic architecture will inform how past processes recorded in these deposits influence the heterogeneous distribution of groundwater quality and chemistry over the same spatial and vertical scales.

Introduction & Motivation

Arsenic is a naturally occurring substance that is toxic to humans and often found in groundwaters sourced from sedimentary aquifers. Some examples of geologic deposits that contain groundwater with high concentrations of arsenic include the deltaic deposits draining the Himalayas (Saunders et al., 2005; van Geen et al., 2008; Guillot and Charlet, 2007), floodplain deposits of river systems (Berg et al., 2008, Weinman et al., 2008; Shah et al., 2008), and alluvial deposits in California’s Central Valley (Anning et al., 2012). In many cases, the concentration of arsenic in the groundwater varies dramatically over short distances (i.e. 10’s to 100’s of meters between wells). This heterogeneity of the groundwater arsenic, in several previous investigations, has been explained by the heterogeneity of the aquifer sediments (McArthur et al. 2011, Popacostas et al. 2008, Weinman et al. 2008 and 2011). In other words, stratigraphic age, architecture, and depositional history are often controlling small-scale differences in groundwater concentrations, making an important linkage between the sedimentary record and what we find in today’s groundwater. Therefore, we think that a better understanding of the sediments that make up our local aquifers—which is also our local sedimentary record—is critical to managing our water resources. Inasmuch, we see this continental drilling initiative as a platform for integrating Earth systems history investigations to directly benefit today’s society.

We see great potential for transferring the information from continental drilling efforts to a critical social health issue right here in California’s Central Valley. The Kings River Alluvial Fan deposits (which preserve a record of the past ~1Myr) are located in an ideal geographic location, such that (1) the interaction between tectonic subsidence of the San Joaquin basin, glacial stream outflow, and sediment supply provide a relatively complete record of deposition (Lee et al., 2010; Weissmann et al. 1999, 2002, 2005) and (2) drilling here will give an understanding of how temporal and spatial heterogeneity of depositional facies and architecture can be used by population centers that draw water from the fan deposits. Since it is within this diverse architecture (10-100m) of depositional facies that the Central Valley sources its water, and since the Valley shows a comparably chaotic patterning of groundwater arsenic (10-100m, Fig. 1a), it is likely that much of the groundwater arsenic heterogeneity is being controlled by the basin’s stratigraphy. This is why we would like to use upcoming drilling
efforts to reconstruct Earth’s history as an opportunity to also give important new understanding to groundwater and aquifer evolution.

![Map of Kings River, California](image)

Figure 1 – Location of the Kings River, California. The Kings River feeds into California’s Central Valley, a sedimentary basin containing Mesozoic–Cenozoic sediment records. Within the sedimentary architecture of the basin is groundwater being pumped for agricultural irrigation and for drinking purposes. Figure 1A shows how heterogeneous groundwater arsenic distributions are for individual wells tapping into the sedimentary deposits (USGS, 2012). Figure 1B is a zoomed-in picture of the Kings Alluvial Fan, which encompasses portions of Fresno, Hanford, and Visalia areas, and shows how variable groundwater arsenic is within a single unit of geomorphology. Initial drilling and sampling along this fan will focus on understanding how the fan and the aquifer co-evolved over the past ~1Ma using aquifer-age dating (optically stimulated luminescence) coupled with geochemical and traditional sedimentology.

**Drilling Plan**

A variety of drilling and sampling methods will be employed in this study. While there is a clear geologic and hydrogeologic goal for the study, there is an equally clear goal related to using a variety of drilling and sampling methods. Understanding and evaluating the efficacy of these various methods in support of scientific research, along with facilitating comparisons between these methods is that goal.

The drilling and sampling includes hollow-stem auger, direct and reverse mud rotary, air rotary casing hammer (ARCH) and sonic drilling. The sediment sampling will range from catch samples of discharged cuttings to continuous cores collected via either drive cores or sonic coring. Groundwater sampling methods will range from Hydropunch sampling as well as include the construction of small-diameter monitoring wells.

In total, 30 drilling sites spanning both sides of the ancient Kings River alluvial fan are planned. Ideally the sites will be located as evenly spaced as possible across the fan, to
facilitate lateral and vertical comparisons across fan. The final locations will be based on access to the sites. The proximal fan locations will be drilled with shallower range methods (e.g. HAS) while the more distal fan locations will be drilled with the deeper ranged drilling methods (e.g. reverse rotary). The sites to be drilled and continuously cored will be held in reserve, and will be drilled where greater resolution in the subsurface is required. The final drilling will involve the placement of the small-diameter monitoring wells at sites selected based on the findings of the previous drilling and sampling. We intend to conduct borehole geophysical logging in each of the fluid-filled boreholes, either before or after sampling, depending on the drilling and sampling method employed. The geophysical logging will include spectral gamma logging, spontaneous potential, short and long normal resistivity, and single point resistivity. Students working on the project will correlate the results to existing well-logs from the USGS and California’s Oil and Gas industry.

Logistically, the sites are all on flat, easily accessible terrain that will facilitate access for drilling, sampling and geophysical work. We anticipate little to no real challenges to the drilling and sampling sites that will be selected. The drilling sites will be initially selected to occur on public land and right-of-ways, with private land being the least attractive drilling sites. Access permitting will be with local cities and Fresno County, and drilling permits will be obtained from Fresno County. There will be limited local impact, as the drilling will be targeted away from populated areas. We anticipate significant local approval of the work, as there are several social, educational and academic benefits to the research.

**Stratigraphic Framework**

This drilling project will build upon existing age estimates and current stratigraphic interpretations of how accumulation, non-deposition, and/or incision within the fan system responded to Pleistocene glacial-interglacial cycles, which in turn, influenced stream discharge and sediment supply (Weissman et al. 2002, 2005). The Kings River Alluvial fan deposits are grouped into allostratigraphic (unconformity-bounded) units with depositional age estimates ranging from Pliocene (Laguna Formation) to Pleistocene (Turlock Lake Formation: \(\sim\)1Ma to 600 ka, Riverbank Formation: 130-330 ka, and Modesto Formation 10-40 ka). The limited age constraints are based on correlations with glacial episodes, carbon dating of charcoal, and ash beds within individual units (Marchand & Allwardt 1981, Lettis 1988, Dundas et al. 2009). The increased spatial and temporal resolution afforded by this drilling project will permit explicit testing of the response of the alluvial fan system to Quaternary climate change and the synchronicity of the unconformities that bound each allostratigraphic unit.

**Post Drilling Analyses**

To interpret the evolution of the fan (and possibly deposits below it), sediment samples will be measured for optically stimulated luminescence age-dating (OSL). OSL is an intermediary dating tool filling time gaps between long and short-lived radionuclides, making it an ideal tool to date the depositional ages of the Kings River alluvial fan—OSL tends to date events between 100-1,000,000 years (Wintle et al., 2006). Coupled with OSL, palynology of mud units will be done to give a more highly resolved record of changes in ecology, aridity, and sediment preservation (including measuring duration of hiatuses) over the past 1My. Groundwater arsenic distributions will then be overlain on the fan’s depositional history and framework to test how past events affect today’s groundwater.
References


Drilling to Elucidate Causes of Extinction During the Oceanic Anoxic Event at the Cenomanian/Turonian Boundary

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Sageman, BB – Northwestern Univ.

Project Summary
The Cenomanian-Turonian boundary (CTB; 94 million years ago), a time interval marked by mass extinction, was also characterized by global oxygen deficiency and likely ocean acidification. Thus, the CTB is an excellent analog for the impact of anthropogenic activity on marine ecosystems. A superb opportunity exits to explore the impact of oxygen deficiency and ocean acidification during the CTB in highly expanded sections from the western and southern margins of the Western Interior Seaway. In Utah, sections of the Tropic Shale contain original ammonite aragonite, as well as remains of large marine reptiles, and preserve an excellent epieric record of the event. In Texas, the Eagle Ford Shale preserves an similar record from the southern aperture of the Western Interior sea, and thus offers the opportunity to compare and contrast changes in epieric and oceanic settings. The two areas include superb outcrop sections that can be back-hoed to unearth pristine fossil shells suitable for environmental proxy analyses. Behind-the-outcrop core sampling will provide equivalent sections that can be scanned to obtain orbital time control and sampled at submillennial resolution. Proxy measurements designed to unravel the nature of the environmental changes will be combined with biomarker and paleontological studies to determine the biological impacts on trophic webs, from microbes to top carnivores. Numerical modeling will explore the relationship between trophic levels and the nature of the environmental controls, both local and global.

The expansion of oxygen-deficient waters, as a result of warming and pollution, can affect all marine organisms through the loss of habitat, alteration of microbial processes, changes in predator-prey dynamics, and availability of nutrients for primary production. Ocean acidification is already impacting the ability of many organisms to grow shells. The geological record contains a series of natural experiments that allow us to address the biological response of the biota to ocean acidification and widespread hypoxia. However, to date, studies of such geological intervals have been hampered by diagenetic alteration of materials for proxy measurements and an inability to obtain sub-millennial resolution required to match the timing of modern ecological studies. The proposed research overcomes these shortcomings and can thus be used to evaluate two fundamental hypotheses regarding the cause of food web upheaval during the CTB and of broader intellectual merit: (1) Introduction of greenhouse gasses from volcanism initiated a gradual sequence of perturbations to habitats that culminated in species extinction and turnover; and (2) Extinction and biotic turnover were systematic and can be directly related to the nature of habitat perturbation combined with the ecology of the taxa. The insight gained from the CTB can be applied to other intervals of biotic upheaval in Earth history and will help improve projections of the impacts of human activities on modern ecosystems.

Proposed work
Drilling of sections from the western and southern margin of the Western Interior Seaway (WIS) has the potential to address why part of the marine food web was decimated at the CTB while other parts appears to have survived unscathed. By unlocking the reasons for this selectivity, as well as the temporal and spatial relationships of assemblage shifts and extinctions, as indicated by proxy records, we hope to unravel the causes of major extinction and assemblage change at centennial resolutions approaching those of interest to modern ecologists.
The cornerstone of the proposed investigation will be development of high-resolution micropaleontological, invertebrate paleontological, organic geochemical, and isotopic data for the CTB from paired outcrop and core sections from the western and southern margins of the WIKS (Fig. 1). We will focus on the 500 kyr interval that was characterized by extinction and sample it in extraordinary detail, attempting to resolve changes that took place at the highest level of resolution (best cases may provide 200 years or less). We will use this framework to reconstruct marine food webs and examine trends in shell mineralogy across the CTB to address complementary, and partially overlapping, hypotheses related to the CTB extinction (see below). A key part of our approach is the combination of backhoe excavated outcrops and cores which will provide adequately-preserved inorganic and organic fossil materials for geochemical analysis and continuous section that can be sampled at extremely high resolution.

Hypotheses to be tested

Hypothesis 1: Volcanism initiated a gradual sequence of perturbations to habitats that culminated in food web disruption and species extinction and turnover. Our aim is to develop a very high-resolution record of environmental proxies and species occurrence in two sections from the western and southern margins of the WIS. This will include careful identification of pristine shell materials for inorganic proxy measurements and unweathered organic-rich strata for organic proxy measurements along with intensive collection of macrofossils and highly detailed observations of microfossils. A key objective will be evaluation of changes in shell mineralogy to test the hypothesis of ocean acidification.

Hypothesis 2: Extinction and biotic turnover was systematic and can be directly related to the nature of habitat perturbation combined with the ecology of the taxa. The exact causes of extinction and turnover at the CTB remain unclear. This is partially because the nature of the environmental perturbations is unresolved and also because there have been no systematic investigations focused on comparing proxies for environment with the fossil record. We plan to remedy this situation. Hypothesis 1 is aimed at reconstructing habitats. Our field campaign, including excavated outcrop and core, is designed to provide fossil and geochemical records at sufficient resolution to achieve temporal separation of environmental and fossil signals. We will use this record, combined with models of the food web, to unravel the nature of species interactions.

Strategies to Address Hypotheses
Our goal is to test the two hypotheses by recovering exceptional stratigraphic records of the CTB and compiling high-resolution proxy records to determine the nature of environmental perturbations. Models will be used to examine the nature of perturbations for which there are no direct proxies and for spatially resolved model-data comparison. We will use these records and modelling studies to evaluate the response of microbes, plankton, nekton and benthos and to determine the causes of extinction. Our strategy is based on recovering pristine fossil materials for geochemical analysis and studying events at the submillennial resolution.

Sections: We have selected two areas characterized by sufficiently high sedimentation rates to yield expanded sections: The Dakota Fm.–Tropic Shale section at Big Water, Utah (Elder, 1989; Leithold, 1994; Tibert et al., 2003; Laurin et al., 2007) and the Eagleford Shale section in west Texas (Lozier Canyon and Antonio Canyon: Donovan et al., 2012). We will study each section in three phases. Firstly, the sections will be studied in the outcrop. Macrofossils will be collected and bed thicknesses will be noted. Following this, the second step will be to backhoe the sections. This will increase our likelihood of finding more pristine macrofossils, which will be essential for any later geochemical work we wish to perform. Finally, we will take core from behind the chosen sections. Coring is essential for good correlation between sections and by sampling from behind the exposed outcrop face, preservation of both microfossil and nannofossils is likely to be superior. Geochemical and micropaleontological studies will be focused on the core material as well XRF scanning.

Development of Chronology: The CTB interval in the WIS has a well established, remarkably high-resolution chronostratigraphic framework. Focused at the boundary stratotype section at Pueblo, biozones, orbital cycles, dated ash beds and the δ13C record can be correlated across the basin (e.g., Elder et al., 1994; Sageman et al., 2006; Laurin and Sageman, 2007; Barclay et al., 2010). As a result, the high-resolution chronostratigraphic framework can be readily imported to our UT study site, and confirmed by new data collection in our TX site. To do so we will combine outcrop observation of macrofossils and correlation of ash beds with microfossil biostratigraphy on the cores and XRF scanning to correlate to the established orbital chronology. Scanning of cores will be carried out on an Avaatech XRF core scanner at UMass. Cores will be analyzed for Ba, Ca, Fe and Ti at 1 cm sample spacing. In addition, an imaging logger will be used to obtain high-resolution images of the cores. Data will be analyzed using standard spectral analytical techniques (e.g., Westerhold et al., 2008; Meyers et al., 2012).

Reconstruction of environments and food webs: The surface and bottom habitat and how it changed across the CTB will be reconstructed using a number of state-of-the-art proxies. Proxy measurements will be made on shell materials including aragonite from ammonites and calcite from foraminifera and inoceramids using a combination of bulk measurements where materials are pristine and laser ablation where preservation is variable. In addition, we will measure trace elements on bulk sediments and stable isotopes on bulk organic carbon. Analyses will also include organic biomarkers to help reconstruct changes in primary producers and microbial processes.

Significance for Continental Drilling

The project described herein represents an effort to tightly integrate scientific drilling of Late Cretaceous strata with the study of outcrops close enough to the drill sites that bed-to-bed correlations are unambiguous. The combination of sites and data sets is critical given the level of resolution that the study seeks to achieve – a level that is only really practical with core material. Although cores provide material that is essential for geochemical and mineralogical analysis because fossil shells and bulk sediment tends to be far less altered by surface weathering, the core sample size is too small to effectively study macrofossils. Linking to adjacent outcrops which will be intensively excavated via backhoeing prior to drilling, provides the best of both worlds.
The Arctic in a Greenhouse World: Drilling within a Cretaceous Deep Time Observatory

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Overview and Justification

Exceptional exposures of Cretaceous sediments on Devon Island in the Canadian Arctic (Fig. 1) provide a unique window on the Cretaceous Arctic that can be utilized as a Deep Time Observatory (Detelon Science Plan, 2011) to shed light on the Cretaceous greenhouse world. We propose to recover numerous short drill cores through marine mudstones using portable drills to investigate late Cretaceous environments through integrative analyses of a sedimentary marine succession revealed by our prior work on Devon Island in the Canadian High Arctic (Chin et al., 2008). High latitude deposits hold clues to the patterns of atmospheric and oceanic circulation that helped control Cretaceous environments. Unfortunately, there is a dearth of continuous sedimentary records from the poles; severe weather in the Arctic has restricted deep sea drilling efforts to recovery of a few meters of Cretaceous drill core. However, subaerial exposures at our target drill sites on Devon Island present a conformable sedimentary succession that spans approximately 20 million years of the late Cretaceous (Cenomanian to Campanian). Other Cretaceous sequences are also identified for potential ship-based drilling off the NE coast of Amund Ringnes Island, where stratigraphic sequences dip off the flank of a Devonian gypsum diapir and continue offshore in a shallow marine setting.

The objectives of this drilling project are to identify the incidence, causes, and implications of key environmental and biotic transitions in the late Cretaceous greenhouse environment of the Arctic. The greenhouse world of the Cretaceous was a unique time in Earth history that has immediate relevancy in view of the rapid warming now occurring on Earth. In addition to having high levels of atmospheric CO₂, elevated greenhouse warmth, and low meridional thermal gradients, the Cretaceous was also characterized by recurring episodes of ocean anoxia, deposition of thick chalks, high rates of ocean crust production and generally high eustatic sea levels (e.g., Takashima et al., 2006; Hay, 2008; Stein, 2008). This suite of features distinguishes the Cretaceous—both from environments of today and the warm Early Cenozoic.

Exposures on Devon Island include approximately 200 meters of marine and terrestrial sediments deposited during a major transgressive-regressive cycle. Analyses of macrofossils and sporadically collected samples have revealed a surprising abundance and diversity of marine diatoms and dinoflagellates, demonstrating high marine productivity that supported a shortened food web of heterotrophic protists, invertebrates, and vertebrates (Chin et al., 2008). We now intend to more systematically sample these exposures to reconstruct a high resolution record of the late Cretaceous. Fieldwork will include recovery of continuous stratigraphic core using portable drilling units, as well as the collection of discrete, closely spaced sediment samples, and collection of macrofossils exposed in outcrop on Devon Island. Larger scale drilling operations on Devon Island could be supported by helicopter from a vessel or from the logistical hub of the Polar Continental Shelf Project (PCSP) located in Resolute Bay on

![Figure 1: Canadian Arctic Archipelago showing Sverdrup Basin and Arctic Platform. Letters indicate field sites.](image-url)
adjacent Cornwalis Island.

The recovery of drill core and closely spaced sediment samples will offer unprecedented temporal resolution of sediment deposition in the Arctic under greenhouse conditions. This work will help us understand the variability of greenhouse environments by identifying palaeoenvironmental transitions and their effects on the biota in the Late Cretaceous.

**Cretaceous Environments**

Cretaceous sediments in the Canadian Arctic Archipelago have been explored and mapped over the last 50 years by the Geological Survey of Canada (GSC). Although this work has provided important palaeogeographic, structural, stratigraphic, and palaeontological frameworks for the region (e.g., Fortier et al., 1963; Miall, 1979, 1991; Embry, 1991), difficult access and the paucity of continuous stratigraphic materials have severely hampered our capacity to interpret Cretaceous Arctic palaeoenvironments.

![Figure 2: Age and thickness of Cretaceous strata exposed at prospective field.](image)

The project will substantially expand our previous studies of Upper Cretaceous (Santonian-Campanian) sediments on Devon Island (e.g., Rigby et al., 2007; Chin et al., 2008; Wilson et al., 2011; Witkowski et al., 2011a) by providing unprecedented high stratigraphic resolution of this interval with multiple types of palaeoenvironmental proxy data integrated with paleoclimate models.

**Geologic Setting of the Arctic: litho- and biostratigraphy**

During the Cretaceous, sediments in the Canadian Arctic were deposited in deep abyssal depths around Alpha Ridge, in the rapidly subsiding Sverdrup Basin (a rift basin), and across the shallow Arctic Platform (Fig. 1). Our research will focus on deposits from the Arctic Platform which record extraordinary preservation in marginal shallow shelf areas; environments which reflect interactions between marine and terrestrial habitats.

Throughout much of the Cretaceous, marine sediments (Christopher and Kanguk formations; Fig. 2) alternate with non-marine clastic deposits (Isachsen, Hassel, and Eureka Sound formations). Many units are also punctuated by layers of bentonite, reflecting recurring episodes of vulcanism (Embry, 1991; Chin et al., 2008). These Late Cretaceous sedimentary rocks are dominated by outer to inner shelf mudstones and delta associated lithoforms (Núñez-Betelu, 1994; Ricketts and Stephenson, 1994). Relatively slow deposition (sedimentation rates of about 3cm/kyr) took place during a phase of thermally driven subsidence and an Arctic wide transgression in the Cenomanian (Ricketts and Stephenson, 1994). This phase was followed by a regressive period beginning in the Coniacian/Santonian. Yet, Late Cretaceous
sedimentation in the Canadian Arctic was not only controlled by changes in eustatic sea level, but was also driven by tectonic subsidence (Ziegler & Rowley, 1998; Núñez-Betelu, 1994).

Analyses of sporadically-collected samples have already produced useful Upper Cretaceous Arctic biostratigraphic zonations for diatoms (Tapia & Harwood, 2002; Witkowski et al., 2011a), dinoflagellates (Núñez-Betelu, L. & Hills, 1992a, b), and silicoflagellates (McCarty et al., 2010, 2011a, b). Presently, Canadian colleagues have undertaken multidisciplinary research on Axel Heiberg and Ellef Ringnes islands characterizing the biostratigraphy, sequence stratigraphy, carbon isotope stratigraphy and paleoclimatic history of the Cretaceous in the Sverdrup Basin (Fig. 1) of the Canadian Arctic (Schröder-Adams et al., 2012, 2013; Herrle et al., 2013). This work will be directly correlative with our proposed work on Kanguk Fm. sediments on the Arctic Platform.

**Drilling approach**

Portable backpack core drills will be used to recover core that is 33 mm in diameter, and 1 to 1.5 m-long sections will be collected. The drilling system we plan to use has recovered cores as long as 18 m, but we favor short cores to ensure recovery of high quality continuous core (Fig. 3). We would also utilize a portable frozen soil-powered auger system that is used to core frozen sediment. These sediment sampling approaches will provide for studies at multiple temporal scales. Estimated rates of sediment accumulation (Balkwill, 1983) suggest that sampling at 0.5-5 m intervals will reflect ~15 thousand years for the Kanguk Fm. Due to the logistical difficulties of working in the high Arctic region, our drilling program is designed for portability and in compliance with logistical constraints. Larger scale drilling operations and longer drill core is possible, but would involve substantial increased in cost and logistical complexity in this region. We are in contact with the Nunavut Government to obtain the relevant permits.

![Sampling of these sediments at Eidsbøn Graben can be accomplished through a series of shallow drillcores 1.3" diameter to construct a composite sequence.](image)

**Collaborations with other Arctic nations**

We are currently collaborating on this project with colleagues from Canadian universities, the Nunavut Research Institute, the Geological Survey of Canada, and the University of Copenhagen, to further address the science objectives outlined above. Our Danish colleagues have considerable experience in successfully using the portable backpack drills. If this project is favorably received, broad international coordination of the logistical operations might be arranged.

**Broader implications**

This proposal intends to establish one of the most highly resolved records of paleoenvironmental and paleontological conditions of the Arctic region during the Late Cretaceous, including the period of peak warming. Polar regions offer particularly compelling insights because of their unique physical and biological features. Presently, our views of Cretaceous Arctic environments are limited to isolated snapshots gleaned from a handful of sites, and the lack of highly resolved time-continuous stratigraphic intervals perpetuates serious gaps in our understanding of these ancient environments. Our proposed systematic study of field sites on Devon Island will provide critical data that will substantially advance our understanding of the Earth-life transitions that occurred in the Cretaceous greenhouse Arctic.
References


Records of glacial advance, retreat, and large-scale deglacial flooding in central North America

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Introduction. A detailed deglacial chronology of outlet glaciers and associated large meltwater floods of the Laurentide Ice Sheet (LIS) is possible through AMS $^{14}$C dating of tundra plant fossils in ice-contact lacustrine deposits associated with dead-ice permafrost (in ice-walled lake plains, and slackwater lake basins). Ice-walled lake plains formed in stagnating ice, and the dateable plant fossils are in environmental context with the decaying ice (Figure 1), the geologic agent that formed regionally extensive moraines. A new time-space diagram for deglaciation of the Lake Michigan lobe, based on radiocarbon ages from ice-walled lake deposits, shows two primary advances of the lobe (Curry and Petras, 2011; Figure 2). We are poised to learn the details of ice movement of adjacent outlet glaciers, and their interactions, across the glaciated part of North America. Other sedimentary environments, such as ice-marginal slackwater basins (Curry and Yansa, 2004; Carson et al., 2012) and wide, shallow hollows on till surfaces (Glover et al., 2011) may yield useful record. Understanding the diachronic relationship among deposits of outlet glaciers will provide the sediment and chronological framework for the history of meltwater production, especially large-scale events such as the Kankakee Torrent which occurred in Michigan, Indiana, and Illinois during collapse of the LIS.

The age and dating errors linked to ice margins (moraines) and meltwater “events” are key components for the continued success of Earth System models, which, among other things, provide our best estimates of modeled sea level (Tarasov and Peltier, 2004; Tarasov et al., 2011). In this sense, distal meltwater deposits may be viewed as the product of a sedimentary system that connects the glaciers to the ocean. Optically stimulated luminescence (OSL) techniques have been used with success in the middle reach of the Mississippi River (Rittenour et al., 2007), and I propose that we add detail to this framework, as well as improving our understanding by promoting research in valley systems marginal to glaciated terrain, as well as downstream to the oceans.

Digital earth system models (e.g. Tarasov et al., 2011) are sensitive to the age and age error of ice margin positions. The models employ the only regional dataset available, the ice margin maps of Dyke et al. (2002), which provide snapshots of ice margins at increments of 500 $^{14}$C years. Although there is significant detail for maximum expansion of the outlet glaciers, there is almost a total lack of data supporting the deglacial ice margins. Similarly, there is a remarkable lack of information constraining the age and architecture of outwash, lacustrine, and other deposits in glacial sluiceways and their tributaries. Detailed sedimentology and chronology of these and similar deposits in other key sluiceways such as the Mississippi and Wabash River valleys will be key in linking glacial and ocean records.

In order to bridge this deficit of key data for a time period spanning roughly spanning from 30,000 to 10,000 calibrated years ago, I propose sampling, evaluating, and processing a relatively large number of short cores. This can be accomplished either by a mobile group of dedicated researchers, or undertaken regionally by local academic institutions. I proposed beginning this exercise in lobes adjacent to the Lake Michigan lobe (the Green Bay lobe to the northwest, and the Huron-Erie, Saginaw, and Erie lobes to the east) because the history of these lobes will encapsulate the meltwater history of the Illinois and Wabash Rivers, which
includes the poorly understood Kankakee and Maumee Torrents. Several students have completed theses on these and related topics, and the quality of their research has been hampered to a large degree by the quality of sediment cores they were able to sample. Sediment cores of ice-walled lake deposits are relatively easy to acquire with a low-cost direct push drilling (e.g., PowerProbe). Sediment cores sampled in glacial sluiceways will likely require more expensive coring operations, and would benefit from pre-drilling shallow geophysics, with independently, or with conductivity sensors or cone penetrometers using direct push drilling.

Ice-walled lake deposits typically occur in ice-marginal stagnation zones (Clayton, 1967; Colgan et al., 2005) and their distribution is widespread (Clayton et al., 2008; Curry et al., 2010; Figure 3). The age of the targeted lacustrine basins ranges from more than 40,000 to about 13,000 cal yr BP (Curry and Grimley, 2006; Curry and Petras, 2011; Jennings et al., 2012). The fossil record in ice-walled lake plains includes ostracodes, chironomids, and tundra plant fossils, most commonly *Dryas integrifolia* and *Salix herbacea*, but including *Vaccinium ugilonosum* and other herbaceous species (Curry and Yansa, 2004; Curry and Petras, 2011). In the absence of organics for dating, the next best option is obtaining OSL ages of (presumably) optically-zeroed shallow lacustrine and riverine deposits. The lower priority stems from larger lab errors associated with OSL compared to radiocarbon methods, typically differences of 5.0% or more vs. 0.25 to 0.5% (post calibration), respectively.

Because most sites are in areas that are privately owned, there are no issues with gaining site access. In most states and provinces, a mandatory two to three-day period is given agencies for locating any underground utilities. The ISGS owns and operates a PowerProbe 9600 direct push rig. It retrieves lined sediment cores to depths of more than 20 m. It took about four hours to sample the cores displayed in Figure 3. More expensive rental drilling, such as with a Rotosonic rig, may be necessary in with thicker, sandier slackwater and riverine successions.

Figure 1. Schematic of ice-walled lake plain genesis in dead-ice permafrost. From Clayton et al. (2008).
Figure 2. Time-space diagram showing the location of the margin of the Lake Michigan lobe of the south-central Laurentide Ice Sheet. The ages below the line are primarily radiocarbon ages of buried wood fragments; the ages above the line are primarily radiocarbon ages of tundra plant leaves and stems from ice-walled lake deposits (modified from Curry and Petras, 2011).

Figure 3. Location of last glacial maximum (green line; Wisconsin Episode), with gray stripes delineating focus areas for study of ice-walled lake plains, and short, yellow lines showing proposed glacial sluiceway transects.
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Continental Drilling Pre-proposal: Pennsylvanian Cyclothsms of the Paradox Basin
Blake Dyer, Adam Maloof

Introduction

Glacial-interglacial climate variability for at least the last 400 Ka is correlated to known variations in obliquity and precession, but mechanistic ties among climate change, the carbon cycle, and orbital variations are not fully understood (Petit and Ranaud, 1999). Knowledge accumulated from recent paleoclimate archives indicates that changes in Earth’s future climate may exceed those observed in the near-time geologic record. Therefore, the key to understanding these future changes lies in building archives of climate variability subject to the unique forcings, feedbacks, and boundary conditions experienced over Earth history. The late Paleozoic is characterized by the following unique conditions: the heaviest sustained $\delta^{13}$C record since the rise of animals (Saltzman, 2005); formation of the last supercontinent Pangea (Domeier et al., 2011); gigantism and radiation of terrestrial arthropods and amphibians (Briggs, 1985; Graham et al., 1995); the widespread colonization of land by plants (Osborne et al., 2004); and the formation of most of Earth’s coal seams (Bluth and Kump, 1991). Many tropical (farfield) late Paleozoic sedimentary deposits in Euramerica are comprised of repeating stacks of shallowing-up facies that are bound by flooding surfaces. These cyclothsms have been interpreted to reflect high amplitude variations in sea level as a result of glacio-eustacy (Ross and Ross, 1985). However, sea-level change estimates from around the world differ from a few meters to well over 100 meters (Rygel et al., 2008). If cyclothsms are generated by predictable variations in Milankovitch style glacio-eustacy associated with the waxing and waning of Gondwanan ice sheets, then individual parasequences can be assigned a characteristic time period for deposition, and a highly resolved cyclostratigraphic age model can be used to constrain rates of transitions between ice house and green house worlds during the late Paleozoic. The magnitude of sea level change will indicate the sensitivity of Gondwanan ice sheets and their capacity for change. Finally, by establishing the Milankovitch frequency band that ice sheets in the Late Paleozoic responded to, we gain insight into understanding the 40 ky to 100 ky transition in the glacial-interglacial frequencies of the Pleistocene.

The Paradox Basin of the western United States (Figure 1) provides the perfect field laboratory to explore the origins of Late Paleozoic cyclothsms. This Late Paleozoic flexural basin is associated with the Uncompahgre Uplift to the northeast (Barbeau 2003). Sediments nearest to the Uncompahgre Uplift, situated in the dry subtropics of the northern hemisphere (Domeier et al., 2011), are characterized by oscillations between evaporites and deep marine shales. Further from the Uncompahgre, near the forebulge of the flexural basin, carbonates accumulated in shallow seas. Shallow carbonates are great archives of past sea-level change because they rapidly fill accommodation space and are are highly responsive to changing environments (Read, 1998; James, 1997). These forebulge carbonates are exposed along the San Juan River near Mexican Hat, Utah, and can be accessed in their entirety by the dynamite blasted Honaker Trail and along the San Juan River at the Raplee Anticline. The carbonate sediments are stacked in hierarchical groups of five (Goldhammer et al., 1991), possibly reflecting the interplay of orbital precession (19-23 ka period) and eccentricity (~100 ka period) on global climate and sea level. Furthermore, Ritter et al. (2002) has established a conodont biostratigraphic framework for the section that can be correlated with midcontinent Late Paleozoic cyclothsms.

Over 150 segments of core from the Desert Creek and Ismay intervals of the Paradox Formation are already available at the USGS Core Research Center in Denver, but no core through the complete section exists for academic study. A complete and continuous record through this interval will provide invaluable insight into the origin of the cyclothsms through the use of continuous metrics that can not be employed in the field, such as: magnetic susceptibility, scanning XRF, and color. Rigorous spectral analysis of these objective metrics will reveal the relationship between 5th and 4th order parasequences, and if possible allow us to tie this relationship to a known physical process. Furthermore, with multiple cores, we can evaluate the lateral consistency of parasequences at the 5th order scale, where basin wide parasequences would be generated by global sea level or regional tectonics, and local discontinuous parasequences would be generated by sedimentary processes within
the carbonate platform (Ginsburg, 1971).

Figure 1: Cartoon sketch of the Paradox Basin on the four corners region of the western United States. Proposed drill sites (green) are close to Mexican Hat, Utah along HWY 163, and are within 20 kilometers of well studied outcrop localities (red). The currently available stratigraphic coverage in core is illustrated on the right in brown juxtaposed against the well studied outcrop localities.

Logistics

Paradox Basin cycloathsms can be accessed in southwest Utah on BLM land where abundant oil and gas drilling already takes place. In the area around Mexican Hat, Utah and to the west for nearly 60 kilometers, these sediments are flat lying and within a few hundred meters of the surface. We propose 2 preliminary target sites (A and B on Figure 1) that are easily accessed by highway, have a nearby water source, and require drilling depths to the Mississippian Pennsylvanian boundary of around 600 meters. These flat lying sediments are a perfect target for continental drilling to study icehouse climate in deep time. Two marker beds, the Gothic and Chimney Rock shales, have been used by geologists to target oil producing intervals of these sections all around the basin, and can be readily identified in the well studied outcrop locations to connect our proposed work with the extensive existing research.

Methods

Magnetic Susceptibility indicates how easily a magnetic field can magnetize a sample. In sedimentary rocks, the magnetic susceptibility is controlled by the abundance and types of minerals present. Where magnetite and clays will become magnetized in a magnetic field, carbonates and quartz will not. Therefore, magnetic susceptibility reflects variations in the lithology and detritus, which at least in modern sediments has been connect to climate change (Shackleton et al., 1999). Magnetic susceptibility measurements are cheap, can be performed rapidly, and are a non destructive means to gleaning climate information from the sedimentary record. Magnetic susceptibility variations could be generated by any combination of changing aeolian dust flux, proximity to detrital sources, or the strength of the carbonate factory.

Color photographs can also be used to gather continuous information about the lithology in a core (Cramer, 2001). Often organic rich sediments are dark or black, and limestones or dolomites are light grey. Therefore, a complete color scan of the Pennsylvanian Paradox Basin cycloathsms will help quantify the cyclicity of these
sediments and may help illustrate whether or not deposition due to orbital forcings is prevalent over the noise of autogenic deposition.

**Scanning XRF** is non-destructive and generates near continuous major and minor elemental concentrations along a core (Jansen et al., 1998). Some elements, such as Fe, should reveal changes in the abundance of detritus and clays (Röhl et al., 2003), and trace element suites should be related to the redox state throughout a parasequence. Additionally, Sr and Mn can be used to explore the dolomitization and diagenesis associated with parasequence caps and exposure to fresh water (evidenced by abundant root systems in the upper part of the section).

**Conclusion**

In order to understand the modern ice house climate system, we must look to the deep past to see how ancient ice house climates behaved in a world with vastly different boundary conditions. The carbonates of the Pennsylvanian Paradox Basin preserve chemical and lithological information about ancient the ancient sea level, carbon cycle, and ice extent. In order to interpret isotopic studies of these sediments, we must first establish a rigorous cyclostratigraphic model of deposition. Only by drilling continuous cores through the entire section can we generate the data necessary to determine the statistical significance of orbital forcings on the deposition of these parasequences. Once complete, this framework will open the door for a new realm of research that can focus on isotopic changes on the glacial-interglacial scale (single parasequences).

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Global change on a Subtropical Shelf: The Eocene-Oligocene Core (EOCore) Project
Pre-proposal for US Scientific Drilling and Evolution of Earth System Workshop
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Summary. We seek support for a series of cores to recover new records of the middle Eocene-lower Oligocene section of the eastern Gulf Coastal Plain of Mississippi and Alabama. The Eocene-Oligocene Core (EOCore) Project is envisioned as a scientific drilling program designed to examine the effects of the transition from an optimal warm climate and subsequent global cooling on the middle Eocene through early Oligocene sedimentary record of a subtropical shelf. The global paleoceanographic and paleoclimatic changes through this interval have been defined primarily in the deep sea. The EOCORE project will provide an opportunity to measure the biotic and sedimentologic response to these changes in a subtropical shelf setting. The sedimentary record is comprised of twelve 3rd order depositional sequences with abundant calcareous and organic walled microfossils. Additionally, the interval contains 8 distinct bentonite beds, 3 with radiometric ages. Poor exposures have limited detailed study of this important section to 3 widely spaced core sites in the region. None of the 3 existing cores recovered the complete middle Eocene-early Oligocene interval. The new records obtained would provide a detailed record of changing sea-level in the shelf environment from the middle Eocene through the early Oligocene. The relatively high sedimentation rates associated with shelf conditions provide an opportunity to develop expanded records of biostratigraphy, magnetostratigraphy, chemostratigraphy, and tephrostratigraphy across this critical interval of Earth history. The new sections would complement the 3 existing core sites at Mossy Grove, Youngs, and St. Stephens Quarry (SSQ) coreholes.

Background. The primary target deposits of this proposed study are the middle Eocene through lower Oligocene Claiborne-Jackson-Vicksburg Groups in the eastern Gulf Coastal Plain of Mississippi and western Alabama. This interval of time includes the Middle Eocene Climatic Optimum (MECO) and the late Eocene-early Oligocene greenhouse to icehouse climate transition through the Oi-1 glacial event (Hurley and Fluegeman, 2003; Miller et al., 2008; Fluegeman et al., 2009) as well as a return to warmer conditions in the early Oligocene post Oi-1. For example, geochemical and eustatic estimates from New Jersey derived from backstripping suggest the growth of a modern-sized Antarctic ice sheet at Oi1 time, near collapse of the ice sheet within 0.5 Myr, and regrowth and collapse several times during the Oligocene (e.g., O.1a, Oi2a, Oi2b time)(Pekar et al., 2002). This dynamic ice sheet challenges models (Deconto and Pollard, 2002) and needs to be tested with sections from other regions such as the Gulf Coast. The unconformity bounded depositional sequences in the proposed study area preserve a record of sea-level response to these broad climate changes in a shelf setting. Most studies of sea-level in the late Eocene-early Oligocene transition in the Gulf Coastal Plain have been based on outcrop studies (Loutit et al., 1988; Mancini and Tew, 1990). However, subsurface core studies provide the greatest potential for unweathered sections suitable for magnetostratigraphic and geochemical studies not possible in outcrops (Echolls et al., 2003; Miller et al., 1993, 2008; Katz et al., 2008; Fluegeman et al., 2009). To date, the MECO has not been identified in the eastern Gulf Coastal Plain and the post Oi-1 warming has only been studied by Miller et al. (2008).
Three cores in the eastern Gulf Coastal Plain have provided much of the biostratigraphic and paleoecologic framework of this interval. The Mossy Grove core in Hinds County, west-central Mississippi (Fluegeman et al., 2009) contains abundant planktonic and benthonic foraminifera within in a thick (186 m) section of the Yazoo Clay (Figure 1). This core additionally contains four bentonites, two with radiometric ages. In eastern Mississippi, the Mobil-Mississippi core project (Echols et al., 2003) contains the traditional Jackson and Vicksburg section best known from exposures in the Chickasawahay River Valley, but these are much thinner than the section in the Mossy Grove core (Figure 2).

The most complete study to date is that of Miller et al. (1993, 2008) on the SSQ corehole. Detailed biostratigraphic, paleomagnetic, and isotope data were collected from the core. They achieved a level of correlation with the global geochronologic scale not seen previously in the Paleogene of the eastern Gulf Coastal Plain and provided stable isotopic and trace metal analyses (Katz et al., 2008), but their study was still limited by the available core material (i.e., many geochemical techniques [Tex-86, U\textsuperscript{37}, and compound specific geochemical analyses] could not
be applied). We seek support to provide a transect of coreholes that will sample the MECO and Eocene-Oligocene transition; the primary objectives of the EOCore project are:

1. Provide a comprehensive record of the MECO in a shelf setting.
2. Develop a robust chronostratigraphic framework for the middle Eocene through the early Oligocene in the eastern Gulf Coastal Plain using planktonic microfossils (foraminifera, nannofossils, dinoflagellates) obtained from the recovered sections in conjunction with magnetostratigraphic data.
3. Reconstruct paleo-water depth values in the recovered sections using benthonic foraminifera. Benthonic foraminifera will also be used to calculate the Planktonic: Benthonic (P:B) ratio. Both of these will provide paleontologic proxies for measuring the response of relative sea-level to the MECO, the Oi-1 Glacial event, and the post Oi-1 glaciations and deglaciations.
4. Cores and logs will provide the basis for cyclostratigraphy and correlation to the astrochronological time scale.
5. Obtain radiometric ages from bentonites recovered in the section.
6. Geochemical fingerprinting of the bentonites will facilitate correlation of bentonite beds across the region.
7. Provide a full suite of geochemical analyses to address variations in paleotemperature, paleosalinity, and seawater $\delta^{18}O$ related to ice volume changes.

The EOCore project will facilitate the utilization of stratigraphic data throughout the region. Numerous short cores are housed at universities and surveys throughout the region. The data obtained from the EOCore Project will enable those sections to be incorporated into the broad chronostratigraphic framework and used to expand our understanding of the middle Eocene-early Oligocene interval in the eastern Gulf Coastal Plain.

**Logistics.** We have had contact with the Alabama Geological Survey and the Mississippi Department of Environmental Quality Office of Geology about the proposed coring. Both agencies have a long tradition of work on the Paleogene section and are supportive of this effort. Both states have contractors with wireline coring capability and the Mississippi Office of Geology operates a wireline coring rig. Drilling permits are not required in Alabama or Mississippi for strictly scientific core holes. Accessibility to drill sites for surveys and drilling requires landowner permission in both states.

The State Geologist of Alabama recommends we seek funds to properly plug and abandon the coreholes after drilling. This will insure the safety of the site in the future by not leaving open wellbores and will protect the research team from liability.

We propose to re-drill two sites: The St. Stephens core and the Mobil-Mississippi Young core. The new St. Stephens core would be drilled deeper to sample obtain a full middle Eocene section. The Mobil-Mississippi Young core drilled through the lower Oligocene but did not recover cuttings. The new Young core would be cored in its entirety to recover the lower Oligocene section and would core deeper to recover the full middle Eocene section. We propose to drill at least 3 additional sites located to obtain optimal sedimentary records across the middle Eocene-early Oligocene interval. Extensive well log databases available at both the Mississippi Office of Geology and the Alabama Geological Survey will help with site selection.
References


ANDRILL Coulman High Project (CHP): CO2 thresholds of past and future ice sheet behavior

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Overview and Justification - - The international ANDRILL (ANtarctic geological DRILLing) program proposes to drill two ~900 m holes into Paleogene to lowest Miocene strata beneath the Ross Ice Shelf (RIS) on the Coulman High (CH) in the Ross Embayment (vic. 77.46° S, 171.4° E). Recovery of targeted strata will provide high-quality stratigraphic records from a period when ice sheets first developed on Antarctica, and atmospheric CO2 was higher than 400 ppm, comparable to concentrations projected for this century. The CH site represents the end-member of a latitudinal drilling transect through the SW Pacific that would link oceanic mechanisms with the amplification of polar temperature and ice sheet collapse.

Geological records from the Antarctic margin provide the only means to acquire direct evidence of past ice sheet behavior. Recent drilling in the Ross Sea sector by ANDRILL, integrated with ice sheet modeling studies, discovered the retreat of the marine-based West Antarctic Ice Sheet (WAIS) during recent Pleistocene interglacials and repeatedly during the Pliocene when CO2 levels rose above 400 ppm [T Naish et al., 2007; T Naish et al., 2009; Pollard and DeConto, 2009]. Ocean-driven melt of marine-based sectors of WAIS resulted in sea-level rise of several meters, raising concern for future stability of these and other marine-based sectors of the East Antarctic Ice Sheet (EAIS).

Ice volume estimates from BEDMAP2 suggest marine-based ice could contribute up to 22 meters of future global sea-level rise [Fretwell et al., 2013]. Reconstructions of proxy-based atmospheric CO2 and geological records indicate that sea level was up to 22 metres higher than at present when CO2 concentrations exceeded a 400 ppm threshold [Foster and Rohling, 2013]. ANDRILL’s recent drilling campaigns (2006-07) recovered two >1 km-long rock and sediment cores that document the last 20 million years of glacial/climate history in the western Ross Sea. ANDRILL seeks to acquire new stratigraphic records to extend this history into older time intervals when atmospheric CO2 levels were persistently higher than 400 ppm, in order to test inferences made from far-field data sets regarding past and future ice sheet behavior. ANDRILL would test, using drillcore results and integrated modeling studies, when threshold levels of CO2, marine and atmospheric temperature, and sea-level would be crossed and Antarctica’s ice sheets would step into different climate stability modes. High-fidelity stratigraphic records achievable with the ANDRILL drilling system (98% recovery of >1000 m core) allow for the identification of orbital cycles in a proximal, but offshore, setting that will allow comparison of Antarctica’s glacial history to coeval records of global climate change from lower latitudes, and existing drillcores in the Victoria Land Basin to the west (see figure).

Sediments deposited during the targeted time intervals offer a window into the range of environments and ecosystems in the Ross Sea region during warm, high-CO2 Greenhouse world of the Eocene into the lower-CO2 and highly variable Icehouse climate of the Oligocene and early Miocene. Antarctica was the keystone in this global climate transition, witnessing the growth of ice sheets and major cryospheric influence on global systems. Results of the CHP will enhance understanding of (1) high-latitude marine and terrestrial coastal environments and climate during the Eocene, prior to the onset of continental-scale glaciation; (2) the cooling and transition to a widely glaciated Antarctic continent during the Oligocene and early Miocene; (3) the influence of climate change and vertical tectonics in West Antarctica on the early development and subsequent variability of the Antarctic cryosphere; (4) the magnitude and frequency of ice volume changes under moderate to low levels of atmospheric CO2 and the impact of these changes on global and regional sea level; (5) the evolution of polar surface (sea and land) temperatures and magnitude of polar amplification during periods of past global warmth; (6) the threshold in marine temperatures that limit marine-based ice expansion and grounding on the continental shelf; and (7) the timing of Antarctic tectonic episodes and the development of Ross Sea sedimentary basins.
The drill sites at CH will build upon prior drilling results in the region by:

- Extending the geologic record in the western Ross Sea beyond the two previous ANDRILL holes AND-1B [T Naish et al., 2007; T Naish et al., 2009] AND-2A [Fielding et al., 2011; D Harwood et al., 2008-2009], and other drill cores in the Victoria Land Basin;
- Adding new data to expand our understanding of tectonic and glacial evolution in the region during important Paleogene transitions between Greenhouse and Icehouse climate states and subsequent early Neogene time;
- Providing additional data from WANT to compare with the Victoria Land margin (e.g., CIROS, Cape Roberts Project) and offshore Wilkes Land (e.g., IODP Expedition 318) for insights on Antarctic Ice Sheet behavior from coastal areas into the open Ross Sea.

**Stratigraphy** - Proposed CH drill sites are located on seismic profile NBP-03-1A0, which is interpreted as faulted acoustic basement and syn-rift sediments (CHS1) truncated by an angular unconformity (CHMU) that separates the faulted sections below from well-stratified sediments (CHS2) above. The faulted unit is interpreted to be older to the west at the level of the CHMU.

The targeted section at CH can be correlated with seismic lines to DSDP Leg 28 sites 273 to the north and 270, 272 to the northeast. We interpret that CHMU is older than all or nearly all of the sediment recovered at DSDP Site 270 (>28 Ma). Therefore, we infer that the CHS1 section is no younger than lower Oligocene, and is possibly Eocene and older.

Drill hole CH-1 is located within an NNW-trending graben that contains the thickest horizontally stratified section at the CH survey site [Decesari, 2006]. We anticipate coring through 565 m (±5%) of CHS2 (below ~50 m of younger section, age unknown) that our correlation model indicates is upper Oligocene to lowermost Miocene. CH-1 will penetrate CHMU at ~600 mbsf. The well-stratified nature of reflections in CHS1 below the CHMU suggests that this unit consists of shallow marine sediments. At drill hole CH-2 we expect to core through ~350 m of CHS2 and penetrate CHMU into sediments in CHS1 that are older than those recovered at CH-1 due to regional dip. CHS1 is interpreted to be ~350 m thick. We expect the lower CHS1 unit at CH-2 to consist of nonmarine deposits. The age of the oldest syn-rift sediments at CH-2 is estimated to be late Cretaceous or Paleocene. Acoustic basement will be penetrated at ~700 mbsf and could be drilled to ~800 mbsf. The basement geology of the Ross Sea is largely un-sampled, so recovery of basement at the CH would add vital new knowledge.

Chronostratigraphy will build on a combination of biostratigraphic, magnetostratigraphic, radiometric, and strontium-isotope dating techniques applied successfully in previous studies of Oligocene shelf strata recovered from the Ross Sea [Acton et al., 2008-2009; D M Harwood et al., 1989; T Naish et al., 2009; T R Naish et al., 2001; Roberts et al., 2003; Wilson et al., 2007].
Site Characterization and Logistics -- The front of the RIS advance at rates of 2.0 m/day. Major calving events are spaced at intervals of decades. Following the calving of iceberg C-19 in 2002, a marine multichannel seismic survey was completed across the CH at the ice-shelf front in 2003–2004 to locate drill sites to recover Paleogene strata, anticipating that the advancing ice shelf would cover the survey lines and provide a drilling platform into target strata. Single-channel and 22-fold multichannel seismic reflection profiles were collected, along with gravity, magnetics, and swath bathymetry on a grid with 11 E–W lines spaced at 2–5 km and three N–S tie lines spaced at 10 km. The IODP Site Survey Panel reviewed the data and qualified it for planning drilling.

Preparatory environmental and geophysical investigations along the route from McMurdo Station to CH and at the CH site were performed, along with engineering studies of the proposed drilling approach. Airborne radar surveys were conducted in 2008-2010 to map RIS parameters and potential sites for crevasse nucleation. These surveys indicate stable ice-shelf conditions within the CH area. During 2010–2011, joint U.S./New Zealand site surveys maintained open holes through 250 m thick ice shelf. Oceanographic moorings indicate diurnal current variability with maximum flow ranging up to 25 cm/s. Sediment cores, gravity data, and seismic velocity data have been analyzed. The CH site passed a Hydrocarbon Safety Review by GNS, New Zealand.

Drill System -- The existing ANDRILL Sea Riser and Drill Rig is proven for a riser deployment of 1,000 m (ice and water thickness). For the CHP bending in the pipe produced by the ~100-m northward movement of the ice shelf needs to be addressed. An analysis of options and a review by ANDRILL engineers identified the “downstream spud-in” method. A cable and weight are attached to the riser to pull it downstream of the rig, where it can spud into the seafloor ahead of the drill rig and achieve the goal of 50 days of drilling with a penetration of up to 1,000 m. A small-diameter ROV is required to attach the plumb bob to the riser and pull it downstream.

International Funding Model -- Seven nations (Brazil, Germany, Italy, New Zealand, South Korea, U.S. and U.K.) are developing the CHP. Support will be divided into two funding streams: Science and Logistics. The proportion of funding that a nation provides to the Logistics stream determines the level of personnel involved. The CHP objectives are aligned with strategic planning documents [NRC, 2011]. International collaboration provides an opportunity for the exchange of scientific information, enhances research, education, and infrastructure in Antarctica science, and enables the CHP to address scientific questions too large for any single nation to address alone. The CHP links both continental and ocean scientific drilling communities in the Antarctic region.

Coulman High seismic stratigraphic nomenclature at drill sites CH-1 and CH-2. The target unconformity CHMU is ~600 m below sea floor at CH-1 and ~350 m at CH-2. RSU5a = Ross Sea Unconformity 5A; CHMU = Coulman High Major Unconformity; CHS = Coulman High Sequence.
References


Fretwell, P., et al. (2013), Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 375-393.


Roberts, A. P., S. J. Bicknell, J. Byatt, S. M. Bohaty, F. Florindo, and D. M. Harwood (2003), Magnetostratigraphic calibration of Southern Ocean biostratigraphic datums from the

The loess/loessoid sediments of Argentina have accumulated since the Late Miocene (~10 Ma; Zárate, 2003 and references therein), are an important terrestrial archive for much of the Late Cenozoic, and provide the opportunity to increase our understanding of southern hemisphere and global climate change across several of the major climate phenomena of the last 10 Myrs. The loess was initially deposited during glacial intervals by westerly winds carrying material from the Andes Cordillera and was later reworked by aqueous agents (loessoid deposits) (Frenguelli, 1957; Teruggi, 1957; Bidegain et al., 2007) and contain discrete paleosols and pedogenic units (Bidegain, 1998; Nabel et al., 1999; Kemp and Zárate, 2000; Zinck and Sayago, 2001; Zárate et al., 2002; Zárate, 2003; Bidegain et al., 2005; Kemp et al., 2006; Schellenberger and Veit, 2006; Bidegain et al., 2007). Sedimentation of the succession began after the regression of the Paranense Sea (5-15 Ma; Hernández et al., 2005) and the sequence composes a large and continuous sedimentary apron with an average thickness of ~100-200 meters. The Late Cenozoic deposits in the Buenos Aires Province are discontinuously exposed at scattered locations that consist of small outcrops restricted to riverbanks, road cuts, quarries and sea cliffs. These sedimentary sequences contain an extensive fossil vertebrate record, which provides the foundation for the South American Land Mammal Ages (SALMA) stratigraphy (e.g., Tonni et al., 1992 and references therein) and an extensive meteorite impact record (Schultz et al., 2004).

Many of the exposed sections have sparse stratigraphic and chronologic controls, limiting their applicability for regional/global correlations. Although some of the younger (<2 million years) sections have magnetic reversal stratigraphies (e.g., Heil et al., 2010), many of the older intervals have limited paleomagnetic and/or radiometric age constraints and have been dated using the relative evolution of the fossil invertebrate assemblages (SALMA). Recent identification of impact-generated glasses, that can be Ar-Ar dated, provide a new approach for constraining these sequences in age, particularly when coupled with a paleomagnetic reversal stratigraphy. Together, these chronostratigraphic tools result in greatly improved age models that improve the record of fossil vertebrate assemblages (e.g., Zárate et al., 2007). Development of a well-defined stratigraphic framework with a consistent, absolute chronology is necessary to further our understanding of the continental paleobiogeography of South America with respect to changes in mammalian diversity and the macroevolutionary process during the Cenozoic, especially in the context of climate change and/or impact events.

Heil et al. (2010) made advances in understanding changes in depositional/post-depositional processes in the eastern central Pampas of Argentina over the last ~2 Myrs and proposed mechanisms relating those changes to major global climate transitions. Their work combined sedimentological evidence and environmental magnetic properties to characterize changes in moisture transport, wind direction, and temperature as they relate to South Atlantic sea surface temperature (SST) and southern hemisphere atmospheric circulation. In addition, Heil et al. (2011; 2013) characterized environmental changes associated with the 3.27 Ma impact event (Schultz et al., 1998) at Chapadmalal sea cliffs in the Buenos Aires province of Argentina, the type sequence of the SALMA chronology and the locality in which a major faunal turnover was identified (Vizcaíno et al., 2004). Their environmental magnetic record suggests that a change in climate occurred prior to the impact event and the faunal turn over. It has been suggested that megafaunal extinctions in South America increased during the latest Pleistocene-earliest Holocene (Prado and Alberdi, 2010) with the onset and intensification of glacial/interglacial cycles. However, prior work (Schultz et al., 1998; Vizcaíno et al., 2004) has suggested that the impact event might have induced regional faunal extinctions by abruptly and briefly altering climate and ocean circulation. Further work is needed to better understand the effect climate changes and impact events have on environmental conditions in these sequences, particularly with respect to understanding the mechanism(s) that drive faunal diversity and abundance.

Argentina Continental Drilling –

The loess/loessoid deposits represent one of the longest terrestrial sedimentary sequences in the Southern Hemisphere and present the opportunity to further our understanding of 1) the geological record of production, transportation, and deposition of physical and chemical sediments, 2) the complexities of
Earth’s deep time (pre-Holocene) climate systems, and 3) dating and measuring the time sequence of events and rates of geological processes of the Earth’s past sedimentary and biological (fossil) record. Despite limited access to exposed sequences, our prior efforts have yielded one of the longest records of paleoenvironmental change from the Southern Hemisphere (Heil et al., 2010). This proposal is intended to highlight the importance of these sequences and identify future drilling targets that would ultimately recover the last ~10 Myrs of loess/loessoid sedimentation in Argentina.

**Drilling Targets – (shown in Figure 1)**

<table>
<thead>
<tr>
<th>Location</th>
<th>Thickness</th>
<th>Age Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gorina Quarry, La Plata</td>
<td>~ 40 meters</td>
<td>0-3 Myrs</td>
</tr>
<tr>
<td>2. Chapadmalal, Mar del Plata</td>
<td>&gt; 100 meters</td>
<td>3-5 Myrs</td>
</tr>
<tr>
<td>3. Bahia Blanca</td>
<td>&gt; 100 meters (?)</td>
<td>4-7 Myrs</td>
</tr>
<tr>
<td>4. Chasico</td>
<td>~ 200 meters</td>
<td>7-10+ Myrs</td>
</tr>
</tbody>
</table>

**Compelling Science Issues –**

The goal of drilling these sequences is to extend the records at each site beyond the previously sampled sections in order to 1) identify depositional/post-depositional changes not previously accessible, 2) differentiate between impact-related changes and climate related changes, 3) test previously proposed models of depositional changes pertaining to global climate transitions, and 4) construct the first continuous record of loess deposition and soil formation for the last 10 Myrs from a terrestrial environment in the Southern Hemisphere. These objectives will require a multi-pronged approach (environmental magnetic proxies, sedimentology, bioegeochemistry and impact identification/characterization) to characterize changes in depositional and post-depositional processes and identify potential mechanisms to explain those changes. Important science issues include:

1) **The changing aspects of life, ecology, environments, and biogeography in past geologic time based on fossil plants, animals, and microbes.**
   - construction of a paleomagnetic stratigraphy coupled with radiometric ages of impact glasses provides a temporal framework to refine the SA MLA and provide the appropriate age controls necessary for defining evolution rates and processes.

2) **All aspects of the Earth’s sedimentary carapace — insights into geological processes recorded in its historical records and rich organic and inorganic resources locked in rock sequences.**
   - providing insight into changes in loess deposition and post-depositional processes as they relate to climate changes and impact events.

3) **The science of dating and measuring the time sequence of events and rates of geological processes of the Earth’s past sedimentary and biological (fossil) record.**
   - addressed in areas of interest 1) and 2).

4) **The geologic record of the production, transportation, and deposition of physical and chemical sediments.**
   - bulk and magnetic grain size characterization provides insight into changes in source region, wind strength and/or direction as well as post-depositional alteration of primary deposits through pedogenesis.

5) **Understanding the complexities of Earth’s deep time (pre-Holocene) climate systems.**
   - construction of the first long and continuous 10 Myr terrestrial climate record from the Southern Hemisphere will provide insight into major global climate changes from the Late Cenozoic.

6) **Cycling of carbon throughout the ocean-atmosphere-land systems.**

![Figure 1. Location of potential drilling targets. Numbers correspond to locations in Table 1.](image-url)
- identifying changes in productivity and land cover over the last 10 Myrs based on changes in the composition, abundance, and distribution of plant-derived organic biomarkers preserved in the loess sequences of Argentina; improving climate projections by providing key inputs for climate models, including projections of future atmospheric CO$_2$ and CH$_4$.

7) The distribution, transport, and transformation of water and energy within the Earth System.

- develop biogeochemical proxies for moisture and temperature changes over the last 10-12 Myrs and further our understanding of the ocean-atmosphere-land pathways of moisture transport and storage.

Stratigraphy and dating –

In Buenos Aires province, the loess/loessoid sequences are up to ~200 m thick distributed in a north-south transect with the younger sequences in the north and the oldest sequences in the south (Figure 1 and Table 1). Although it is unlikely that the complete sequence can be recovered at one location, the individual sections each represent several million years and, when combined, are likely to provide a complete record of sedimentation following Andean uplift. Results from the younger sequences (<2 Myrs) identify persistent 100-kyr orbital cycles with intermittent 41-kyr and (less prominent) 20-kyr cycles (Heil et al., 2010). Relatively low sedimentation rates (~1cm/kyr) and compound pedogenesis are likely the reasons for inconsistent recording of orbital cycles. However, it is evident that these sequences record major climate transitions (e.g., the mid-Pleistocene Transition) (Heil et al., 2010).

The sequences are sedimentologically complex in that the pedogenic process commonly results in the welding of adjacent paleosols (Zárate and Imbellone, 1998) and, as a result, soil horizons are often not preserved or are secondarily altered and are difficult to differentiate. It is necessary to consider the successions in terms of cycles or phases of sedimentation and pedogenesis and micromorphological analysis is used to decipher the nature and order of events recorded in the polycyclic or welded horizons (e.g., Kemp and Zárate, 2000; Zárate et al., 2002).

Magnetic reversal stratigraphies have provided an important tool for placing the loess sequences of Argentina in a chronological framework (e.g., Orgeira et al., 1987; Ruocco, 1989, Bidegain, 1998, Zárate et al., 2007, Heil et al., 2010). Early reversal stratigraphies were constrained using an extensive fossil vertebrate record (e.g., Tonni et al., 1992 and the references therein) and the SALMA. More recently, the identification of impact events and impact-generated glasses provided a medium for radiometric dating ($^{40}$Ar/$^{39}$Ar) beyond the relatively short $^{14}$C-dating window (e.g., Schultz et al., 2004). The reversal stratigraphies then provided a means for refining the timing of the fossil record and placing the impact events (and their effects) in a broader temporal context (e.g., Schultz et al., 1998). The loess/loessoid deposits of Argentina generally provide robust magnetic reversal stratigraphies since the dominant magnetic remanence carrier in the loess and paleosols is magnetite that is generally in the larger pseudo-single domain size range (Bidegain et al., 2007; Heil et al., 2010).

Drilling Logistics –

Existing stratigraphic, paleontologic, and magnetic data were collected from outcrops throughout Buenos Aires province. Although these exposures are limited relative to the thickness of the sequences, they provide the opportunity for supporting drilled sequences. Geophysical data is very limited in the area, but the generally flat and open terrain lends itself to acquisition of that data prior to drilling. The intent is to drill as close to the outcrop exposures as possible, so that the geophysical data can directly link the drilled sequences to the outcrops. The target locations are remote enough to limit the impact of drilling operations on the local communities, however, there is sufficient access to these locations with existing roads. Our Argentinian colleague (M. Zárate) has been able to get access to all of these locations in the past (land-owner permission) and has also identified a possible drilling company that is familiar with the difficulties in drilling and, perhaps more importantly, recovery of these sediments. One of the biggest challenges will be recovering intact sediments that are rich in carbonate nodules as these nodules tend to disturb the sediment, particularly during rotary drilling.
References Cited –


SUMMARY

In the Eoarchean (>3.7 Ga) Isua Greenstone Belt, Greenland, a thin (~2 m) exposure of quartzite (meta-sandstone) has been found with rhythmically bundled sets of planar laminae. Thin sections reveal mm-scale quartz/meta-clay layering in a pattern that is reminiscent of Proterozoic-Phanerozoic tidalites. Analysis of the pattern from rock face photographs supports an interpretation of tidal deposition, and an Earth-Moon configuration for a 14.3-hour day. At >3.7 Ga, this result is as close to a “time origin” as will likely ever be found for tidal observations on Earth. The next oldest tidal evidence is from 2.45 Ga. The implication for early Earth-Moon dynamics science is transformational. However, rigorous investigation is now needed to confirm this interpretation. Coring the succession is the only way to develop tightly controlled measurements of the laminations. Here we propose to use a portable drilling system to core a set of vertical transects through the quartzite, to reconstruct the 3-D geometry of the deposit and to obtain multiple, extended time series of lamination stratigraphy for detailed statistical analysis and modelling. We seek funding in 2014-2015 for (1) purchase of a portable drill, (2) travel to SW Greenland to carry out the drilling in Summer 2014, (3) processing and curating the cored material (2014) and (4) salary support (2014-2015).

SCIENCE

Location and age of target deposits

The Eoarchean Isua Greenstone Belt (IGB) is located in SW Greenland (Fig. 1a). The proposed study area is situated in the tectonically less deformed northeastern part of the IGB, and includes well-preserved, original sedimentary layers, pillow lava structures, and bedded conglomerates, dated at more than 3.7 Ga (Appel et al., 1998; Fédo & Appel, 2000; Nutman & Friend, 2009). The location of the meta-sandstone drilling target is indicated by the black square (Fig. 1b). The drilling target outcrops along the side of a low hill, and has a field association with thin-beded, banded cherts (Fig. 1c).

Figure 1. Location of the drilling target in the Eoarchean Isua Greenstone Belt (IGB). (a) Location of the IGB in southwestern Greenland (white square). (b) Outcropping of the IGB; target field area is in the lesser deformed supracrustal belt (black square). (c) Generalized stratigraphy of the target and associated rocks suggesting shallowing-upward facies, from deep-basin, shelf, to tidal flat.
**Stratigraphic completeness, continuity and resolution**

The drilling target formation is a 2-m thick quartzite that is exposed along a low-lying hill. A detached block of the quartzite was found near the base of the hill, with a flat rock face revealing the fine-scale laminations that are analyzed here (Fig. 2). The relationship between the quartzite and adjacent banded cherts could represent a shallowing-upward marine succession but this interpretation needs further evaluation (see *Science Issues* below). As yet there are no published descriptions of this succession, and in general, sedimentological interpretations of Isua supracrustal rocks remain controversial on account of the high-grade metamorphism that is associated with the complex.

![Image](image-url)

**Figure 2.** Analysis of laminations in the target Isua quartzite (meta-sandstone). (a) Quartz/metamorphosed mud laminations. Arrow b indicates the location of image in b; the rectangle indicates location of a high-resolution photograph used to obtain the grayscale scan in c. (b) Petrographic slide highlighting three successive bundles of laminations, interpreted as a semidiurnal tidal record over 3 fortnightly cycles. N=neap tide, S=spring tide. The record of every other neap tide displays a similar fabric, suggestive of an alternating low spring tide, high spring tide typical of mixed tidal regimes. (c) A grayscale scan taken at a resolution of 0.11 mm over 12.5 cm from a close-up photograph of the area indicated by the rectangle in a. The horizontal line indicates the projected position of the thin section displayed in b. The heavy line is a weighted average to emphasize the lamination bundling, interpreted as fortnightly cycles. (d) The 2π power spectrum of the grayscale scan with spectral peaks exceeding the 99% confidence level labeled in mm. The inset displays the 2π amplitude spectrum over [0, 0.18 cycles/mm]. The laminations occur at two scales, 1.1 mm and 0.55-0.62 mm, interpreted as evidence for diurnal and semi-diurnal tidal forcing. The inset provides estimates of the lamination bundling at 13.23 mm and 34.19 mm, interpreted as evidence for fortnightly and monthly cycles. Assuming that the lunar tides forced these laminated deposits, the analysis indicates 34.19 mm/1.1 mm = 31.08 days per lunar month, an Earth-Moon distance of 74.5% of present-day, and a 14.3 hour day (Eq. 12 in Runcorn, 1979).
Science issues
The goals of this project are as follows:

1. Establish that lamination occur throughout the quartzite exposure
2. Determine metamorphic grade of the quartzite (microprobe study)
3. Search for tephra and/or detrital zircons for U-Pb dating
4. Test alternative hypotheses for penetrative deformation of other protoliths, e.g., tonalite, conglomerate
5. If primary sedimentary fabrics are not ruled out, measure cored lamination sequences
6. Characterize lamination with sub-mm XRF scans and photo-grayscale scans
7. Analyze lamination sequences for tidal signatures
8. Infer early Earth-Moon dynamics

The microprobe study will search for trace element evidence to determine metamorphic grade. The preliminary evidence suggests that penetrative deformation of protoliths unrelated to tidal sediments is unlikely. Another objective is to seek zircons suitable for U-Pb dating. The cores will be assembled into a 3-D reconstruction of the deposit. Lamination sequences will be analysed in the manner presented in Fig. 2d, and used to infer Earth-Moon distance, Earth length-of-day, and possibly, lunar orbit eccentricity. This will extend knowledge of Earth-Moon dynamics from 2.45 Ga (Williams, 2000) to >3.7 Ga. The results in Fig. 2 suggest that the Eoarchean Earth-Moon system was operating similarly to the present, with a closer Moon (75% of today’s Earth-Moon distance) and a faster length of day (14.3 hours).

LOGISTICS

Travel plan
The trip will place in July-August of Summer, 2014. PI’s Noffke and Hinno and a field assistant will travel from Washington, DC to Copenhagen, and from there to Nuuk, Greenland. From here, the party will be transported by helicopter to the base camp in the study area. The cost for transportation and supplies for one month in the field for three is ~65,000 USD. The PI’s will rely on CH2M HILL Polar Services (http://www.polar.ch2m.com) which operates under a contract with the National Science Foundation (NSF) to provide logistics support for NSF-sponsored research projects in Greenland.

Drilling
The PI’s will purchase a portable drill from Shaw Tool Company (http://www.backpackdrill.com), which is designed for use in remote locations. The model under consideration is the 41 mm OD Drill Kit, for a total cost of ~5,000 USD. This drilling system has a typical depth range of 5 to 32 feet, which is appropriate for this project. The PI’s and field assistant will test the drill in advance and train in repair and trouble-shooting. The plan is to drill the meta-sandstone at multiple, closely spaced sites along strike, including the detached block (in Fig. 2). The base camp is next to a small pond, which will serve as a source of drilling water, to be carried in multiple 20-liter containers to the drill site (0.5 km distance).

Permitting issues
The PI’s must comply with permitting requirements of Greenland. The requirements are given on the Ministry of Domestic Affairs, Nature and Environment website (http://www.nanoq.gl/expeditions).

Estimated cost

<table>
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<td>Total direct costs:</td>
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REFERENCES

Cretaceous Foraminiferal Lagerstätte from Coastal Sections in Tanzania

Brian T. Huber (Smithsonian Institution)
Kenneth G. MacLeod (University of Missouri)

Overview

Over the course of three drilling seasons from 2007-2009 the Tanzania Drilling Project (TDP) recovered over 1.7 km of core spanning most of the middle and Late Cretaceous (~120-65 Ma) as well as a brief interval in the early Paleocene (~63-62 Ma) (Jiménez Berrocoso et al., 2010, 2012). Cenozoic and Cretaceous samples from this region are known for their exceptional preservation, which is a great boon for taxonomic and, particularly, paleoclimatic studies that assume preservation of near original isotopic ratios in fossil material. Although pristine preservation was not present in all samples recovered, we did find exceptionally well preserved foraminifera and nannofossils across the entire Turonian (Wendler et al., 2011, in press), which is the time of peak Cretaceous warmth (Huber et al., 2002; MacLeod et al., in review), as well as portions of the Cenomanian, the Coniacian through the Campanian (times of warming and cooling before and after the Turonian, respectively) and the early Paleocene. Our drilling also obtained stratigraphic intervals spanning the late Aptian-early Albian (~115-111 Ma) and the late Campanian-Maastrichtian (~74-66 Ma).

Unfortunately, two primary drilling targets, the Cenomanian-Turonian boundary (CTB) and Cretaceous-Paleogene Boundary (KPB), were not recovered despite repeated drilling attempts (Fig. 1). Recovering these intervals was given high priority because they are times of significant disruption of Earth systems and Tanzania is removed from most studied sections providing an important global prospective. Further, the high sedimentation rate and extraordinarily good preservation would enable an unprecedented opportunity to reconstruct changes in surface and bottom water paleotemperatures, organic and carbonate carbon isotopes, nitrogen isotopes and species composition.

We expect both boundary intervals exist in the coastal region of Tanzania. For the KPB this confidence is based on the presence of both latest Maastrichtian and earliest Danian biomarker planktic foraminifera in samples from the region of Lindi Village (Pearson et al., 2004; Fig. 2). For the Cenomanian-Turonian boundary, it seems unlikely that the East African passive margin would have been emergent or been selectively bypassed by sediment during the Cenomanian-Turonian boundary interval, the time considered to be the highest stand of global sea level during the past 250 m.y. Failure to obtain either of these boundary intervals, thus, was surprising. A major limitation of site selection in southeastern Tanzania is lack of outcrop control. The few outcrops present are found on steeper gullies on hillsides and the presence of this topography could reflect structural complexity. That is, lack of success at recovering these intervals could be attributed partially to lack of subsurface seismic control for determination of where the most complete stratigraphic sections should be drilled. In addition, we
often were drilling without borehole casing, and, because the rocks are so poorly lithified, borehole stability was a major problem, especially in relatively sandy intervals across the CTB, and highly variable lithologies across the KPB. Finally, high sedimentation rates mean there is little room for error given that we were using a drill rig that was unable to drill deeper than 170 m.

Science

I. Location and age of target deposits
   a. Southeast Coastal Tanzania: from Ngurukuru Junction in the region of Kilwa southward to the region southwest of Lindi village
   b. Mozambique: Geologic maps show the stratigraphic sequence along coastal Tanzania continues into Mozambique, but we have not had a field program to determine potential drilling targets.

II. Compelling science issues
   a. Cretaceous/Paleogene Boundary
      i. Obtain first high resolution earliest Danian record with exceptionally well preserved foraminifera to reconstruct history of changes in surface and bottom water oxygen isotope paleotemperatures, carbon and nitrogen isotopes (paleoproductivity proxies) and organic biomarkers
      ii. Characterize shell/plate microstructural and taxonomic changes during the early evolution of calcareous nannofossil and planktic foraminiferal lineages to determine rates evolution in both microfossil groups.
   b. Cenomanian/Turonian boundary
      i. Obtain first high resolution, Indian Ocean record of surface and bottom water temperature changes correlated with carbon and nitrogen isotope and organic biomarker data across Oceanic Anoxic Event 2 to test the productivity vs. preservation models for explaining this major carbon isotope and organic carbon burial event (e.g., Jenkyns, 2010)
      ii. Characterize the timing of planktonic species turnover relative to geochemical shifts and changes in the vertical structure of the water column to determine the cause for the extinction of deep water species.

III. Stratigraphic completeness, continuity and resolution
   a. Presence of latest Maastrichtian and early Danian planktic foraminifera in soil surface samples southwest of Lindi village and near TDP Site 5 (Pearson et al., 2004) indicates a complete KPB exists in the region.
   b. Lower Turonian sediments were cored at TDP Sites 22, 30, and 36 and upper Cenomanian sediments were cored at TDP Site 24 (Jiménez Berrocoso et al., 2010, 2012), indicating that a complete CTB must exist in the region.

IV. Existence of baseline stratigraphic, and paleontologic data
b. No field samples collected from Mozambique; inference for existence of CTB sequence based on satellite images and Google Earth maps

V. Existence of, or potential to collect, supporting data from correlative outcrops, geophysics or prior drilling
   a. Land-based seismic survey will be essential for successful site selections in Tanzania in order to avoid structural complications that would result in drilling of incomplete sections.
   b. We have had good success in obtaining biomarker planktic foraminifera and calcareous nannofossils from ditch, soil surface and roadcut outcrops in Tanzania.

VI. Existence of, or potential to collect, a robust age model through the target interval
   a. Samples from Tanzania contain the key marker species of planktic foraminifera and calcareous nannofossils that are used for correlation of standard subtropical/tropical biozonations.
   b. Standard biomarker species should also be present in Mozambique.

Logistics
I. Challenges to drilling the site and obtaining subsurface information (e.g., suitable terrain for site-survey geophysics)
   a. Limited road access for large vehicles
   b. Trees, scrub, and thick bush may need to be cleared for seismic surveys and some drill sites, but use of heavy equipment (e.g., bulldozer) would be expensive, requiring long distance transport
   c. Sources of fresh water for drilling may distant and hard to obtain if there is an extensive drought

II. Access for drilling equipment
   a. Main road from Dar es Salaam to southwest of Lindi Village is paved, but the few roads connecting with the main road are poorly maintained dirt roads or footpaths
   b. Terrain in Tanzania and Mozambique is generally rolling hills covered by trees and thick bush

III. Permitting issues
   a. Excellent logistical support for national science permits and local permits for drilling by the Tanzania Petroleum Drilling Program.
   b. Permitting issues unknown for Mozambique

IV. Complexity of operations, local impact/cooperation (community and environmental)
   a. Most lands in Tanzania and Mozambique are not privately owned and environmental and community controls are very lax
b. STAMICO contractor provided reliable drilling crew and achieved good core recovery for our low-budget NSF-funded operation; situation in Mozambique uncertain

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Drilling the Ediacaran-Cambrian TRANSITION in South China

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Introduction

Sedimentary successions deposited across the Ediacaran-Cambrian boundary preserve a paleontological archive of the most critical transition in the history of animal life on the planet, including the evolution, diversification, and extinction of the enigmatic soft-bodied Ediacara biota, and the subsequent explosion of most Modern animal phyla in the Cambrian radiation. The tempo and mode of these biological events is, however, complicated by significant unconformities and the facies-dependence of many fossil forms, as well as the thermal maturity of ancient sedimentary libraries and the general lack of radiometric age constraints. The Ediacaran-Cambrian transition is further characterized by an extraordinary variability in surface environments likely associated with major tectonic, climatic, and environmental perturbations. The sedimentary response to these events is recorded in the detailed sequence architecture of the depositional basins and in time-series geochemical studies of seawater proxies.

Among the most accessible, continuous, and paleontologically important Ediacaran-Cambrian sections are those preserved on the Yangtze Platform in South China, which are the focus of our proposed drilling activities and scientific exploration. In particular, we propose to bore through strata of this antiquity in both shallow and deep water environments in Yunnan and Guizhou provinces of South China. We have specifically chosen these regions to avoid the effects of hydrothermal alteration and high burial temperatures, which have been recognized in Hubei Province where most previous studies have been based, and because enhanced fossil preservation in far southwestern China suggests a lower metamorphic grade. These regions were further chosen to provide a more comprehensive assessment of biological and environmental events across the basin – coupled with our long history of field studies, as well as published results from existing scientific boreholes, in addition to a new borehole drilled by our Chinese colleagues at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences (NIGPAS) through equivalent deep marine strata in southern Anhui Province.

Strategy

Our team of scientific experts includes: Ariel Anbar (ASU, trace element geochemistry), Ganqing Jiang (UNLV, sedimentology), Kaufman and Aaron Martin (UMD, carbon isotope chemostratigraphy and geochronology), Xiao and Benjamin Gill (VPI, paleontology and sulfur isotope chemostratigraphy), and Roger Summons (MIT, organic geochemistry). We propose an initial site selection field excursion followed by drilling of continuous cores with water and fluorescein dye to monitor the depth of penetration into the cores, but specifically no organic-based drilling fluids. Samples for organic analysis will be selected at the well site and transferred to gas-tight Teflon bags flushed with an inert gas and then frozen. Potential volcanic ash levels recognized in the fresh core material will be investigated and collected in field exposures wherever possible. Cores will be shipped to NIGPAS where they will be split, thin sectioned, and one half archived in China. The second half will be shipped to the US core facility at Arizona State University for selection of samples and further processing prior to distribution of powders or chips to investigators.

Scientific Agenda

The goals of our integrated geochemical and paleontological research are to address issues related to the extinction of the Ediacara fauna and the subsequent Cambrian Explosion, specifically whether these events reflect environmental, ecological, or developmental factors, or some combination of all three. Environmental factors related to the redox structure of the depositional basin (i.e., oxidized and well mixed vs. stratified or silled) and potential elemental and isotopic gradients in seawater, as well as the flux of materials from the deep ocean and continents to shallow shelves, will be evaluated through detailed sedimentology and sequence stratigraphy coupled to high-resolution time-series geochemical measurements of interbedded carbonate, shale, and phosphorite. The geochemical analyses will include
 elemental and isotopic abundances of carbonate and organic matter (including biomarkers and their isotopes as indicators of biological source and thermal maturity of sediments), sulfate, sulfide, and phosphorite, as well as trace metal and REE abundances and iron-speciation. Ecological factors will be evaluated through microfossil distributions and compositions relative to facies, time, and environment across the Ediacaran-Cambrian transition in South China and compared globally. Finally, if zircon-bearing volcanic ash horizons are discovered in these cores and these yield reliable discrete ages, we will be able to constrain developmental rates through a more formal subdivision of terminal Ediacaran and Early Cambrian time. A more rigid time frame would also aid in the understanding of rates of tectonic, climatic, and environmental change through this key transitional interval of Earth history.

Representative Hypotheses

(Anbar) We will construct time-series trends in trace metals (including REE) and redox sensitive isotopes (Fe, Mo, U) to examine the extent of Early Cambrian ocean anoxia, and specifically whether the Early Cambrian interval of carbon cycle instability is coincident with rapid fluctuations in the degree of oxidation of the water column.

(Gill) The proposed sulfur isotope study will test for a basinal gradient in marine sulfate during Ediacaran-Cambrian transition and whether there are global, secular trends within the marine sulfate sulfur isotope record.

(Jiang) Sedimentological and sequence stratigraphic investigation will test whether sea-level changes may have played important roles in controlling the carbon, sulfur, nitrogen, and iron cycles and redox fluctuations in the late Ediacaran-Early Cambrian ocean.

(Kaufman) We set out to test the hypothesis that at various times across the Ediacaran-Cambrian transition there was a pronounced surface-to-deep gradient in seawater dissolved organic matter abundance and isotope composition driven by modulations in primary productivity from above and fermentative processes from below.

(Martin) Armed with new dates and our basin wide sequence analysis, we will be particularly interested to test the duration of the Fortunian Stage of the Terrenuvian Series, which metaphorically corresponds to the fuse leading up to the Cambrian Explosion of animals.

(Summons) Biomarker studies will test whether molecular fossil proxies of water column redox (e.g. homohopane ratios, gammacerane index and carotenoid pigment residues, among others, will show strong correlations with sedimentologic and inorganic geochemical indicators.

(Xiao) The paleontological hypothesis that will be tested in the proposed research is that the Cambrian radiation of eukaryote phytoplankton was driven by top-down ecological processes such as mesozooplankton grazing.

Logistics

We propose to drill in four widely separated sites across South China delineating a shelf-to-basin transect. The first site will be located near Meishuncun (loc.1), about 75 km southwest of Kunming in Yunnan Province. This area has well-preserved small shelly fossils, trilobites and trace fossils (Zhu et al., 2005; Steiner et al., 2007). This is also the area where several U-Pb ages (Jenkins et al., 2002; Compston et al., 2008; Zhu et al., 2009) were reported. Well-preserved soft-body fossils in this region indicate that the strata are of low thermal maturity and hence amenable for biomarker studies. Our second proposed drill site is near Songlin (loc.2) in northern Guizhou Province. This area is characterized by highly
condensed Early Cambrian strata from outer shelf depositional environments (Jiang et al., 2009) containing abundant and diverse sponge fossils and trilobites (Zhao et al., 1999; Peng et al., 2005). Strata in this region are flat-lying and are easily accessible for drilling. Our third proposed location is a slope section near Taoying in eastern Guizhou Province (loc. 3). Strata in this region are condensed and fossiliferous (Zhao et al., 2005; Tang et al., 2008; Wang et al., 2008; Zhu et al., 2008); furthermore they are flat-lying and readily accessible. Our last proposed drill site is in deep basinal facies near Long’e in eastern Guizhou Province (loc. 4), which is dominated by shale with carbonate interbeds.

**Core Facilities**

Storage for core materials for this project is secured in both Nanjing and Tempe. In Nanjing, core will be stored in an air-conditioned room (~400 sq. ft) with shelving adjacent to a thin section laboratory. The new cores drilled for this project will be split with half archived in the Nanjing facility where the thin sections will be produced. In Tempe, the half core will be housed in the RSS5 building at Arizona State University. This is a small auxiliary research facility adjacent to the Anbar laboratories and the School of Earth & Space Exploration. All repository rooms are equipped with shelving for core storage, as well as tables for core sampling and inspection. The RSS5 building also houses equipment for rock preparation, including table saws, tile saws, and ball mills. The entire facility is air conditioned, powered, and secure.

**Access and Permitting**

In order to facilitate field work and our ambitious drilling project in South China, the proposed research requires considerable international cooperation. Our Chinese collaborators, including Drs. Xunlai Yuan and Chuanming Zhou at NIGPAS have recent experience with drilling through these strata, so their assistance will be mission critical. Personnel at NIGPAS will provide the infrastructure within China necessary to conduct drilling activities. These include pre-drilling site selection, purchase of core boxes, obtaining necessary permits and contracting drilling and transportation companies, as well as the archive and splitting of cores in the NIGPAS core facility where thin sections will be produced. Our close colleagues at the China University of Geosciences Beijing, Drs. Xiaoying Shi and Shihong Zhang, and their students are also eager to collaborate with our team on this project and provide on-the-ground support for the field and drilling activities, in part based on their related projects funded by the Ministry of Science and Technology and NSF-C. Our outreach activities will support the training and research of these Chinese students, and include lectures and workshops at various institutions throughout China on the co-evolution of life and environment across the Ediacaran-Cambrian interval. Chinese students will be financially supported by our collaborators’ existing NSF-C funds and they will apply funds from the China Scholarship Council to visit the PIs institutions for collaborative study. The NSF-C Program Director in the Department of Geosciences, Dr. Liu Yu, who has co-sponsored seven China-US workshops on critical transitions, has strongly supported our drilling initiative. Letters of support and details of work plans by US and Chinese collaborators are available upon request.
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Pre-Proposal for Scientific Drilling and the Evolution of the Earth System:  
“ONSET: Observing the Neoproterozoic Snowball Earth Transition”

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1. Introduction  
We propose a multidisciplinary international research effort that will utilize drilling to accelerate research of the environmental and biological evolution and re-organisation of the Earth System during the Neoproterozoic, arguably one of the most profound transitions in Earth history. The initiative will require coordinating the drilling and coring of numerous key successions that archive the main biogeochemical events of Neoproterozoic time on several cratons. We propose here to begin with a drilling program of Neoproterozoic strata in South China, and expand to other successions, particularly the Chuar Group of Arizona, USA, and through Neoproterozoic strata on the Amazon craton of Brazil, when logistics and funding fall into place. We envision that these efforts and the ensuing research programs would be structured and managed through an alliance of integrated research teams, leveraging support of NSF with other national and international agencies.

2. Why the Neoproterozoic?  
The Neoproterozoic Era (1.0 to 0.541 Ga) experienced supercontinental tectonics, global-scale glaciations (i.e. Snowball Earth), a putative second global oxygenation event (termed the Neoproterozoic Oxygenation Event, or NOE), and the diversification of eukaryotes followed by the rise of animals. Such a concentration of hallmark events in the evolution of our planet is unparalleled and are the focus of numerous exciting areas of study that in many instances define the forefront of interdisciplinary research between climatology, paleobiology, geochemistry, geochronology and geology. However, many key outstanding questions remain to be answered.

2.1 Extreme climate change—In general, the Earth system is marked by long periods of time during which states of quasi-stasis are maintained, interspersed by times when thresholds, or tipping points, are crossed and the system enters a substantially different state (Pierrehumbert et al., 2011). The Neoproterozoic Era, in the context of the preceding Mesoproterozoic and subsequent Phanerozoic Eras, represents a markedly different state in Earth system characterized by large-magnitude changes in climate and biogeochemical cycling. Neoproterozoic glacial deposits mark a bold return to climatic extremes that are unprecedented in subsequent Earth history and epitomised by a suite of associated sedimentary deposits that range from being unique (cap carbonates) to extraordinary (BIFs) (Hoffman and Schrag, 2002). These rocks pose an intriguing problem for climatologists, described by some as “Neoproterozoic weirdness” (Pierrehumbert et al., 2011). Out of this “weirdness”, though, has come the realisation that Earth can exist in two climatic equilibria: one defined by global glaciation and the other ice-free. Although geochronological calibration of Cryogenian events is progressing (Macdonald et al., 2010), the timing, duration and synchronicity of the Snowball Earth glaciations have not been established unequivocally and modelling their conditions remains squarely in the realm of informed speculation.

2.2 Evolving composition of the oceans and atmosphere—The many efforts to characterize Neoproterozoic successions are predicated by our ability to reconstruct robust records and model the conditions of Earth’s ocean-atmosphere-climate system and determine the nature of the inter-relationship(s) with the developing biosphere. Documenting and integrating these records is essential to understanding which changes catalysed the advent and radiation of metazoans (Erwin et al., 2011) and the purported
concomitant rise in oxygen (Canfield et al., 2007). Ancient oceanic and atmospheric compositions are inferred via proxy records exemplified by the intriguing, often co-varying patterns of isotopic excursions documented in multiple isotopic systems such as C, B, Ca, Li, S, Nd and Sr obtained for Neoproterozoic strata (Halverson et al., 2010). Some of the more striking profiles are the large-amplitude perturbations in the global C cycle, many of which occur in concert with the Snowball-Earth-related climatic shifts, but whose origin remains debated.

2.3 Rise of animals—For nearly 2 billion years, life on Earth was dominated by archael and bacterial communities. Then, over the span of a few hundred million years (ca. 800 to 530 Ma) eukaryotes diversified and all major extant crown groups of modern eukaryotes emerged and diversified (Knoll et al., 2006). Paleobiological studies in N America, Australia, Namibia, and Asia are uncovering a rich microfossil record preserved in rocks of mid-Neoproterozoic age (Bosak et al., 2011; Cohen and Knoll, 2012). Biomarker analysis has been used to infer a fossil record of demosponges in the Cryogenian, earlier than suggested by the record of body fossils (Love et al., 2009). Importantly, these recent discoveries converge with molecular data, which increasingly place the key divergences of early animal taxa within or just prior to the Cryogenian Period (Erwin et al., 2011). What these and other findings reveal is an apparent diverse and ecologically complex biota living sometime prior to, and surviving through, the Snowball Earth glaciations. As informative as those findings are, the diversification of eukaryotes and origin of animals remains debated and unresolved.

3. Why Start in South China? Although enormous advances have been made in the past decade in documenting and interpreting Neoproterozoic events, significant gaps remain: the timing of many of the key events is unknown, their durations remain poorly constrained, and techniques for interpreting physical conditions during these events range from satisfying to speculative. Because both the relative and absolute timing of these events is so critically under-constrained, we focus our initial efforts on successions that have the best potential for geochronology. Mixed carbonate and siliciclastic Neoproterozoic strata in South China preserve a rich microfossil record and organic-rich shale ideal for biomarker studies and Re/Os geochronology, with numerous interspersed tuffs, containing zircons dateable with U/Pb ID-TIMS (Condon et al., 2005; Zhou et al., 2004). Existing ages bracket at least two glacial events between 800 and 635 Ma. The numerous ashes that have already been described will enable us to assess the stratigraphic completeness and continuity of these records. We have already begun to collect supporting data from correlative outcrops. We propose here to put our first two drill cores through the Yangtze platform, and then build off this effort with additional coring of the Chuar Group of Arizona, USA (Karlstrom et al., 2000).

Two preliminary drilling sites through Cryogenian shelf and slope sections on the Yangtze platform of South China have been identified. Although we do not yet have geophysical data, preliminary stratigraphic and geochronological studies from outcrop have indicated these sections are stratigraphically complete. We intend to visit and refine these sites in September. These outcrops are near large roads, which should simplify logistics. Logistics related to permitting, drilling equipment, and export of the core are being arranged by our collaborators at the Nanjing Institute of Geology and Paleontology, headed by Maoyan Zhu.

Questions to be addressed with the drilling program that will begin in South China include:

- What controls the initiation and timing of global glaciations, their durations and which feedbacks moderated their reoccurrence? For example, data now indicate that the Sturtian glaciation was of long duration (some +50 Myr), the Marinoan could be as little as 1 Myr to as much as +20 Myr in duration, and the Gaskiers was short-lived, likely less than 1 Myr (e.g. Rooney et al., 2012; Bowring et al., 2007).
- Do the geochemical proxy records through Cryogenian strata record regional or global events, and are distinct patterns synchronous or diachronous? Particularly are large perturbations to the C-cycle such as the Tayshir-Trezona event (Johnston et al., 2012) global or basinal?
What was the magnitude and tempo of the purported pO₂ rise and how does it relate to the diversification of eukaryotes, increased complexity in ecosystems and the appearance of animals?

To date very few drilled archives have been exploited for Neoproterozoic Earth System research. Two notable exceptions are Oman (South Oman Salt Basin) and Australia (Centralian Superbasin) and these resulted in benchmark papers on, for example, the study of S isotopes, biospheric evolution, geochronology, micropaleontology and even one of the earliest papers on cap carbonates (Amthor et al., 2003; Bowring et al., 2007; Fike et al., 2006; Kennedy, 1996). Progress in understanding the Neoproterozoic Earth system is hindered severely by being restricted to study of surface outcrops and the requirement to correlate between multiple sections and basins in order to integrate disparate data sets. Many South China, South America and central African sections are weathered deeply and buried under thick soil and vegetative cover. An additional motivation for undertaking a scientific drilling program is the combined opportunity to obtain high-quality archives with the ability to access key sections that are otherwise inaccessible (due to lack of good exposure). In our case, there is a second major motivation: the opportunity to construct a robust and efficient data archival system. The Neoproterozoic research community is acquiring an increasing dataset of field observations, palaeontology, geochemistry (δ¹³C, δ¹⁸O, ⁸⁷Sr/⁸⁶Sr as well as various other non-traditional stable isotopes and other proxy records), geochronology and paleomagnetics. The global datasets are becoming difficult to manage and manipulate, and the lack of accessible, well-catalogued samples is severely impeding scientific progress. As such there is considerable interest from Neoproterozoic researchers to embrace and contribute to efforts that improve sample access and data management, hence extending the longevity and utility of datasets.

4. Summary This pre-proposal aims to develop of a scientific drilling research initiative charged with accelerating Neoproterozoic research. The Neoproterozoic time slice challenges the Earth science community with a hierarchy of questions, from the broadly profound, such as ‘why did complex, macroscopic life evolve on this planet?’, and ‘how likely is it that other Earth-like planets may have experienced similar climactic and biotic transitions?’, to the more detailed, such as ‘how do different but broadly coeval stratigraphic sections that contain distinctly different proxy records relate to one another?’, or ‘what was the duration of the Marinoan glacial event?’ These questions center on the when, how and why of the biogeochemical conditions and causes that transformed Earth into a planet inhabited by metazoans and one that is richly oxygenated. The proposal builds upon discussions at the recent Fermor Meeting (The Neoproterozoic Era – Evolution, Glaciation, Oxygenation) held in September 2012 at the Geological Society, London, where the kernel for this initiative was fertilized. More than 100 participants attended the Meeting, highlighting that we are a mature and active research community prepared to embark on a collaborative initiative aimed at addressing fundamental questions about the behavior of the ancient Earth system.

What we are proposing is an initiative that will engage the Earth science community for a decade and likely longer. We envisage a program of scientific continental drilling that, for the Neoproterozoic, will match in spirit and scope that of the IODP for advancing understanding of Cenozoic climate and life co-evolution. It will involve multiple drilling projects funded by different sources and engage with as wide a spectrum of the Earth science community as possible, being open to and inclusive of researchers hailing from Universities, Colleges, Geological Surveys and other national academic agencies/foundations and Industry-related research groups. Our aim is to have this proposed program serve as a catalyst for establishing a worldwide alliance of collaborative, integrated scientific research and data archiving that will leave a legacy for the understanding of complex Earth systems in deep time.
References


Pre-proposal for scientific drilling in the Green River Formation

Malka Machlus, Sidney Hemming (LDEO) and Samuel Bowring (MIT)

The early to middle Eocene Green River Formation contains several high-resolution lacustrine archives of paleoclimate and cycle-stratigraphy (Bradley, 1929; see figure) contemporaneous with rapid mammal evolution that is recorded in the respective lake-margins during the warm Early Eocene Climate Optimum (Clyde et al., 2001). Organic rich micro-laminated carbonates (oil shales) of both open and terminal lakes were suggested to record annual deposition of micro-laminae on sub-millimeter scale (Bradley, 1929; Fischer and Roberts, 1991) and in some locations these possibly varved sediments are continuous over hundred thousand years with little change in lithology. Volcanic ashes are abundant in all basins and contain zircons that can be dated by U-Pb Chemical Abrasion Thermal Ionization Mass Spectrometry (CA-TIMS) with uncertainties in the order of single precession cycle (Machlus et al., in prep).

The Green River Formation was studied and drilled extensively as interest in producing oil from oil shales rose and fell, but surviving cores have limited usefulness for comprehensive study of the scientific issues listed here. For example, the longest record of distinctly cyclic, continuous, ~annual lacustrine deposits is in the Piceance Creek Basin. All 70 cores that span this whole record contain long intervals of scattered small fragments that are free to mix in their boxes and this state precludes a continuous scan of the whole record (e.g., XRF, color values). Key intervals are missing from all these cores, and the existing surfaces are altered in a way that original textures and colors are distinctly different from fresh cores, lowering the usefulness of partial core and XRF scans. Those fresh cores obtained in the last few years by oil companies are highly confidential, and unfortunately, the data kept most confidential is the oil yield values, that are also used as the stratigraphy of the basin and is absolutely essential for any down-core study. In addition to problematic state of existing cores, two areas of importance lack cores in the Piceance Creek basin and the Bridger basin and available data from thousand of cores allows for study of cyclicity (though with many missing intervals) but does not resolve sub-Milankovitch variability.

The recently renewed interest of producing oil from oil shales led the USGS to compile online databases containing all available data for each of the three basins and provide summary cross sections and isopach maps for key beds. The data include Fischer assays (essentially a proxy dataset to TOC and lake level), geophysical logs and comprehensive stratigraphy (USGS Oil Shale Assessment Team, 2010a; 2010b; 2011).

There are four scientific issues that can be addressed through drilling the Green River Formation combined with outcrop study:

(1) Testing the orbital forcing hypothesis: Hypothesized orbital forcing was suggested for the Green River Formation of all basins (e.g., Fischer and Roberts, 1991; Roehler, 1993) but available uncertainties support different orbital age models that cannot be resolved (Smith et al., 2010). Recent U-Pb ages of ashes from the Bridger basin, Wyoming (Machlus et al., in prep), have sub-precession uncertainties and for the first time provide the opportunity to test the orbital hypothesis directly without any assumptions (i.e., no orbital tuning). Such test will be the first direct testing of pre-Neogene cyclic record. A comprehensive test requires dating many more ashes that correlate to a core with numerical record of the cyclicity (e.g., TOC) from the most basinal and complete record. Ashes for dating can be sampled from outcrops and correlate to cores within a meter scale “precessional” cycle. Ashes from about half the hypothesized precession cycles are already sampled in the Bridger Basin, and sampled less densely in other basins.

(2) Cross calibration of the Global Polarity Time Scale (GPTS) with U-Pb ages and cycle-stratigraphy: The early and middle Eocene portion of the GPTS (Ogg, 2012; Vandenberghe et al., 2012) implies a large change in mid-ocean ridges spreading rate and is calibrated mainly by $^{40}$Ar/$^{39}$Ar ages, two with large associated uncertainties (0.5 m.y.), some from un-published sources, and all from different locations. Here we propose a unified calibration that will be supported by an order of magnitude smaller uncertainties (U-Pb CA-TIMS ages) and cycle-stratigraphy (possibly orbital in origin). The measured magnetic polarity can be obtained both from intercalated ashes in basinal cores or outcrops (see method of Tsukui and Clyde, 2012) and from dated magnetic polarity sections at the margins (e.g., Clyde et al., 1997; 2001). Ashes from lake marginal deposits where magnetic polarity sections exist can be also dated by $^{40}$Ar/$^{39}$Ar in order to compare directly to the existing, mostly Ar-calibrated, GPTS.
(3) Is mammal evolution coeval with climate?: Faunal turnover in the Greater Green River Basin occurred during a global period of warmth (early Eocene climate optimum; Clyde et al., 2001), but the link between the two is controversial. We propose to examine this question using a record of lake level (i.e. climate proxy record) from a core near the basin center and a combination of age control points, such as: dated volcanic ashes from fossil sites (U-Pb CA-TIMS and $^{40}$Ar/$^{39}$Ar ages), dated volcanic ashes from the basin center, existing magnetic polarity records and newly obtained magnetic measurements from volcanic ashes in cores and outcrops (see Tsukui and Clyde, 2012). If the orbital forcing hypothesis is supported, the resulting cycle-stratigraphy will be directly correlated to mammal evolution.

(4) What is the climate variability on annual to decadal scales before, during and after the early Eocene climate optimum? Micro-laminated (oil shale) records that are potentially annual (varved) exist in all basins and originate in open, relatively fresh-water lakes and terminal, hypersaline lakes (Bradley, 1929; 1964). High-resolution XRF and spectral gamma ray scans of fresh basinal cores can serve as ~annual paleo-lacustrine record, and further linked to climate through longer trends that follow sedimentary indicators for lake level. Other high-resolution records, possibly decadal (millimeter resolution), that can be obtained from color values (requires fresh core) and micro-resistivity imaging log (if the borehole is large enough for the logging tool). These two latter measurements are potential proxy for high-resolution organic matter content that correlates with dark color and permeability in oil shale beds.

Though all these questions can be addressed in the Bridger Basin, Wyoming, it is worthwhile to consider drilling other basins (see figure). The longest continuous high-resolution (~annual) record is in the Piceance Creek Basin and it contains the most pronounced cyclic record as well. If only a single core is to be obtained, this would be the highest priority (~600 m length, bottom is ~1 km below surface). The record of the Piceance Creek Basin can be easily extended to younger ages in the Eastern Uinta Basin. The table below compares the merits of studying the four scientific issues in each of these three basins. A balanced alternative to drilling all three basins may be to study a suite of cores drilled in different depositional environments, an important issue concerning spatial variability of lacustrine deposition (Aswasereelert et al., 2013). In this proposal we deliberately list several options for drilling project to allow for discussion with interested colleagues who would like to collaborate on drilling the Green River Formation. We do not list the western Uinta Basin as a target here, because this project may require further preliminary research that was already carried out in other basins. Nevertheless the western Uinta Basin is potential for future drilling because it contains the longest lacustrine record, possible from the Paleocene through early Eocene.

Additional criteria for consideration summarized from the “Call for pre-proposals”:
- Location/age: see table below.
- Continuity, completeness and resolution: see table below.
- Baseline stratigraphic data and support data: extensive database was compiled recently for all basins by the USGS and is available online (USGS Oil Shale Assessment Team, 2010a; 2010b; 2011).
- Paleontologic data: Available mostly for the Bridger Basin and other basins of the Greater Green River Basin (see Clyde et al., 1997; 2001).
- Age model, existing and potential: Published geochronology (Smith et al., 2010) has relatively high uncertainties (> 0.1 m.y.); seven U-Pb ages with low uncertainties (~0.02 m.y.) are from the Bridger Basin (Machlus et al., in prep), ashes containing zircons are abundant and many were already sampled from outcrops (see table); Published magnetic polarity sections and magnetic polarity of volcanic ashes exist in the Bridger Basin (Clyde et al., 1997; 2001; Tsukui and Clyde, 2012).
- Challenges to drilling, obtaining subsurface information, access for drilling equipment, complexity of operation: Challenges are probably minimal because areas relevant to the scientific issues were drilled in the past, and access is through graded roads. Roads are improved in the Piceance Creek Basin due to tight-gas and gas shale operations.
- Permitting issues: Most lands are BLM lands, but some areas in the Piceance Creek Basin are leased to oil companies or are company owned (oil and mining companies).
<table>
<thead>
<tr>
<th>Location</th>
<th>Age*</th>
<th>Scientific issues (see text for details)</th>
<th>Age model</th>
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<tbody>
<tr>
<td>Bridger Basin</td>
<td>Tipton, Wilkins Peak and Laney members: ~52 to ~49 Ma.</td>
<td>(1) Orbitally forced cycles? Less than ideal location for this test, but ideal for studying all 4 issues. Target interval is the Wilkins Peak Member, ~51.6 to 49.7 Ma. Cycles are laterally extensive across basin. (2) GPTS Calibration Best location for this scientific issue. Magnetic polarity data already exists. The astrochronology part is for the Wilkins Peak Member. (3) Mammal evolution and climate Best location for this scientific issue. The astrochronology is for the Wilkins Peak Member. (4) Availability of ~annual intervals Intermittent intervals, &lt; 20 k.y. long in the Wilkins Peak Member, with gaps of ~10-50 k.y. (?). Order of 50 - 100 k.y. (?) in the Laney or Tipton member.</td>
<td>Availability** of ashes, magnetic sections Abundant volcanic ashes in the basin center with datable zircons, less in areas of magnetic polarity sections at the west and north margins.</td>
</tr>
<tr>
<td>Piceance Creek Basin</td>
<td>~51.5 to ~48 Ma.</td>
<td>The best location for this test. Cycles extend across the basin, and lacustrine sedimentation is continuous. Age control is best at about 51 to ~48 Ma. This study depends on the success of measuring magnetic polarity on thin ashes.</td>
<td>NA</td>
</tr>
<tr>
<td>Eastern Uinta Basin</td>
<td>~49 to ~47 Ma.</td>
<td>Potential extension to the Piceance Cr. Basin.</td>
<td>Potential extension to the record of the Piceance Cr. Basin.</td>
</tr>
</tbody>
</table>

* Ages are based on Smith et al. (2010), Machlus et al. (in prep) and on un-published preliminary U-Pb age data of ashes from Piceance Creek Basin.

** Availability of ashes in the Piceance Creek Basin is confirmed in selected intervals of the upper part of the record, in cores and outcrops across the basin.

Figure: Aerial extent of the Green River Formation (modified from Grande, 1984)
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US Participation in the Return to Mochras: 
A New Global Standard for Early Jurassic Earth History 
Pre-proposal for US Scientific Drilling and Evolution of Earth System Workshop
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Summary. We seek US support of an international drilling project to recover a complete Lower Jurassic sedimentary record at the site of a previously drilled corehole at Llanbedr (Mochras Farm), on the eastern margin of the Cardigan Bay Basin, West Wales. The new record would comprise an exceptionally thick (1300 m) and biostratigraphically complete succession of marine mudrocks recording a critical interval of Earth history. The attributes of the succession are ideal to provide the basis for an integrated biostratigraphy, magnetostratigraphy, chemostratigraphy, and cyclostratigraphy that would become the international standard for these 25 million years of Earth history. The new materials and data would be applied to obtain a comprehensive understanding of the Earth system during the Early Jurassic and its history of change, including some of the most extreme environmental change events in the Mesozoic, the Triassic/Jurassic mass extinction and Toarcian Ocean Anoxic Event.

Background. We seek to pursue an unparalleled opportunity to develop high-resolution paleoceanographic and paleoclimatic records for the Early Jurassic by drilling a corehole at the Mochras site in Wales. The original Llanbedr Mochras Farm corehole (Mochras Hole A) was drilled on the coast of West Wales in 1967-1969, recovering a 1300-m thick Lower Jurassic succession (Woodland, 1971; Fig. 1) that contains all ammonite zones. This is approximately three times the thickness of the same age strata known from other UK coreholes or from the globally important coastal exposures in Dorset and Yorkshire (including several GSSPs). The succession is remarkable not just for its thickness, but also for the relative uniformity of argillaceous lithology and biostratigraphic completeness.

Although the Mochras Hole A succession has figured prominently in discussions of regional Jurassic paleogeography and basin development, its true potential to shed light on global processes and Earth history has never been realized because drilling predated the advent of chemostratigraphy and cyclostratigraphy. The cores and samples are both well preserved and well curated for some intervals, but recovery was not complete across the Triassic/Jurassic boundary and, moreover, there is not enough of the original core available for high-resolution sampling. In sum, much of the existing material is unsuitable for application of modern high-resolution methods. Hence, S. Hesselbo (Oxford), K. Miller (Rutgers), B. van de Schootbrugge (Frankfurt), C. Bjerrum (Copenhagen), and J. Riding (British Geological Survey) were funded by ICDP for a workshop to plan a return to Mochras.

The workshop was held March 20-21, 2013 in Oxford, England to plan drilling and logging of the Mochras corehole. The PI's of this pre-proposal attended along with over 30 international participants. The workshop was highly successful in articulating scientific objectives. Among the goals and questions that this corehole project will address:

![Figure 1. Stages, ammonite zones, lithologic log, $\delta^{13}$C bulk carbonate and paleodepth changes inferred from benthic foraminifers. Modified after van de Schootbrugge et al. (2005).]
1) It will provide a global template for Early Jurassic Earth systems interactions, an interval of major tectonic change (e.g., supercontinent breakup and eruption of the Central Atlantic Magmatic Province [CAMP, one of the largest known large igneous provinces]), biologic change (e.g., radiation of eukaryotic phytoplankton), and climate change (e.g., the transition from an icehouse to a super greenhouse associated with the Toarcian-Ocean Anoxic Event).

2) The core will allow construction of the first complete biostratigraphically calibrated magnetostratigraphy for the entire Early Jurassic interval based on a single section.

3) Core and logs will provide a cyclostratigraphy that will yield an astrochronology timescale for the entire Early Jurassic with the resolution of a precession cycle.

4) Integration of various geochemical proxies will address how supercontinent breakup influences the Earth-Ocean-Biosphere system.

5) The new corehole will provide a critical record of the Triassic/Jurassic mass extinction (the 3rd largest in Earth history, but poorly recovered in the first corehole), particularly the recovery of Early Jurassic marine and terrestrial carbon cycles, biospheres, and oceans from the extinction and the effects of CO2 and other volatile releases from CAMP.

6) Paleo-water depth reconstructed from the new borehole will provide a record of Early Jurassic relative sea level change that will be crucial in addressing changes during the icehouse of the late Pliensbachian and the ensuing super greenhouse of the Toarcian.

7) Cores will provide a record of interdependencies among environmental change, primary productivity, and other microbial metabolisms.

**Geochronology and astrochronology.** Milankovitch-scale cyclostratigraphy is visible through much of the existing Mochras Hole A (Fig. 2). This raises the prospect for creating a continuous astrochronology for the entire Early Jurassic time scale correlated with ammonite biozones. The absolute time scale of the basal Jurassic and Hettangian has been dramatically improved (Blackburn et al., 2013). The remaining Early Jurassic time scale is far less precise, comprised of an opportunistic scattering of ash dates obtained with outmoded procedures. Therefore, cyclostratigraphy will be essential for development of a highly resolved Early Jurassic time scale. Geophysical logs from the original Mochras Hole A provide a tantalizing preview of cyclostratigraphy through the upper 2/3 of the corehole. For example, in the gamma ray series, 30-32-m cycles incorporate 3-4 shorter cycles, many of which are bifurcated (Figs. 2A, B). The power spectrum (Fig. 2C) indicates variance at specific wavelengths: 20-32 m, 6-9.7 m, and 2.5-2.9 m. Assuming that the 32 m cycles are 405-kyr scale, the 6-9.7 m wavelengths are ~100-kyr scale, and the 2.5-2.9 m cycles are 31-36 kyr scale, suggestive of eccentricity and obliquity forcing. The sample-rate of the log was too low to resolve shorter ~20-kyr scale cycles indicative of precession forcing. Redrilling the Mochras site includes a plan to log the corehole with state-of-the-art, high-resolution tools to recover precession-band cyclicity, which can be observed visually in the original Mochras Hole A core at the 1.0-1.5 m scale.

**Paleobiology and paleoecology.** Detailed records of biostratigraphically relevant macro- and microfossils will be generated at m-scale resolution. Coordinated action by an international team with expertise in the taxonomy and paleoecology of ammonites, dinoflagellates, pollen, calcareous nannofossils, and benthic foraminifera, will be the key to understanding biotic change through the Early Jurassic and to construct a high-resolution biostratigraphic framework. Benthic foraminifera are used both as ecological indicators of environmental change, and as paleobathymetric indicators of sea level change. Phytoplankton (dinoflagellate cyst and nannofossil) data are essential for describing the early radiation of these groups, and for understanding mechanistic links between primary production and carbon cycling, especially during carbon cycle perturbations (e.g., the Toarcian OAE). Pollen records serve to: 1) document terrestrial flora changes in the aftermath of the end-Triassic mass-extinction; 2) reconstruct continental floral changes during times of de-oxygenation in the oceans; and 3) ground-truth records of charcoal delivered to the oceans from forest fire burning. The latter proxy can be used to constrain atmospheric oxygen content which models suggest reached an all-time Phanerozoic low of 10-15%.
Geochemistry and paleoenvironmental change. The proposed corehole will provide an exciting opportunity for new geochemical studies. Initially, inorganic (including $\delta^{13}$C\textsubscript{carb}, $\delta^{18}$O\textsubscript{carb}, $\delta^{34}$S\textsubscript{CAS}, $\delta^{34}$S\textsubscript{Pyrite}, Fe speciation, redox sensitive trace metals) and organic (including $\delta^{13}$C\textsubscript{org}, $\delta^{13}$C\textsubscript{alkanes}, lipid biomarkers) proxies will be measured in moderate (m-scale) resolution over the length of the entire core in a coordinated effort by multiple laboratories to generate first-order chemostratigraphic records of environmental and ecological change (that can then be evaluated for cyclicity). These data will guide a second phase of analysis to address critical intervals of change, constructing high (mm to cm-scale) resolution bulk and in situ biogeochemical records and testing specific, higher-order hypotheses (e.g., oceanic redox state controls rates of planktonic extinction and recovery).

The “Return to Mochras” plan. A detailed coring, logging, and sampling plan was articulated at the Oxford workshop. The corehole will be drilled in October 2015-March 2016 with a large diameter (38-10 cm) core and 9-10 logging runs. Onsite descriptions will consist of minimal measurements (onsite photos, general lithology, grain size, sorting, roundness, bedding, color, fossil content, ichnofabric, physical structures, cement, accessory minerals, contacts). Cores will be transported to the British Geological Society (BGS) core repository where they will be split into thirds (archive, working, and macrofossil) and scanned (Geotek, XRF, and photoscans). A detailed core description and sampling party (lasting approximately 1 month) of all participants will be held about 6 months after drilling. We anticipate a similar number of samples as are obtained from a typical IODP succession of similar thickness (~10,000 samples). The core will be archived at the BGS and data archived in numerous public databases. Scientific papers will have target date of 2.5 years after a Scientific Results meeting (October 2018) in an online, open access journal.

This is a low risk, very high yield project. The BGS will provide logistical support and some funding, and the site has already been revisited and found suitable logistically (access, permitting, operations). Offshore seismics are available, though some onshore work is still needed. Drilling is conventional and on the same scale as the successful ICDP Chesapeake Bay Impact Structure, Eyreville, VA borehole (Gohn et al., 2008) or the recent ICDP Snake River Plain coreholes (Shervais et al., 2013). We anticipate a drilling budget of ~2 million US$, with ~60% from ICDP, support-in-kind for all logging (Hannover), and some support from other partners. We would seek US drilling support and support for the PI’s to participate in the drilling, and to carry out detailed analytical plans.

Figure 2. Gamma ray log from the original Mochras Hole A, digitized from original analog graphs. A. Entire series after removing a long-term irregular trend. B. Interval from the upper part of the corehole highlighting ~32 m cycling interpreted as 405-kyr cycles, (green) and 6-9.7 m cycles interpreted as ~100 kyr cycles (purple). C. Multitaper power spectrum of the entire gamma series and preliminary Milankovitch interpretation.


Core Drilling the Grove Center Late Paleozoic Outlier in Western Kentucky

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Synopsis. We propose to drill a continuously cored hole 1,100 to 1,500 feet (305 to 336 m) deep to sample an outlier of uppermost Pennsylvanian and Lower Permian (?) rocks near Grove Center in Union County, western Kentucky. This site is one of two small, down-faulted blocks containing rocks of this age midway between the Dunkard basin and Kansas. The other Kentucky outlier, at Cap Mauzy Lake, was core-drilled circa 1980, yielding the youngest known Paleozoic rocks in the Illinois basin. This core reveals a succession transitional between the fully terrestrial Dunkard basin and largely marine correlatives in Kansas. It also displays a marked upward change from cyclic, coal-bearing rocks to beds lacking coal and containing a much greater proportion of non-marine limestone and mudstone. The limited rock material from the Cap Mauzy core has been depleted by more than 30 years of sampling and general deterioration. The Grove Center outlier is tightly constrained by industry drilling, indicating that it contains strata younger than any at Cap Mauzy. We have assembled a team to investigate multiple aspects of regional and global correlation along with depositional environments and paleoclimatic conditions. Local drillers are available who routinely acquire the types of samples we need. No special difficulties are anticipated in site access, drilling, or well logging.

Justification. The Grove Center outlier in Union County, western Kentucky presents an opportunity to core the youngest Paleozoic rocks in the Illinois basin. This site lies midway between the fully terrestrial Dunkard basin, 650 km northeast, and largely marine rocks of central Kansas, some 650 km west. Grove Center and the Cap Mauzy graben, 18 km east (Fig. 1), are the only places in the Illinois basin where rocks of this age are preserved. Both occupy narrow downthrown blocks along the Rough Creek fault system.

Cap Mauzy graben and Gil 30 core. The Cap Mauzy graben was mapped by (Kehn, 1975). Subsequently, the Kentucky Geological Survey drilled a continuously cored test hole, Gil 30, 1,841 feet (561 m) deep. Gil 30 penetrated approximately 200 m of strata not known elsewhere in the basin. Fusulinids of genus *Triticites*, indicating Early Permian age (as then defined), were recovered from limestone at a depth of 195 feet (59 m) (Kehn et al., 1982; Douglass, 1987).

The rock succession above 340 feet (104 m) depth in Gil 30 differs markedly from that below and is assigned to a new unit, the Mauzy Formation (Kehn et al., 1982). In contrast to dominantly siliciclastic, coal-bearing, cyclothemic rocks below 340 feet, younger strata in Gil 30 contain a much greater proportion of non-marine limestone and mudstone. These alternate with three intervals of marine and deltaic rocks and a single interval of fluvial(?) channel sandstone. A single layer of dull, shaly coal is less than 3 cm thick (Kehn et al., 1982; Nelson et al., 2011). Overall, the Mauzy implies a marked shift in depositional and climatic conditions near the Carboniferous-Permian boundary. Also, this formation appears to record depositional conditions intermediate between the Dunkard basin, correlative rocks of Kansas, and older Pennsylvanian rocks of the Illinois basin.

The Gil 30 core is a wonderful resource, yet seriously limited. The lower part of the core is only 1-inch (2.5 cm) diameter. The core is further depleted by incomplete recovery, previous sampling, and more than 30 years of weathering. Clay-rich intervals have particularly suffered. Most paleosols are badly degraded; marine intervals lack sufficient material for conodont extraction.

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1 According to subsequent upward revision of the international Carboniferous-Permian boundary, these rocks are probably now uppermost Pennsylvanian. They are unquestionably the youngest Paleozoic strata in the Illinois basin.
Grove Center outlier. Near the Illinois border, Palmer (1976) mapped a graben where the Springfield Coal is projected to lie more than 2,400 feet (732 m) below sea level. Data include the electric log of an oil-test hole (John N. Partin #1 Lovell) and driller’s logs of two coal exploratory holes drilled by Peabody Coal Company. These indicate that the base of the Mauzy Formation is 590 feet (180 m) deep, compared to 340 feet (119 m) in Gil 30. By this reckoning, the Grove Center graben should contain at least 61 m of rocks younger than any encountered in Gil 30.

Additional well records enable correlation between the two outliers and the rest of the Illinois basin. These include a Cities Service oil test in the Cap Mauzy graben and the Shouse oil test a few km west. Close to the Shouse well, Peabody Coal continuously cored two deep test holes, P-47 and P-49. Survey geologists published written and graphic logs of both cores (Smith and Smith, 1967). Although P-47 and P-49 cores did not include Mauzy Formation, both sampled Pennsylvanian strata among the youngest known in the basin. A distinctive layer of limestone rich in ostracods in P-49 also occurs in the Gil 30 core and is believed to lie at 920 feet (280 m) in the Lovell hole and may lie as deep as 1,085 feet (330 m) in the C-2 coal test in the Grove Center outlier, providing a target depth for the proposed core.

Regional implications. The proposed core should yield valuable data for paleoclimate studies concerning Late Paleozoic Ice Age transitions, global changes in atmospheric CO₂ concentrations, basin subsidence and uplift history, and stratigraphic correlation between the Dunkard basin and the Midcontinent. Our proposal is particularly timely, coming shortly after a field conference on the Dunkard basin (Harper, 2011) and coinciding with an international conference on the Carboniferous-Permian transition (New Mexico Museum of Natural History & Science, May 2013) and a forthcoming special volume of *International Journal of Coal Geology* devoted to the Dunkard basin.
Proposed program of study. Multiple lines of research will be pursued on the Grove Center core. The following have expressed interest in participating.

- John Nelson and Scott Elrick (Illinois State Geological Survey, Champaign) and David Williams (Kentucky Geological Survey (KGS), Henderson: Lithologic core descriptions and correlations via physical stratigraphy; sampling and thin sectioning for petrographic study.
- Cortland Eble (KGS): Palynology (a correlation tool) and petrography of coal
- Philip Heckel (University of Iowa, Iowa City): Extraction and identification of conodonts for regional and global correlation (Heckel et al., 2011).
- Neil Tibert (University of Mary Washington, Fredericksburg, Virginia): Identification of ostracodes for regional and global correlation and environments of deposition, e.g. Tibert et al. (2011).
- Neil Tabor (Southern Methodist University, Dallas, Texas): Examination and geochemical analyses of paleosols to help establish depositional and paleoclimatic conditions.
- William A. DiMichele (Smithsonian Institution): Characterization of fossil plants, which are sensitive indicators of environmental and paleoclimatic conditions, with comparisons to other U.S. basins of similar age (e.g. DiMichele et al., 2005, 2011a and 2011b).
- Bradley Cramer (University of Iowa, Iowa City) and Kate Tierney (Denison University, Granville, Ohio): Stable isotope geochemistry of carbonate rocks, including calcareous shales, to achieve regional and global stratigraphic correlation as a supplement to or a substitute for biostratigraphic correlation. A core across the Pennsylvanian-Permian boundary in Kansas is under investigation.

Logistics. The deep graben mapped by Palmer (1976) is 2 km wide and 2 km long. Our preferred drilling site is adjacent to the Peabody Coal #C-2 borehole, which encountered the thickest section of Mauzy Formation. This site is adjacent to an all-weather county road. The overall graben area is gently rolling upland in mixed row crop fields, pastures, and woodlots. County roads and farm lanes provide access for drilling equipment. No unusual problems in site access or drilling are anticipated. The site is in the coal and oil-rich southern Illinois basin and close to the Illinois-Kentucky fluorspar district. Local drilling contractors routinely drill continuous wireline cores in excess of 1,000 feet (330 m) deep for coal and mineral exploration. With the Kentucky Geological Survey overseeing operations, no permitting problems are anticipated. Gaining landowner permission can always be an issue, but the 2 km-square target area encompasses numerous landowners.

Minimum coring depth should be approximately 1,100 feet (360 m) to reach a distinctive limestone unit identified in the Gil 30 and Peabody No. 49 cores. This limestone bed contains abundant ostracods, which are almost as useful for biostratigraphy as conodonts. We would prefer to carry drilling to about 1,500 feet (450 m), penetrating numerous additional marine units and enhancing probability of establishing definite inter-basinal correlations (Heckel et al., 2011). To ensure ample material for laboratory procedures and adequate hole diameter for logging, minimum hole diameter should be HQ core, which produces borehole inside diameter of 3.9 inches (100 mm) and core outside diameter of 3.0 inches (76 mm).

The Illinois State Geological Survey has well-logging equipment and crew capable of running the following logs to a depth of approximately 2,900 feet (880 m): spontaneous potential (SP), single-point and induction resistivity, gamma-ray including spectral gamma-ray, full waveform sonic, 3-D acoustic imaging, borehole deviation, and mechanical and acoustic caliper. Alternatively, numerous commercial logging companies are active in the Illinois basin.
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Plio-Pleistocene Environments of Tropical East Africa:
Continental Drilling in Lake Tanganyika

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Motivation and Objectives

The East African Rift Lakes offer unparalleled opportunities to investigate the climatic and environmental evolution of the tropics during the late Neogene. The lakes' sediments record changes in tropical rainfall, temperatures, and atmospheric circulation across 20° of latitude on both sides of the equator on interannual to geological timescales from the Miocene to the present. Fossil material in these basins chronicles the environmental evolution of the landscapes in which our own species evolved, and records the explosive evolutionary radiation of literally thousands of species of fish, snails, and other aquatic organisms endemic to East Africa's lakes. Drilling these lakes will provide insight into the geological processes that shape the largest active continental rift system on Earth today.

The past decade has witnessed many advances in our efforts to obtain long paleoenvironmental records from East Africa, highlighted by scientific drilling in Lake Malawi (Scholz et al., 2011). Planned drilling in paleolake basins in Ethiopia and Kenya as part of the Hominin Sites and Paleolakes Drilling Project should provide 0.5 to 1 Ma-long “snapshots” of climate evolution since the mid-Pliocene. While these drillcore will provide valuable new records of African paleoenvironments, they are ultimately limited by their short and/or discontinuous nature. We need a long and continuous record of climate and environmental change spanning the Pliocene to the present – a terrestrial “master record” – against which these shorter and/or discontinuous records will be compared. Within East Africa, Lake Tanganyika is the only site at which this master record can be obtained (Russell et al., 2012).

Our overarching goal in drilling Lake Tanganyika is to understand the patterns and mechanisms of the Plio-Pleistocene climate evolution of Africa. The Plio-Pleistocene witnessed many fundamental reorganizations of global climate. The northern hemisphere ice sheets formed, expanded, and waxed and waned at 21, then 40, then 100 kyr rhythms (Imbrie et al., 1992). Collision between the Australian and Asian plates closed Indonesian seaways (Cane and Molnar, 2001), and may have influenced the development of the tropical Pacific's eastern equatorial cold tongue and the modern-day El Niño-Southern Oscillation system (Fedorov et al., 2006). The East African plateau continued its uplift, influencing the circulation of the Indian summer monsoon (Sepulchre et al., 2006). Numerous outcrop and marine sediment records, as well as global climate models indicate that East African climate is strongly sensitive to all of these phenomena (Brierley and Fedorov, 2010; DeMenocal, 1995). However, the short and/or discontinuous nature of existing records limits our understanding of the governing mechanisms and sensitivity of African climate to these phenomena. A clear understanding will require long and continuous climate records extending into at least the Pliocene to observe East African climate responses across multiple events and time-scales. A long and continuous record of East African climate from Lake Tanganyika could resolve many of these issues, including:

- What are the dynamics of Plio-Pleistocene (last ~5.5 Ma) African climate as a consequence of the mid-Pliocene termination of a permanent El Niño, ocean circulation change associated with the closure of the Indonesian seaway, and the onset, intensification, and changes in the periodicity of Northern Hemisphere Glaciation?
- What is the sensitivity and spatial variability of East African hydrology and temperature to orbital insolation forcing? Are megadroughts such as those observed at Malawi present
at sites to the north, and are they antiphased in their timing relative to those in Malawi as predicted by the precessional insolation forcing model?

- How do the rates and amplitudes of East African climate change on millennial to decadal time-scales vary as a function of mean climate state? What are the mechanisms underpinning this time-scale of variability?

Tanganyika drill cores would provide considerable new insight into many fundamental questions in the biological and geological sciences – not just paleoclimate. The East African rift lakes harbor some of the best examples of explosive speciation on the planet (Martens, 1997), and Lake Tanganyika is one of the most biodiverse lakes on Earth, with endemic species flocks of fishes, snails, and ostracodes, among others. Key questions remain concerning the modes of speciation that gave rise to these extraordinary faunas (Cohen, 2011). Drill cores could thus illuminate the environmental forcing of one of the most spectacular evolutionary radiations in the world. The rich fossil records preserved in many rift basins indicates the strong potential for our cores to recover a fossil record of the phylogeny of these radiations to address the rates of change, linearity, and sensitivity of the evolution of these species and ecosystems. Perhaps more importantly, drilling in Tanganyika will provide a continuous record of environmental change from a single location in Africa against which we can compare the entire span of the Plio-Pleistocene hominin evolution, a key recommendation of the National Research Council (Hamilton et al., 2010).

Tanganyika drill core could provide insight into the timing and dynamics of rifting, land surface dynamics, and hydrocarbon resource generation in the East African rift system. We have a limited understanding of the intertwined processes of rift tectonics, magmatism, erosion, and sedimentation and their evolution in space and time, as in today’s rift basins we see only the end-products of these processes integrated over millions of years (Ebinger, 1989). ‘Textbook’ models of rifting process fail to explain the rates and complexity of rift initiation, propagation, and growth, and Tanganyika is in many ways a model system for an amagmatic rift basin, with very clear examples of rift segmentation and fault behavior. Drill core integrated with seismic stratigraphic datasets could help to evaluate the rates of border fault slip in the basin and how they relate to geothermal gradients and volatile concentrations, the relationships between long-term fault slip rates and short-term seismic hazards (e.g. paleoseismites), and the coupling between long-term erosion rates, climate and landscape development, and sediment accumulation, and their temporal variability.

Lake Tanganyika: Prior Work

Tanganyika (~5° - 9° S, 30° E) is the largest, oldest, and deepest lake in East Africa, with an estimated age of 9-12 Ma (Cohen et al., 1993). It is one of the most biodiverse lakes on Earth, hosting flocks of endemic cichlid fish, snails, ostracodes, crabs, and other organisms, and lies within the vast but poorly understood Miombo woodland ecosystem of SE tropical Africa. Tanganyika lies within the core path of the Intertropical Convergence Zone’s migration over central Africa, and is close to the Congo Air Boundary that separates Atlantic and Indian Ocean monsoonal flow. Its late Quaternary climate history is largely out of phase with Lake Malawi (Barker and Gasse, 2003), indicating that Tanganyika acts as a “northern hemisphere site” despite its location (Tierney et al., 2008).

Tanganyika is comprised of four major sub-basins separated by deep-water horsts. Recent work has documented thick sections of sediment with extremely slow sedimentation rates on these deep-water horsts (ca. 1 m/10 kyr), putting early Pliocene-age sediment within feasible drilling depths (McGlue et al., 2008). The Kalya and Nitiri Horsts in Tanganyika’s southern basin, in particular, lie in deep water (500-700 m) below the depth of maximum lake lowstands, and appear to house long and continuous sedimentary sections (McGlue et al., 2008). Moreover, recent work has demonstrated the potential of these sediments to record climate processes at orbital, millennial, and even interannual time-scales, as the sediments contain a wealth of climate proxies preserved in often laminated sediments (Cohen et al., 2006; Tierney et al., 2010; Tierney et al., 2008). It is unlikely that any other lake in Africa could provide
such a long, continuous, and high-resolution record of African climates and environments of the Plio-Pleistocene. While dating these records could be challenging, paleomagnetic approaches combined with tephr stratigraphic ages have proven successful in generating a reliable age model from Lake Malawi to the south (Johnson et al., unpublished).

Seismic reflection datasets from Project Probe provide low-resolution (both vertical and spatial) coverage of much of the Tanganyika basin (Rosendahl and al., 1988), but do penetrate to bedrock providing a broad stratigraphic context for our study sites. Beach Energy has recently completed a seismic survey of all of southern Lake Tanganyika in Tanzanian waters. Southern Tanganyika contains the best drilling targets on deep-water horst environments, and Beach has previously indicated that they can make sections of this data available. While these data will provide an excellent seismic-stratigraphic framework for interpreting drill core records, it is unlikely to have the resolution needed to detect small-scale unconformities and to select optimal drilling sites. Additional intermediate to high-resolution data and shallow piston cores over deep-water horsts in Tanganyika’s southern basin are needed to site appropriate drilling targets and identify major sedimentary facies likely to be encountered in scientific drilling. The modern limnology of Tanganyika is very well-known through decades of large-scale limnological monitoring efforts (Descy et al., 2005).

Site Logistics

The primary challenge of drilling in Tanganyika are the logistics (and cost) of drilling a long hole in deep water. Drilling entire Plio-Pleistocene sections is likely to require recovery of 500 m of mud in 700 m of water in a very large lake. Subsurface gas and other deposits could be hazards, and current seismic datasets are not of high enough quality to detect them. However, our workshop participants felt that the potential significance of a continuous, high-resolution, Pliocene-present record for tropical paleoclimatology and paleoenvironments outweigh the significant time and investment required to move the Tanganyika record forward.

Moreover, many aspects of the site logistics at Tanganyika are relatively straightforward. There are many vessels that could be modified to serve as drilling platforms and support boats on the lake, as well as vessels that could be used for pre-drilling seismic surveys. A deep-water port and shipyard is available at Kigoma, Tanzania, which also provides an airport, daily cargo train to Dar es Salaam, and other facilities to serve as a regional base of operations. We have strong local contacts and collaborations in the Tanzanian Fisheries Research Institute in Kigoma, as well as the Lake Tanganyika Authority, a four-country coordination unit of the UNDP dedicated to sustainable management of the Tanganyika Basin. Provided that drilling occurs in Tanzanian (not Congolese) waters, permitting and local cooperation is relatively simple.

Future Steps:

The US National Science Foundation, Past Global Changes (PAGES), and Brown University sponsored a workshop on scientific drilling in the East African lakes in November, 2011. Forty scientists from the US, Africa, and Europe attended this workshop, contributed to the science priorities above, and ranked Lake Tanganyika as the highest priority target for lake drilling in East Africa. The next steps to building the Tanganyika drilling project are to improve site geophysical and sedimentological datasets though a seismic reflection and sediment coring survey focused on the Kalya and Nitiri Horsts, followed by an international workshop to review existing datasets and to develop a science team to carry the project forward.
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Scientific drilling in the Great Rift Valley: the 2005 Lake Malawi Drilling Project- an
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Proposed Continental Drilling Project: Recovering a 3 to 5 million year paleolimnologic record from Butte Valley, California

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We propose to core Butte Valley, near Meiss Lake, Siskiyou County, California (Fig 1) to recover a unique carbonate-rich Pliocene-Pleistocene record that likely extends to about 4 and possibly 5 million years in age. In 1991, the USGS cored this site and recovered a 3.3 million year paleolacustrine record (Adam et al., 1994, 1995; Roberts et al., 1996). Drilling stopped and analyses were limited due to lack of funds, but there was every indication that a longer record was available. Here, we provide background and reasons to return to Butte Valley and recover a full record that includes the Pliocene. Renewed interest in this site has come about through a search for existing Pliocene-Pleistocene records in North America that contain carbonates and calcite microfossils for paleoclimatic and paleohydrologic study. Novel approaches using organic biomarkers, as well as diatom and pollen analysis are planned, along with age-dating of the numerous tephra deposits.

Science Background: The USGS drilling project at Butte Valley was part of an effort to recover Plio-Pleistocene records from marine sites and western basins outside the Great Basin (the Correlation of Marine and Terrestrial Records Project: CMTR, summarized in Adam et al., 1995). In that effort, the sediment cores from Tule Lake, Upper Klamath Lake, Buck Lake, Clear Lake, Carp Lake, and Grass Lake, among others, were recovered. The Butte Valley core chronology is based on magnetostratigraphy, which shows that the core penetrated beyond the Matuyama/Gauss boundary (Roberts et al., 1996). Excluding Butte Valley, only Tule Lake (~ 3 my) has a record that extended beyond the Pleistocene and none has a carbonate record. Other Late Cenozoic paleolacustrine cores from North America, such as those from San Augustin Plains, Owens, Bonneville, Summer, Bear Lake, and Lahontan do not extend beyond the Pleistocene, although outcrop sections exist (see table). Also, numerous sections from well cuttings, outcrops, and partial recovery of Pliocene cores exist for sites throughout western North America but do not include continuous sediment cores (for summary, see Thompson, 1991).

Table 1: Continuous Paleolacustrine Late Cenozoic Core Records in North America with ages of at least 100 kyr.

<table>
<thead>
<tr>
<th>Lake Record</th>
<th>Age</th>
<th>Citation</th>
</tr>
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<tbody>
<tr>
<td>Butte Valley, CA</td>
<td>3.3 my ++</td>
<td>Roberts et al., 1996</td>
</tr>
<tr>
<td>Searles Lake, CA</td>
<td>3.2 my (brine minerals)</td>
<td>Hay et al., 1991</td>
</tr>
<tr>
<td>Tule Lake, CA</td>
<td>3 my++ (no carbonates)</td>
<td>Bradbury, J.P., 1992</td>
</tr>
<tr>
<td>San Augustin Plains, NM</td>
<td>1.6 my</td>
<td>Markgraf et al., 1984</td>
</tr>
<tr>
<td>Owens Lake, CA</td>
<td>800 kyr</td>
<td>Smith, G.I. &amp; Bishoff, J., 1997</td>
</tr>
</tbody>
</table>
Scientific Reasons to Return to Butte Valley, California: The USGS Butte Valley core is the only carbonate-rich paleolimnologic core record in North America extending into the Pliocene, although there were gaps in recovery (Adam et al., 1994). The core contained well-preserved fossil ostracodes, pollen, and diatoms. We propose to collect a continuous and longer core at BV, in order to undertake a multiproxy analysis of the Pliocene to Holocene history of northern California. Included in our analysis will be a novel suite of tools and approaches not available in the earlier study of BV. These records, individually and collectively, will help address several important scientific problems currently under debate:

1. **How did western North America respond hydrologically and climatically during the transition from Pliocene warmth to the Pleistocene glacial-interglacial cycle?** Recent studies (Federov et al., 2010) have linked Pliocene warmth to sustained El Niño conditions. Although this view of permanent El Niño conditions has been challenged (Watanabe et al., 2011) by evidence from the Pacific coral record, the existence of large, deep, Pliocene lakes in western North America argues for a supply of precipitation consistent with sustained El Niño conditions (Brierley & Federov, 2010). With the closing of the Isthmus of Panama around 3 mya (Keigwin, 1982) and consequent onset of ice-sheet development, the shift to a cyclic El Niño pattern developed in early Pleistocene time, and the large Pliocene lakes of western North America gradually disappeared. Lake basins in tectonically active areas, such as BV, were also strongly affected by a growing rain shadow from the uplift of the Cascades. Pliocene drainage patterns changed drastically, leaving a trace of these patterns in the fossil distribution of endemic species from ancient Lake Idaho southward through the Klamath region (Smith & Adam, 1993). Full recovery of the BV record, therefore, could track the transition from Pliocene warmth through the onset and establishment of the present glacial-interglacial cycle, and provide information on the response of western N.A. to changing hydrology and climate in a tectonically active setting, as has been shown for the late Pleistocene Great Basin lakes (Lyle et al., 2012). This kind of record is needed to understand the implications of sustained global warming for modern regional hydrology.

2. **How did precipitation patterns in western North America change during the Pliocene-Pleistocene transition and how do these patterns compare with similar records throughout the Northern Hemisphere?** BV is located in a region where the climate is highly seasonal, dominated by the westerly storm tracks in winter and an expanded northeastern subtropical high pressure system in summer. As such, the site should be sensitive to changes in the strength and position of the jet stream and the intensity of summer drought as they relate to orbital variations in insolation. The acquisition of multiple proxy records from BV, including pollen, diatoms, ostracodes, isotopes, organic biomarkers, sedimentology and paleomagnetism will allow us to reconstruct past environmental and climate conditions at the site. Ostracodes (microscopic crustaceans) are important in the BV record as tracers of
past drainage histories and hydrologic conditions, through their ecological significance and the geochemical composition of their shells (Ito & Forester, 2009; Smith & Palmer, 2012). The extant taxa in the Pliocene section of the BV core include well-known cosmopolitan forms such as *Cytherissa lacustris* and several *Limnocythere* species, all with good ecological data available (Curry et al., 2012). Isotopic and ecologic analysis will allow this record to be compared with those of similar age throughout the western U.S. and the northern hemisphere, including those from Northern Spain, Northern Greece, Mongolia, Russia, China and Japan (Anadon et al., 2008; Frogley et al., 2001; Muller et al., 2001; Mischke et al., 2010; Colman et al., 2007; Dowssett et al., 1994; and Fuji, 1988). By filling in this gap in the North American Pliocene-early Pleistocene record, we will be able to test hypotheses about the climatic controls that governed regional hydrology, climate variability, and possible climate teleconnections.

3. **How do limnobiota respond evolutionarily under continuous environmental pressure resulting in a transition from permanent, deep lake conditions to shallow, variable lake conditions?** The USGS-BV core provides a key window into a phenomenon known as biogeographic parthenogenesis. *Cytherissa lacustris*, a well-known, cosmopolitan species with northern hemisphere distribution, arose in Lake Baikal about 5 mya (Schön et al., 2012). The first known record of this species in North America is in the BV core, where it occurs in its syngamic form (males and females), just as it exists in Lake Baikal today. However, only the parthenogenetic form (females only) is found throughout the later North American and European Pleistocene and Holocene record, a condition it still retains (except for Lake Baikal populations). The BV record of syngamic *C. lacustris* is the only such site outside of Lake Baikal, and suggests that the change to parthenogenesis must have happened in the Pliocene. Genetic studies exist that show the phylogeny of this taxon, therefore it is possible to independently test the appearance of the parthenogenetic form at this site, marking the transition to a new reproductive state for that species. This biogeographic record is significant in explaining the evolutionary drivers of changes in reproductive strategies as they are linked to environmental pressure.

4. New geochemical proxies (organic biomarkers) are now available to track hydroclimatic changes as well as paleolimnologic changes. Applying these new methods to the BV record, in conjunction with isotopic and microfossil analyses will provide new information about past changes in regional hydrology and drainage history. Such studies recently conducted in Pleistocene records of New Mexico have brought to light detailed drought history not previously available (Fawcett et al., 2011).

**Logistics: Coring Location and Access:** This site is fully accessible by road, and will not involve open water drilling. Although Meiss Lake still occupies the western portion of the basin, the eastern portion is under cultivation or grassland. The BV basin is tectonically active, with numerous fault scarps and a subsurface basalt flow of the Butte Valley Basalt. The previous reconnaissance by the USGS identified an ideal location for coring, and this site is still accessible. The paleolake is now part of the USDA National Grasslands, and is accessible by permit through the National Grasslands road system.
Figure 1: Location of Butte Valley and Meiss Lake, CA. Inset map is Butte Valley drainage basin (from King, 1991, Figure 2). Blue triangle is 1991 USGS-BV1 Core site, in USDA National Grasslands. BV1 Location: 41°53'34.60"N, 122°01'29.57"W, elevation 1295 m
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Drilling Workshop Pre-Proposal: Documenting Tropical Climate During Earth’s Last Icehouse Collapse: The Permian of Western Equatorial Pangaea (Oklahoma)

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The Permian: Fundamental Shifts in All Earth Systems

The Permian records a fundamental reorganization in climatic, tectonic and biologic components of the Earth System. Final plate collisions leading to Pangaeic suturing culminated by middle Permian time, manifested in equatorial Pangaea by construction of the Central Pangaeic Mountains and associated orogenic systems. The global icehouse of the late Paleozoic peaked in Early Permian time yielding to full greenhouse conditions by Late Permian time (e.g. Crowell, 1978; Frakes, 1992; Fielding, et al., 2008). Various researchers have posited fundamental shifts in greenhouse gases (Royer, et al., 2004, Royer, 2007; Montañez et al. 2007), atmospheric circulation (Parrish, 1982; Kutzbach and Gallimore 1989; M. Soreghan et al., 2002; Tabor and Montañez, 2002; 2004) and tropical aridity (summarized in Tabor and Poulsen, 2008). The terrestrial biosphere underwent major changes that resulted in the evolution of “modern” terrestrial ecosystems with food webs centered around carnivores consuming large, grazing herbivores (Olson, 1966; Sues and Reisz, 1998). These changes may have ultimately contributed to the end-Permian mass extinction (Gastaldo, et al., 1996; DiMichele et al., 2001; Twichett et al., 2001). Extreme conditions during the Permian are well documented in the form of voluminous dust deposits (Soreghan et al., 2008; Sweet et al., 2013), low pH brines (Benison et al., 1998), remarkably high continental temperatures (Benison and Goldstein, 1999; Zambito and Benison, 2013), and major plant and animal extinctions and extirpations from tropical Euramerica (DiMichele et al., 2006; Sahney et al., 2010; Tabor, 2013). Geochemical indicators also point to dramatic changes across the Permian, with the notable decline in \(^{87}\text{Sr}/^{86}\text{Sr}\) starting just before the Carboniferous-Permian boundary and dropping to one of the lowest values in the Phanerozoic by the late Permian. The rise in \(^{87}\text{Sr}/^{86}\text{Sr}\) across the Permian-Triassic boundary represents a return to pre-decline values with the steepest rise in the Phanerozoic. This rise in \(^{87}\text{Sr}/^{86}\text{Sr}\) is accompanied by similar rapid swings in other isotope systems as well as in major elements such as \([\text{Mg}]\).

Location and age of target deposits

The Anadarko Basin of the southern midcontinent (OK, KS, TX, CO) preserves perhaps the most complete record of Permian continental climate in the western hemisphere, extending from the basal Permian to the Permo-Triassic boundary (e.g. Johnson, 1988; Geissman et al. 2012).

Compelling science issue(s)/hypotheses to be addressed by drilling

This time interval captures a near-complete continental record of Earth’s last transition from fully icehouse to fully greenhouse conditions on a planet with a highly evolved terrestrial biosphere. A few key questions that could be addressed with drilling include the following:

• Under what climatic and hydrologic conditions were these continental strata (redbeds, evaporites, basal carbonates) deposited?
What are the uncertainties in interpreting paleoenvironmental conditions from continental strata such as redbeds, evaporites, and lacustrine carbonates, which are important components of the geological record in many places and eras of geologic time on Earth, and suspected as prominent on Mars?

Do specific climatic parameters such as paleotemperature and atmospheric PCO$_2$ change in response to regional and global climatic change as indicated from other Pangean records of Permian climate?

How did the Pangaean monsoon affect equatorial precipitation variability on glacial-interglacial timescales and over the course of the Permian?

What are the origin and transport mechanism(s) for the voluminous fine-grained siliciclastic material? Where was the source and what does it signify in terms of mega-drainages of the Central Pangaean mountains, atmospheric circulation, and the dust loading of the atmosphere?

Does this record preserve evidence of highland tropical glaciation, as well as records of temperature extremes?

What were the climate dynamics that drove apparent tropical aridification-- a unique aspect of the Permian?

Can this nearly complete record of Permian terrestrial strata be used as a magneto- and chemostratigraphic record to draw stratigraphic correlations to other outcrops in the Anadarko basin and among other terrestrial basins globally?

Stratigraphic completeness, continuity and resolution

The sedimentary section preserved in the Anadarko basin extends through the entire Paleozoic record, but is particularly complete for the Pennsylvanian-Permian interval, particularly in the proximal foreland. Basin subsidence peaked in the Pennsylvanian, but continued through the Permian, such that ~2000 m of Permian strata are preserved (Soreghan et al., 2012; Fig. 1), consisting predominantly of continental and marginal marine strata (Johnson, 1988).

Existence of baseline stratigraphic, and paleontologic data

Permian strata of the Anadarko basin have been dated with invertebrate as well as vertebrate fauna, palynology, chemostratigraphy, magnetostratigraphy, and geochronology (tephras), with much work occurring in the last several years (e.g., Fay, 1964; Denison et al., 1998; Steiner, 2006; Lupia et al., 2010; Tabor, 2011; Geissman et al., 2011; 2012; Foster, 2013). Acquisition of core would greatly facilitate and accelerate dating refinements in these predominantly continental
redbeds owing to better preservation and minimal weathering and oxidation of weathering-susceptible materials (e.g. carbonates, evaporites, tephras, mud-rich strata).

Existence of/potential to collect supporting data from outcrops, geophysics or prior drilling
Permian strata crop out throughout western Oklahoma and correlative strata exist in outcrop in the nearby Palo Duro basin to the south, and indeed represent most of what is known about the Permian of this region. Yet outcrops are limited in vertical extent owing to the low relief of the region. However, extensive seismic data exist as part of the very mature hydrocarbon exploration and exploitation of the region. Furthermore, the opportunity exists to obtain additional geophysical data in this low-relief region.

Existence of, or potential to collect, a robust age model through the target interval
We envision the opportunity to greatly refine age models through this interval using: 1) Chemostratigraphy: Sr isotopes have been applied to carbonate and sulfate-rich strata in the Permian (Denison et al., 1998), but great potential exists to build on this, particularly because of the dramatic decline in the $^{87}$Sr/$^{86}$Sr through the proposed study interval. In addition, carbon isotope stratigraphy of early diagenetic dolomitic cements in the upper Permian and Permo-Triassic boundary strata from the nearby Palo Duro basin suggest that carbon isotope stratigraphy may be a viable means of stratigraphic correlation among Ochoan red bed strata in this region (Tabor et al., 2011). 2) Magnetostratigraphy: Although the Permian encompasses the Kiaman Superchron, the Permian of the Anadarko Basin captures the termination of the superchron, and the subsequent record of reversal stratigraphy (Steiner 2006; Foster, 2013). 3) Paleontological data. Paleobotanical data correlate very strongly with facies, reflecting the ties of plants to climate. However, there are regional trends in the appearance and relative abundance of key marker taxa from both wetland and seasonally dry assemblages that can be tied to well characterized sections in north-central Texas and central New Mexico, thereby facilitating an understanding of regional vegetational patterns. Additionally, conodonts and fusulinids are abundant in the lower Permian section; 4) Geochronology: tephras are well recognized in the youngest Permian strata of the region, and are currently undergoing dating (Tabor et al., 2011; Geissman et al., 2011; 2012). Additionally, detrital zircon geochronology can shed light on depositional ages where young zircons are encountered, and detrital zircons are abundant in these strata (Sweet et al., 2013; Foster 2013; Kane, 2013).

Challenges to drilling the site and obtaining subsurface information
The Anadarko Basin of Oklahoma is an extremely mature drilling target, hosting at least 200,000 wells as a result of extensive hydrocarbon exploration and production. However, the vast majority of these wells target hydrocarbons in the pre-Permian section, with the exception of the Lower Permian section in the distal Anadarko Shelf (Hugoton region of Kansas); selective core through the Permian exists here, but owing to its position on the distal shelf, major unconformities occur. Targeting the proximal Anadarko basin will enable acquisition of a very complete section, and enable testing of additional hypotheses linked to highland proximity.

Drilling Equipment Access, Permitting, Community/Environmental Issues
The low relief of Oklahoma makes drilling here relatively straightforward. Furthermore, owing to its long history as a hydrocarbon province, the site of drilling equipment is an everyday occurrence for residents in rural regions, hence we expect no obstacles for permitting, negligible environmental impact, and ready access to the relevant equipment
References


THE TERRESTRIAL GREENHOUSE TO ICEHOUSE TRANSITION (EOCENE-OLIGOCENE) OF THE NORTHERN GREAT PLAINS: A PRE-PROPOSAL FOR CONTINTENTAL DRILLING IN SUPPORT OF ESTABLISHMENT OF A DEEP-TIME CRITICAL ZONE OBSERVATORY

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Abstract: The global climate shift ca. 33.7 million years ago from Hothouse conditions of the late Eocene to Icehouse conditions of the early Oligocene (EOT) is arguably the most profound climate event of the Cenozoic. Glaciomarine sediments, ice rafted debris, and high resolution oxygen isotope records from the oceans around Antarctica indicate the rapid growth over 350 ky of southern polar ice sheets to about 50% of their modern size during this transition. The terrestrial record of the EOT, which is marked by changes in vertebrate faunas, sedimentology, paleosols, and a dramatic drop in temperature, is very well preserved over several hundred meters of strata within the White River Group (WRG) of the Northern Great Plains (Fig. 1). Recent revisions in geochronology and lithostratigraphy of the WRG across this region present an unparalleled opportunity to compare the rate and magnitude of terrestrial paleoclimatic change across the EOT in North America to contemporaneous terrestrial and marine records across the globe.

Figure 1: Deposits of the White River Group, key outcrop locations, and potential drilling sites. B = Badlands NP, SD; D = Douglas, WY; F = Flagstaff Rim near Casper, WY; and T = Toadstool Park north of Crawford, NE.

Science and implications: The case for a Terrestrial Deep-Time Critical Zone Observatory for the EOT

When put in a regional spatiotemporal framework, the deposits of the WRG become an ideal candidate for establishment of a Deep Time-Critical Zone Observatory as outlined in the NSF-Transitions position statement (Parrish, 2012). In particular, all three critical directions of research outlined in Transitions (Deep-Time Climate, Landscapes, and Biology and Environment) can be addressed within the WRG during a time of global transition from Hothouse to Icehouse conditions (see below).

The lithostratigraphy and geochronology of the WRG has recently undergone significant revision. New lithostratigraphic correlations between NE and SD have filled in gaps in the stratigraphic record, resolved the position of the Eocene-Oligocene boundary, and have established a key lithostratigraphic tie point between deposits in SD to those in east-central WY (LaGarry, 1998; Terry, 1998; and Terry and LaGarry, 1998). U/Pb analyses of zircons were performed on numerous volcanic ashes at Toadstool Geologic Park in northwest NE and Flagstaff Rim in east-central WY, and samples for paleomagnetism were collected every 0.5 to 1 m (Sahy et al., 2010, 2012). The combination of new U/Pb data, which suggests revised age date of up to 0.5 Ma for many of the ashes, and magnetostratigraphic correlations between these sections has significantly changed previously published geochronologic interpretations. With the addition of core from several key locations (Fig. 1), the spatiotemporal framework for the WRG from WY to SD can be completed and will allow a singular, overriding hypothesis to be tested (within a series of goals) in order to draw comparisons with contemporaneous global records of the EOT.

Hypothesis: The terrestrial EOT is a diachronous paleoclimatic event that progressed from west to east and south to north across the northern Great Plains: Previous analyses of paleosols and sedimentology in the WRG led to this hypothesis that aridity increased diachronously from west to east and south to north across this region (Evanoff et al., 1992; Terry, 2001). We will be able to test this hypothesis by using an interdisciplinary, multi-proxy approach (paleosols, stable isotopes of soil carbonates, facies analysis, vertebrate and ichnofossil assemblages, and phytolith analysis) to constrain the rate and timing of climate change in the mid-continent across the EOT.

Goal 1: Reconstruct climatic and environmental consequences of the EOT in the continental interior of North America: Not all paleoclimate proxies and interpretations for these strata agree. Are these differences due...
to the preliminary nature of some of our data sets, an issue of signal fidelity of different proxies, or real differences due to regional climate variations? Data from outcrop studies will be tied together with core samples using tephro- and magnetostratigraphy and evaluated within the philosophy of the Transitions initiative, including:

- Regional variability of paleosols across the EOT and along specific landscapes, as defined by ash beds (Landscapes, Deep-Time Climate).
- Regional variations in Chadronian, Orellan, and Whitneyan CALMAs, phytothall assemblages, sedimentation rates, and facies across the EOT (Landscapes, Biology and Environments).
- Regional integration of stable isotope records from pedogenic carbonates and vertebrates (Deep-Time Climate)
- Comparison of subsurface units to outcrops to evaluate expanded vs. condensed sections (Landscapes).

Goal 2: Compare the terrestrial EOT in the continental interior of North America with global records: The results from Goal 1 can be used to investigate numerous interdisciplinary questions that are global in scale and that address the need to understand the range of Earth-Life process behaviors as outlined in Transitions (Parrish, 2012):

- Several late Eocene bolide impacts are known (Paag et al., 2003), but the majority of investigations of potential climate influences are based on marine records. With the spatiotemporal framework of the terrestrial EOT established it becomes possible to evaluate potential terrestrial disturbances due to these impact events.
- The timing and magnitude of the terrestrial EOT in North America can be tightly correlated and evaluated with respect to other terrestrial EOT sites (both in outcrop and from extant cores) across the globe, including China, South America, Spain, France, England, and other sites in North America (Kohn et al., 2004; Grimes et al., 2005; Hamer et al., 2007; Retallack, 2007; Urban et al., 2010; Abels et al., 2011; Stromberg et al., 2013).
- Understanding the rate and timing of the terrestrial EOT provides critical information to establish linkages with paleoclimatic signals in contemporaneous marine environments, such as shifts in stable isotopes, sea levels and circulation patterns, and extinction events. These data in turn can be used to develop global climate models for this critical time in Earth history and can be used to test the hypothesis that climates behave differently under greenhouse conditions vs. current icehouse conditions (NRC, 2011; Parrish, 2012).

The marine and terrestrial records of the EOT:

The late Eocene is characterized by a decrease in pCO₂ leading up to the EOT (Pagani et al., 2005). Glaciomarine sediments and ice rafted debris in sediment cores from the oceans around Antarctica indicate the growth of southern polar ice sheets to about 50% of modern size rapidly during the earliest Oligocene. The oxygen isotope composition (δ¹⁸O) of benthic foraminifera in cores from all oceans that recover the Eocene-Oligocene boundary records a global positive shift of about 1‰ due to the growth of Antarctic ice sheets and a possible decrease in deep water temperatures of several degrees. High-resolution δ¹⁸O records indicate that the ice sheet grew in less than 350 ka and included at least two separate glacial pulses. The carbon isotope composition (δ¹³C) of foraminifera in southern ocean sites record a positive excursion of about 0.7‰ that is interpreted as increased export production and burial of organic matter resulting from increased surface winds and upwelling in southern oceans in response to the glaciation. The conventional explanation for these climatic changes and the onset of glaciation is the thermal isolation of Antarctica following the opening of southern ocean gateways that allowed the development of the Antarctic Circumpolar Current (Murphy and Kennett, 1986; Kamp et al., 1990; Miller, 1992; Prothero, 1994; Diester-Haasse and Zahn, 1996; Zachos et al., 1996; Salamy and Zachos, 1999). However, recent results from Ocean Drilling Program sites around Tasmania suggest that changes in greenhouse gas concentrations, and not ocean gateways, may be the actual cause (Huber et al., 2004; Stucyke et al., 2004). Recent results also suggest that these gateways were not fully open until later in the Oligocene (Lyle et al., 2007).

The terrestrial WRG is composed of volcaniclastic and siliciclastic claystones and siltstones, sandstones, and limestones deposited within fluvial, lacustrine, and eolian environments, and are well known for their vertebrate fossils, the collection of which formed the basis for much of the early biostratigraphic and lithostratigraphic research in this region (Meek and Hayden 1857, 1861; Hatcher, 1893; Darton, 1899; Wanless, 1922, 1923; Ward, 1922; Osborn, 1929; Clark, 1937; Schultz and Stout, 1955; Bump 1956; Clark et al., 1967; Schultz and Falkenbach, 1968).

Badlands National Park in southwest SD is the most well known part of the WRG, although these deposits stretch for hundreds of miles across the northern Great Plains (Fig. 1). From west to east and south to north, these deposits vary in their sedimentary composition, age, and degree of exposure, which has resulted in differences in stratigraphic nomenclature for these sediments across the study region. They are recognized as a group in NE, SD, and ND; as the Chadron and Brule Members of the White River Formation in Douglas, WY; and as the undifferentiated White River Formation at Flagstaff Rim, WY. Some locations preserve an almost complete record of the EOT, whereas others are condensed or missing large spans of time. The reasons for this wide disparity in composition and preservation include proximity to sediment sources and structural influences on basin
accommodation. In general, the WRG is preserved in greater detail to the southwest into northwestern NE and east-central WY, and in lesser detail toward the north in northwestern SD and southwestern ND. According to Swinehart et al. (1985), certain formations within the WRG of western NE are, in certain places, several hundred feet thicker in the subsurface than in outcrop.

Previous studies of late Eocene to early Oligocene climate change in western and central North America focused on leaf margin analysis and taxonomic changes in paleofloras (Wolfe, 1978, 1992, 1994; Retallack et al., 2004a; Stromberg 2004), faunal and isotopic data from fossil vertebrates and invertebrates (Hutchinson, 1982, 1992; Evanoff et al., 1992; Bryant et al., 1996; Markwick, 1998; Retallack et al., 2004a; Zanazzi et al, 2007, 2009; Boardman and Secord, 2013), analyses of paleosols (Retallack, 1983; Terry, 2001; Retallack et al., 2004b), and sedimentological data (Evanoff et al., 1992). In general, these records all suggest climatic changes from the late Eocene to the early Oligocene, including: a decrease in mean annual temperature of up to 13° C, an increase in the mean annual range of temperature from about 5° to 25° C, and either stable or increasing aridity. In the northern Great Plains, climate appears to have changed from subtropical conditions in the latest Chadronian North American Land Mammal Age or NALMA (34.7-33.7 Ma) to warm-temperate conditions in the late early Orellan NALMA (33.0-33.5 Ma). However, the studies supporting these interpretations are generally limited by either temporal resolution or geographic extent. For example, Wolfe’s leaf margin analyses (1978, 1992, 1994) covered a broad region of western North America, but the temporal resolution was limited by the resolution of correlations among geographically widespread sites. In contrast, Retallack (1983) examined paleosols in a limited area (the Big Badlands of SD) and demonstrated local environmental change from late Eocene forests to early Oligocene open mixed woodlands and grasslands based on changes in paleosol development and morphology. Unfortunately, the EOT proper is not preserved in Badlands National Park due to an unconformity of approximately 1.7 my, thus the exact nature of the EOT in the Badlands is unknown. The EOT is preserved to the southwest in Toadstool Geologic Park near Crawford, NE where Terry (2001) interpreted upward changes in paleosol morphology as a manifestation of progressively drier conditions leading up to and across the EOT.

Supporting Data:
In addition to excellent exposures of the WRG at key localities, numerous oil and gas exploratory wells have been drilled across the region, although in Nebraska the only surviving data are geophysical logs. Core was not collected. These geophysical logs can be reinterpreted using current lithostratigraphic models to clarify outcrop/subsurface relationships once core is retrieved. Paleontological collections across the EOT are readily available at the University of Nebraska State Museum, Smithsonian, and American Museum of Natural History.

Logistics:
The greatest challenges related to this proposal are drilling fluids, permits, and establishment of a permanent repository for core samples. A biodegradable drilling fluid that will not expand smectite clays must be used in order to retrieve core. Previous attempts at collecting very short core segments (ca. 2m) using water alone were successful, but generated core rinds up to ½ of the core diameter (Terry, 1996). The requirement for a biodegradable drilling fluid will make permitting on various federal land management areas easier to secure. Permits for drilling will be needed from the Bureau of Land Management (BLM), U. S. Forest Service (USFS), Pine Ridge Reservation/Bureau of Indian Affairs (BIA), and possibly the National Park Service (NPS) depending on the proximity of drilling operations to NPS lands. Target sites are on flat land with immediate road access.

Two potential repositories for core are the University of Nebraska State Museum in Lincoln and the Museum of Geology at the South Dakota School of Mines and Technology in Rapid City. Both institutions are logical choices based on proximity to field sites and their extensive collections of vertebrate fossils from the WRG.

Local impact/cooperation:
The most notable potential impact is scientific education. Several of the target areas are on or near lands administered by the Pine Ridge Indian Reservation, which hosts the Oglala Lakota College (OLC). Collaboration with OLC’s program in Science, Technology and Mathematics presents an unparalleled opportunity to incorporate under-represented Native American students in research and technology. Other nearby universities which would benefit from this activity include Chadron State College in NE, and the School of Mines and Technology in Rapid City, SD. Educational activities, research, and community outreach are all possible in association with this project. Data can also be used by BLM, USFS, OLC/BIA, and NPS staff for the development of educational materials for students and the general public.
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Drilling through Holocene fossil reefs on the Caribbean coasts of Panama and Colombia to document geochronology, pristine reef paleobiology and paleo sea level (geophysical) significance in an unstudied subequatorial region.

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We are assembling an international team interested in reconstructing Quaternary paleoclimates, pre-anthropogenic pristine reef paleoenvironments, paleogeologic histories of uplift, event deposition and geophysical phenomena, and records of sea level change preserved in accessible, potentially regionally continuous, coral reef units situated along the Caribbean side of the Isthmus of Panama and the Caribbean coast of Colombia. We are formulating a field research plan which is currently centered on trenching of limited areas, but which would ideally include drilling as the most practical method for determining the spatial extent and depth ranges of these deposits, which are situated at or slightly above present sea level in areas of zero to minimal uplift. There are few outcrops landward of coastal scarps, and no stream cuts accessing these units. If we are limited to trenching, we most likely cannot recover the full time and spatial ranges of critical records in these units.

Science

Location and age of target deposits – A recently excavated, elevated (+1 m) Holocene reef on the Caribbean coast of Panama is likely correlative to a +1 m, laterally extensive fossil reef along the Caribbean coast of Colombia. The Panama section has several new TIMS U-Th dates of ~ 7 kyrs (O’Dea, unpublished) from approximately -5 m (taken on dredged material), but the full stratigraphic section and top remain undated pending fresh excavations or obtaining cores into the paleo reef. This area is presumed to be tectonically stable1; however earthquakes have occurred in the past 10 years.

The fossil reef in Colombia was 14C-dated for a 1986 consulting report2 to the Colombia Geological Survey, in an attempt to calculate rates of tectonic uplift which presumably raised the reef deposits above their original elevation, in part determined by an assumed mid-Holocene relative sea level highstand due to hydro-isostatic processes in low latitude areas. The non-conventional 14C dates, ranging from 2065-2960 yrs BP (3000-1800 cal BP ) were determined on 12 unidentified corals, several shells and one wood sample (8975 yrs BP; 10,056 cal BP), all of which were taken from the surface at un-surveyed elevations of +0.5 to +3.2 m MSL. The full age range of this reef system, or of multiple systems within the sequence, is as yet unknown.

Stratigraphic completeness, continuity and resolution – A thick Panama outcrop was recently excavated to at least 5 meters depth to create a new canal for a waterfront development in the town of Bocas del Toro, Isla Colon, which was subsequently never built. Prior to flooding the new canal, one of our team (O’Dea) attempted to gain access to the excavation for research purposes but was prohibited by the owner and developers. The excavated area was then flooded, leaving only spoil material accessible from the surface. The full thickness of the reef is unknown, but the dated material came from the bottom of the 5-m deep excavated area. The aerial extent is also unknown, but other surface outcrops of reef material have been noted at the surface, just above high tide level near the Smithsonian Tropical Research Institute Field Station at Bocas del Toro. Further reconnaissance is needed to map the occurrence of the reef on Isla Colon and elsewhere in the area. Additional outcrops of a potentially regionally extensive paleo reef system are possible based on previous work in the modern reef systems of Caribbean Panama3, 4; confirmation of the existence of a regional system requires further land-based reconnaissance along the coast of Panama, connecting into Colombia.

As in Panama, the stratigraphy, paleobiology, paleoenvironment and lateral extent of the Colombian fossil reef are not fully documented. The 1986 consulting report5 addressed only the surface expression of coastal terraces, thus none of the (unidentified) dated corals were sampled in context of reef facies, and the interior structure of the reef is unknown. As in Panama, the full thickness of the deposit has not been determined, nor has the full age range, or the records of possible multiple sea level excursions, climate events, biotic shifts, tectonic events, tsunami deposits, etc.
Compelling science issue(s)/hypotheses to be addressed by drilling, focusing on topics in paleoclimate, paleoenvironments, paleobiology, and/or extreme events

This research collaboration involves sea-level researchers, coastal geologists, geochemists and paleontologists. With comprehensive aerial/vertical (drill core plus excavation and outcrop) access to the stratigraphic records preserved in this regional paleo reef system, our multidisciplinary team will be able to pursue several lines of research, including high-precision geochronology, ecosystem and pre-anthropogenic reef productivity reconstruction, identification of extreme events and reef organism shifts or turnover, and development of proxy and indicator data for paleo seawater temperatures and water clarity. In addition we will be well poised to produce high-caliber sea level indices from diagnostic paleo-shallow water indicator species, to produce a southwestern Caribbean sea-level curve reconstruction, and be able to work with the geophysical modeling community to calibrate sea level models predicting mid-Holocene sea level highs. We will thus be creating an unprecedented paleo-reef archive of paleoclimate, paleo diversity and paleo sea level information at the highest possible resolution into this reef system. We hope to be able to determine true Holocene baseline paleontologic inventories indicative of coral reef health and diversity, for comparison to periods of human and climate change pressure leading to the present day worldwide degradation of coral reef ecosystems.

Sea level reconstruction and Calibration of Geophysical models for the southwestern Caribbean region – Stable Holocene reefs occur below present sea level, from -28 m (11,000 yrs ago) to -1 m (modern)\(^5\,^7\). In contrast to regional sea level reconstructions\(^5\,^7\), geophysical sea level model curves predict a relative sea level highstand at 4 ka (possibly due to a geophysical phenomenon; e.g. equatorial ocean siphoning, but in an area thought to be within the zone of subsidence due to forebulge collapse\(^8\)). This modeled highstand generally creates a 1-2 m misfit with coral reef geological data\(^5\). The tops of the Holocene reefs in Panama and Colombia are situated at 2-3 m higher than expected elevations for their age, either as a result of a mid-Holocene modeled highstand and/or tectonic uplift. If uplift has occurred in the Colombian system due to mud diapirism in specific areas places along this coast\(^5\,^7\), we will attempt to determine the rate of uplift by plotting sample ages/elevations against regional sea level curves, our current reconstruction for Caribbean Panama (Figure 1), including geophysical model predictions and glacial isostatic adjustment corrections to estimate the elevation change and timeframe of the uplift.

Figure 1 – Currently known sea level data compilation for Panama and nearby areas, from mangrove peat and coral index points, compared with the Caribbean sea level curve of Toscano & Macintyre (2003), and geophysical model curves (W. R. Peltier, unpublished). The large misfit between the model curve and the subsea coral data may be explained by new data from the fossil reefs in this proposed study, provided uplift is not a definitive factor in the reef elevations.
Paleogeologic record of climatic events with sea level signatures, episodic uplift, multiple sea level excursions – these extensive reefs will contain a sedimentary record that can potentially record sea level excursions and/or uplift events\(^\text{12}\), subaerial exposure (paleosols and caliche crusts), extreme event deposits (storms, tsunamis, floods\(^\text{13,14}\)), etc. The full reef sequence recovered in drill cores sequence may include several episodes of reef development separated by such events.

**Paleoclimatology, paleoecology (pre-anthropogenic)** – Paleobiology, pre-anthropogenic Fossil reefs also represent periods of pre-anthropogenic ecosystem diversity, health and paleoclimate, and contain significant fossil records of these complex ecosystems. Reef species’ deterioration has been witnessed on many timescales\(^\text{15-24}\). Paleoecologic reconstructions of fossil coral\(^\text{25}\), fish, mollusk, crustacean, sponge, foraminifera and echinoid communities of these more pristine reefs of the past will address shifting baselines in the modern ocean. The results from this study will reveal reef function and processes under pristine conditions, and aid in anthropologic investigations in the region. In addition, analysis of paleo reef communities will identify diagnostic shallow water indicator species to enhance sea level studies discussed above. The coral *Acropora palmata* is the primary species used to reconstruct paleo sea levels to within 5 m water depths\(^\text{5,6}\), but this species may exist off the reef crest in deeper water, adding considerable elevation error to sea level curves. The ability to drill long transects will reveal reef geomorphology, i.e., paleo reef crests, but will also provide evidence of the diagnostic species associations that may ultimately constrain paleo sea level elevations and produce accurate paleo water levels from coral data.

**Existence of baseline stratigraphic, and paleontologic data** – In the case of the Panama section, we have minimal samples material gained from dredge spoil, which has been studied as much as possible. In the case of Colombia, we have 17 dates on unidentified coral out of stratigraphic context\(^\text{2}\), hence the need for drilling. Outcrops or stream cuts through the Colombian reef may be identified if uplift is indeed raising this section.

**Existence of, or potential to collect, supporting data from correlative outcrops, geophysics or prior drilling** – we have access to other potential outcrops in Panama, in addition to a body of previous work by Ian Macintyre and colleagues, who studied the Holocene reefs at Galeta Point and Holandes Cays\(^\text{3,4}\). We have excellent physical monitoring in place at the STRI Bocas del Toro laboratory, including a new COCONet permanent GPS station, which will provide modern indications of vertical change in local land elevation.

**Existence of, or potential to collect, a robust age model through the target interval** – We have collaborative working relationships with high precision thermal ionization mass spectrometric Uranium-Thorium dating laboratories (e.g., Carleton University; lab of Joyce Lundberg) and excellent working relationships with radiocarbon labs, particularly the University of Georgia Center for Isotope Studies, and Beta Analytic, Inc. (both provide AMS dating with 3 week turnaround). The Smithsonian department of Mineral Sciences operates a state of the art X-ray diffraction lab which is available for in-house use for determining mineralogic purity of samples for dating purposes.

**Logistics**

**Challenges to drilling the site and obtaining subsurface information (e.g., suitable terrain for site-survey geophysics); Access for drilling equipment** – In both places the drilling sites are directly accessible. In Panama the main site can be accessed via boat or land, and is a very short distance from the STRI Station at Bocas del Toro. Elevation data can be easily obtained via GPS using the Lab’s COCONet station as a base station. Other potential reef outcrop sites are accessible on the lab property by foot, and other sites on Isla Colon and in the region would be accessible by car and on foot. In Panama we will have the facilities of STRI Labs at Bocas del Toro and at Galeta Point at our disposal. In Colombia most sites are accessible by car, farm vehicles, foot and if necessary, horseback. The area we have chosen to work in Colombia is within a safe corridor along the coast, and on private property for which we have landowner access. We will have the participation and assistance of colleagues and students from the Universidad EAFIT and the Colombia Geological Survey, and access to incidental equipment and housing.

**Permitting issues** – Permits are in progress for both locations. For **Panama** the permit process is thoroughly outlined and assisted by the Smithsonian Tropical Research Institute. For Holocene (“dead”) corals we will obtain an ARAP collecting permit specifying weight of samples to be shipped. The forms are downloadable from the STRI webpage. Once we have obtained the ARAP permit we must apply for an export permit. STRI personnel will guide
us through the process. If our samples are older than Holocene, we will need a Recurses Minerales permit, downloadable via STRI, with STRI assistance in the process. In Colombia, permits for fossil corals are authorized by the Ministerio del Medio Ambiente y Desarrollo Sostenible (MADS). We have the format required to apply for the permit and a contact in the MDAS Oficina de Asuntos Internacionales.

**Complexity of operations, local impact/cooperation (community and environmental)** – we hope to conduct reconnaissance of both areas prior to drilling to ascertain accessibility and other requirements. We have the collaboration and support of local institutions in both areas, including personnel and basic equipment, housing, vehicles and assistance with local issues, although none are anticipated based on our previous work.

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Potentially Extensive Plio-Pleistocene Earth System Records at Yardi Lake, Middle Awash, Ethiopia

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Geological Setting of Yardi Lake: The Middle Awash region, a volcanic, tectonic, and geomorphic transition zone between the Main Ethiopian and the Afar Rift basins, contains some of the world’s most important paleoanthropological sites (WoldeGabriel et al., 2013). There is growing concern with the effects of global climatic change on the emergence of our species (Committee on the Earth System Context for Hominin Evolution, 2010) and a drilling at Yardi Lake could provide significant information to understanding these compelling issues. The sediments beneath Yardi Lake, centrally located in the Middle Awash valley, have the strong potential of providing a near-continuous record of the environmental changes that molded the emergence and extinctions of an exceptionally diverse mammalian fauna, including the human lineage. The lake is uniquely located in the middle of very important paleoanthropological localities spanning the past 6 million years (Asfaw et al., 1999, Clark et al., 1994, 2003; White et al., 1993, 1994, 2003, 2006, 2009; Haile-Selassie, 2001). The geological, tectonic, and paleoenvironmental processes and conditions at each of these localities are well documented (White et al., 1993; Clark et al., 1994; WoldeGabriel et al., 1994, 2001, 2009, 2013; Renne et al., 1999).

Published paleobiological records (>20,000 fossils) from the Middle Awash study area suggest that diverse faunal and floral species, including hominids, inhabited the region since the late Miocene (<6 Ma). Thus, data from a continental drilling at Yardi Lake has the potential to greatly benefit from the published and unpublished data actively collected from the nearby locations at Bouri, Wadayemero, Asa Issie, Aramis (CAC), Asa Koma (western margin), Bodo, and Maka by the Middle Awash project (Fig. 1). Data from drilling at Yardi Lake would greatly complement the Hominin Sites and Paleolakes Drilling Project activities planned elsewhere in the eastern African rift.

Location and age of target deposits: Yardi Lake (N12°13’32.52” E40°28’52.39” 562 m asl) was formed by uplift of the NW-trending Bouri horst, subsequently rotated and tilted to the west, blocking an ancestral Awash River during the late Pleistocene (Clark et al., 2003). Today, Yardi Lake represents the modern aspect of the late Pleistocene body of water, now approximately 14 km long and 7 km wide, excluding the adjacent extensive swamp and riverine forest. Widespread adjacent exposures of coarse and rounded beach gravels, well-sorted sandstone, and laminated limestone deposits of the Upper Herto Member of the Bouri Formation provide a glimpse of the substantially larger size of the immediately ancestral lake. Furthermore, on the northeast side of the lake, the west-dipping section of the Bouri Horst reveals more than 80 m of Plio-Pleistocene fluvial and lacustrine sediments and interbedded partially zeolitized, bentonitic, and diatomaceous tephra of the Bouri Formation, which consists of the Hata, Daka, and Herto Members in ascending stratigraphic order (WoldeGabriel et al., 2008 and references therein).

The early Pleistocene Hata Member in the lower half of the Bouri Formation yielded the 2.5 Ma Australopithecus garhi (Asfaw et al., 1999). The A. garhi species and nearby zooarchaeologic evidence
recovered from the same stratigraphic level were significant discoveries and additions to the meager hominid record between 2 and 3 Ma. The archaeological evidence suggests that the *A. garhi* species was possibly the first stone-tool maker and user to incorporate extensive meat and marrow in its diet by 2.5 Ma (de Heinzelin et al., 1999). *A. garhi* lived along with grazers and aquatic animals that inhabited broad, featureless terrain of open grasslands adjacent to a fluctuating lake margin.

Abundant vertebrate fossils, thousands of basaltic handaxes, and a 1.0 Ma hominid calvaria assigned to *H. erectus* were discovered within the overlying Daka Member (1.0-0.8 Ma) at Bouri. The *H. erectus* discovery was key in confirming the close resemblances and relations between the Asiatic and African records. The late Pleistocene Lower Herto Member, which is in fault contact with the Daka Member contains rich Acheulean lithic assemblages and fauna. It is overlain by a ~250 kyr bentonite, and then unconformably by the Upper Herto Member that yielded anatomically modern *H. sapiens* fossils dated to 0.16 Ma. The *H. sapiens idaltu* species inhabited lake shores and adjacent open plains, using mixed Acheulian and Middle Stone Age tools to process big game such as hippotamus and large buffaloes (Clark et al., 2003). The 0.15 Ma WAVT tephra caps the Herto Member (Clark et al., 2003; for a contrary view, see Brown et al., 2012).

**Scientific issues to be addressed:** the published paleobiological, geological, tectonic, paleoenvironmental and paleoclimatic records, coupled with results from Yardi Lake cores, provide a great opportunity to test several competing hypotheses foundational to the following research questions:

1. How were the fauna, flora, and paleoecological conditions impacted by local dynamic tectonic (i.e., subsidence and uplift), volcanic (i.e., proximal and distal climactic and voluminous tephra eruptions), and geomorphic (i.e., marginal versus axial horst and graben topography within the rift basins) processes during the Plio-Pleistocene rift development?
2. How did the fauna and flora respond to strong and sometimes sudden local, regional, and global environmental and climatic changes and variabilities during the Plio-Pleistocene?
3. How do the continental paleoclimatic and paleoenvironmental records compare with contemporaneous marine data from the nearby Gulf of Aden and the NW Indian Ocean (DSDP 231; ODP 722A, etc) and other regions within the Afar Depression and the rest of the eastern African rift to the south?
4. What evidence related to major climate-forcing records is preserved in the sedimentary sequence beneath Yardi Lake? Published information from tropical eastern Africa and marine sediments suggest that there is evidence, indicating the impact of complex events related to orbitally-driven changes in insolation, changes in global ice volume and atmospheric greenhouse gas concentrations, long-term reorganizations of the principal modes of sea-surface temperature variability such as El Niño-Southern Oscillation (ENSO), and tectonically-driven changes in oceanic and atmospheric circulation (Cane and Molnar, 2001; Russell et al., 2012 and references therein).
5. Was the Middle Awash region a dispersal corridor consistent with continuous records of hominin habitation in the region in the past 6 million years?
6. Are the major tephra units identified in the continental and marine sediments of the Omo-Turkana Basin of southern Ethiopia and northern Kenya and the Gulf of Aden and the NW Indian Ocean present within Yardi Lake sediments consistent with dispersal patterns from sources located in the central sector of the Main Ethiopian Rift?
7. How does the quality of biomarkers from continental and marine drill cores (Feakins et al., 2005, 2013) compare with outcrops from correlative Plio-Pleistocene stratigraphic sections such as Bouri, Asa Issie, Aramis, Maka-Bodo, Wadayemero, and western margin?

Published Plio-Pleistocene stratigraphic information from the Bouri Horst along the northeastern margin of Yardi Lake and the nearby paleoanthropological localities of Asa Issie, Wadayemero, Aramis, western margin, Maka, Bodo (Fig. 1), contain continuous outcrops of thick fluvial and minor lacustrine sediments and interbedded distal tephra beds and significant paleobiological records, including hominids dating back to about 6 Ma (Fig. 1). Late Miocene to early Pliocene (3.8-6.13 Ma) basaltic lavas and tephra deposits underlie these sedimentary deposits. However, without seismic data, it is difficult to predict whether some of these deposits might be reached by coring at Yardi Lake.
Yardi Lake is located to the west of the Quaternary axial rift zone, which is marked by linear cinder cones, fissural flood basalts and central silicic volcanoes. Based on the the Plio-Pleistocene stratigraphic sections at Bouri, Asa Issie, Aramis, Wadayemero, Maka-Bodo, and western margin, which are located to the west, north, and northeast of Yardi Lake, respectively, it is considered unlikely that volcanic lava flows younger than 4.0 Ma would be reachable (or even present) beneath the lake. However, it is very probable that several layers of fallout and ash-flow tephra beds from Ayelu, a Quaternary silicic volcano about 20 km to the SE of Yardi Lake, exist beneath the lake (Fig. 1). Hence, the sedimentary deposits and interbedded proximal and distal tephras beneath Yardi Lake are likely to provide a continuous and high-resolution stratigraphic record for the Holocene and at least the later part of the Pleistocene. The 80 m section of the Bouri Formation (>2.5 Ma - <0.15 Ma) exposed along the northeastern margin of the lake provides detailed baseline stratigraphic, archaeological, paleobiological information that will support the geophysical interpretation of the subsurface geology and structure of the lake. Moreover, geochronological and geochemical data from tephra units interbedded within the Bouri Formation plus fallout and ashflow tuff deposits along the southeastern part of the lake are likely to provide robust age control for the subsurface stratigraphy beneath the lake.

**Access for drilling equipment, permitting issues:** Yardi lake is very close to the main Addis-Djibouti paved highway. It is bounded by a commercial farmland to the south and could be accessed from there to conduct geophysical surveys and to bring drilling equipment to the site. Yardi Lake is easily accessed by vehicle from the west or south. With regard to logistics, collaborators from Addis Ababa University and other members of the proposing team have extensive experience with securing permits and mobilizing drilling equipment to many places within the rift valley and the highlands of Ethiopia for conducting paleoenvironmental investigations in numerous other lakes.

![Figure 1](image.png)

Figure 1. Location of Yardi Lake within the Middle Awash study area in the SW Afar Rift. Detailed chronostratigraphic data from nearby sections provide significant baseline information for geophysical survey and expected subsurface geology beneath the lake (solid stars represent stratigraphic positions of eight hominid species, spanning the past 6 million years).
Reference


Post-eruptive maar sediments from the Giraffe kimberlite: potential for a world-class continental record of Middle Eocene paleoclimate from northern Canada

NSF Workshop pre-proposal: Scientific Drilling and the Evolution of the Earth System

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1. INTRODUCTION

As the planet continues to warm under enhanced greenhouse-gas forcing due to anthropogenic activities, there is an increasing need to benchmark future climate scenarios against past intervals of warmth driven by CO₂ concentrations higher than present, but within the likely range anticipated for the next century. Although ice cores have proven instrumental in ascertaining the correlation between greenhouse-gas concentrations and climate over recent glacial-interglacial cycles, atmospheric [CO₂] is already well above any natural interval of the last million years. Viable analogs for the future must therefore be sought from deeper geological time, and in this regard the Eocene is considered a particularly apt example1,2. However, well-preserved and stratigraphically continuous records of Eocene paleoclimate are largely restricted to specific ocean basins, greatly limiting the confidence with which inferences can be drawn for continental environments. Here, we describe the potential to develop an outstanding Eocene paleoclimate record from northern Canada through scientific drilling of the Giraffe kimberlite pipe.

2. THE GIRAFFE KIMBERLITE PIPE

Kimberlites are mantle-derived, occasionally diamondiferous, ultramafic volcanic rocks that outcrop near the surface following highly volatile phreatomagmatic events. Commonly, kimberlite pipes evolve towards the surface as a broadening diatreme that may form, in exceptional cases, a maar crater that is amenable to post-eruptive sedimentation. Over the last 20 years, aggressive diamond exploration in the Slave Province of northwestern Canada has identified hundreds of kimberlites, of which a select few have proven economic and been subsequently developed as diamond mines. Unlike African counterparts where a surface expression is evident in the absence of Quaternary glaciations, Canadian kimberlites are till-covered and must be pinpointed by judicious combinations of aeromagnetic surveys and drift prospecting for diamond-indicator (mantle-borne) mineral suites. Joint mapping of till mineral concentration trends and gravity anomalies have been corroborated by exploration drilling in many parts of the Slave Province. For example, tens of km of exploration core have been obtained by BHP Billiton Diamonds Inc. in the Lac de Gras kimberlite field alone. The Giraffe pipe is among the kimberlites thus initially explored and drilled; it comprises the target of this proposal’s scientific objectives, based on ongoing observations from an exploration core obtained from BHP (Fig. 1).

From the diamond perspective, Giraffe is unremarkable and does not figure on the mine plan. With an intrusion age of 47.8±1.4 Ma, based on robust 87Rb/87Sr measurements from kimberlitic phlogopite (from the base of core 98-06), it is also a very young kimberlite that forms part of a Middle Eocene cluster that arises among additional pipes with older (Paleocene and Cretaceous) emplacement ages3,4. What is remarkable about the Giraffe system is that tens of metres of undisturbed, stratified lake sediment and peat have accumulated sequentially in the diatreme following the eruption, with no evidence of secondary magmatic events, brecciation, or metamorphic alteration of any type. Over recent years, from analyses of a single sub-optimal core offered up to study by BHP and the Geological Survey of Canada (core 99-01), the two principal investigators and their colleagues have demonstrated that this is likely to be the best-preserved continental sequence of Middle Eocene sediments known to date. A series of peer-reviewed publications in the international literature details the progression of findings to date, and highlights the various qualities of the site5-14.
However, the presence of these sediments was only noted by industry as an afterthought and it is largely serendipitous that these intervals were conserved at all, given they have no bearing on kimberlite petrology and hence the ultimate goals of BHP’s exploration program. Indeed, post-eruptive sediments from an earlier and more complete core (98-06), which unlike 99-01 reached the kimberlite body yielding the phlogopite that dates the emplacement (Fig. 1B), was tragically discarded. What we propose here is the development of a strategy for renewed drilling of the Giraffe locality with a single and focused objective in mind: retrieving the finest record yet of Middle Eocene paleoclimate from a terrestrial setting for investigation by a multi-disciplinary international scientific team. The expense and logistics of such an operation are considerable, and it is with this in mind that we turn to this NSF initiative to develop the best possible strategy for success. However, the scientific outcomes are likely to be of great importance, including refined estimates of temperature sensitivity to enhanced greenhouse-gas forcing for the northern high latitudes, which are widely acknowledged as a region that is currently warming at an accelerated pace. While we fully recognize that outstanding continental Eocene records exist elsewhere (e.g., the Eifel maarls), including the Canadian Arctic (Axel Heiberg Island and correlatives), we emphasize that nowhere have we witnessed the quality of morphological and molecular preservation witnessed in Giraffe sediments. Furthermore, both lacustrine and paludal (peatland) sediments are preserved in an organized and datable sequence that records the progressive infilling of the lake and subsequent terrestrialization of the maar. Thus, it is not only in the quality of preservation witnessed throughout the sequence, but in the diversity of paleoenvironments captured as well, that we bring this locality to this community’s attention at this time.

3. PROOF OF CONCEPT

Although core 99-01 is fractured and jumbled in many places, we have managed to assemble a reasonable first-order stratigraphy (Fig. 1). When vertically restituted (the core was collared at 47°), we estimate the total recovered organic sequence to represent ~84 m, noting that the total sediment thickness is likely considerably greater because the core bottomed out in the diatreme’s lateral wall (i.e., Proterozoic granodiorite) and not in the basal underlying kimberlite. We are thus lacking the critical early stages of the maar lake’s ecological and climatic history. Nevertheless, of the ~84 m sequence represented, the lower 51 m are lacustrine organic-rich mudstones and the upper 34 m are peat. These thickness estimates are fraught by the realities of drilling in anticipation of the target kimberlite body, with little a priori consideration of the potential scientific value of the overlying...
sedimentary sequence. Accordingly, logging was somewhat cursory in the sense that that marked depths on the core boxes do not always correspond to the actual lengths of core within them.

Despite these caveats, where the core is well-preserved we are able to demonstrate a quality of preservation that has not been hitherto proven from any materials of comparable age. Two calc-alkaline rhyolitic airfall tephra beds, 13 and 26 cm thick, occur near the stratigraphic transition from lake to peatland paleoenvironments. These tephras are not kimberlitic; glass geochemistry suggests their most likely source was southwestern Alaska, where extensive Eocene volcanism is recognized. Moreover, glass fission-track ages obtained from them are statistically indistinguishable from 38 Ma, implying that this dates the termination of the lacustrine phase and marks incipient terrestrialization of the maar. Given that kimberlite emplacement is dated to 47.8±1.4 Ma, it is likely that a complete core will yield a continuous ~8 million year lacustrine record. Coupled to the younger overlying peat, the composite record thus spans the critical Middle Eocene climate transition during which secular cooling was punctuated by short-lived warm-cold oscillations during glacial initiation\textsuperscript{15,16}. The CO\textsubscript{2}(atm) transient associated with these events is well captured by the Giraffe sediments\textsuperscript{12}.

Due to the protracted tectonic and thermal stability of the Slave Province, preservation of sedimentary organic matter is outstanding. Pollen is diverse and abundant throughout. Diatoms, chrysophytes, sponges spicules, and other siliceous microfossils are abundant and pristine in the lacustrine sequence\textsuperscript{5,11,13,14}. Many (but not all) lacustrine facies are finely, and likely annually, laminated, implying considerable unexplored potential for chronostratigraphy. In the overlying peat, wood preserves genuine cellulose, foliage is autofluorescent, and leaf stomata of Dawn redwood (\textit{Metasequoia}) compare directly to modern counterparts. Cellular preservation, including plastids, is not uncommon. We therefore anticipate the potential for outstanding organic biomarker and stable isotopic records. While we are already exploiting various aspects of this remarkable preservation to address paleoclimatic, paleoecological, and evolutionary questions, it remains that these results suffer from the incomplete nature of the material currently available for study.

4. DEVELOPING A NEW CORING STRATEGY

Obtaining new cores from the Giraffe kimberlite will be neither easy nor inexpensive, as the site is remote (~300 km NW of Yellowknife) and must be accessed by charter aircraft. The surrounding landscape combines boggy tundra, black spruce forest, and extensive lakes and ponds, with occasional outcrops of glacially-scoured country rock. Up to 50 m of glacial overburden, but potentially less pending the exact coring site selected, will need to be drilled prior to entering the target sedimentary body. Late winter or spring, when the surrounding landscape remains frozen but air temperatures are sufficiently warm so as not to hinder mechanical operations, are likely the best windows of opportunity. Furthermore, environmental impacts are a significant concern in the Canadian north; Federal, Territorial, and First Nations regulations must be abided at all stages. On the other hand, the proximity to active diamond mines and drilling equipment, and the availability of aeromagnetic survey data, will considerably facilitate the task at hand. Over recent years, the two principal investigators have built solid working relationships with BHP staff, who are amenable to assisting scientific efforts on non-diamond aspects of kimberlite pipes staked on their Lac de Gras property. Although this landscape has recently changed with the sale of the Ekati property to Harry Winston gems Inc., it seems unlikely that Giraffe will enter the master mine plan, and thus we anticipate full disclosure of geo-referenced geophysical data and indeed the complete Giraffe file, including drilling notes. All materials requested thus far from BHP (mainly core logs, but equally information pertaining to other potentially fossiliferous pipes) have been provided without reservation, and company geologists are quite aware of our scientific interests and activities.

Given a range of parameters involved, we restrain from presenting a detailed budget, although it is envisaged that up to USD 1,000,000.00 will be needed to cover total costs. We cautiously mention that some drilling infrastructure may already be available near the target site given considerable exploration in the region. Were this project moves forward to the next phases of activity, the principal investigators will investigate exhaustively all possibilities to leverage funding and cut costs without compromising scientific objectives, in consultation with coring engineers and an international science team. Our ambitious science plan is commensurate with the potential outcomes of recovering the complete sequence from Giraffe: an unequalled continental paleoenvironmental archive from a critical region for a critical interval of geological time.
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Project pre-proposal to drill Mono Lake, California
Submitted by Susan Zimmerman, Sidney Hemming, and Alan Deino, and the Mono Lake Working Group

Mono Lake, California (Figure 1), is a terminal lake in an arid basin at the foot of the eastern Sierra Nevada, on the tectonic boundary between the Pacific and North American plates. Most of the water input to the lake is from snowmelt in the Sierra Nevada, the major source of water for California’s cities and multi-billion dollar agricultural industry. During glacial periods the Sierra Nevada ice cap fed mountain glaciers, and the Mono basin moraines (Figure 1) are among the classic expressions of this (Putnam, 1950; Phillips et al., 1990; Bursik and Gillespie, 1993; Schaefer et al., 2006). The accumulated sediments reach back to at least the Bishop Tuff (767 ka; Crowley et al., 2007) (Lajoie, 1968) and potentially to the Pliocene (Reheis et al., 2002a), and preserve an exceptional record of the climatic, hydrologic, biologic, paleomagnetic, tectonic, and volcanic processes that have shaped the eastern Sierra Nevada.

The hydrologic history of the basin is well-known for the past 4000 years from geomorphic and sedimentologic work (Stine, 1990), supplemented by sediment cores extending back to the early Holocene (Newton, 1994; Davis, 1999; Benson et al., 2003; Zimmerman et al., 2012; Zimmerman et al., 2013). Study of exceptional exposures of the late Pleistocene Wilson Creek Formation (WCF) around the lake (Lajoie, 1968; Benson et al., 1990; Benson et al., 1998; Sahajpal et al., 2011; Zimmerman et al., 2011a; Zimmerman et al., 2011b) has established a lake level record through the last glacial cycle (Figure 2), as well as a high-fidelity record of Earth’s magnetic field, due to the abundant fresh magnetite in the glacial flour (Denham and Cox, 1971; Liddicoat and Coe, 1979; Lund et al., 1988; Zimmerman et al., 2006). The many inter-bedded tephra (Figure

Figure 1.
(right) Bathymetry of Mono Lake (Raumann et al., 2002) and CHIRP lines (Colman et al., in rev.) overlain on DEM of the Mono basin. Pink star indicates type section of the Wilson Creek Formation (WCF), sediments of the last glacial period, which are laminated or finely bedded in many deep lake sections (above left). Colored dots in lake indicate coring locations; two cores near the western shore have recovered long laminated sections, including the early (above center) and late Holocene.
2) preserve a history of the abundant active volcanism of the region (e.g., Hildreth, 2004; Bailey, 2007).

Finely laminated sediments and multiple targets for chronology are major appeals for coring the Mono Lake basin. Laminated (mm-scale) Holocene sediments and finely bedded (cm-scale) WCF sediments indicate that high-resolution (decadal to semi-annual) intervals are likely (Figure 1). The tephras within the WCF (Figure 2) and the Paoha Island sequence will enable intrabasin and intracore correlation. Recent work by Deino et al. (2012) follows a history of $^{40}$Ar/$^{39}$Ar dating in the WCF (Chen et al., 1996; Kent et al., 2002), and shows excellent progress toward precise $^{40}$Ar/$^{39}$Ar ages in stratigraphic order. Intriguing discrepancies between the $^{40}$Ar/$^{39}$Ar ages and U-series disequilibrium (Vazquez et al. 2012) and (U-Th)/He (Cox et al. 2011) ages are currently under investigation. In addition, correlation of the magnetic field paleointensity correlation with high-resolution global stacks (Channell et al., 2009) will provide a high-resolution chronology between tephra-rich intervals, following the work of Zimmerman et al (2006).

The goal of the proposed coring is to exploit the thick package of lacustrine sediments below the current lake to recover the longest and most complete stratigraphic sequence possible (i.e., fewest low-lake hiatuses). Our preferred approach would be to drill at two main sites (with potentially several cores at each site), one in the southeastern quadrant of the basin, indicated by the seismic lines to be the least disturbed location, and a second in the western embayment, closer to the major inputs of sediment and water from the Sierra Nevada. The southeastern site is likely to contain finer-grained sediments, with a lower accumulation rate, while the west side may be thicker, higher-resolution, and more variable.

Land ownership in the basin is split between the Inyo National Forest (USFS) and State Tufa Reserve (CA), with some private ownership, and we have negotiated the necessary access to property without difficulty. The non-profit conservation organization The Mono Lake Committee (www.monolake.org) is a strong force for science and education in the basin, and has facilitated and encouraged our work in a number of ways. Lake access for heavy equipment is straightforward along the western shore, and the greatest challenges to drilling at Mono Lake are strong afternoon winds and the meter-thick, coarse tephra layer underlying the sediments across much of the lake.

Scientific Questions:
1. What is the nature of environment and ecosystem variability through multiple glacial-interglacial cycles in the Mono Lake basin?
   Pre-WCF lake sediments on Paoha Island, as well as wildcat drilling logs, suggest multiple glacial cycles are preserved under the lake (Lajoie, 1968), and interbedded tephras of Mono Craters-Long Valley affinity have been collected during exploratory visits to Paoha. Many of the previous interglacials are represented by thick diatomites, very different from the Holocene carbonate-rich and diatom-poor sediments, suggesting that wetter conditions and fresher lake waters prevailed during earlier interglacials.

2. What is the evolution of the paleomagnetic field in western North America over the last million years? High-resolution records of magnetic field variability over 1.5 Ma from marine sediments have recently been combined and correlated to the marine oxygen isotope curve (Channell et al., 2009). Mono Lake is a prime target for broadening the view of Earth’s magnetic field to include Pacific-region and terrestrial information.
3. How has the hydrology of the western Great Basin changed through time? The weight of the evidence suggests that Mono Lake remained hydrologically closed through the last glacial cycle, but it is not clear when the lake last overflowed. Overflow requires a prolonged extremely wet climate, and has important implications for biologic systems (Reheis et al., 2002b) and geochemical balance (Anderson et al., 1982; Bischoff et al., 1991; Bischoff et al., 1993; Tomascak et al., 2003; Sahajpal et al., 2011). In addition, it appears that the direction of overflow switched from the north (into the Lahontan system) to the south (into the Owens system) via volcanic and tectonic processes, but the timing is poorly constrained, to sometime around 1 million years ago (Reheis et al., 2002b).

4. What is the volcanic history of the eastern Sierra Nevada? A companion proposal more fully describes the potential of a drilling campaign for tectonic and volcanic questions, but the stratigraphic history of regional tephas likely to be recovered by a long core will provide a time-history of the regional volcanism, perhaps back to the catastrophic explosion of Long Valley caldera at 767.1 ka, or beyond.

5. What is the evolutionary history of the extreme biota currently found in the Mono Lake basin? Mono Lake hosts an unusual assemblage of microbiota (Roesler et al., 2002; Kulp et al., 2008; Wolfe-Simon et al., 2011), evolved to exploit the highly saline and alkaline lake waters, anoxic sediments, and deeply-rooted volcanic hot springs with highly variable chemistry. Beyond this modern snapshot, very little is known about the history of life at Mono Lake, and the cycling of elements like As, Se, S, and Fe that have controlled its unusual evolution.

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Appendix B: PreProposal Documents (White Papers)

DRILLING ACTIVE TECTONICS AND MAGMATISM: VOLCANICS, GEOPRISMS AND FAULT ZONES POST-SAFOD

MAY 28-30, 2013
PARK CITY, UTAH
Conveners: JOHN SHERVAIS, JAMES EVANS, VIRGINIA TOY, JOHN EICHELBERGER, AMANDA CLARKE, JAMES KIRKPATRICK
White Papers

Presented at the NSF-Sponsored Workshop:

Drilling Active Tectonics and Magmatism
(Volcanics, Geoprisms, and Fault Zones Post-SAFOD)

Treasure Mountain Inn, Park City, Utah, 28-30 May 2013

Steering Committee:

John W. Shervais, Utah State University
James P. Evans, Utah State University
Amanda Clarke, Arizona State University
John C. Eichelberger, University of Alaska, Fairbanks
James Kirkpatrick, Colorado State University
Virginia Toy, University of Otago
Drilling Active Tectonics and Magmatism (Volcanics, Geoprisms, and Fault Zones Post-SAFOD)

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Magmatic-Hydrothermal Transitions In Active Extensional Regimes Of The Western U.S.: The Need For Drilling To Assess Physico-Chemical State
INTRODUCTION. The Sangre de Cristo fault zone (SCFZ) in the San Luis basin of southern Colorado comprises a complex network of faults accommodating late Quaternary extension of the northern Rio Grande rift (McCalpin, 1982). As is common in many mountain-basin settings, this region has undergone numerous tectonic epochs, leading to controversy surrounding the evolution of the Rio Grande rift and the role of pre-existing structures in rifting. Furthermore, there are few observations of fault zone internal structures and associated fault rocks and none exist at depth, leaving major questions about the role of fault zone geology in crustal weakening, the triggering of seismic slip, and heat and fluid transport in the San Luis basin. Scientific drilling through multiple and representative elements of the SCFZ presents opportunities to better understand the processes of fault system evolution within an intracontinental rift and provide an analog to other extensional terranes. In-situ fault zone characterization, rock sample collection, hydraulic and thermal experimentation, and in-situ stress determination would provide the subsurface ground truth and monitoring necessary to evaluate hypotheses for tectonic evolution, modern strain accommodation, and the heterogeneity created by faults. Recent studies have generated high-resolution, multidisciplinary data for the region surrounding the SCFZ, providing the fundamental geologic and geophysical framework for a successful drilling project. Integration between these existing data and scientific drilling data will lead to more informed hypothesis testing and more holistic approaches in future research.

A WELL-STUDIED REGION. The region surrounding the SCFZ and the northern Rio Grande rift has been extensively studied, including its geology, geophysics, geochemistry, geodetics, geothermics, and geochronology. Recently acquired airborne LiDAR data and high-resolution aeromagnetic, electromagnetic and gravity surveys of the San Luis basin have better defined the basin geometry and improved mapping of the fault framework (fig. 1) (Drenth et al., 2012, 2013; Grauch et. al, 2010, 2012; Bedrosian et al., 2012; Grauch and Ruleman, 2013, Ruleman et al. 2013). These airborne surveys are supplemented by ground electromagnetic, magnetotelluric, gravity, and seismic reflection data. Paleoseismic studies and characterization of Quaternary fault traces have further refined the geologic history and understanding of past surface rupture patterns along the SCFZ (McCalpin 1982; Colman et al., 1985; Ruleman and Machette, 2007; Ruleman et al., 2013). The USGS is presently undertaking new high-resolution surface geologic mapping that supplements decades of prior study. Integrated interpretation of these data facilitate the development of realistic tests of the tectonic history and neotectonic activity in the Rio Grande rift and identify well-constrained, shallow fault targets in a variety of lithologic settings. These diverse background data yield a detailed and regionally extensive view of the SCFZ as a potential drilling target.

RIFT EVOLUTION REMAINS POORLY UNDERSTOOD. Both low and high angle faults are found in the San Luis basin and adjacent Sangre de Cristo range. Because rift extensional structures overprint contractional structures formed during the Ancestral Rockies and Laramide orogenies, age relations between these fault styles as well as their roles, if any, in rift inception and evolution are controversial. A commonly cited paradigm for rift evolution involves an early phase of low-angle detachment-style faulting followed by high-angle normal faulting with attendant basin subsidence (Morgan et al., 1986). Others suggest that early phase high-angle normal faults were later rotated to shallower dip (Baldridge et al., 1995) or that extension has primarily been accommodated on low-angle extensional detachment faults or by movement along reactivated Laramide thrusts (Watkins, 1996; Fletcher et al., 2006). Recent geophysical studies confirm that low-angle surfaces of some sort do extend into the basin; however, the
sense of motion along this surface cannot be determined without direct sampling. These data also identify a series of buried, high-angle normal faults with significantly larger displacements than the range-front fault (Bedrosian et al., 2012; Grauch et al., 2012; Grauch and Ruleman, 2013).

The extensive data surrounding the SCFZ have helped refine the various rift evolution hypotheses into specific and readily testable questions:
(1) Are low-angle faults active in the modern rift or simply relict contractional features?
(2) How do fault structures vary from surface to depth, and does this variability translate to differences in earthquake surface rupture patterns?
(3) Can multiple fault strands be coseismically activated during large (> Mw 7.0) earthquakes?
(4) Are there distinctive fault zone architectural styles associated with protolith lithology, and how might these control strength, initiation, propagation, and arrest of an earthquake?
(5) What is the relative age and sense of motion of individual faults, and what implications does this have for the tectonic development of the rift?

These questions can be evaluated through drill core analysis, borehole geophysical logging, and the development of new, well-constrained mechanical models. Direct borehole observations of the SCFZ system will provide an opportunity to document the fault zone architecture of individual faults, fault rock composition and absolute age, possible weakening mechanisms, and the distribution of deformation. Using existing data, strategically selected, representative vertical and angled drilling transects from hanging wall to footwall through the SCFZ could also document the density and types of faults, to be compared with those mapped at the surface and derived from geophysical data. Deep boreholes would permit pore pressure and strain measurement and facilitate comparison to the observed surface strain rates measured as part of Earthscope and the Rio Grande Rift GPS experiment (Berglund et al. 2012). These measurements could be tied together with the new high-resolution geophysical data, surface mapping, and borehole geophysical and thermal logging data to improve our understanding of the seismic hazards presented by the SCFZ and analog structures.

FAULTS AS HYDRAULIC, THERMAL, AND MECHANICAL HETEROGENETIES. Faults create significant heterogeneity in fluid and heat flow systems and can have substantial local and regional influence on the processes surrounding these systems (e.g., Forster and Smith, 1988; Lopez and Smith, 1995, 1996). The geologic character of an individual fault zone impacts its strength and permeability (e.g., Caine et al., 1996, Lockner et al., 2000); as such, detailed fault structure and mineralogical changes control its ability to transmit pore pressure and perhaps control sensitivity to rupture, influence crustal-scale fluid and heat circulation patterns, host hydrothermal mineral deposits, compartmentalize aquifers, and alter regional recharge processes (Manning, 2009; Caine and Minor, 2009). The SCFZ presents a series of lithologic juxtapositions that may control the geologic character of a fault. As such, scientific boreholes drilled through the SCFZ can systematically examine the in-situ variability in fault geology and mechanics between rock-rock, rock-sediment, and sediment-sediment protoliths under otherwise similar tectonic conditions. Geologic observation, geophysical characterization, thermal profiling, and in-situ hydraulic testing within the SCFZ will advance our understanding of the SCFZ as a hydrogeologic, geothermal, and mechanical heterogeneity. These data will also lead to improved physical conceptualization of fault zones in a variety of lithologic settings and better numerical representation of faults in fluid, heat, and mechanical models.

DRILLING PLAN. The section of the SCFZ near Deadman Creek (A-A’, fig. 1) presents an ideal drilling target. Prior oil-and-gas exploration wells identify and qualitatively describe a low-angle fault with unknown shear sense at this location. Multiple geophysical and geologic datasets overlap near Deadman Creek (fig. 1b), and integrated analysis has led to a well-constrained conceptualization of the subsurface (fig. 1c). The location of large-displacement faults in the crystalline basement (X, fig. 1c) have been constrained by numerical forward models of potential field data (Grauch et al., in review);
resistivity imaging has revealed that some of these faults offset lacustrine clays in the upper 300 m (Bedrosian et al., 2012). At the Sangre de Cristo range front, incision by Deadman Creek has exposed northeast vergent thrust faults while additional Laramide thrusts have been mapped to the east. Because the faults are well-located and known to extend from the basement through the basin deposits, Deadman Creek is an ideal location for testing rift evolution hypotheses and characterizing the fault zone geology with minimal drilling depth and risk. We propose to drill two boreholes (fig. 1c):

1. Drilling a pilot hole with two angled offshoots through the high-angle range-front fault will sample the fault strand typically associated with the most recent seismicity and preserved surface rupture. Angled offshoots would sample two lithologic juxtapositions characteristic of the SCFZ: sediment-rock and rock-rock. This hole will also sample the controversial low-angle fault.

2. Drilling a pilot hole with three angled offshoots through one of the geophysically constrained, buried, high-angle faults will facilitate the testing of fault timing between the different strands, will allow the evaluation of fault zone properties under different lithologic juxtapositions (sediment-sediment, sediment-rock, rock-rock), and will allow comparison of the observed fault zone properties between faults with substantial differences in displacement.

**BROADER IMPACT.** Scientific drilling of the SCFZ would have multiple societally relevant implications. (1) Colorado is typically considered to be tectonically stable and seismically dormant because large magnitude (> M_w 7.0) earthquakes haven’t been recorded in the written record. However, paleoseismic evidence from the range-front fault zone suggests recurrence intervals for large >M_w 7.0 earthquakes to be 10–50 k.y. (McCalpin, 1982; 1986; Widmann et al., 1998; Crone and Machette, 2005; Ruleman and Machette, 2007). Contemporary seismic and geodetic data indicate that the SCFZ is capable of producing M_w 7.5 earthquakes on a time scale of 1-4 k.y. (Charlie et al., 2002; Bilham, 2012). New subsurface drilling data would improve regional seismic hazard assessments and benefit evaluation of seismic hazards in other rift systems. (2) Insights gained through drilling the SCFZ would enhance natural resource assessments. The San Luis basin is a major agricultural area relying heavily on groundwater irrigation. The basin also contributes to the headwaters region of the Rio Grande River, a primary water source of populous New Mexico and Texas. Faults within the SCFZ are generally oriented parallel to the Sangre de Cristo range front (fig. 1b), and as such are optimally oriented to influence mountain block recharge to basin aquifers. The high heat flow associated with the rift also makes the basin an area of geothermal resource potential. (3) By focusing drilling efforts in locations with a wealth of geophysical, surficial, and outcrop data, direct geologic observations and borehole geophysical signatures can be compared. Interpretations of geophysical and surface geologic data can thus be improved for the surrounding area and may improve interpretations of similar extensional tectonic environments elsewhere.
Figure 1. (a) Extensional basins associated with the Rio Grande Rift. (b) Distribution of selected datasets near the Sangre de Cristo fault zone (SCFZ) for the San Luis Valley (PS, paleoseismology; LiDAR, light-detection and ranging; SR, seismic reflection; AGG, airborne gravity gradiometry; AEM, airborne electromagnetics; AM, airborne magnetics); ground-based gravity, EM, magnetotelluric geophysical data not shown. (c) Conceptualized cross section near Deadman Creek showing geophysically constrained buried normal faults, reverse and normal faults constrained by surface mapping and indicated in oil and gas exploration wells, and potential drilling targets 1 and 2. Inferred structures are indicated by dashed lines. Modified from Grauch et. al (in review) and Lindsey et al (2013).
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Capturing the Seismic Cycle: Sampling and Instrumenting an Earthquake Nucleation Patch

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Sampling, down-hole measurements and instrumentation of active faults at seismogenic depths throughout the world have produced significant advances in our understanding of fault zone evolution, structure, composition and mechanical behavior. These efforts have advanced our understanding of the physics of faulting and earthquake generation by addressing the following key questions of Earthscope, GeoPRISMS, ICDP, IODP and US Scientific Drilling: How do earthquakes start, propagate and arrest? How do fault zone structure and composition evolve over time, including during the seismic cycle? What is the absolute strength of faults? What are the mineralogy, deformation mechanisms and constitutive properties of fault rocks? What are the processes that lead to spatial and temporal variations in slip behavior, including the transition from creeping to locked (seismogenic) behavior? What are the physical and chemical processes that control faulting and earthquake recurrence? These questions are especially relevant for large, plate-boundary faults capable of producing damaging earthquakes. It is critical that future fault-zone drilling projects build off previous efforts to bridge the gaps that remain in our understanding of fault-slip behavior over all spatial and temporal scales.

In light of the above, future scientific drilling should target an accurately located, repeating seismogenic (nucleation) patch in a well-characterized fault system where new observations from recovered material, downhole measurements and monitoring can be directly compared to previous studies. Only by studying the composition, properties and in-situ behavior of a known seismic patch through multiple earthquake cycles can we begin to tie laboratory data and rupture dynamics models to observations of fault behavior. The SAFOD borehole (Fig 1.) provides one of the best opportunities to sample a repeating earthquake nucleation patch, located within an otherwise creeping segment of the San Andreas Fault (SAF). In this region, three repeating microearthquake clusters are located in the vicinity of the borehole (Fig. 1), with the Hawaii cluster located ~100 m beneath the main SAFOD borehole and within reach of a new, multilateral core hole. Although the original intent of SAFOD was to core through both the creeping SAF and one of these repeating microearthquakes, drilling difficulties made it possible to complete a core hole and set up the SAFOD observatory only in the creeping fault. The work completed to date has defined the geophysical and geologic conditions in the SAFOD borehole and surrounding region to an unprecedented extent, and through exhaustive studies of SAFOD downhole measurements and recovered core, led to fundamental discoveries about fault zone structure and evolution and the physical and chemical processes responsible for fault creep. The existing SAFOD borehole has also enabled near-field observations of these repeating microearthquakes using removable seismic instruments, which made it possible to define the locations and rupture properties of these events to an extent heretofore impossible.

In this paper, we propose that an additional multilateral borehole be drilled off the main SAFOD borehole to penetrate the Hawaii repeating earthquake patch. Before such a project can be undertaken, however, a multi-level seismic array should be installed in the current SAFOD borehole to total depth. This array would allow for wide-aperture observations and accurate
absolute location of the HI target earthquake, as needed to ensure that a new multilateral core hole would penetrate the seismogenic rupture patch. Sampling of fault and country rocks, downhole measurements and long-term fluid pressure, deformation and seismic monitoring within this new multilateral would provide unique information on the composition, physical properties and deformational behavior of a repeating earthquake patch, for direct comparison with similar samples and observations already obtained in the creeping SAF directly overhead. With the infrastructure now in place from SAFOD, we could then test numerous hypotheses explaining the existence of these isolated, repeating earthquakes within the San Andreas Fault zone. Previous studies suggest that these repeating microearthquakes may reflect variations in fault zone geometry/width, fault-gouge composition and/or fluid pressure. The opportunity to penetrate, sample and instrument a repeating earthquake-generating patch from SAFOD would allow us to realize one of the original goals of SAFOD and EarthScope, providing an unprecedented window into the SAF and enabling us to answer fundamental answers about the physics and chemistry of earthquake generation.


Figure 1: Repeating earthquake clusters in the SAFOD target zone. (A) Three-dimensional view of the volume surrounding the SAFOD borehole, with microearthquakes shown as black dots. Axes are in km. (B) Location of repeating microearthquakes within the plane of the SAF, showing the borehole intersection point (asterisk). The three patches, SF-San Francisco, LA-Los Angeles and HI-Hawaii, produce regular and nearly identical microearthquakes (M~2) every few years. (C) Cross-sectional view of the same microearthquake clusters looking parallel to the SAF. The two active fault traces that deform the SAFOD wellbore are the Southwest Deforming Zone (SDZ) and the Central Deforming Zone (CDZ). The HI cluster occurs on the downward extension of the SDZ about 100 m below the borehole whereas the LA and SF clusters appear to occur on the upward extension of the NBF. The SDZ and Northern Boundary Fault (NBF) mark the edges of the SAF damage zone (Zoback et al., 2011). Here we suggest that an additional multilateral be drilled off the main SAFOD borehole to allow for coring, downhole measurements and monitoring directly within the HI cluster.
Introduction

A-type granites and rhyolites are commonly defined by the tectonic setting in which they form; they are characteristically found in “anorogenic” or “within plate” settings such as continental rifts, hotspots, or mantle plumes and unrelated to plate convergence. Other definitions focus on their distinctive compositions—their alkaline affinities, high temperatures, low water and oxygen fugacities, enrichments high-field strength elements as compared to the much more common rhyolites related to subduction (Bonin, 2007). Moreover, they are commonly isotopically unevolved (e.g., high εNd) and many have low δ18O. Thus, even the definition of A-type granites is problematic and a few petrologists have proposed that the term should be dropped completely (e.g., Frost and Frost, 2011). Given these complications, it is not surprising that the origin of A-type magmas is also controversial; many different theories have been proposed for their origins ranging from fractional crystallization of mantle-derived basalt to shallow melting of caldera floors.

The rhyolites on the track of the Yellowstone hotspot are the classic example of this setting and the study of surface outcrops is maturing rapidly. However, in the central part of the track, where silicic volcanism is most voluminous and compositionally distinctive, study of the magma systems has been hindered because their eruptive sources are buried by subsequent basaltic volcanism. The study of deep drill core is the only way to effectively circumvent this drawback and acquire a more complete picture of an A-type magma system.

Major Science Issues

Rhyolites of the Snake River Plain-Yellowstone system are distinct from “normal” calc-alkaline rhyolites associated with island arc systems: they were very hot (850°-1000°C) dry melts with low viscosity and anhydrous mineral assemblages (e.g., Christiansen and McCurry, 2008). They have geochemical affinities to A-type granites which are common in plume-related silicic provinces. Rhyolite eruptions from the central Snake River Plain produced very large volume (>200 km³), low aspect ratio lavas, vast (∼1000 km³) intensely welded pumice-poor ignimbrites and lava-like ignimbrites, and regionally widespread ashfall layers with little pumice (Branney et al., 2008). Rhyolitic volcanism here is recognized to be an important but little understood category of silicic volcanism, Snake River-type volcanism, which has occurred at several times in earth history. In short, the rhyolites of the Snake river Plain are the youngest and best-preserved example of an important type of magmatism, but their eruptive centers are concealed beneath basalt.

The absence of exposure of proximal deposits severely limits our understanding of the eruptive processes, eruptive volumes, and the nature of the source volcanoes and their
underlying magma chambers and so the glimpses provided by drill core will be highly instructive.

Major issues include those related to A-type rhyolites and more generally to large silicic magmatic systems:

1. What is the origin of the SRP rhyolites and hot, alkaline A-type rhyolites in general? Although fractional crystallization of plume-derived basalt is commonly used to explain the characteristics of A-type rhyolites, recent oxygen isotope studies (Bindeman et al 2001; Boroughs et al 2012) have shown that low $^{18}$O rhyolites are common and are due to assimilation of hydrothermally altered rocks, which were either shallow rhyolites from earlier eruptive events, older altered intrusions such as the Idaho batholith, or altered gabbroic rocks in the midcrust.

2. How much plume-derived mafic magma is required to produce the rhyolites and what does this tell us about total magma flux in the Snake River-Yellowstone plume system (e.g., Nash et al 2006; McCurry and Rodgers, 2009. Determining the mass transfer and heat budget associated with these melts will be critical to our understanding of plume-continent interaction.

3. What is the nature of intracaldera fill? Can the timing of caldera collapse be determined from core through an intracaldera deposit?

4. What is the structure of large pre-eruptive rhyolite magma chambers? The large volumes of rhyolite buried beneath the Snake River Plain preserve a record of magma chamber processes that cannot be seen in surface exposures, such as fractional crystallization, magma recharge and mixing, separation of melt from mush, assimilation of continental crust or lithosphere, and variations in the composition of the rhyolite source regions.

5. Drilling provides a unique opportunity to investigate the concealed proximal deposits and eruptive centers of the youngest and best-preserved example worldwide of A-type magma systems and of a distinctive type of silicic volcanism.

Proposed Work

With the acquisition of a 2 km deep core through thin basalt and two thick sequences of rhyolite at Kimberly, Idaho (Shervais et al., 2013), the time is ripe to study the petrology and volcanology of these A-type rhyolites and address the science issues listed above. These objectives can be met through detailed logging of the core, petrographic and mineral chemical studies coupled with major, trace element, and isotopic studies (O-Pb-Sr-Nd). The data thus acquired can be compared with the experimental investigations to determine melting and eruptive conditions and the controls of the evolution of volcanic systems. Geochronologic work--U-Pb zircon, $^{40}$Ar/$^{39}$Ar and paleomagnetis--are also key to understanding the temporal evolution, correlation with distal volcanic deposits, importance of antecrysts, and the ages of the magma source materials. Ultimately, such volcanologic, geochemical, and geochronological studies will
increase our understanding of how A-type silicic magmas form and their significance in the geologic record.

The cost of such value-added studies is a small fraction of the cost of drilling, down hole geophysical logging, and sample curation. These expenses were covered by the U.S. Department of Energy, the International Continental Drilling Program, and collaborating universities. It is critical in cases where other agencies support drilling operations and core recovery that the National Science Foundation support science investigations of already acquired core.

References
Testing the Extensional Detachment Paradigm: A Borehole Observatory in the Sevier Desert Basin

by Nicholas Christie-Blick, Mark H. Anders, Gianreto Manatschal, and Brian P. Wernicke


Low-angle normal faults or detachments are widely regarded as playing an important role in crustal extension and the development of rifted continental margins (Manatschal et al., 2007). However, no consensus exists on how to resolve the mechanical paradox implied by the gentle dips of these faults and by the general absence of evidence for associated seismicity (Sibson, 1985; Wernicke, 1995; Axen, 2004). As part of a new initiative to rationalize geological and geophysical evidence and our theoretical understanding of how rocks deform, a group of forty-seven scientists and drilling experts from five countries met for four days on 15–18 July 2008 to discuss the present status of the paradox and a borehole-based strategy for resolving it. The workshop was held at two venues in Utah (the Utah Department of Natural Resources in Salt Lake City, and Solitude Mountain Resort in the adjacent Wasatch Range), with a one-day field trip to the Sevier Desert basin of west-central Utah (Figs. 1, 2) to examine the general setting of potential drill sites and the footwall geology of the Sevier Desert detachment (Canyon Range).

Interest in the Sevier Desert detachment (Fig. 3) relates to its large scale, geometric simplicity, severe misorientation with respect to $\sigma_3$, comparatively shallow depth, and compelling evidence for contemporary slip, as well as its accessibility from more or less flat public land (Von Tish et al., 1985; Niemi et al., 2004; Wills et al., 2005). The fault was first recognized in the mid-1970s, on the basis of seismic reflection data and commercial wells, as the subsurface contact between Paleozoic carbonate rocks and Cenozoic basin fill (McDonald, 1976). It is thought by most workers to root into the crust to the west of the Sevier Desert, to have large offset (as much as 47 km; DeCelles and Coogan, 2006), and to have been active since the late Oligocene at or near its present dip of 11° (GPS data and prominent Holocene scarp on steeply inclined hanging-wall faults that appear to sole downward into the detachment; Von Tish et al., 1985; Oviatt, 1989; Wernicke, 1995; Niemi et al., 2004). Whether the detachment fault crops out today at the eastern margin of the Sevier Desert basin is unresolved (Otton, 1995; Wills and Anders, 1999). No modern scars have been observed there. Although no historic seismicity has been documented on the detachment, its scale is consistent with earthquake magnitudes at least as large as Mw = 7.0 (Wernicke, 1995). It is also possible that slip is currently taking place by aseismic creep. While dozens of low-angle normal faults have been recognized, at numerous locations in both extensional and orogenic settings—and by low angle we refer to the dip of a fault today, not necessarily its dip when it was active—the Sevier Desert detachment is one of very few that is sufficiently well-documented, active, and accessible from the surface that it might reasonably yield new insights about the conditions under which such faults slip.

A two-step drilling strategy emerged during workshop discussions. The first step (a pilot hole) is to re-enter one of several wells drilled by petroleum companies in the Sevier Desert basin (Wills et al., 2005), to deviate a few tens of meters above the base of the Cenozoic section, and to core through the detachment level to at least several tens of meters below the top of the Paleozoic section. Before embarking on a dedicated main hole, it is imperative to demonstrate that a fault is present (i.e., that fault rocks are present). The detachment interpretation, though generally accepted, currently depends entirely on geophysical data, not direct observation. It may be necessary to deviate and core through the detachment more than once to obtain definitive samples. The well provisionally selected for the
pilot hole, and for technical as well as geological reasons, is ARCO Hole-in-Rock in the southern Sevier Desert (AHR in Figs. 2, 3B). The detachment is sufficiently deep at the Hole-in-Rock well (2774 m), and its hanging-wall offset is sufficiently large that fault rocks ought to be well-developed in both Cenozoic strata above and Paleozoic strata below. At the same time, the existence of late Pleistocene to Holocene fault scarps to the east of the well is consistent with recent displacement on the detachment at this location.

The second step (main hole) is to core, log, and make in situ measurements at a location between a few tens of meters and 4 km west (down-dip) of ARCO Hole-in-Rock, and intersecting the interpreted detachment at a depth of 2800–3500 m (Fig. 3B). All surface scarps appear to be east of the Hole-in-Rock well at this latitude. The selection of a site 4 km or more to the west of ARCO Hole-in-Rock would permit the detachment fault to be penetrated within Paleozoic or Neoproterozoic strata west of the intersection between the basin’s western bounding fault and the detachment.

The principal objective of the second hole is to establish an observatory at a depth and location most likely to allow monitoring of the full rate of extension across the Sevier Desert (~0.35 mm yr⁻¹; Niemi et al., 2004), and yet not so deep as to be prohibitively expensive. Among in situ measurements to be made in the vicinity of the detachment are the following: pore pressure, fracture permeability, fluid chemistry (including He), temperature, the orientation of stress axes, and the magnitude of differential stress. A borehole seismometer will be installed as part of a local array. A second objective of this main hole is to investigate the history of sediment accumulation and how the timing of basin development relates to exhumation of the detachment’s footwall (based upon already published fission-track data for the Canyon Range; Stockli et al., 2001). A full suite of downhole logs (especially acoustic logging) will allow confident correlation with seismic reflection data. A byproduct of stratigraphic and geochronological analyses will be an extended lacustrine record of continental climate change since the late Oligocene.

A priority before any drilling is undertaken is to acquire new seismic reflection data in a grid encompassing both ARCO Hole-in-Rock and candidate locations for the proposed main hole. These data will be essential in establishing confidence in three-dimensional stratigraphic and structural geometry. Other pre-drill data that may be particularly useful—among many excellent ideas raised at the workshop—include high-resolution seismic and GPR (ground-penetrating radar) data combined with trenching across prominent fault scarps, and the establishment of closely spaced GPS stations aimed at determining more precisely how contemporary extension is distributed across the Sevier Desert.

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Understanding the evolution of a back-arc bimodal shield volcano, Newberry Volcano, Oregon

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Newberry Volcano is located within the Newberry National Volcanic Monument in the Deschutes National Forest in central Oregon, about 50km east of the central axis of the Cascades volcanic arc. It is a large bi-modal Quaternary volcano and is one of the largest Quaternary volcanoes in the continental United States. The volcano is positioned near the junction of three geologic provinces: the Cascade Range to the west, the High Lava Plains portion of the Basin and Range to the south and east, and the Blue Mountains to the northeast. Newberry Volcano has been active for the past 600,000 years and has had at least two caldera-forming eruptions. The present central caldera is roughly 7 km wide west to east and 6 km wide north to south. The entire volcanic edifice has the shape of an elongate shield, 60 km north to south and 30 km east to west. It covers an area of approximately 1,600 km² and has a volume of approximately 450 km³ (MacLeod & Sherrod, 1988). The volcanism consists of predominantly basalt and basaltic andesite flows, pyroclastic deposits, and cinder cones. The most recent major caldera-related eruptions resulting in significant silicic ash and pyroclastic deposits occurred approximately 300,000 and 80,000 years ago (Donnelly-Nolan et al., 2004). A large-volume basaltic eruption occurred about 72,000 years ago, resulting in the widespread Bend Lavas which extend approximately 70 km to the north of the central caldera. 6,000 years ago numerous basaltic eruptions occurred along a northwest fracture zone. The most recent eruption, a silicic obsidian flow and associated pumice fall vented from within the caldera, has been dated at 1,300 years ago (MacLeod and Sherrod, 1988). The summit caldera is likely the result of multiple caldera collapse events based on the apparent nested caldera walls. This is most readily seen on the northwestern and southern portions of the caldera. Two voluminous ash-flow tuff units mapped on the flanks of Newberry Volcano have been proposed as evidence of two large caldera creating events.

The nature of the heat source beneath the volcano is still being debated. There are two main models that have been proposed for the location of Newberry. Jordan (2004), has attributed Newberry volcano and the high lava plains to the east to a mantle source linked with the Yellowstone hot spot. Alternatively, other work at Newberry links it with the Cascade Range and identifies a slab component in the erupted lavas. A better understanding of the magmas that are feeding Newberry could give new insight into the source of magma and help answer the question of why Newberry is where it is.

The volcano has been the site of repeated geothermal energy exploration studies since the mid-1970s. The USGS drilled two test wells at Newberry in the early 1980s. Newberry-2 was sited within the caldera and reached a temperature of 265 °C at depth of 932 m below the caldera floor. Based on these measured temperatures there is potentially a magma body within 2-3 km of the surface (Fitterman, 1988 and Sammel et al., 1988). The temperature data shows that two aquifers were intersected by the well bore, with temperatures of 40 °C and 100 °C. Details of the lithology
and alteration of the USGS well and other wells drilled at Newberry can be found in Barger & Keith (1999). The volcano has a thermal anomaly covering an area of ~280 km² with a surface heat flux approximately twice as high as the regional background, which makes it one of the most promising targets for engineered geothermal power generation in the lower 48 states.

Drilling at Newberry has the potential to answer questions related to the evolution of magmatic systems, back-arc magmatism, caldera formation, timing and duration of magma chambers, and regional tectonics. In addition to providing insight into Newberry Volcano, a project here would provide experience and knowledge into drilling in other large volcanic terrains. The High Cascade Range for example is would be a logical next target for U.S. continental drilling in magmatic systems. Drilling and interpretation experiences gained from Newberry would likely be transferable to other systems. The benefit to beginning with Newberry is the relatively large amount of pre-existing data (geologic, geochemical, and geophysical) that is available for the volcano that could be used to target wellbores, interpret structures, and correlate stratigraphy. The volcano is also very accessible with Forest Service roads on all flanks of the volcano and a paved road into the caldera.

A project of this type would attract a number of proponents from various universities and research groups who are interested in the geology, geochemistry, geophysics, and geohazards of large volcanic terrains. As a Cascades volcano, work at Newberry is applicable to the larger research goals of Geoprisms’ Cascadia Initiative and Earthscope’s convergent margin processes research. Southern Methodist University would be able to provide insight into the overall thermal regime of the volcano, interpretation of well logs and well data, and analysis of thermal properties of lithologies encountered in wells.

References

Volcano Structure and Hawaiian Plume Heterogeneity Based on New Drilling of Mauna Kea

Proponents (alphabetically): D. DePaolo (U.C. Berkeley), M. Garcia (U. Hawaii), E. Haskins (U. Hawaii), N. Lautze (U. Hawaii), J. M. Rhodes (U. Massachusetts) and D. Thomas (U. Hawaii)

Introduction. Mantle plumes, such as the one that formed the Hawaiian Islands, have strongly influenced our views of Earth’s deep mantle (e.g., Steinberger and Torsvik, 2012). Lavas from these areas are the principal geochemical probes into the mantle, and a testing ground for understanding Earth’s mantle convection, plate tectonics, volcanism, and changing magnetic field (Stolper et al., 2009). Study of the petrology and geochemistry of oceanic volcanoes has contributed immensely to our present understanding of Earth processes (e.g., Weis et al., 2011; Huang et al., 2011). Drilling is essential to evaluation the temporal evolution and structure of mantle plumes because surface exposures typically reveal only a small fraction of a volcano’s stratigraphy (e.g., ~3% of the 10- to 15-km height of Hawaiian volcanoes).

The Hawaii Scientific Drilling Project (HSDP) was conceived in the mid-1980s to address the lack of surface exposures on Hawaiian shield volcanoes. The goal of the project was to continuously core to a few kilometers into the distal flank of Mauna Kea Volcano. The site was chosen far from the summit of the volcano (~50 km) to maximize the potential of capturing a longer time record of the volcano’s history, although it sacrificed temporal resolution by sampling only 1-3 flows/1000 years (Garcia et al., 2007). Two holes were drilled near sea level in Hilo, Hawaii (Fig. 1): HSDP1, a pilot hole, was drilled to a depth of ~1050 m in 1993 (Stolper et al., 1996) and HSDP2, to ~3520 m, from 1999-2007 (Garcia et al., 2007; Stolper et al., 2009; Rhodes et al., 2012). An integrated set of investigations characterized the petrology, geochemistry, geochronology, and the magnetic and hydrological properties of the core and the borehole, which resulted in more than 60 papers in peer-reviewed journals (see ICDP website, http://www.icdp-online.org/front_content.php?idcat=1120 mostly in two journal collections (Journal Geophysical Research, 101, B5; Geochemistry, Geophysics, Geosystems, 2003-2012).

New Opportunity. The US Army has funded (~$6 M) the drilling of two, ~2,000 m deep boreholes in search for water on the upper flank of Mauna Kea Volcano on the Island of Hawaii (PTA, Figure 1). The first hole, located ~10 km from the volcano’s summit, is now ~1320 m deep, with operations scheduled to continue for about 6-12 months to complete the two holes. Drilling operations, coordinated by Don Thomas, started in Feb., 2013, using a truck-mounted Boart Longyear LF230 diamond core drill rig. The first hole was drilled with PQ-sized bits (8.5 cm diameter) to ~1 km and casing was set to base of the hole. Drilling is proceeding with a HQ-sized bit (6.3 cm diameter) to ~2 km. Core is being continuously collected and curated by a team of geologists led by Eric
Haskins, with NSF grant support to Nicole Lautze. Core recovery rate has been excellent (88% overall, improving with depth to 99% for last 500 m). Logging has shown mixture of flows (mostly pahoehoe) with multiple intrusions (12) and fragmental debris. These two holes provide an unprecedented opportunity for detailed examination of the volcanic history of a Hawaiian volcano and will allow many issues to be examined including:

1. **What are the magma production and lava accumulation rates for Hawaiian volcanoes?** Lava accumulation rate estimates based on dating HSDP2 core are minimum values because of the location of the drill site 50 km from the volcano's summit and the problems encountered in dating the core, which was mostly deposited submarine sea level where rapid quenching and secondary minerals are common (Sharp and Renne, 2005). The PTA section will be entirely subaerial. Thus, easier for Ar-Ar dating allowing us to better constrain production rates.

2. **What is the scale of heterogeneity and variation in partial melting in the Hawaiian plume?** The PTA site location allows finer resolution of the volcano's geochemical variation and assessment of the structure of the Hawaiian mantle plume than the HSDP2 core. Work on historical lavas of Kilauea volcano has shown fine-scale
source variations that are cyclical on scales of decades to centuries (Marske et al., 2007; Greene et al., in review).

3. **What is the nature of the transition from shield to post-shield volcanism?** The PTA core will provide an exceptional record of the timing and duration this transition as the volcano moves off the hotspot causing lower degrees of melting and change in source components (e.g., Hanano et al., 2012). Current studies indicate a 6 ka break in volcanism (Wolfe et al., 1997), which may be related to sampling constraints.

4. **How do Hawaiian and other volcanoes grow (internal vs. external growth)?** Francis et al. (1993) proposed 2/3 of the growth of Hawaiian shield volcanoes is by endogenous (intrusive) growth. A new gravity study (Flinders et al., in press) suggest the intrusions represent <30% of the mass of Hawaiian volcanoes. The close proximity of the drill site to the volcano’s summit will allow us to evaluate this new interpretation. Twelve intrusions have been recovered in the upper 1.3 km of the hole.

5. **What is the heat flow within an oceanic volcano?** Unlike the HSDP sites, the PTA site should not be affected by circulation of cold seawater, so its temperature profile will be more representative of the heat flow above the Hawaiian mantle plume, which is poorly known.

6. **What is the extent of explosive volcanism for Hawaiian volcanoes?** Kilauea’s Holocene deposits record numerous major violent events and suggest its explosive frequency is on par with Mt. St. Helens (Swanson et al., 2011). Adjacent Mauna Loa is thought to have had a large explosion associated with a major debris avalanche (Lipman, 1980). Careful examination of the fragmental material in the core will provide insight into the frequency of explosive eruptions for this, and the other, major shield volcanoes on Hawaii Island, which will have implications for hazard mitigation and planning.

**Summary.** Resource characterization studies such as the PTA water drilling program provide potential economic and societal value to organizations and communities but can also be opportunities to address fundamental scientific questions at costs substantially below those of basic research drilling projects. There is much we still do not know about how Hawaiian and other volcanoes grow, which has natural hazards implications. The new Mauna Kea Volcano drilling provides an exceptional opportunity to gain a detailed understanding of crustal and mantle processes within plume-related and other volcanoes at no cost to NSF for drilling.
References


Coring and studying clay gouges from mature active fault zones

Jafar Hadizadeh (University of Louisville, KY), Thibault Candela (Pennsylvania State University, PA /UC Santa Cruz, CA), Joseph C. White (University of New Brunswick, Canada), François Renard (University of Grenoble, France)

We investigated phase 2 and 3 SAFOD drill cores. Relevant to this white paper, our findings indicated that shear strain is localized in narrow clay-rich zones where, by most accounts, more than a single deformation mechanism was involved (e.g. White and Kennedy 2010, Holdsworth et al. 2011, Jansen et al. 2011, Gratier et al. 2011, Mittempergher et al. 2011, Hadizadeh et al. 2012). Our studies identified evidence of competing pressure solution creep, grain-scale frictional sliding, and healing processes. The SAFOD core material from the active creep zones provided a significant window into the processes of development of the mechanically critical low-friction gouges.

Low-friction shear zones

There is broad consensus that the SAFOD clay gouges were involved in strain localization in narrow 0.1-1m shear zones with friction coefficients less than 0.3 (e.g. Lockner et al. 2011). This finding correlates well with the general creep behavior of the SAF north of Parkfield, California. However, it is important to further investigate the association of shear localization with creep. The relative importance, to the mechanical behavior of a fault zone, of intrinsic mineral weakness and the development of microstructures like cataclastic foliation is not well understood; a closely related question is the role of pressure solution in the development of foliation in low-friction gouges.

Spotting zones of highly localized shearing

It is understood that zones of shear localization hold information on deformation history as well as being the potential sites of latest movement and weakest fault rocks. The main damage zone of a fault may be identified by geophysical logs as zones of anomalous porosity and spiking phyllosilicate content. However, where shearing is so narrowly localized and is probably part of a complex structural network at meter scale or larger, we do not have reliable criteria to identify the active, or lately active, strands from
the drill cores alone. The discovery of intervals of casing deformation in the SAFOD Main Hole, subsequently identified as CDZ and SDZ by Zoback et al. (2010), was significant because it unequivocally located the weakest region of the fault core. Had it not been for this knowledge, we were unable to locate the site of activity by examining cores from the lateral holes, which were drilled in the projected path of the active intervals. The exact extent of the deforming intervals and distribution of shearing rates along the deforming intervals based on down-hole calipers proved to be a challenge during SAFOD operations. Whether detection of active shearing based on reliable down-hole instrumentation could be designed into the drilling process remains an interesting question.

**Sampling the drill cores and orienting the samples**

The main damage zone of the SAF encountered in SAFOD included intervals of incohesive, fragile clay gouge that would significantly degrade upon exposure to air moisture and physical manipulations such as sub-coring and billet removal. As a result, distribution of material from these important sections were greatly delayed or deadlocked. There are not many good sample cutting practices that satisfy all investigators trying to study the same fragile core interval. One possibility is to avoid longitudinal splitting of the encased core sections containing sensitive or incohesive gouge if the material could be pre-characterized by x-ray scanning or log data. Instead, core lengths may be transversely sectioned to leave a ring of the casing that protects the sample slice. Gouge material could then be carefully extruded from the ring as a 3-4 cm thick intact disc.

The foliation and sense of shear indicators in the SAFOD gouge could not be reliably correlated with the SAF shear plane attitude. In some studies deformational features were only referenced to gouge foliation. This method is useful if multiple representative foliation could be referenced to an oriented core section marker, or other fiducially-oriented markers, in order to establish a universal fault plane reference for the cores.
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Isotope Geochemistry and Mantle Source Regions for Plume-Lithosphere Interaction

Barry B. Hanan
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A leading hypothesis for the time transgressive nature of the YSRP system is that it results from a deep-seated mantle plume that is fixed relative to the continental lithosphere that over-rides it (e.g., Armstrong et al. 1975; Smith and Braille 1994; Pierce et al. 2002). However, the association of Yellowstone hotspot magmatism with a mantle plume remains controversial. Non-plume models proposed for the origin of the YSRP volcanic system include a propagating rift (Christiansen and McKee, 1978), edge-driven convection (King and Anderson 1995; King 2007) and a plate-parallel convective roll or hotline driven by self-sustaining convection (Humphreys et al., 2000).

Leeman et al. (2009) recently concluded that SRP basalts are not derived from a plume but instead are the result of partial melting of the subcontinental lithosphere in a region of known extension. Others suggest that the basalts result from the melting of hydrated lithosphere formed by low angle subduction of the Farallon plate during the middle Cenozoic (e.g., Carlson and Hart 1987).

In contrast, on the basis of S-wave and P-wave tomographic images, James et al. (2011) suggest a subduction-related process where volcanism along the SRP-Yellowstone hotspot track results from slab fragmentation, trench retreat, and mantle upwelling at the tip and around the truncated edges of the descending plate. In this model a sub-horizontal slab separated from the subducting Farallon plate resides in the mantle transition zone (400–600 km) directly beneath the SRP/Y track. Upward mantle flow around the tip of the sinking slab is thought to decompress and melt, forming a plume-like upwelling.

The multi-tracer approach, using Pb, Sr, Nd, Hf and He isotopes, along with major and trace element variations, allows us to determine how the contribution of mantle and lithospheric sources changed spatially and through time for the SRP basalts, and to develop models for interaction between mantle sources (plume-derived, subducting slab, enriched mantle wedge, and asthenospheric MORB source) and continental lithospheric mantle and overlying crust. Such models cannot be rigorously tested solely with surface basalts exposed along the SRP. A proper test requires information from a continuous section of basalts at a single locality, plus samples from along the SRP that are spatially well-constrained with respect to the initiation of basaltic volcanism.

Helium isotope studies in the western U.S. have revealed the presence of a uniquely elevated $^3\text{He}/^4\text{He}$ signature for the Yellowstone-Snake River Plain province (Figure 9); this observation supports the notion of a significant deep mantle flux of He beneath this area (Craig 1997; Graham et al. 2009), consistent with the presence of a mantle plume inferred from seismic tomography. The elevated $^3\text{He}/^4\text{He}$ extends into the Miocene (~8 Ma) SRP basalts and includes the Columbia River Basalt group (Graham et al. 2009). High $^3\text{He}/^4\text{He}$ is therefore a characteristic of both young and old
basalts in this region, but we have no knowledge of the temporal variability nor its relation to the inferred Yellowstone plume location in the past. High $^3\text{He}/\text{He}$ ratios are absent elsewhere in the western U.S., making the Columbia River Basalt–Yellowstone–Snake River Plain system unique, and a prime location for investigating the potential interactions between a deeply sourced hotspot and continental lithosphere via temporal studies of lavas obtained through drilling.

The involvement of different mantle sources during petrogenesis can be deduced from the covariations of He, Sr, Nd, Hf, and Pb isotope ratios in basaltic rocks. Isotope signatures of continental basalts, in comparison to oceanic lavas, are often more difficult to interpret because of interactions with continental crust and sub-continental lithosphere mantle (SCLM). In Snake River Plain basalts, the limited range of major and trace element compositions, the presence of essentially mantle $\delta^{18}\text{O}$ and $^3\text{He}/\text{He}$ signatures, and the lack of correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ (or $\delta^{18}\text{O}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$) and major and trace elements indicate minimal crustal interaction (a notable exception being lavas from Craters of the Moon; Menzies et al., 1983, 1984; Leeman, 1982; Carlson, 1984; Hart, 1985; Church, 1985; Shervais et al., 2006).

Major element, trace element, and He isotope systematics of the basaltic rocks are consistent with a deep, sub-lithospheric mantle source, similar to the source of many ocean island basalts (e.g., Shervais et al. 2006; Graham et al. 2009; Shervais and Vetter 2009). However, the radiogenic Pb isotopes in the SRP basalts are indistinguishable from melts derived from the ancient Wyoming cratonic lithosphere that underlies the SRP, while Sr, Nd, and Th isotope ratios are intermediate between depleted mantle and lower crust or lithospheric mantle values (Church 1985; Leeman et al. 1985; Reid 1995; Hughes et al. 2002; Hanan et al. 2008).

To explain this apparent paradox, we hypothesize a model in which lithospheric components contribute steadily decreasing amounts of material as more deep-mantle OIB- (plume-like) melts pass through the lithosphere (Hanan et al., 2008). Lithosphere beneath the eastern Snake River Plain and Yellowstone Plateau became stabilized in the Late Archean to Early Proterozoic. It’s Pb and Sr initial isotope ratios are higher, and the Nd initial ratios are lower, than expected for a depleted upper mantle source of Late Archean age (Wooden & Mueller 1988; Menzies et al 1983). The isotope data for these basalts, and Os, Sr, Nd, and Pb isotopes of mantle xenoliths (Carlson & Irving 1994), suggest that the North American cratonic lithosphere underlying the SRP has been rejuvenated by recycled crustal material that was mixed into, and thereby enriched, the SCLM during Late Archean subduction and later Proterozoic metasomatic events (Church 1985; Wooden & Mueller 1988).

According to the lithospheric interaction model (Hanan et al. 2008), OIB-like chemical compositions coupled with SCLM isotope signatures in SRP basalts occur because incompatible trace element concentrations in the mantle plume source are low compared to this enriched SCLM (or associated lower crust). Consequently, small degree partial melts of the ancient continental material can be significantly elevated in Sr, Nd, Pb and Hf (by more than an order of magnitude) compared to plume source melts. Ancient cratonic lithosphere like that of the Wyoming Province will superimpose its inherent isotopic composition on sublithospheric plume or
asthenospheric melts, until that ancient lithosphere becomes sufficiently thinned by thermal or mechanical erosion, or depleted in low-temperature melting components, so that sublithospheric melts may pass through with little or no pollution. This is apparently the case beneath the Great Basin today, where lithospheric thinning has proceeded to the extent that sublithospheric melts arrive at the surface with isotopic compositions similar to their primary source region.

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A proposal to drill active faults and magmatism in a major intracontinental fault zone, Mono Lake Basin, Walker Lane, Western Great Basin, USA.

This proposal addresses process of active magmatism, faulting, and fracturing over the time frame of one million years in a major intracontinental fault system.

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Introduction: The Mono Basin contains an exceptional record of Quaternary tectonic processes. The basin lies within a regional transtensive intra-continental fault system that (a) accommodates ~25% of relative Pacific-North American plate strike-slip motion, and (b) lies at the foot of one largest normal fault scarps in North America. Active tectonic and magmatic processes in the Mono Basin (Fig. 1) are linked to reorganization of the Pacific-North American plate boundary east of the San Andreas fault zone along the Walker Lane. The basin contains deposits of the 0.76 million year old Bishop Tuff, one of the largest known eruptions in North America. Eruptions from the Mono Lake Islands and the nearby Inyo-Mono Craters are the youngest volcanic features in the Great Basin and the youngest non-arc volcanoes of the conterminous United States. This volcanic complex includes the only volcanic vents less than 1000 years old south of Mt Lassen and north of the Gulf of California. The Mono Basin is seismically active. The largest historical earthquake (M₅.7, M₅.0) occurred a couple kilometers northwest of Black Point at the north end of the Mono Basin volcanic complex. Larger (~M₆.1 to ~7.3) post-glacial and Holocene earthquakes have been documented by paleoseismic studies near Mono Lake, and by high resolution seismic reflection collected from the lake. The stratigraphic record of multi-facted tectonism within the basin extends back at least several hundred thousand years.

Drilling in Mono Basin can test hypotheses for dike intrusion, expand upon our understanding of magmatic intrusive processes gained from Continental Drilling of the Inyo Craters in the early 1980’s, illuminate the mechanics of major intra-continental faulting, including low-angle normal faulting, and shed light on how these various processes interact.

Drilling would be supported by recent geologic mapping and geophysical data collected by USGS scientists and colleagues from 2009 to 2011 including high resolution (hr) seismic reflection, hr-gravity and hr-magnetic data that clarify the near-surface structure of the Mono Lake volcanic system, including imaging of new offshore faults and submerged volcanic features. The site lies near a region of active geothermal exploration.

Scientific objectives and specific questions:
Fracturing and magmatic processes can be explored both instantaneously and over a million-year period by drilling in Mono basin. Specific questions that can be addressed are diverse. Are eruptions coeval with large local earthquakes? Do faults provide pathways for separately stored magmas to mix? Do hydrothermal systems retard melt propagation by chilling dikes? What is the soft sediment response to active volcanism? Do magmas ascend primarily along pre-existing structures (e.g., faults) or are
magmatic conduits independent of the fault zones and control by the stress field? Is this region a discrete focus of mantle upwelling or the active leader of a propagating rift? Does the stress field of the region dominantly reflect strike-slip faulting or normal faulting? Much of the critical data needed to address these issues can only be obtained by drilling.

Potential Targets: Diverse types of volcanic and tectonic processes could be investigated best by a coordinated series of drill holes. The Mono Basin volcanic complex (Black Point, Mono Lake Islands lavas, Mono Craters, Oh Ridge volcano and adjacent mafic vents, Inyo Craters and adjacent late Holocene rhyolithic vents) contains over 40 vents that have erupted lavas varying compositionally from basalt to high-silica rhyolite (Fig. 2). The vent array is about 50 km long and lies east of the Sierra Nevada escarpment. The Inyo-Mono and Mono Lake volcanic chains trend nearly north-south, ~15-20° oblique to the trace of the Sierra Nevada frontal fault zone (Figs. 2 & 3). Vents in the southern part of the chain were drilled in the 1980’s (ref. 1) to test structural models for siliceous dome emplacement and to illuminate magmatic processes associated with dike injection. A follow-up study in the northern part of the Mono Craters chain can be optimized to test mechanical models for dike intrusion (see ref. 2) and dike-driven faulting. A second candidate drill site near the Black Point volcanic center along the north shore of Mono Lake could probe whether the eruptive vents are along faults and might shed light on whether particular eruptions are associated with individual slip events along faults. This candidate site is near two active basin-bounding faults, the normal-right oblique-normal Mono Lake fault zone west of the lake and the left-oblique Trench Canyon fault zone (Fig. 3). Stress measurements from drill holes near Panum Crater and Black Point could characterize the stress field, illuminate the mechanics of the basin-bounding faults, and clarify whether the main intrusions are controlled by pre-existing faults or by the modern stress field of the basin. Core from a complimentary drill hole through the deepest part of the basin to basement would (a) reveal the record of magmatic events coeval with evolution of Mono Basin and Long Valley caldera, and (b) permit a detailed characterization of the microbial and the paleo-biogeochemical environment of the volcanic-lacustrine stratigraphic sections.

Summary: Scientific objectives that can be pursued by drilling at this site are multidisciplinary and include understanding fracturing near active dike systems; constraining the relative timing of dike intrusions and fault rupture events; evaluating interaction of magmatic fluids and faults within a structural releasing bend; and documenting the stress field in a basin with active faults and active volcanoes. Likewise, identification of subsurface intrusions that did not erupt at the surface, documentation of degassing of magmas, temperature measurements, stress measurements, and documenting fractures near dikes (now covered by lavas) can only be done with boreholes. Stratigraphic findings that are unique to core samples can be used to develop a model for the interaction of faulting and dike intrusion since initiation of the basin ~4 Ma before present. Drilling in Mono Basin would constrain models for fluid/magmatic activity within the fault zones, hydrothermal processes, and magmatic linkages to the adjacent to Long Valley caldera and reveal the environmental history of one of the oldest tectonically active lake basins in the United States. The integration of research efforts would illuminate the processes and events within one of the most dynamic tectonic settings in North America.

Selected References:


KOYNA – WARNA SEISMIC ZONE, WESTERN INDIA: AN UNIQUE INTRAPLATE SETTING FOR DRILLING FOR AN ACTIVE FAULT ZONE UNDERLYING A BASALTIC PILE.

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The Koyna – Warna seismic zone in western India is characterised by several unique features. Low magnitude sustained seismicity has been recorded (including the largest M ~ 6.3 event of 10 Dec, 1967 and about 22 events with M > 5) for a period of more than 5 decades. The seismicity is recorded in a small restricted area of roughly 20 km x 30 km; that forms a part of the Deccan Plateau underlain by the Deccan Basalts; earlier considered to be a stable continental region, adding to the enigma of this seismicity. The focal depths of these events are concentrated largely within the depth zone of 5 – 7 km below the surface. The average elevations of the epicentral zone are ~ 650 m above mean sea level; and are underlain by about 1000 m thick Deccan Basalts.

The N-S trending escarpment of the Western Ghats that rises abruptly to over 1000 m above the sea level, fringing a narrow (50 – 70 km wide) coastal zone runs across a distance of more than 500 km within the Deccan Volcanic Province of Terminal Cretaceous – Early Palaeocene age. In a region where there is no obvious surface expression of a fault; Reservoir Triggered Seismicity is the more popular model used to explain the seismicity, based on statistical studies of water impoundment in the Koyna and Warna reservoirs that are located within the seismically active zone.

Deep continental drilling is proposed to be undertaken in this unique setting. The National Geophysical Research Institute, Hyderabad is the nodal agency that is spear-heading this effort with the support from the Government of India, Ministry of Earth Sciences. The ICDP has been appraised of this program and the work on was initiated in 2011. In the preparatory phase, detailed investigations of various geological and geophysical parameters are being undertaken, supplemented by an initial plan of 4 – 6 trial bore holes. The first 2 of the trial bore holes were initiated earlier this year. The main deep drill is projected to penetrate more than 7 km below the surface; and intends to transect the active fault zone that is perpetuating the seismicity in the region.

The unique combination of geological setting, low magnitude sustained seismicity (that is arguably linked to the surface reservoirs) and the paucity of surface expressions of a fault zone make this an exciting location for deep continental drilling. It is projected that this will enable direct measurements of rocks properties (physical and mechanical), pore-pressures, fluid dynamics, thermometrics and other parameters of an intra-plate active fault zone; before / during / after seismic events. Amongst other key benefits that will accrue are the ability to have a clear stratigraphic log of the Deccan basaltic sequence, direct sampling of the Trap-basement relations; and more importantly to assess if there are any sedimentary rocks between the crystalline basement and the Deccan Traps. In conclusion, many exciting, multifaceted and multidisciplinary earth science aspects of this region will be available for study as this project progresses.
Geological CO₂ storage: constraints from scientific drilling of natural CO₂ reservoirs, leaky faults and travertine deposits of the Colorado Plateau

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Introduction
Natural CO₂ reservoirs of the Colorado Plateau and southern Rocky Mountains region represent the accumulation of significant volumes of magmatically derived mantle volatiles in the continental crustal, sourced from regional late Cenozoic volcanism (Fig 1; Allis et al., 2001; Gilfillan et al., 2008). The abundance of these supercritical CO₂ and CO₂ gas accumulations, the variety of reservoir lithologies, deep and shallow crustal reservoirs, and secure and leaked accumulations makes this region a unique natural laboratory in which to study the behaviour of CO₂ in the subsurface. Studying such sites can address important questions about the security of CO₂ in geological reservoirs, the interactions of mantle and crustal fluids and the role of magmatism, tectonics and climate in controlling the flux of mantle volatiles to the Earth’s atmosphere.

CO₂ storage site analogues: objectives
Several of these CO₂ reservoirs are currently being studied in detail as important natural analogues to engineered anthropogenic CO₂ storage sites (e.g. Gilfillan et al., 2009; Kampman et al., 2009) and archives of mantle derived volatiles (e.g. Ballentine et al., 2005). The critical sites include leaking accumulations at Green River, Utah and St Johns Dome, Arizona and commercially producing fields at Bravo Dome, New Mexico and Farnham Dome, Utah. Geological carbon storage will require that less than ~0.1% of the mass of CO₂ stored escapes per year if significant climatic impacts are to be avoided (Hepple and Benson, 2005). This requires that the geological storage sites retain much of the CO₂ for more than 10,000 years.

In order to understand the long-term behaviour of supercritical CO₂ in engineered storage sites we need observations from natural CO₂ accumulations that can only be accessed by drilling. Critical questions for geological CO₂ storage that can be addressed by drilling such accumulations include;

1) The effects of supercritical CO₂ and CO₂-charged brines on reservoir caprocks;
2) The effects of supercritical CO₂ and CO₂-charged brines on fault rocks and fault zone permeability;
3) The long-term behaviour of CO₂ in reservoirs including its impacts on porosity/permeability,
4) The significance of fluid flow and diffusive CO₂ transport on CO₂ dissolution
5) The significant of CO₂ mineralization as a permanent trapping mechanism;
6) The use of travertines and fault zone carbonate mineral deposits to reconstruct fault hosted CO₂-leakage and its mechanisms and controls.
Many of these questions are best addressed by recovering core and fluid samples from natural CO₂ reservoirs that integrate the physical and geochemical processes over the relevant geological timescales. Core from reservoir, caprocks and fault zones document the relevant mineralogical and geochemical changes and fluid geochemical measurements record the thermodynamic driving force, and where spatial and temporal fluid samples are available preserve information on the rates of the fluid-fluid and fluid-mineral reactions. Such coupled fluid transport, fluid-fluid and fluid-rock interactions can only be understood by studying natural sites that integrate these processes over spatial and temporal scales unavailable in the laboratory, and their study is vital to inform the modelling of engineered CO₂ storage reservoir security. Further, the complex long term hydraulic behaviour of faults, which control the leakage of some of these natural sites, and which will ultimately form the most vulnerable aspect of any engineered CO₂ storage site, can only be understood by integrating field studies of this kind, using rock core recovered from faults that currently host CO₂-leaking or which have formed conduits for CO₂ and CO₂-charged fluids in the geological past.

The origin of the CO₂ and processes controlling the stability of the reservoirs may be investigated where subsurface gases and fluids are accessible through commercial CO₂ production wells at sites like Bravo Dome (e.g. Lollar and Ballentine, 2009), or where these sites currently leak fluids and gases to the surface through exhumed faults such as at Green River (e.g. Dockrill and Shipton, 2010; Kampman et al., 2009). Unfortunately, such commercial activities do not recover rock core from crucial aspects of the systems, such as fluid hosting faults or reservoir caprocks, and rarely provide high quality fluid and gas samples. Initial scientific drilling of one such fault-leaking CO₂ accumulation at Green River, Utah is currently providing critical information on the interaction of this CO₂ with reservoir, fault-rocks and caprocks in the shallow subsurface (<300 m; Kampman et al., 2013a). Continued study of these sites necessitates further scientific drilling campaigns because, despite the wide occurrence of natural CO₂ reservoirs, the critical parts of these active reservoirs are buried and can only be accessed by drilling. Information on the impacts of supercritical CO₂ on caprocks, faults and reservoirs is critical to inform models of CO₂ behaviour in CO₂-storage sites, but such accumulations are only accessible by deep (>800m) drilling. If caprocks, reservoir rocks or fault systems within reservoirs are exposed, not only will the CO₂-bearing fluids escape, but the mineralogy and chemistry of the rocks will be altered by diagenetic and weathering reactions, thus the critical aspects of the system can only be inferred by indirect means. Further, the recovery of high-pressure fluid and gas samples from these reservoirs and faults, with their dissolved volatile load intact, is crucial for recovering information on the driving fluid-fluid and fluid-mineral reactions, and for interpreting the impacts of the CO₂ and CO₂-charged fluids. Kampman et al., (2013b) have recently shown how such samples can be recovered using wire-line downhole sampling methods.
A final caveat is that drilling CO₂ reservoirs has inherent technical challenges. Drilling into reservoirs containing supercritical CO₂ and high-pressure CO₂-charged brines, that will rapidly expand or degas CO₂ following a reduction in pressure, creates a challenging drilling environment. Recovering core and fluid samples from such systems requires continued improvements in drilling, coring and fluid sampling technologies. But such improvements are critically required, not only for the drilling of natural CO₂ reservoirs but also for drilling observation and injection wells in on-going CO₂ storage projects.

Reservoir Caprocks
Understanding the long-term geochemical and geomechanical behaviour of low permeability rocks, such as siltstones, mudstones and shales, that form CO₂-reservoir seals, especially where they are exposed to supercritical CO₂, is essential for predicting the long-term security of engineered storage sites. The advective-diffusive transport of CO₂ and CO₂-charged brines in these low permeability rocks is poorly understood, being influenced by strongly coupled reactive transport processes, and fracture formation governed by coupled geochemical and geomechanical processes. Recovery of these sealing layers from core drilling is critical for such studies as these clay-rich rocks are highly sensitive to degradation and weathering at the Earth’s surface, which destroys much of the information in exhumed outcrops. Geochemical, mineralogical and petrophysical profiles through caprocks exposed to supercritical CO₂ and CO₂-charged brines can be used to reconstruct the impacts of the CO₂, and when combined with advective-diffusive modelling or isotopic dating, used to constrain the rates of the alteration.

Fault hosted fluid flow, CO₂ leakage and the geochemical, tectonic and climatic controls on the long-term hydraulic behaviour of CO₂-leaking faults
Where these sites leak to the surface in the present day, or have leaked in the geological past, they deposit carbonate minerals and surface carbonate deposits (travertines) which provide rare and invaluable archives of fault hosted fluid flow. Much success has been had using U-series isotopic methods to date these fault-hosted and surface deposits, from which the geological history of these sites may be reconstructed, and physical and geochemical processes interrogated (Burnside et al., 2013;

Figure 2 ~135 k.y. paleo-leakage history reconstructed for the CO₂-degassing fault at Green River, Utah. U-Th dated carbonate veins in the fault zone record changes in paleo-groundwater chemistry related to pulsed filling of the CO₂ reservoir following periods of climatic warm, with a periodicity controlled by climate driven changes in groundwater recharge rates and in crustal stresses related to unloading of the continental ice-sheet and associated draining of nearby Lake Bonneville. These climatic and tectonic processes triggered dilation of fractures in the fault damage zone, thus facilitating enhanced escape of CO₂ (Kampman et al., 2013)
Embid and Crossey, 2009; Kampman et al., 2012). Paleo-leakage histories can be reconstructed using trace element, stable and radiogenic isotope measurements of the dated deposits (Fig 2.). Such records provide constraints on paleo-groundwater geochemistry, fluid-rock interaction, fault hosted fluid transport and the coupling of geochemical, tectonic and climatic processes that control degassing of the reservoirs. The recovery of core from CO₂-leaking fault zones would allow further investigation of the long-term hydraulic behaviour of the faults, where carbonate mineralized fracture networks could be dated and contemporary strain rates and fracture permeabilities accessed. Additionally, reservoirs such as that at the Springerville–St. Johns Dome CO₂ field in eastern Arizona and western New Mexico, contain massive surface travertine deposits (>33 km²) that record episodic CO₂-leakage from the reservoir through local normal faults, with volumetric CO₂-leakage rates in the geological past that were significantly larger than leakage rates in the present day (Embid, 2009). These mounds and platforms can be up to 40m thick and drill coring of the mounds would provide a continuous travertine stratigraphy, from which the sequential layers of travertine may be dated and records of CO₂-leakage and its geochemical, tectonic and climatic controls assessed.

References


Data and information management is a critical component of scientific drilling endeavors, and its relevance is growing due to recent developments in governmental policy for open access to research results\(^1\) as well as NSF’s major investment in cyberinfrastructure development (CIF\(^2\), EarthCube\(^3\)). Data management for CSD needs to support efficient and comprehensive capture of data generated in the field during drilling operations and subsequently in repositories and analytical labs, ensure preservation and broad dissemination of the data in a professional and sustainable manner, and facilitate the integration of CSD data into existing and merging interoperable, cross-disciplinary data networks.

Tools are currently available for data capture and storage that constitute major improvements over the ad hoc procedures developed in the past for individual projects and abandoned afterward. However, the existing systems have tremendous deficiencies that must be addressed in order to allow the CSD community to reach its full potential and respond to the evolving requirements of data identification, data citability, metadata standards, interoperability, as well as usability, portability, flexibility, and scalability. The ICDP Drilling Information System provides a rigorous data storage architecture for a wide range of drilling projects and goals, but it requires complex installation of expensive commercial server and database software; it is unstable and lacks fault tolerance, particularly for the process of data input; and the user interface is challenging even for experienced IT personnel, and does not fit basic workflows in the field or lab. These impediments to routine use create a disincentive for adoption, which has led many CSD projects to employ ad hoc systems and to avoid the DIS except for end-of-project data storage.

Alternative systems have been developed such as the LacCore Drill Site Database, which is comparatively cheap and simple to set up and requires minimal training for new users. It is well-tailored to the workflow of drill site data capture, core handling, and for providing continuous feedback/guidance to ongoing drilling operations, especially for soft-sediment/lake drilling projects. But it lacks a comprehensive architecture for the full range of scientific drilling projects. Several recent CSD projects supported by ICDP and LacCore have used the LacCore database as a data capture portal, followed by data migration to the DIS and LacCore curatorial database for permanent data archiving, but this is a cumbersome process.

CSD has established a Drilling Informatics Committee to work with the community on planning the collaborative development of a modern, comprehensive data management tool based on open-source software, well-designed to fit workflows during drilling and in the lab, and fully interoperable with existing data management resources. This effort leverages past and ongoing work by Lehnert, Noren, and many others to establish standards and protocols for efficient data and sample management, including data capture, visualization, storage, retrieval, and discovery. These include registering samples with International Geo Sample Numbers (IGSNs) for persistent and unique identification that allows linking sample data across systems and throughout the life cycle of data generated from those samples; visualization with the CoreWall Suite (Correlator, Corelyzer, CoreRef, PSICAT) and other applications; curation with the Digital Environment for Sample Curation (DESC), an emerging shared cyberinfrastructure for sample curation; linking with suitable data collections hosted by IEDA (Integrated Earth Data Applications) and others; and utilizing appropriate World Data Center archives for long-term data stewardship. ICDP will continue to be a partner throughout the development process, building on the collaboration that has already yielded standards for data exchange and refinement of existing systems. The committee will remain highly involved with the NSF EarthCube initiative to ensure that new resources are fully compatible with the large data integration apparatus now in the initial design phase.

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1. [http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf](http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf)
Stresses within the Earth control faulting and fracturing at the surface and in the subsurface. The direct and indirect results have broad scientific relevance and practical impact. The total stress field in tectonically active regions tends to be complex though, reflecting both the ambient regional stress field that drives regional deformation and local stress perturbations caused by faulting, jointing, and dike intrusion. A dedicated characterization of the stress field through deep drilling has the potential to yield new insights into both the ambient regional stress fields as well as the local perturbations associated with major geologic structures. Most scientific drilling projects to date, however, have focused on matters other than the stress state. The few scientific drilling projects that have focused on stress measurements (e.g., KTB, SAFOD, Olkiluoto) have targeted settings favoring strike-slip and/or thrust faulting. Normal fault systems, the systems most intimately associated with volcanism and geothermal fields, have been largely unexplored. Enhanced understanding of these systems has practical benefits for areas ranging from hazard mitigation to hydrology to energy resource recovery. An understanding of the mechanics of these systems, which commonly is counter-intuitive, can help unite geologic and geophysical data, bridge the gap between observations of the surface and the subsurface, and provide a data base to test theoretical models of the state of stress in the crust.

Four immediate technical questions could be addressed by thoroughly investigating an area containing normal faults. These are:
1. What is the state of stress?
2. How does it vary?
3. How sensitive is the total stress state likely to be to perturbations caused by faulting?
4. How do measurements compare to model predictions?

The mechanical effects of normal faulting near the surface are reasonably well constrained. Normal faulting causes the surface of the hanging wall to be flexed concave up and the footwall to be flexed concave down. As a result, the horizontal stresses are expected to be compressive at the surface of the hanging wall, and tensile at the surface of the footwall (Fig. 1). The predicted magnitude of the near-surface elastic stresses is sufficient to cause widespread fracturing of different styles on the opposing walls of the fault.

The subsurface stress field near a normal fault is likely to be complicated, even for a simple fault geometry. For example, in the model of Fig. 2, contours of the horizontal stress field were horizontal before faulting, but not after faulting (Fig. 2a). Contours of the vertical stress field also were horizontal before faulting; they are little changed after faulting near the surface but are substantially altered near the fault on the footwall at depth (Fig. 2b). The trajectories normal to the most tensile
stress were everywhere vertical before faulting, but after faulting they locally are rotated by 90° to horizontal on the footwall (Fig. 2c). Under the stress field of Fig. 2, vertical (or subvertical) fractures would be expected on the hanging wall, whereas near the surface of the footwall, subhorizontal sheeting joints would be expected. These different fracture orientations would likely result in different hydrologic behaviors on the opposing walls of the faults, as well as different behaviors of subsequent igneous sheet intrusions: dikes would be more likely to erupt on the hanging wall than the footwall. The orientations of hydraulic fractures on the opposing walls also would be likely to vary.

Figure 2. Theoretical two-dimensional total stress fields (plane strain) in the upper 5 km after slip on the model fault of Fig. 1. (a) Horizontal stress. (b) Vertical stress. (c) Trajectories normal to the most tensile stress (proxies for the orientation of opening mode fractures). Trajectories at the surface to the right of the fault are horizontal.

Figures 1 and 2 show a simple idealized case with a single planar normal fault, but real normal fault systems typically involve grabens, horsts, and/or subparallel faults. The stress fields in real settings thus are likely to be more complicated than Figs. 1 and 2 indicate, but if the major faults can be identified, the stress field could still be modeled.

In contrast to the drilling project at SAFOD, a drilling project to investigate the stress field around a normal fault would best be served by a combination of holes that are distant from the targeted fault(s) as well as near the faults. Distant holes would be most likely to capture the ambient stress field. Holes near the fault(s) would be best positioned to capture the stress perturbation associated with faulting.

A simple normal fault system would be best to target to effectively gauge its stress field. Normal fault systems by their nature tend to be complicated though, so even a simple system is likely to contain a variety of challenging scientific opportunities. For example, in many places normal faults are associated with hydrothermal or geothermal activity. In addition, in many places lavas are associated with normal faults. A drilling project in such a location might be able to address a “chicken-and-egg problem”: do the faults exploit feeder dikes, or do the feeder dikes exploit faults?

Many places in the Basin and Range could provide suitable sites for a continental drilling campaign that targets the stress fields associated with normal faults. The east side of the Sierra Nevada is particularly well-suited on technical grounds because several stress measurements to depths of ~200m have been made in the Sierra Nevada. These measurements consistently show horizontal compressive stresses of 4-13 MPa near the surface, consistent with model predictions of normal faulting and the requirements for sheeting joints (“exfoliation joints”). Steeply-dipping joints are exposed on the footwall in several places, again consistent with the model predictions. The region also hosts operating geothermal plants (e.g., Coso, Mammoth Pacific, Steamboat Springs) and is a site of continuing geothermal exploration.
Sampling and In-situ Observations of Okmok (SINOOK)

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Scientific Questions addressed by SINOOK:

1. How reliable are estimates and uncertainties for internal processes and structures of volcanoes, determined from geophysical surface observations? SINOOK will verify geophysical models determined from seismic tomography, reflection, and anisotropy; gravity; and geodesy. For example, are the in situ or laboratory based rock properties (collected by SINOOK) within uncertainties of surface-based geophysical models? Results will have important implications for the reliability of geophysical models for Okmok volcano and elsewhere, as well as influence the justification and scope of major geophysical data collection initiatives for other volcanoes.

2. What is the magma migration and storage and eruption style in space and time? What are the systematic and asystematic aspects of eruption cycles? Results and implications may be transferrable to the general understanding of other volcanoes in island arc settings.

3. What is the basic structure of the magma chamber? Is it a single finite chamber, an assembly of dike and sill structures, or a multiphase mush zone? The answer to this question has important implications for magma migration and storage, as well as understanding the conditions that lead to specific eruption styles.

4. What is the rheologic structure of the transition zone separating the magma chamber from the country rock? Results that combine in situ observations and laboratory experiments will have implications for understanding the magma replenishment, as determined from geodetic data.

5. What are the characteristics and interactions of the shallow groundwater and deeper hydrothermal systems? How do these fluid systems influence the eruption style? The 2008 hydrovolcanic eruption was very different from the effusive 1997 eruption, even though both eruptions tapped the same magma source. The answers to these questions have important implications for understanding the evolution of eruption styles for other volcanoes, as well as for unraveling the complexity volcanic geothermal systems.

6. How does dike propagation couple to the local stress field and loading in the complex domain of a caldera? Results have strong implications for geothermal and hydrocarbon production, as well as nuclear waste disposal strategies, and are thus aligned with Energy and Economic interests.

7. How do eruption cycles integrate with ecological and local societal systems? Eruption cycles present examples of stress and recovery episodes with relevance to interdisciplinary ecological, societal, and economic systems.

8. What are the long-range ash plume or climate impacts? Determining the frequency, scale, and style of eruptions will have important implications for major civilian and military air traffic corridors that intersect Aleutian airspace.

Although scientific drilling of Okmok’s caldera is the kernel of SINOOK, the project will include both pre- and post-drilling components that span field, laboratory, remote sensing, and computational activities. While these activities are dominated by geologic and geophysical studies, the scientific questions above demonstrate great potential for interdisciplinary studies that naturally integrate Earth science with ecology, cultural studies, economics, and energy interests.

Pre-drilling geophysical surveys (e.g., gravity, MT, EM, and seismic) will sharpen our understanding of the caldera’s interior and provide guidance for drilling operations. Furthermore, these high resolution 3D models, developed using state-of-the-art geophysical instruments and methods, will be confronted with in situ observations in verification analyses. Auxiliary boreholes will be drilled to collect complementary information before, during, and after the main drilling operation. Downhole geophysical instruments will be deployed in the main borehole to collect geophysical information that will leverage co-drilling measurements and provide a basis for future complementary studies of this dynamic volcano.
Okmok Volcano: An ideal target

Okmok volcano is one of the largest and best studied volcanic shields of the Aleutian arc. A central caldera, having a radius of 5 km, dominates the physiography of Okmok. The existing caldera is the result of two separate caldera-forming eruptions having ages of 12,000 and 2,050 years b.p. [Finney et al., 2008; Larsen et al., 2007]. Post-caldera eruptions are effusive or phreatomagmatic and basaltic to andesitic [Burgisser, 2005]. The most recent eruption in 2008 originated from several new vents surrounding Cone D near the eastern rim of the caldera, while the three previous eruptions in 1945, 1958, and 1997 originated from Cone A near the southwest rim of the caldera [Larsen et al., 2009]. Geochemical analyses of erupted materials are consistent with primitive magma from depth and brief storage in shallow reservoirs [Finney et al., 2008]. Over the past decade, Okmok was instrumented with GPS instruments [Fourier et al., 2009; Miyagi et al., 2004] and seismic networks [Caplan-Auerbach et al., 2003; Haney, 2010; Johnson et al., 2010; Masterlark et al., 2010]. Okmok also hosts a site of the Aleutian infrasound array [Arnoult et al., 2010]. Remote sensing data remain essential for monitoring Okmok [Dehn et al., 2000; Lu, 2007; Lu et al., 2003; Patrick et al., 2004] and future satellite radar imagery will be available from a successful proposal to JAXA 4th ALOS Research Program for ALOS-2. Okmok is an excellent target for this project because of its location, activity, and internal structure. Okmok is well instrumented and has been well studied from a variety of perspectives that used different type of geologic, geophysical, and remote sensing data. SINOOK will provide opportunities to discriminate among different conceptual configurations of Okmok’s interior (Figure 2).

The assumed treatment of Okmok’s weak shallow caldera materials strongly influences interpretations of Okmok’s magmatic system, based on analyses of observed deformation (InSAR and GPS). For example, standard elastic half-space (EHS) analyses predict a magma chamber depth of 3 km, whereas models that account for weak caldera materials predict that the magma chamber is significantly deeper (~4 km) [Masterlark, 2007; Masterlark et al., 2012]. Furthermore, contrasts in material properties between the weak shallow caldera versus stiff subcaldera regions fundamentally influence dike propagation that transports eruption materials from the magma chamber at depth to the surface of the volcano [Masterlark et al., 2010]. These prediction differences are substantial and have important implications for our understanding of Okmok’s magmatic system. Available seismic tomography models provide constraints on the distribution of material properties in the shallow caldera [Masterlark et al., 2010; Ohlendorf, 2010] and observed VLP tremors [Haney, 2010] constrain active magma migration in space and time. SINOOK will provide a rare opportunity to verify these tomographic models and interpretations of seismic data. Therefore, SINOOK presents an avenue to advance our fundamental understanding of magma migration and storage within active volcanoes. No fewer than 12 publications describe investigations of geodetic data to estimate the characteristics of Okmok’s subcaldera magmatic plumbing structure associated with the 1997 and 2008 eruptions, as well as various pre-, post-, and inter-eruption intervals [Biggs et al., 2010; Masterlark et al., 2012 (and references therein)]. All of these studies suggest the observed deformation is caused by magma migration and storage into (or out of) an isometric magma chamber that is somewhat stationary in space and time. However, the specific characteristics of this geodetically-determined source vary considerably, as demonstrated for the case of Okmok’s 1997 eruption:

- shallow chamber embedded in an EHS domain [Lu et al., 2005, 2000; Masterlark, 2007; Masterlark et al., 2012]
- shallow chamber + sill embedded in an EHS domain [Mann et al., 2002]
• deep chamber embedded in a heterogeneous elastic domain [Masterlark, 2007; Masterlark et al., 2012]
• deep chamber embedded in a heterogeneous viscoelastic domain [Masterlark et al., 2010]

Additional proposed deformation sources include viscoelastic or poroelastic deformation of the caldera substrate caused by gravitational loading by the lava field [Lu et al., 2005]. All of the preceding deformation mechanisms can be cast as formal competing hypotheses and tested with data collected by SINOOK. Such analyses can identify the most likely model, or refine the range of plausible models of Okmok’s interior. Calibrated deformation models can predict the internal stress field of Okmok and account for characteristics of dike propagation that transport eruption materials from the magma chamber to the land surface. The presence of weak caldera materials accounts for co-eruption magma migration (diking) from the caldera-centered magma chamber to extrusion points near the caldera rim [Masterlark et al., 2010]. However, it is unclear why extrusion shifted from Cone A (near the southwest rim of the caldera) during the 1997 basaltic eruption to Cone D (east rim of the caldera) during the 2008 basaltic/andesitic hydrovolcanic eruption. Changes in the deformation pattern after the 2008 eruption suggest that this eruption has altered the subsurface magma storage and plumbing system beneath the volcano; the post-eruption inflation seems to have occurred at a shallower depth than the post-1997 inflation. In situ stress measurements will help solve this puzzle. Likewise, an understanding of the characteristics and interactions of the shallow groundwater and deeper hydrothermal systems will reveal why the 2008 hydrovolcanic eruption style was very different from the effusive 1997 eruption, even though both eruptions presumably tapped the same magma source. While SINOOK will allow us to verify geodetic methods and provide a basis for understanding the volcanic system specifically for Okmok.
the results will have important implications for analyses of geophysical data that seek to estimate the characteristics of magma migration and storage for active volcanoes worldwide.

**Broader Impacts and Initiatives**

Seismic tomography, gravity, and EM methods are regularly employed to image subsurface structure using inverse methods and observations of the respective geophysical fields at the Earth’s surface. These inverse methods provide models having precisely defined quantitative estimates, uncertainties, and resolution of internal structures (e.g., Aster et al., 2005). Likewise, surface geophysical observations (e.g., deformation and gravity) are routinely analyzed using inverse methods to define internal processes, such as magma migration and fault slip distributions for earthquakes at depth. SINOOK provides rare and precious opportunities to verify (ground-truth) these geophysical models of subsurface structure and processes for the case of Okmok. These tests of routinely employed geophysical methods will have far-reaching implications for the geophysical community.

Dike propagation in the presence of a complex distribution of stress, fluid pressure, and material properties is precisely analogous to fracture propagation studies for geothermal, hydrocarbon, and nuclear waste interests. As such, studies of dike propagation in Okmok’s caldera, as constrained by in situ stress measurements and material property characterizations, will have important implications for energy-related initiatives, as well as for dike propagation within volcanoes elsewhere. Similarly, hydrologic investigations of Okmok’s shallow groundwater and deep geothermal systems will provide results that cut across scientific and energy interests.

The geophysical analyses of deformation and stress discussed above can be thought of as physical impulse-response experiments. By simulating the impulse and comparing predictions to the observed response, we can infer the internal structure and processes within the volcano. We can develop interdisciplinary collaborations that use the same principles to study ecological and cultural impacts of volcanic activity revealed by the drilling. One can envision studies of stress (volcanic eruption) and the time-dependent recovery (societal and ecological response). Such studies could integrate nearby Native American communities (e.g., Nikolski, Figure 1), or alternatively investigate stress and recovery of the large-scale economic fishery operations served by Dutch Harbor (Figure 1), which leads the nation in terms of amounts of fish landed [www.noaa.gov].

SINOOK spans many important scientific and societal interests and, therefore, has the potential to tap an array of funding sources. Individual elements of the project are aligned with standard topical NSF programs (e.g., EAR Geophysics). However, the interdisciplinary scope of the project lends itself to cross-cutting NSF programs. For example, Okmok is located in a research corridor of the NSF GeoPRISMS Aleutians Primary Site. Alternatively, the interdisciplinary nature of SINOOK is well aligned with the objectives of NSF FESD. Additionally, the anticipated computational requirements for modeling and analyses of SINOOK data could serve as the basis for an NSF Geoinformatics initiative. Remote sensing data, such as InSAR imagery, continue to play a key role in understanding Okmok volcano (Figure 2). Thus SINOOK may be of interest to ongoing or future missions sponsored by NASA, JAXA, or ESA. The energy analogies may provide opportunities to engage the interest and support of private industry, as well as the Departments of Energy and Defense. Potential ecological (e.g., fishery) aspects of the project may be of interest to NOAA. Finally, the project may integrate with the interests and evolution of the local Native American community of Nikolski (Figure 1). For example, what are the modern socio-economic impacts of the episodic eruptions? What are the archaeological impacts? Could SINOOK lead to geothermal energy resources for the region?

**References**


WHITE PAPER: STUDY OF THE THERMO-MECHANICAL ASPECTS OF EXTENSIONAL FAULT SYSTEMS BY SHALLOW CONTINENTAL SCIENTIFIC DRILLING INTO PALEO BRITTLE-DUCTILE TRANSITION ZONES AND TOP OF CHANNEL FLOW IN THE BASIN AND RANGE PROVINCE, USA

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Introduction

Rifting is one of the fundamental tectonic processes on Earth, leading to formation of ocean basins and oceanic crust. Normal faults develop as a consequence of rifting in continental crust and provide important controls on sedimentary basin development and oil and gas migration/sequestration. Normal faults are usually associated with high heat flow and magmatism and serve as conduits for hydrothermal systems and ore-bearing fluids. In active tectonic settings, normal faults pose earthquake hazards. Rift-related normal faults are thus important fault systems to understand because of their broad relevance to our societal and economic well-being.

Understanding the deep-seated processes that drive seismogenic active faults in continental settings is viewed as a top scientific challenge in the earth sciences (e.g. Handy et al., 2007) but also a difficult one because of the minimum 5-10 km depth to the seismogenic base of the elastic crust. For reasons discussed below, normal fault systems in the Basin and Range province of the western U.S. are unusual and provide ready access to detailed scientific investigations of the paleo seismogenic base of the crust and the processes that occur beneath this zone. Targeted shallow continental drilling of normal fault systems in well-studied areas can provide outstanding data sets that cannot be collected in another fashion—data sets that will greatly improve our knowledge and understanding of the mechanics of fault systems, their accompanying thermal regimes and how deformation is coupled between the deep and shallow crust. In particular, the Basin and Range province of the western U.S. provides a world-renown natural laboratory for the study of extensional fault systems and is the birthplace for models of normal faults used world-wide for the exploration of natural resources. Given these facts, it is surprising that the scientific community holds such disparate views regarding the geometries, evolution, thermal histories and driving mechanisms of extensional fault systems. The broader, overarching aspects of continental extension also remain highly controversial—these include the primary driving processes for continental rifting and their relationship to earlier crustal thickening and to magmatic activity.

Significant advances have been made in terms of our fundamental understanding of rift processes along oceanic spreading ridges in the deep ocean (e.g. John and Cheadle, 2010; Whitney et al., 2013), despite their inaccessibility and the high costs involved. Given the comparative ease of study and opportunities presented by extensional fault systems in continental settings, we lag behind in the sense that fewer resources have been devoted to similar studies in the continents, despite their societal importance and their controversial nature. Continental drilling of specific sites in the Basin and Range would bring together a broad and diverse set of geoscientists to tackle these outstanding problems and place us in a position to write future textbook chapters on the myriad of structures developed in continental extensional settings, their origin and evolution with respect to deformation in the deeper crust, their thermal histories, and the role they play in the location of natural resources and earthquake hazards.

This short discussion and a description of one, of many, potential study sites is inspired by the potential use of continental scientific drilling as both a means of investigation and a science-based approach that could be superbly utilized in the Great Basin region of the western U.S. Here, a variety of shallow drilling targets have the possibility of providing ground-breaking information on the thermal and mechanical aspects of normal fault systems at depth and how deep and shallow crustal deformation...
histories are linked and evolved across paleo seismogenic zones, information not available to us by any other means of study. In sum, there are compelling intellectual and opportunistic reasons to include the potential study of these fault systems within any U.S. or international-based continental scientific drilling program because of how much they can ultimately tell us about how continental crust deforms.

**What makes the Basin and Range province unique for the study of continental fault systems?**

The Basin and Range Province is a unique region to study fault systems and especially normal fault systems because the rifting process has not gone to completion and the region still resides above sea level. Here, magmatism played a role both early, during and late in the extensional history of the crust, leading to an inferred high degree of mobility and flow of the deeper crust during parts of this history (e.g. Gans, 1987; Block and Royden, 1990; Buck, 1991; McKenzie et al., 2000; Whitney et al., 2013). Although crustal flow is broadly recognized as taking place in a wide variety of continental tectonic settings, its role in the generation and uplift of extensional fault systems is far less appreciated and only locally documented in a quantitative fashion. In contrast with the end stages of rifting which lead to continental separation and passive margin development, earlier stages of continental rifting can be accompanied by significant flow of crust at depth (generally into more extended regions) which produces differential vertical uplift of normal fault systems (Fig. 1). Across a given region, both the upper and the deeper levels of normal fault systems, including their ductile underpinnings, are either exposed at the surface or are predicted to lie in the shallow subsurface (Fig. 1). Similarly, normal fault-bound sedimentary basins are often structurally inverted by continued extension, their vertical component of uplift related to differential flow of the crust at greater depth. Detailed geologic mapping and cross-section-based structural and coupled metamorphic and thermochronologic studies help constrain relative vertical components of uplift, temperature gradients in the crust and outline many potentially excellent sites where relatively shallow drilling of fault systems would help us truly understand their genesis and their linkages to ductile processes at depth. This broader understanding of extensional fault systems in turn provides greater insight into the thermo-mechanical evolution of the elastico-frictional to viscous transition zone in continental crust and how processes and interactions across this zone might generate earthquakes, dictate hydrothermal circulation, mineralization and the formation and subsidence history of extensional sedimentary basins.

**Proposed Drilling**

A potential drill site, the problems to be addressed, and a possible team of diverse investigators are described below, with focus on the most problematic class of normal faults, low-angle detachment faults associated with “extreme” ductile deformation of footwall rocks in metamorphic core complexes.

Low-angle extensional detachment faults were first mapped and defined in Cordilleran metamorphic core complexes (e.g. Coney, 1980) and their origin and mechanism(s) of formation continue to remain controversial. These faults were initially explained as large offset (~50 km+) normal faults that originated at low angles and cut to deep levels of the crust to the mantle, a model launched with the Snake Range metamorphic core complex as its type example (Wernicke, 1981). Since then, the low angle normal fault concept has been widely applied to extensional provinces worldwide. Other workers initially interpreted metamorphic core complex detachment faults as exhumed in-situ ductile-brittle transition zones (or top of ductile channel flow) in the crust, representing high local extension but much less offset (e.g. Rehrig and Reynolds, 1980; Gans and Miller, 1983; Miller et al. 1983, 1988). More than twenty years after these initial interpretations, a wide spectrum of views still exist on their formation, ranging from low-angle normal faults (e.g. Howard, 2003, for the Ruby Mountains core complex), “rolling hinge” faults (Buck, 1988; Lee, 1995 for Snake Range) to diapirically-driven, partial melt-laced gneiss domes (e.g. Whitney et al., 2004; Rey et al., 2009; Whitney et al., 2013).
From a historical perspective, the original proposed low-angle extensional detachment fault model centered on the geometry and kinematics of these fault systems, but not on the actual processes and conditions (e.g. heat flow, rheology, melt, magnitude and rates of extension, and degree of coupling between upper and lower crust) that drive the development of these faults. More recent thermal-
mechanical models of continental crust show that variable thermal regimes and rates and magnitude of extension result in different upper plate, detachment fault, and lower plate geometries in terms of styles of deformation, kinematic, and thermal histories (e.g. Triel et al., 2008; Rey et al., 2009a, b; Allken et al., 2011; Whitney et al., 2013). These models address mainly the wholesale deformation or flow of the ductile crust but provide a set of predictions that are testable in several regions using a combination of existing data and new data from proposed drill holes that can provide a 4D perspective on the evolution of fault related deformation, strain rates, and both the kinematic and thermal evolution of the detachment fault systems.

Proposed Drill Site—The Northern Snake Range: The northern Basin and Range province (Figs. 2 and 3), is arguably the best mapped core complex with the greatest amount of exposure of both upper plate (brittle) and lower plate (ductile) rocks. The two are separated by an impressive domed detachment fault, the northern Snake Range décollement (NSRD), exposed along the entire length and width of the range (Gans et al., 1999a, b; Lee et al., 1999a, b, c; Miller et al., 1999; Miller and Gans, 1999) (Figs. 3 and 4). Many important controversies regarding this and other core complexes could be solved by a single shallow drill hole which would provide the data with which to understand the nature and movement history of these faults, the thermal regime during development of these faults, document strain rates, and improve our fundamental understanding of the linkages between deep and supracrustal deformation, thus addressing the ultimate origin and genesis of these enigmatic extensional structures.

The northern Snake Range metamorphic core complex is located in east-central Nevada where up to 14 km of continental shelf sediments, consisting of a Late Precambrian to Lower Cambrian sandstone and shale sequence overlain by a Middle Cambrian to Permian predominantly carbonate sequence were

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**Figure 2.** Simplified geologic map of east-central Nevada showing location of the northern Snake Range (modified after Miller and Gans, 1989). Box shows location of Figure 3. Cross-section A-A’ is shown in Figure 1.
Figure 3. Simplified geologic map of the northern and southern Snake Ranges showing major lithologic units, the Snake Range extensional detachment fault separating lower and upper plates, and major normal faults.
deposited (Fig. 2) (Stewart and Poole, 1974; Hose and Blake, 1976; Gans and Miller, 1983; Rodgers, 1987). In the northern Snake Range, three metamorphic events are recorded in the upper Precambrian and lower Paleozoic sedimentary rocks exposed in the lower plate of the NSRD. The first event was a contact metamorphic episode associated with a mid-Jurassic plutonic complex (Miller et al., 1988). The second metamorphic and deformational event occurred during the Late Cretaceous and affected a broad portion of the lower plate (Miller et al., 1988; Lewis et al., 1999; Cooper et al., 2010). Along the eastern flank of the range, a series of mineral-in isograds in upper Precambrian pelitic units trend east-west suggesting an increase in metamorphic grade both northward and with depth (Geving, 1987; Huggins, 1990). Quantitative thermobarometry indicate pressures of 6-8 kbar (23-30 km) and temperatures of 500-650°C and no burial gradient eastward on the east side of the range (Lewis et al., 1999; Cooper et al., 2010). U/Pb geochronology on metamorphic monazites and zircons yielded metamorphic ages ~78-82 Ma for this event (Huggins and Wright, 1989; Cooper et al., 2010).

The third event was characterized by lower to upper greenschist facies metamorphism of Tertiary age that affected much of the lower plate and retrogressed older Late Cretaceous metamorphic assemblages. This metamorphic event was accompanied by ductile thinning and stretching of lower plate units, resulting in a subhorizontal, bedding parallel foliation and WNW-ESE trending mineral elongation lineation. Mesososcopic structures and finite strain measurements indicate a dramatic west-to-east increase in strain from a low on the west of 6:1 (X:Z) to a high on the east of 100:1 (X:Z); on average lower plate rocks were plastically extended ~300% (Miller et al., 1983; Lee et al., 1987) (Fig. 4). Quartz microstructures and quartz lattice preferred orientations (LPOs), along with finite strain measurements and mesoscopic structures, document a ductile extensional strain history of early coaxial strain that was overprinted by deformation with an eastward increasing component of top-to-the-east noncoaxial strain (Lee et al., 1987; Gebelin et al, 2011) (Fig. 4). Quartz LPOs and quartz microstructures suggest that metamorphic grade associated with the mylonitic fabric increases both with depth (400-500°C to 500-600°C, suggesting a collapsed metamorphic field gradient in the lower plate of 100-200°C/km) and across the range parallel to...
the stretching direction (from ~350°C in the low strain west side of the range to ~550°C in the high strain east side of the range) (Fig. 4).

Published potassium feldspar, mica $^{40}$Ar/$^{39}$Ar, and apatite fission track thermochronology data suggest that mylonitic deformation in the lower plate is bracketed between ~37 and 21 Ma, and that cooling and exhumation of lower plate rocks, and normal slip along the NSRD began as early as 48 Ma and continued episodically with an important component of cooling and inferred exhumation of the fault system at ~17 Ma (Lee & Sutter, 1991; Lee, 1995; Miller et al., 1999; Gebelin et al, 2011).

Based on stratigraphic considerations alone, the Snake Range metamorphic core complex represents a minimum of 10-15 km of differential uplift of footwall rocks with respect to rock strata in adjacent ranges (Fig. 2). In contrast, quantitative geobarometry place lower plate rocks of the Snake Range at 23-30 km depth in the Late Cretaceous (Lewis et al, 1999; Cooper et al., 2010) requiring major Late Cretaceous structures that duplicated the crust. Furthermore, the quantitative thermobarometry implies a relatively cool geothermal gradient of 15-20°C/km (Fig. 5). This subdued geothermal gradient is approximately half as high as estimated for east-central Nevada based on conodont alteration index values from supracrustal rocks and on geochronology and mineral assemblages from metamorphic rocks (~35°C/km; Gans et al., 1987; Miller et al., 1988) (Fig. 5). These two models for the Late Cretaceous geotherm make distinct predictions as to the minimum depth of partial melting in the crust at that time. If Late Cretaceous magmatism was a product of crustal anatexis only (tested in deep crust section), model geotherms may be extrapolated towards a zone of partial melting (red stars, Fig. 5). The cold geotherm required by quantitative P-T determinations predicts partial melting to occur at great depth (>7-10 kbar, >28 km, dependent on H2O activity), whereas the hot geotherm inferred by field observations predicts melting shallower in the crust (<5 kbar, <18 km; Fig. 5).
**Site characterization:** The mouth of Hendry’s Creek in the northern Snake Range (Fig. 3) offers accessibility and ease of drilling through a highly attenuated section of the lower plate. The amount of attenuation of units together with existing thermochronology of lower plate units and the implied paleotherm-thermal gradient suggests that drilling to depths of less than a km can answer the following general questions about metamorphic core complex detachment faults and specific aspects of this particular fault system and core complex.

**Characterizing the 4D Mechanics and Architecture of Normal Fault Systems and Metamorphic Core Complex Detachment Faults**

*General questions related to normal fault systems and metamorphic core complexes:*

- What changes in stress, mechanical properties, and slip processes occur along normal faults from the surface to the ductile-brittle transition?
- How do the mantle, lower crust, and upper crust interact, via the physio-chemical properties of fault system conduits/barriers and crustal flow/channel flow to transfer mass, fluids, and heat?

*Specific questions related to core complex detachment faults:*

- What are the physical conditions, such as fracturing, permeability, pore pressure, fluid chemistry, temperature and temperature gradients, during brittle slip along detachment faults? How do these conditions contribute to the formation and slip history along these faults?
- What are the physical-chemical conditions, such as thermal history, stress, finite strain, fluid flow, and kinematics of mineral plasticity, during ductile extensional deformation of lower plate rocks? Are the ductilely thinned and stretched rocks a zone of finite width or the top of channel flow in the deep crust?
- What is the exact timing of ductile deformation and how is this linked to exhumation histories? For instance, how does the timing of deformation at deeper levels of the crust compare to the timing of brittle motion or slip along detachment fault? Are they temporally distinct, or do they represent a progression and over what kind of time-span?
- How does the thermal structure of the crust and/or rates of extension control the formation, evolution, and slip history along detachment faults?

*Specific questions related to the northern Snake Range metamorphic core complex (also relevant to other regions because the Snake Range embodies most of the contentious questions about core complexes):*

1. Is the NSRD a low-angle fault capping a finite thickness of mylonites that, in turn, overlies a rigid footwall beneath? Or does it define the top of a ductile-brittle transition zone (DBTZ) or top of channel flow in the crust? Current exposure of the lower plate is insufficient to definitively say there is a bottom to the mylonites, but at deepest exposed levels, quartzites are inferred to be deforming by intra-crystalline and grain boundary mechanisms that indicate temperatures of ~550°C and suggest a condensed metamorphic field gradient in the lower plate of ~100-200°C/km. A relatively shallow drill hole should either access rocks that were hotter (or even partial melt-bearing) that are equally deformed or penetrate through the mylonites into a semi-rigid footwall.

2. What are the temperature gradients in the crust during formation of this low-angle detachment fault and its associated mylonites? This is probably the most important question that can be directly addressed by drilling as it provides the additional depth-related temperature data to couple with that known from existing exposures (above). Documenting the thermal history is also important to testing predictions of thermal-mechanical models which show that different thermal regimes yield different styles of detachment fault systems (e.g. Rey et al., 2009a, b).

3. The age of the extensive and spectacular mylonites developed in the northern Snake Range are controversial as they are not directly dated (cf. Lee & Sutter, 1991; Lee, 1995; Gebelin et al, 2000)
Drilling Active Tectonics & Magmatism (NSF Workshop, May, 2013)

Complexity is added to the question of their age by geobarometric studies that suggest rocks beneath the northern Snake Range detachment resided at ~28 km depths in the Late Cretaceous, requiring both 10-20 km of burial and subsequent uplift of rocks between the Late Cretaceous and Tertiary, leading to the suggestion that the mapped ductile attenuation fabrics may be partially Mesozoic (e.g. Cooper et al., 2010; Lewis et al., 1999). Both the temperature gradient and geochronology/thermochronology of appropriate minerals with depth by drilling can help provide definitive answers to these questions. Characterizing the thermal gradient in metamorphic core complexes is also important for understanding the forces that drive extension. Low geothermal gradients lead to a stronger lower crust coupled to the upper crust and mantle; high geothermal gradients imply a weak lower crust. The former might imply that plate boundary conditions might drive extension and the latter might imply that gravitational potential energy is important in driving extension (e.g. Whitney et al., 2013).

4. Is the Snake Range a gravitationally and diapirically driven feature or gneiss dome? Given the temperature gradient documented in lower plate rocks, will drilling encounter evidence for the presence of magmatic rocks at shallow depths beneath the structural levels that are currently exposed and thus provide an argument for the rise of low-density partial-melt laced rocks or granitoids? Is there an increase in metamorphic grade based on mineral isograds and if so what age are they? If evidence for magmatism is found, does it facilitate extension (by weakening the crust via a reduction in viscosity and through strain localization) or result from extension (isothermal decompression leading to development of melts)? (e.g. Rey et al., 2009a, b)

Advantages of the Snake Range
1) Extensive detailed geologic map database.
2) Excellent exposure of upper plate (brittle) and lower plate (ductile) rocks, the detachment fault, and a well-known stratigraphy with well-documented unit thicknesses.
3) Detailed structural and kinematic data on the lower plate ductile deformation and upper plate brittle normal faulting.
4) Detailed thermochronology data set—tantalizing to complete with shallow drilling.
5) Geobarometry
6) Easy access for drilling (flagstone quarries are present).

Example of a Potential Team of scientists (in progress)

Elizabeth Miller, Stanford University—Regional Tectonics
Jeffrey Lee, Central Washington University—Lower plate ductile strain and kinematics
Brad Hacker, UC Santa Barbara—Lower plate ductile strain and kinematics
Marty Grove, Stanford University—Ar/Ar thermochronology
Trevor Dumitru, Stanford University (AFTA thermochronology)
Jeremy Hourigan, UC Santa Cruz—(U-Th)/He thermochronology
Roger Buck ? (geophysics and modeling)
Barbara John and Mike Cheadle (long term continental and oceanic core complex expertise; magmatism)

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Large Igneous Provinces (LIPs) and the IODP Connection

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LIPs represent magmatism on an unprecedented scale that is difficult to explain by conventional plate tectonic theory [1]. LIPs include flood basalt provinces and volcanic chains, and occur in ocean basins and on continents. Scientific ocean drilling has expanded our understanding of these enigmatic features through exploration of oceanic flood basalt provinces (oceanic plateaus) and volcanic chains as these, unlike their continental equivalents, do not exhibit crustal contamination (Fig 1). However, the drawback to drilling ocean LIPs is that the thickness often exceeds several 10s of kilometers (e.g., [2] and after drilling through up to 1 km of sediments, penetration into igneous basement rarely exceeds 200 meters. As shown by the Snake River Plain and Hawaiian Scientific Drilling Project, much greater penetration depths into igneous rocks are possible on land because of the more stable drilling conditions and, if money is available, a longer drilling schedule is possible.

**SCIENTIFIC OCEAN DRILLING & LIPs.**
During 2007, the Large Igneous Province (LIP) community met in Coleraine, Northern Ireland to discuss how scientific ocean drilling could advance our understanding of the origin, evolution and environmental impact of these magmatic constructs. Four of the key findings of this workshop were that ocean drilling could: 1) advance our understanding of the mode(s) of eruption during LIP formation; 2) better define the duration of LIP volcanism; 3) examine LIP source variability over time; and 4) establish relationships between oceanic LIPs, Oceanic Anoxic Events (OAEs), and other major environmental changes [4]. A combination of oceanic and continental drilling would be a logical way to establish a comprehensive program to better understand flood basalts, their relationship to long-lived volcanic chains [5], and address the four key findings of the Coleraine workshop. Examination of Figure 1 shows there are several

![Figure 1: World “LIP” map. Red = flood basalts, blue = long-lived volcanic chains. From [3]. Green arrows = LIPs drilled by DSDP/ODP/IODP. Light red arrows = potential IODP expeditions.](image-url)
examples of LIPs with subaerial and submarine portions that could facilitate a combined drilling approach. The LIPs emphasized in this white paper are the Deccan Traps, Ontong Java Plateau, and Parana-Etendeka.

**Deccan Traps (Fig. 2):** The Deccan volcanism is commonly attributed to the upwelling of a deep mantle plume beneath the northerly drifting Indian subcontinent in the late Cretaceous (e.g., [5,6]). The time progressive chain of volcanic ridges including the Laccadives–Maldives–Chagos ridges and Mascarene plateau in the Indian Ocean are believed to represent the hotspot track linking the Deccan Traps to the Reunion hotspot [7]. Onshore drilling through the lava pile could recover the initial flows of Deccan volcanism and yield a definitive starting age and minimum duration of flood volcanism. Continuous recovery of the stratigraphic section down the drill hole will allow an assessment of source variability during flood volcanism. Combined with basement recovery by IODP drilling along the Laccadives–Maldives–Chagos ridges (basement on the Mascarene Plateau was recovered by ODP Leg 115; [8]). ODP Sites 713 (40 m basement, Chagos Ridge) and 715 (76 m basement, Maldives Ridge) of Leg 116 are the only samples available from the linear chain extending from the Deccan Traps to the Reunion hotspot. Target basement drilling will address the outstanding LIP issues 1-3 from Neal et al. [4], and recovery of syn-Deccan Trap sediments offshore will address issue 4.

**Ontong Java Plateau (Fig. 3):** This has been drilled by DSDP Leg 30 (only a few meters of basement were recovered from Site 289) and ODP Legs 130 & 192. Fieldwork on subariel obducted OJP basement in the Solomon Islands [9-11] has allowed the top 3.5 km of igneous basement to be analyzed. Results from drilling and fieldwork have allowed more targeted drilling to be considered, such as using erosional and structural features to recover a much deeper section of this >30 km thick edifice [2] and recovery of syn-OJP sediments to study environmental effects. Onshore drilling on Ontong Java Atoll would allow investigation of the relationship of the enigmatic seamounts to the OJP. In addition, recovery of coralline sediments above the seamount basement would yield a host of paleoclimate and environmental data since the seamount formed.

**Parana-Etendeka (Fig 4):** During the opening of the Atlantic, the Parana-Etendeka flood basalt province formed, with a distinct aseismic ridge leading to hotspots Tristan da Cunhar and Gough
(Fig. 4). The aseismic ridge is divided into the Walvis Ridge closest to Namibia and the Guyot Province closest to the hotspots; the Guyots have been visited by several dredging expeditions to recover igneous basement to age data the various volcanoes. Targeted onshore drilling through (or at least deep into) the Etendeka lava pile coupled with offshore drilling on the Walvis Ridge will allow LIP issues 1-3 [4] to be addressed. It is unlikely that syn-LIP sediments will be available for this particular LIP.

**SYNOPSIS**

A long term, comprehensive drilling strategy to investigate different LIPs is required to address the origin, evolution, and environmental impact of these massive magmatic events. Can one model explain all LIPs? Are LIPs the cause of or a product from continental break-up? Do LIPs facilitate mass extinctions? These are a few of the many questions that can be addressed by targeted onshore-offshore drilling projects. In addition, the continual recycling of the Earth’s surface by plate tectonics makes this planet unique in the Solar System. Volcanism on Venus, Mars, and the Moon (and possibly Mercury) occurred on one-plate planets, most commonly through hotspots and LIP formation. Understanding how LIPs form and evolve on Earth will facilitate comparative planetology opportunities to better understand how the terrestrial planets have evolved.

**References**

Drilling Investigations on the Mechanics of Faults; Downhole measurements to detect time variation of in-situ stress

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Fault zone drilling provides valuable insights to understand the dynamics, physical property, and structure of active faults. Especially, downhole test in borehole is the only way to estimate in situ stress magnitudes in the crust. Recently, in-situ measurements of stress magnitude and orientation by hydraulic fracturing and/or borehole breakout method were applied in deep boreholes in and around fault zones not only on land (Ikeda et al., 2001; Hickman and Zoback, 2004; Lin et al., 2007; Kuwahara et al., 2012; Yabe and Omura, 2011 ) but also on sea floor (Ito et al., 2013; Lin et al., 2013). The variation of stress state in and around different faults may reflect different stages in the earthquake preparing process during the earthquake recurrence cycle. How the fault strength recovers and how the recovery is extrapolated to the next earthquake are important issues for understanding earthquake recurrence cycle, and the stress state of a fault may be an important factor for forecasting a future earthquake.

For example, Nojima fault, south-west Japan, that slipped at the 1995 Kobe-Awaji Earthquake was drilled just after the earthquake (1 year latter). We got much of valuable results on stress state, material distribution, physical properties, e.t.c., as well as results based on seismic and geomagnetic survey and field observations. Post-slip in-situ stress measurement indicates the orientation of maximum horizontal stress is nearly perpendicular to the strike of the Nojima fault. It was interpreted that the strength on the fault became weak due to fracture on the fault.

While, the case of Gofukuji fault, central Japan, the orientation of the maximum horizontal principal stress adjacent to (about 300 m distance) the fault was oblique to the fault trace and the magnitude is equivalent to the stiff rock frictional strength (Yabe and Omura, 2011). The Headquarters for Earthquake Research Promotion, Japan evaluated the Gofukuji fault has not activated for time longer than the mean earthquake recurrence interval (http://www.jishin.go.jp/main/index-e.html (in Japanese)). The Gofukuji fault may be so strong to sustain shear stress on the fault after a long time since the last earthquake. The findings on the stress states suggest that the strength of fault recovered to as hard as the host rock surrounding the fault from the weak strength just after the earthquake, and that the orientation and magnitude of the stress near the fault changes during the inter-seismic period of the earthquake recurrence cycle.

To explore the time variation of stress state, installing the observation station in the borehole and monitoring the state of fault is a direst method. In addition, we suggest drilling and in-situ stress measurement in the fault that once we have drilled at the same site are another direst method. Nojima fault may be one of good targets. Some seismological investigation, S-wave splitting and focal mechanism of aftershocks, indicate the change of stress direction: from perpendicular to oblique to the strike of Nojima fault during several years after the earthquake. It is expected to detect the change of stress state after 20 year since the last earthquake. Other possibility is to measure in-situ stress in and around different faults. Those faults may be in different stages during the earthquake recurrence cycle. It is probable that stress states of different faults reflect different level of the strength recovery and stress accumulation on the fault plane.


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Project Hotspot: Investigating Subsurface Basalt Using Wireline Logs

Katherine Potter, Utah State University

Abstract:
We seek to explore the relationship between borehole geophysical wireline data and lithologic observations derived from core logging. The subsurface of the Snake River Plain contains some of the most intriguing evidence for mantle hotspot impingement of continental crust, with a continuous, un-eroded record of bi-modal volcanism extending over 12 Ma to the present. Through ICDP/DOE Project Hotspot, almost 2,000 m of continuous basalt core was recovered from the Kimama drill site, located in central Idaho along the axis of the Snake River Plain. The location of the Kimama core hole coincides with the Axial Volcanic High, a region of relatively dense volcanic centers and high eruptive output. The 1,912 m Kimama core provides the longest continuous record of volcanic processes of the central SRP. Preliminary stratigraphic sections for the Kimama drill hole were based upon borehole geophysical logs. Basalt facies changes, indicating separate flow units, intercalated sediment, indicating lulls in regional volcanism, and anomalous geochemical trends, indicating distinct basalt flow groups, are evident as variations in neutron and natural gamma signals and accurately predict subsurface stratigraphy. 526 basalt flow units were identified and seven chemically evolved basalt flow groups were identified using neutron and natural gamma logs. 505 basalt flow units were identified during the lithologic logging of the Kimama core.

Introduction
Project Hotspot was established to determine the existence of geothermal resources beneath the Snake River Plain (SRP) and to better understand the evolution of Snake River Plain-Yellowstone Plateau (SRP-YP) volcanism through time. Investigations of subsurface stratigraphy in continental volcanic provinces such as the SRP-YP are limited by the limited depth and spatial distribution of cored wells. In the SRP, down hole geophysical logging is commonly performed to measure the extent of the Snake River Plain aquifer and the subsurface transport of water and water-borne contaminants. The measurement of natural gamma and neutron signals in a borehole is significantly less costly than obtaining, logging, and curating core. On the SRP, neutron and natural gamma logs provide a record of subsurface lithofacies, geochemistry, and volcanic stratigraphy that correlate well to measurements directly obtained from core. The use of wireline geophysical logs in the identification and interpretation of lithologic variation will allow broad, regional subsurface models to be constructed without the presence of core. We rely on the integration of geophysical, lithologic, magnetostratigraphic, and geochemical logging tools to interpret the timing, extent, and source of regional volcanism.

Over 1,912 m of continuous core was recovered from the Kimama site along the axis of the Yellowstone hotspot track. Integrated models of basalt flow facies were used to identify a total of 505 individual basalt flow units during lithologic logging of the Kimama core. Flow units are subdivided into 26 basalt flow groups based upon stratigraphic relationships and magnetostratigraphy. Intercalated eolian and fluvial clay and sand deposits represent lulls in regional volcanic activity and correlate well to polarity reversals representing thousands of years of time.
**Methods:**

Detailed lithologic logging was accomplished through the direct observations of core and through the use of high-resolution core photographs. Attributes such as vesiculation, oxidation, and rubble were documented, and anomalous features were photographed and/or sampled. Lava flow and flow unit boundaries were identified through the entire 1912 m of Kimama core using the model of Self et al. (1998), who suggest that individual pahoehoe lava flows and their constituent flow units display three distinctive zones: oxidized, rubbly, and highly vesicular textures within the flow surface, massive to diktytaxitic textures with rare and isolated vesicle structures within the flow interior, and minor vesiculation and rubble within the flow base (Figure 1). Kuntz et al. (1992) observed and utilized the textural and morphological characteristics of cored basalt to designate individual flow units and flow groups on the surface and within the subsurface at the Idaho National Laboratory.

Natural gamma and neutron measurements were recorded using a wireline detector with readings made in tenth of a foot increments for the entire length of the borehole, using American Petroleum Institute (API) units. Natural gamma radiation (NGR) is emitted by radioactive isotopes of K, U, and Th, which are typically concentrated in intercalated sediment. In SRP basalts and sediments, ^{40}K is the most common radionuclide and is the primary tool for determining the presence of sediment and stratigraphic breaks between flow groups. Natural gamma logs are used to identify individual flows if they contain measurable differences in naturally occurring radioisotopes (Twining et al., 2007). Lines and peaks showing dramatic shifts usually represent fluctuations in K$_2$O concentration and correspond to changes in geochemistry such as those occurring between flow groups (Keys, 1990).

**Figure 1:** Facies model of typical inflated basalt flow units in the SRP subsurface after (Self et al., 1998). The depth from the surface to basal facies is 6.2 m.

Neutron well logs provide measurements of stratigraphy under a variety of lithologic conditions. Neutrons are absorbed by hydrogen in fluid-filled vesicles and fractures, allowing the stratigraphic measurement of hydrogen. Above the 3150 m water table, neutron logging measured moisture content, while below the water table, neutron logs record porosity and vesicularity. Pore spaces such as vesicles and fractures are densely focused in rubbly lava flow tops and flow bases and record the lowest neutron counts. Within massive, lower porosity flow interiors, more neutrons reach the detector, resulting in a higher count rate (Keys, 1990).
Results

Lithologic logging of the Kimama core has identified 505 basalt flows ranging in thickness from 0.1 m to 50 m (FIGURE 6: Stratigraphic Log of Kimama Core). Twenty six flow groups, 13 m to 170 m thick (most 20 m-100 m thick) are distinguished by overlying sediment interbeds that range in thickness from 0.2 m to 50 m; the total sediment thickness of 113 m represents 6% of the total 1,912 m of recovered core. Sharp variations in natural gamma and neutron signals identified at least 500 basalt flow units (0.1-50 m thick) that are grouped into 34 flow groups, 13 m to 170 m thick (most 20-100 m thick). A relatively consistent natural gamma response of 0-100 API is apparent through much of the core hole and appears to vary little to 1763.7 m depth. Greater fluctuations in signal response are evident in the neutron log and demonstrate increased neutron signal-hydrogen interaction within the more fractured, rubbly, vesicular, and sediment-rich lava flow unit and flow boundaries (Figure 2). Anomalously high natural gamma and neutron responses are observed near the base of the core hole, from 1763.7 m to 1818.3 m. The high temperatures at this depth range caused the wireline instrument to record higher amounts of signal noise, translating into falsely high detection.

At two depth intervals, increased natural gamma signal response is observed without a corresponding K-rich sediment package. Geochemical analyses of samples from 319 m and 1078 m depth demonstrate high K2O and high Fe2O3 (2.0 wt. % and 19.0-21.0 wt. %, respectively) relative to the olivine tholeiite composition (0.25-1.00 K2O wt. %; 13.0-17.0 wt. % Fe2O3) observed in the majority of the core. Elevated K2O and Fe2O3 compositions are observed basalt compositions, similar to those observed at Craters of the Moon, ~20 km to the northwest.

Conclusion:

Compiled lithologic and geophysical logs demonstrate an overall agreement in the locations of basalt flow boundaries. Sedimentary interbeds are imaged by sharp increases in natural gamma cps, impermeable basalt flow interiors are imaged by higher neutron cps, and flow unit boundaries are shown by decreased neutron detection. The offset of lithologic and wireline stratigraphic intervals may be explained by the yo-yo-ing of the probe tool string as it traveled down the core hole. Further statistical analyses and filtering of wireline measurements are required to accurately constrain and evaluate stratigraphic variations and correct for depth errors.

The Kimama core provides an unprecedented sequence of basalt and intercalated sediment through which the volcanic history of the central Snake River Plain may be characterized and temporally constrained. Subsurface geophysical data provide an accurate proxy to lithologic observations made from cored basalt and sediment of the Kimama drill hole. The identification of individual basalt flow units and flows is possible through the use of natural gamma and neutron well log data. Combined with magnetostratigraphic and geochemical logging tools, geophysical logs enable the interpretation of subsurface basalt flow group stratigraphy and the characterization of volcanic processes.

References:


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Figure 2: Composite lithologic, natural gamma, and neutron logs a cored section of basalt from a cored section of basalt and sediment. The correlation of facies observations and wireline log signals are evident as signal variations at intervals of intercalated sediment and rubbly flow and flow unit surfaces.
Proposal to drill into the Puysegur Subduction Zone: Investigating the complex role of peridotite and serpentinite in the seismicity of the subduction zone interface

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To assess seismic hazards associated with plate boundaries, we need to understand not only the rapid moment release during earthquakes but also the gradual release that occurs during slow slip events. Subduction zone thrust faults slip at a range of rates and styles, from completely aseismic to seismic (Peng and Gomberg, 2010) with significant consequences for the relationship between seismic hazard and accumulated tectonic moment (or stored elastic strain energy) release. Understanding the physical mechanisms accommodating this variation in style is needed for broader mechanical models of subduction zone processes that must include realistic constitutive laws for subduction zone materials (e.g. Tan et al., 2012). Peridotite and its retrograde derivative serpentinite are significant components to many subduction zones (e.g. Park et al., 2004). Peridotite is mechanically strong, but undergoes significant weakening with as little as 10% serpentinization (Escartín et al., 2001). Serpentinite can be velocity strengthening promoting aseismic slip or velocity weakening with the potential for seismic slip, depending on the slip rate, temperature, and pressure (e.g., Reinen et al., 1991; Moore et al., 1997; Chernak and Hirth, 2010; Takahashi et al., 2011).

Prior to the 2011 Tohoku-Oki earthquake, it was commonly assumed that the seismic and aseismic portions of the fault were distinctly different types of fault segments. However, during this earthquake, the largest slip was accumulated in the creeping area. Thus conditions for seismic slip may be imposed on otherwise aseismic serpentinite-bearing parts of faults by rupture propagation from adjacent areas (e.g. Noda and Lapusta, 2013), and that faults containing these materials may then accommodate large slip due to their frictional weakness (e.g. Faulkner et al., 2011; Kohli et al., 2011). Consequently even the shallowest parts of subduction thrust faults, which have traditionally been thought to be barriers to earthquake rupture (Lay and Bilek, 2007) play an important mechanical role in the rupture process. These shallow regions are accessible via scientific drilling (e.g. Chester et al., 2012).

The study of exhumed material yields insight into the physical processes influencing subduction zone mechanics. The use of numerical models developed from this insight and that obtained through laboratory experiments is a critical step since it provides key information on how the various slip modes modify the timing and magnitude of potential future earthquakes along the plate margin (e.g., Noda and Lapusta, 2012).

To interpret past behavior of subduction zones from exhumed material, and to determine likely future behavior, we need to be able to link mechanical behavior to material and its microstructure (cf. Ikari et al., 2011). Peridotite and serpentine microstructures formed during laboratory experiments yield important information of the processes and
mechanisms that operate during slip (e.g. Chernak and Hirth, 2010, Reinen 2000). However laboratory experiments are not able to access the full range of conditions (e.g., strain rate, scale) at which natural deformation occurs in these materials. Thus, we propose to examine material that is currently being deformed in a rather unique natural setting, where we can link the microstructural record of recovered materials to its mechanical behavior through a number of geophysical datasets.

The Puysegur trench, SE of New Zealand (Fig. 1) is an active subduction zone with very recent seismological record of fairly large (e.g. Mw7.8 in 2009; Beavan et al., 2010) events. Bathymetric data suggest that very young (>12Ma) oceanic lithosphere between the Macquarie and Resolution Ridges is presently being subducted into the Puysegur trench (Lamarche et al., 1997; Fig. 2). Sediment input to this subduction zone is low, and the only subaerial exposure of this ridge complex (Macquarie Island; e.g. Rivizzigno and Karson, 2004) is composed of peridotite thus the subducting material is likely also dominated by ultramafics, making this a good candidate for study. We already have some good paleoseismic records (e.g. Barnes, 2009; Howarth et al., 2012; Berryman et al., 2012) and there are numerous onland and offshore opportunities to obtain more (e.g. Otago University has an active program to study seismite deposits and date organic material in cores from the Fiords). Moves are already afoot within the context of the GeoPRISMS program to obtain a better understanding of the current and recent inputs to the subduction system through dredging, and to perform geophysical transects across the zone, to collect seismic reflection and magnetic/magnetotelluric data. We propose to build on results of that research and enhance its impact by drilling into the subduction thrust zone to recover material affected by rupture propagation during the recent earthquakes. Thus we will be able to link the observed seismogenic behaviour to the composition and microstructures of materials within the subduction thrust.

References


Fig. 1 (left): Topographic map of New Zealand and the surrounding oceans, illustrating the Pacific-Australian plate boundary. Puysegur Trench is at lower left.

Fig. 2 (right): Bathymetric maps from Lamarche et al. (1997) illustrating the abyssal hill morphology of the subducting oceanic crust between the Macquarie and Resolution Ridges. Inset shows a stylized representation of major tectonic components of the area.
Mauna Loa: Drilling the Other Side of the Hawaiian Plume

J. Michael Rhodes (University Massachusetts), Frank A. Trusdell (Hawaii Volcano Observatory, U.S.G.S.), Michael O. Garcia (University of Hawaii).

A major impediment to understanding the long-term magmatic history of Hawaiian volcanoes, and consequent constraints on the structure and composition of the Hawaiian mantle plume, is a lack of stratigraphic sections to provide a more complete record of the 800 to 1500 ka of volcano growth [Garcia et al., 1995]. Sub-aerial sections of Hawaiian volcanoes reveal only a small fraction (5 - 10%) of this history and are biased towards the late stages of volcano growth. Deep drilling is the only solution.

The Hawaii Scientific Drilling Project (HSDP) made a significant advance towards addressing this problem by drilling on the eastern flank of Mauna Kea volcano [Stolper et al., 2009]. This international, multi-disciplinary study documented around 450 ka (~200 - 650 ka) of Mauna Kea’s magmatic history. Major results include:-

1. Information on the internal structure and growth of a large oceanic volcano over a significant portion of its life history.
2. Change in magma production from a vigorous submarine shield-building stage, followed by a marked decline in magma production as the volcano reached its post-shield stage.
3. Diversity of magma compositions erupted during the shield building stage
4. Geochemical and isotopic diversity in the lavas requiring complex source heterogeneity in the plume.

These results have significantly contributed to recent discussions on the nature and structure of the Hawaiian mantle plume [Farnetani and Hofmann, 2010, 2012] and the relative roles of peridotite and pyroxenite as a source of plume-related magmas [Jackson et al., 2012]. Current drilling (funded by the US army; current depth of 1500 m) on the Humuala Saddle between Mauna Loa and Mauna Kea should provide even more detailed records and insights into the growth of Mauna Kea, including endogenous growth, subsidence, explosive volcanism and heat flow. Of particular importance will be lava accumulation rates as a guide to melting in the plume during the transition from shield-building to post-shield magmatism, as Mauna Kea moved away from the axis of the Hawaiian plume.

Why Drill Mauna Loa?

Mauna Loa, the world’s largest active volcano, is an appropriate target in its own right. There are other compelling reasons. The strategy behind the Hawaii Scientific Drilling Project was premised on the concept of a plume that was radially zoned, both thermally and compositionally [DePaolo and Stolper, 1996]. It was assumed that, as the Pacific Plate moves over the stationary Hawaiian plume, a volcano should sample magmas produced in different thermal regimes and from varying plume source components during its long-term magmatic history. However, a major result of recent Hawaiian studies is the resurrection of the concept of an asymmetrical plume in which volcanoes along two en-echelon trends exhibit distinct major element and
isotopic compositions \cite{Abouchami et al., 2005; Weis et al., 2011}. This asymmetry in plume source components is attributed to heterogeneities in the lowermost mantle \cite{Weis et al., 2011; Farnetani et al., 2012}. In addition to HSDP, previous work on Hawaiian shield volcano sequences has focused on the Kea side of these trends \cite[e.g. HSDP; Haleakala,]{} Ren et al. 2009; Kilauea, Marske et al. 2008). By contrast, the Loa side has not been as well studied.

In contrast with Kea trend volcanoes, Loa trend volcanoes have major element and isotopic characteristics that are attributed to a greater contribution of re-cycled crustal material. A related, unresolved and contentious, problem is whether Loa magmas result from melting this crustal material, present as discrete lithological domains (pyroxenite/eclogite) within the plume, or whether they reflect melting of peridotite fertilized by pyroxenite/eclogite melts \cite{Jackson et al., 2012}. In order to understand volcano growth, melt production and the identity, composition and lithology of plume components it will therefore be necessary to drill a Loa-trend volcano to obtain comparable information obtained by the HSDP for Mauna Kea, a Kea trend volcano.

Mauna Loa is the obvious candidate because a great deal more is known of its recent history (< 120 ka) and also of its earlier (600 - 400 ka) submarine growth than other Loa trend volcanoes \cite[Rhodes, submitted]. Consequently, more informed questions can be raised and solved through drilling. For example, $^{39}$Ar/$^{40}$Ar dating of lavas from Mauna Loa’s submarine SW rift \cite{Jicha et al., 2012} show that the lavas are over 2 ka older than predicted by Hawaiian volcano growth models \cite[Depaolo and Stolper, 1996; DePaolo et al., 2001]. Clearly, Hawaiian volcano growth models need revising in the light of the new data. Additionally, lava accumulation declined dramatically from 18-20 mm/yr to 1-2 mm/yr around 300-400 ka. Does this mean Mauna Loa entered its post-shield stage at this time and has limped along ever since, or did volcano growth shift to other parts of the edifice, or has magma production waxed and waned? Recovery and dating of core between 30 and 300 ka will answer these, and many more, questions. For example, recurring themes at the recent (2012) AGU Chapman conference on Hawaiian volcanism were: how limited our knowledge of the interiors of volcanoes is; how volcanoes grow; the role of explosive volcanism in Hawaiian volcanoes; how magma production in the plume relates to volcano growth; and the importance of this information for understanding the

\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig1.png}
\caption{Numerical simulation of Hawaiian plume asymmetry \cite{Farnetani et al., 2012}.}
\end{figure}
nature of mantle plumes and how they work. Further drilling on Hawaii on the Loa side of the plume, will contribute enormously to our understanding of these questions.

**Potential Drilling Locations.**

1. **The Pahala Region** on the southern flank of the volcano. The advantage to this region is that it is moderately developed, so finding an acceptable drill site should not be difficult. It is blanketed by the Pahala Ash (~ 30 ka) and drilling could start in old lavas. The distinct advantage is that it is located in hazard zone 6, a “lava shadow” area, protected by topography from SW rift zone flows [Lipman et al., 1990]. Therefore, although the record will be punctuated and incomplete, lavas from the critical time period (100 - 300 ka) could be obtained immediately and only a moderate depth hole is needed (~1 km).

2. **The Honamalino Area** on the SW flank. Although starting in younger lavas (historic to ~ 4 ka), we are more likely to get a more complete section, especially over the critical interval 36 - 400 ka where data are currently extremely sparse. An added bonus would be that it should be possible to identify and date the disconformity between pre-South Kona landslide lavas and lavas that subsequently filled the amphitheater left by this giant landslide, thereby providing the timing of this momentous event. Current thinking places it around 100 -200 ka.

![Figure 2 Potential Mauna Loa drill sites (shown as blue stars).](image-url)

3
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Earthquake Triggering and Fault Zone Drilling

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Scientific Rationale

Understanding how earthquakes nucleate, propagate and arrest is a current priority in earthquake and fault mechanics. Nevertheless, direct observations of the basic processes that link parameters such as stress, pore pressure, and slip on a fault are lacking. By monitoring a fault at depth, we can make crucial measurements of the transient processes that control earthquake nucleation, in particular the hydrologic parameters that govern pore fluid pressurization and permeability changes around faults.

We understand at a very fundamental level that high pore fluid pressure lowers effective normal stress and fault strength (1). The last few decades of experimental friction studies show that there are more complex effects, as well. While lowering effective normal stress weakens faults, it also alters their frictionally stability, that is the tendency of a fault to slip in earthquakes vs. creep (2). Thus, slip triggered by a pore pressure transient may be slow, not seismic. Furthermore, pore pressure is not constant, as both static and dynamic stresses can change the permeability structure of fault zones and lead to changes in fluid flow (3, 4). These changes occur on a timescale much shorter than the time scale for tectonic loading, potentially allowing the effective normal stress term to dominate the balance between shear stress and frictional strength. Similarly, the re-strengthening of faults after earthquakes may in large part depend on the healing of permeability.

Currently, our ability to study earthquake rupture is hampered by seismic network density in most regions, because of the low likelihood of small earthquakes occurring near a seismic sensor (5). In order to study the interaction between fault slip, damage creation, and permeability changes using aftershocks requires very accurate (meter-scale) earthquake relocation. However, capturing an earthquake at depth would side step these problems. We propose to develop a long-term fault observatory at depth that incorporates seismometers, pore pressure sensors, thermistor strings, and strain meters that would enable us to understand the poromechanics of the rupture process.

A key challenge will be selecting a fault to instrument. The probability of capturing a natural earthquake in the exact fault patch that has been drilled is miniscule, thereby limiting what we can learn about the rupture process through fault zone drilling. However, recent developments in unconventional energy extraction
suggest a solution. With our current knowledge of the role of fluid pressure changes in induced earthquake triggering and hydraulic fracturing, we could safely stimulate small events by temporarily increasing fluid pressure in a drilled fault zone.

**Drilling Strategy**

We have known since the Rangely experiments that raising pumping pressures in a fault zone can trigger earthquakes in predictable ways (6). Recent induced earthquakes in the otherwise seismically quiet Midwestern US, have offered additional lessons. In several cases, water injection directly into a fault zone has caused an immediate uptick in along-fault earthquakes, which cease shortly after pumping is shut down (7, 8). We envision using carefully controlled fluid injection to capture fault stability transitions in situ.

At neighboring boreholes, we could study the interaction processes between induced slip and secondary triggered earthquakes (9, 10). An initial characterization of the sub-surface geology and permeability structure would be made with hydraulic pump tests, active source seismology, near surface geophysics and downhole observations made with logging while drilling or wireline logging. By subsequently monitoring seismicity, pore fluid pressure and strain in two or more additional holes located along and across the fault, we could directly observe the time and slip dependent poroelastic properties of a geologic fault. In situ experiments with induced earthquakes would therefore answer fundamental questions regarding earthquake physics and triggering.

Specific questions this experiment would address are:

1) What is the strength of faults during earthquakes?
2) Is there an observable earthquake nucleation signal? Does it scale with the size of the earthquake?
3) What is the size of the stress perturbation needed to trigger seismicity relative to the strength of the fault?
4) Does the size of the pore pressure perturbation correlate with the size of the triggered earthquake?
5) Can changes in fluid pressure along the fault halt rupture propagation?
6) What are the feedbacks between pore fluid pressure and fault stability?

Location of the project would depend strongly on lack of potential hazard to people and infrastructure, while still maintaining a local water source for fluid injection. The Basin and Range, particularly in Nevada, might provide an ideal environment, especially as normal faults are easier to trigger than thrust or strike-slip faults. Other sites might include places where there has already been seismicity induced from fluid injection such as Paradox Valley, CO, or in geothermal areas that often have small events from fluid injection, such as in the Snake River Plain.
References

Borehole Geophysics - Applications and Limitations in Extreme Environments
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Abstract
The application of standard logging types is discussed and how they are implemented to overcome limitations imposed by geological or acquisition environments. We also focus on the use of such borehole methods in extreme subsurface environments encountered by scientific drilling near faults and volcanoes.

I. Introduction
Borehole geophysics is applied to measure and constrain physical rock properties and geological structure. These measured physical properties can be applied to better understand in situ conditions and geology. Borehole geophysics uses a suite of standard and specialized geophysical log tools to accomplish qualitative and quantitative interpretations. Figure 1 shows the configuration of the logging vehicle relative to the down-hole logging tool.

![Diagram of borehole geophysics setup](image)

Figure 1. General configuration of borehole geophysics set up.

II. Borehole logging tools
There are a variety of logging tools the user may implement to address their scientific project goals:

<table>
<thead>
<tr>
<th>Logging Tool</th>
<th>Property</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>Temperature</td>
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<td>Pressure Transducer</td>
<td>Pressure</td>
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<tr>
<td>Caliper</td>
<td>Borehole Geometry</td>
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<tr>
<td>Dipmeter</td>
<td>Borehole Geometry, lithology orientation</td>
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<tr>
<td>Natural &amp; Spectral γ</td>
<td>U, Th, K</td>
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<tr>
<td>Neutron</td>
<td>Measure of H content, Proxy for porosity</td>
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<tr>
<td>γ-γ Density</td>
<td>Rock Density, Estimate porosity</td>
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<tr>
<td>Magnetometer</td>
<td>Magnetic Susceptibility &amp; Field</td>
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<tr>
<td>Electrical Logs</td>
<td>Resistivity; Conductivity; Self Potential, Fluid resistivity</td>
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<tr>
<td>Borehole Televiewer</td>
<td>Oriented unwrapped images</td>
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<td></td>
<td>(ultrasonic or optical)</td>
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<tr>
<td></td>
<td>of borehole wall</td>
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<tr>
<td>Sonic</td>
<td>P &amp; S Wave Velocity</td>
</tr>
<tr>
<td>Borehole Seismic</td>
<td>Two Way Time, Reflectivity, Seismic Velocity</td>
</tr>
<tr>
<td>Wireline Packers</td>
<td>Stress measurement, Pressure testing</td>
</tr>
<tr>
<td>Fluid Samplers</td>
<td>Fluid chemistry, gases</td>
</tr>
<tr>
<td>Flow Meters</td>
<td>Motion of fluids within wellbore</td>
</tr>
</tbody>
</table>

Table 1. Geophysical borehole logging tools commonly available in slim-hole scientific drilling campaigns and the physical properties or conditions that they measure.

Nuclear logging tools measure natural and spectral radiation and gamma ray bombardment (density and...
photoelectric). Natural radiation measures equivalent levels of the radioactive elements thorium and uranium, and percent potassium. This method is effectively applied in both sedimentary and volcanic environments. Abundant radioactive materials are concentrated in shale due to clay content while sandstone and carbonates have low gamma measurements. Primary and secondary volcanism allows for stratigraphic and alteration interpretation. For example potassium feldspar-rich granites will result in a prominent contrast to volcanics depleted of potassium. Neutron logs measure the loss of energy when a neutron collides with a hydrogen atom, which is of equal particle mass. This makes neutron logs ideal for measuring water or hydrocarbons contained within a clay-free rock mass. An abundance of hydrocarbons (high porosity) or shale is described by low energy values.

Electrical logs were the first logging tools used. Electrical logging tools measure electrical properties of the rock; specifically resistivity, conductivity, and spontaneous self-potential. Resistivity measures the amount and salinity of fluids within a rock formation. Salt water is a conductor and results in a low resistivity value. Alternatively hydrocarbons and fresh water are insulators and therefore result in a high resistivity value. Certain minerals, such as clays and alteration products too, can strongly influence the electrical conductivity.

Delineation of fractures is achieved with electrical logs depending on the relative resistivity of the rock to the infiltrated fluids. This is particularly possible with what is called the ‘single point resistance’ log that gives indications of open fractures with fluids. Resistivity also highlights mineralized zones as ferrous minerals are electrical conductors. Spontaneous self-potential is the generation of an electrical current due to permeability contrasts and variations in salinity between the borehole and natural connate fluids. In a sedimentary environment this is demonstrated by the contrast between the highly permeable sandstone and the less permeable shale. This permeability contrast indirectly provides a quick means to assess porosity of a rock unit.

The presence of primary or secondary magnetic minerals is measured using magnetic susceptibility and vector magnetic field measurements. Relative contrasts in magnetic mineral content enable the user to map lithologies, alteration, or fracture delineation. These magnetic measurements in combination with laboratory measurements also allow for paleomagnetic interpretations.

Acoustic logging tools measure velocity of sound propagation and identify petrophysical rock properties. These petrophysical properties are dictated by either lithological or fracture variations. Full waveform sonic logging provides in-situ constraints on the elastic properties of the rocks, which is important in assessing tensile strength. Vertical seismic profile (Figure 2) identify complex fractures at a variety scales and provides insight on degree of seismic anisotropy. Seismic measurements in conjunction with sonic logging highlight lithological contacts. An ultrasonic acoustic teviewer generates a 360° view of the borehole wall rock through transmission of ultrasound pulses. These images are then correlated with extracted core through visually identification of lithological variations and fractures.

Figure 2. Processed vertical seismic profile from Huntwell borehole, Alberta (A). Red lines indicate tube waves. To identify reflectors and multiples the data is represented as a corridor stack (B).
Comparison of geophysical and core scan logs provide a comprehensive outlook on subsurface geology and structure; that no one geophysical log may provide. Figure 3 shows a segment of the Kimama 1B Borehole from the Snake River Plain, Idaho.

Figure 3. Comparison of geophysical and core scan logs through a massive basalt flow, 1362–1378 m in the Kimama 1B borehole. The logs shown are the observed natural gamma radioactivity (in counts per second, CPS), the returning scattered neutron response (in reversed counts per second), the lateral electrical resistivity log (linear scale in Ω-m), and the Spontaneous Potential (SP) log (in reversed mV). (C) The borehole televiewer (BHTV) amplitudes are normalized, and black indicates lost signal; the BHTV log has been rotated to align with geographic north. (D) The unwrapped core scans are from RGB images; these have not been oriented. (E) In the sonic log display the arrivals of the P- and S-waves are highlighted by right and left pointing arrows, respectively. (F) Basic lithology shows massive basalt and sediment.

III. Limitations

Standard drilling practices of casing and fluid injection impose limitations on efficient and accurate well logging. Well logging should be ideally conducted on open holes; however many holes are encased in steel to mitigate caving. Unfortunately only gamma ray and neutron logs can provide effective measurements in this environment. Proximal fluids of a borehole are altered by infiltrating drilling fluids such as mud and brine. These drilling fluids are used to
equilibrate hole pressure, drill bit lubrication, prevent freezing in arctic environments and circulate rock fragments broken from the wall rock during the drilling process.

Macroscopic and microscopic fractures may occur along the borehole during the drilling process. These include breakouts, induced tensile fractures, and induced core fractures (Figure 4). Oriented logging tools such as calipers, electrical resistivity imagers, and ultrasonic borehole televiwers are used to locate and interpret breakouts. The calipers use extendable arms pressed against the rock wall to measure the diameter of the borehole. A breakout is measured when there is an inconsistency in borehole diameter due to one arm extending beyond the rock wall into a breakout gutter. Acoustic televiwers allow for measurement of breakout geometry including azimuth and width. The benefit to identification of breakout and fractures geometry is confident in-situ stress magnitudes, stress directions, and faulting environment estimates.

There are some special considerations when drilling near, or in, faults and near igneous structures. In the context of scientific drilling, one issue is that the boreholes or coreholes drilled most often are relatively small diameter. Standard core hole diameters from the wireline drilling systems usually employed range from 122.6 mm (PQ) through to 75.7 mm (HQ). Consequently, the tool diameters too must be relatively small; and are often referred to as slim-line systems in comparison to the much larger diameter logging tools employed in larger petroleum boreholes. The diameter of these slimline tools are usually about 50 mm in order that they can fit comfortably within the HQ holes. This has a number of consequences. First, the logging tools may not be able to withstand pressures as great as could be designed for in larger petroleum based tools. Second, and perhaps more importantly in the present context, the smaller size and thermal inertia reduces the capacity of such tools to withstand high temperatures for extended times. Most such logging tools are designed to withstand temperatures of about 70°C, although tools that withstand 125°C for extended periods are commercially available.

One way to attempt to overcome this limitation is by drilling larger diameter holes. This unfortunately also comes with added costs and increased difficulties in obtained continuous cores. Even with this

**IV. Conclusion**

Diligent selection of logging tools is critical to accurate subsurface interpretation of general, reservoir, and structural geology. Each logging tool measures different physical rock properties and has an optimal geological and drilling environment. Ideally an array of complimentary logging tools should be applied to formulate a comprehensive analysis.
V. References


Introduction

The question of geochemical flux in the mantle wedge during subduction is critical to our understanding of arc volcanism, and forms an important aspect of the global geochemical flux. Quoting from the MARGINS program announcement: “At convergent margins, raw materials... are fed into the "subduction factory" where many processes... under changing physical and chemical conditions shape the final products... with significant environmental consequences. In practice, it has been difficult to investigate processes and estimate fluxes through the "factory" owing to poor constraints on the volumes of magmas, fluids, and volatiles produced.”

These processes may be observed indirectly in active subduction systems by measuring inputs and outputs – the approach followed in the first MARGINS program – but this approach does not permit direct observation of dynamic processes within the mantle wedge source of arc magmas. Direct observation of mantle wedge peridotites is possible, however, by studying outcrops of mantle peridotite that underlie supra-subduction zone (SSZ) ophiolites. This mantle reflects the processes that have affected it through time, including melt extraction, fluid phase enrichment, and melt refertilization, which have been frozen in place by cooling and emplacement. It also preserves structural and microstructural processes that reflect deformation, alteration, and metamorphism of the mantle wedge at different stages in its evolution.

A primary advantage of this approach is the fact that large tracts of supra-subduction peridotite are commonly exposed at the base of many SSZ ophiolites, allowing us to examine their petrology, geochemistry, and structure directly and on larger length scales than is currently possible in any active system (e.g., Kelemen et al 1997; Batanova and Sobolev 2000; Bizimis et al 2000; Barth et al 2005; Batanova et al 2008; Choi et al 2008a, 2008b).

The Josephine ophiolite preserves the largest exposed tract of mantle peridotite in North America, and represents the fore-arc of a paleo-Cascadia subduction zone. It is one of the best places in the world to study chemical flux, structure, and subduction zone processes in a sub-arc mantle wedge. Microstructures and macrostructures that document deformation processes the mantle wedge are also well preserved, along with alteration and mineralization that document low to intermediate temperature metamorphism within the mantle wedge. Major questions we will pose include the cumulative extent of melt extraction and the nature of the melt extracted, the nature and extent of mantle-melt interactions subsequent to melt extraction (e.g., addition of melt from deeper in the asthenosphere), and the nature, source, and extent of fluid flux to SSZ peridotites. A primary goal is to constrain the nature and extent of these fluxes, as documented by whole-rock major oxide and trace element analyses, by mineral analyses using electron microprobe and laser ablation ICP-MS techniques, and by isotopic analyses of ultra-pure, hand-picked mineral separates.
**Forearc Peridotites and the Mantle Wedge**

Peridotites associated with oceanic crust provide important information on the process of melt generation, fluid phase enrichment, and mantle-melt interactions subsequent to melt extraction (e.g., Dick and Bullen 1984; Dick and Fisher 1984; Dick 1989; Elthon 1992; Menzies et al 1993; Pearce and Parkinson 1993; Arai 1994; Pearce et al 2000; Seyler et al 2001; Hellebrand et al 2002). Abyssal peridotites recovered largely by dredge hauls have been studied extensively (op. cit.) and this important work forms the basis of comparison by which we may study peridotites that form above subduction zones.

Fore-arc peridotites are more difficult to obtain than abyssal peridotites and have been studied in much less detail; they also tend to be highly serpentinized (e.g., Parkinson et al 1992; Ishii et al 1992; Fryer 1992; Arai 1994; Parkinson and Pearce 1998; Fryer et al 2000; Pearce et al 2000; Widom et al 2003). Nonetheless, these samples provide our best indication of the composition of the mantle wedge above subduction zones. It is generally agreed that this wedge represents normal MORB-source asthenosphere that has been modified by fluids and melts derived from the subducting slab (Pearce and Parkinson 1993; Pearce et al 1995).

Fore-arc peridotites are characterized by spinels with much higher Cr#, which range from around 38 to over 80, indicating significantly higher fractions of partial melting compared to abyssal peridotites (Ishii et al 1992; Arai 1994; Gaetani and Grove 1998). High fractions of partial melting are confirmed by whole rock incompatible trace element concentrations, which are strongly depleted when compared to abyssal peridotites (Parkinson et al 1992; Parkinson and Pearce 1998; Pearce et al 2000). Ion probe analyses of relict Cpx in other SSZ ophiolites show that they are more depleted than abyssal Cpx in the heavy REE, but have been re-enriched in the LREE and other incompatible elements as a result of metasomatism by subduction zone fluids (Bizimis et al 2000; Takazawa et al 2003). Hydrous melting not only promotes higher fractions of melt production, but also changes mineral-melt partitioning (Ayers et al 1997; Ayers 1998; Gaetani and Grove 1998; Gaetani et al 2003).

**Chemical and Isotopic Composition of Supra-Subduction Mantle**

Determining the composition of hydrous fluids that metasomatize the mantle wedge during subduction has long been an important goal of those studying island arc volcanism (e.g., Arculus and Powell 1986; Tatsumi et al 1986; Tera et al 1986). Fluid-mobile elements, such as B, Li, Pb, Rb, Sr, and Ba, can be used to constrain the composition and flux of these hydrous fluids – derived from the down-going slab – which interact with the mantle wedge during melting (e.g., Ayers 1998; Ionov et al 2002; Bebout et al 2007; Pelletier et al 2008). Inverting the compositions of relict pyroxenes in equilibrium with this slab-derived fluid can be carried out if partition coefficients are known for these elements, and for the less mobile elements, in response to hydrous melting (e.g., Ayers et al 1997; McDade et al 2003; Ottolini et al 2009).
**Josephine ophiolite as paleo-Cascadia Forearc**

The Josephine ophiolite encompasses large swaths of the Klamath Mountains in NW California and SW Oregon (Fig 2). The crustal section of this ophiolite has been studied extensively by Greg Harper and colleagues (Harper 1984; 2003a, 2003b), who document a complete ophiolite crustal section overlain by a thin, siliceous volcano-pelagic sequence and turbidites of the Galice formation. Harper and co-workers interpret the Josephine ophiolite as back-arc basin crust, based on the observed rock associations, and on its position west of the Chetco arc complex (Harper 1984, 2003a, 2003b). It formed during a subduction cycle that preceeded the current Cascadia subduction zone, but which has been continuous since at least the Triassic.

The Josephine peridotite forms the base of the ophiolite. This 800+ km² alpine-peridotite consists of harzburgite with less common dunite, wehrlite, pyroxenite, and chromitite (podiform chromite deposits) that represent the residues of partial melting and magmatic deposits from this magma (Himmelberg and Loney, 1973; Loney and Himmelberg, 1976; Dick, 1977a, b; Kelemen et al., 1992; Kelemen and Dick 1995). Dick, 1976, 1977b, showed that dunite “dikes” and layers in the Josephine peridotite represent melt flow channels where pyroxene was dissolved and olivine precipitated at relatively low pressures in the mantle, presumably in response to upwelling at an oceanic spreading center (Kelemen et al., 1992; Kelemen and Dick 1995). Work on the Vulcan Peak harzburgite by Himmelberg and Loney (1973) and Loney and Himmelberg (1976) document extremely depleted compositions in pyroxene and spinel that are consistent with hydrous melting of a suprasubduction ophiolite (Dick & Bullen, 1984).

The Josephine peridotite represents one of the largest and best exposed tracts of mantle peridotite in North America. The extensive vertical relief (over 1000 m) provides exposure in a third dimension that is not found in many other massif peridotites.

Drilling to Sample the Mantle Wedge

Drilling the Josephine peridotite has several advantages over normal field based studies. First, it provides fresh, unweathered peridotite suitable for high precision analysis of critical trace elements and volatiles. Moreover it will recover a continuous vertical sample through a long section of nearly pristine mantle ending in the recovery of the intact basal thrust on which it was emplaced. This will permit direct assessment of melt flow through the peridotite in the melting regime at varying levels, and the subsequent effects and pattern of fluid flow from along the thrust contact during emplacement to shallow crustal levels. At the present time there is no other way that the variations in mantle chemistry with depth can be reliably examined due to discontinuous nature and spacing of outcrops at peridotite massifs. These samples will be especially valuable if oriented core is taken so that fully oriented structural and microstructural studies can be carried out. Another advantage is that drilling will allow in situ testing of mantle rock properties, e.g., seismic velocity studies by vertical seismic profiles, or by testing between offset holes at appropriate spacing. Drilling will also allow comparison between an exposed analogue site and active subduction systems, for which direct sampling is not possible.

References

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Introduction

Mantle plumes are thought to play a crucial role in the Earth’s thermal and tectonic evolution. They have long been implicated in the rifting and breakup of continents, and plume-derived melts play a significant role in the creation and modification of sub-continental mantle lithosphere. Much of our understanding of mantle plumes comes from plume tracks in oceanic lithosphere, but oceanic lithosphere is recycled back into the mantle by subduction, so if we are to understand plume-related volcanism prior to 200 Ma, we must learn how plume-derived magmas interact with continental lithosphere, and how this interaction effects the chemical and isotopic composition of lavas that erupt on the surface.

Hotspot volcanism in oceanic lithosphere has been the subject of focused recent and ongoing studies by the Hawaii Drilling Project, the Rekjanes Drilling Project, and IODP. These studies will provide base-line information about where mantle plumes originate, how they behave, and the volcanic products of these processes (DePaolo & Manga 2003). However, hotspot volcanism within continental lithosphere has not been studied in such detail, and is potentially more complex.

The Yellowstone-Snake River Plain (YSRP) volcanic province, which began ≈17 Ma under eastern Oregon and northern Nevada and is currently under the Yellowstone Plateau, is the world’s best modern example of a time-transgressive hotspot track beneath continental crust. Recently, a 100 km wide thermal anomaly has been imaged by seismic tomography to depths of over 500 km beneath the Yellowstone Plateau (Yuan & Dueker, 2005; Waite et al 2006). The Yellowstone Plateau volcanic field consists largely of rhyolite lavas and ignimbrites, with few mantle-derived basalts (Christiansen 2001). In contrast, the Snake River Plain (SRP), which represents the earlier track of the Yellowstone hotspot, consists of basalts that are compositionally similar to ocean island basalts like Hawaii and overlie rhyolite caldera complexes that herald the onset of plume-related volcanism (Pierce et al 2002). The SRP preserves a record of volcanic activity that spans over 12 Ma and is still active today, with basalts as young as 200 ka in the west and 2 ka in the east. Thus, the Snake River volcanic province represents the world-class example of active time-transgressive intra-continental plume volcanism. The SRP is unique because it is young and relatively undisturbed tectonically, and because it contains a complete record of volcanic activity associated with passage of the hotspot. This complete volcanic record can only be sampled by drilling. In addition to this complete record of hotspot volcanism, the western SRP rift basin preserves an unparalleled deep-water lacustrine archive of paleoclimate evolution in western North America during the late Neogene.

Motivation and Goals of Drilling

The central question we plan to address is: how do mantle hotspots interact with continental lithosphere, and how does this interaction affect the geochemical evolution of mantle-derived magmas and continental lithosphere? Plumes modify the impacted lithosphere in two ways: by thermally and mechanically eroding pre-existing cratonic lithosphere, and by underplating plume-source mantle that has been depleted in fusible components by decompression melting to form flood basalts or plume track basalts. The addition of new material to the crust in the form of mafic magma represents a significant contribution to crustal growth, and densifies the crust in two ways: by adding mafic material to the lower or middle crust as frozen melts or cumulates, and by transferring fusible components from the lower crust to the upper crust as rhyolite lavas and ignimbrites, leaving a mafic restite behind. Thus, the structure, composition, age and thickness of continental lithosphere influence the chemical and isotopic evolution of plume-derived magmas, and localizes where they erupt on the surface.
Major Science Issues for SRP Drilling Project

The central science issue for crustal drilling of the Snake River volcanic province is: how do plumes interact with continental crust and mantle lithosphere, based on the differences we see between clearly established oceanic plumes (e.g., Hawaii Deep Drilling Project) and a plume system that has interacted with continental lithosphere over a prolonged time frame (the Snake River-Yellowstone plume system). We know from studies of surface basalts and existing core that these differences reflect in part variations in lithospheric age, composition, and thickness, magma fractionation and recharge in crustal storage systems, and assimilation of older crust, as well as input from the deep-seated mantle plume and adjacent asthenosphere. Questions to be addressed within this context include:

1. How do the variations in magma chemistry, isotopic composition, and age of eruption constrain the mantle dynamics of hotspot-continental lithosphere interaction?
2. What do variations in magma chemistry and isotopic composition tell us about processes in the crust and mantle? Is melting continuous or pulsed? To what extent is magma chemistry controlled by melting, fractionation, or assimilation of crustal components, and where do these processes occur?
3. Is the source region predominately lithosphere, asthenosphere, or plume? What are the proportions of each? Are there changes in the magma source/proportions through time?
4. How does a heterogeneous lithosphere affect plume-derived mafic magma? Effect of crust-lithosphere age, structure, composition, and thickness on basalt and rhyolite chemistry, from variations in lava chemistry along the plume track.
5. Interactions between primary melts with crust or lithosphere. What do the super-cycles in volcanic chemo-stratigraphy tell us about crust-basalt interactions? Melting?
(6) What is the time-integrated flux of magma in the Snake River-Yellowstone volcanic system? Is it consistent with models of plume-derived volcanism, or is this flux more consistent with other, non-plume models of formation?

(7) Can we establish a link between the purported “plume head” volcanic province (Columbia River Basalts-northern Nevada rift zone), and the “plume tail” province (Snake River Plain)?

Rhyolites of the SRP are distinct from normal calc-alkaline rhyolites associated with island arc systems: they were very hot (850º-1000ºC) dry melts with low viscosity and anhydrous mineral assemblages. They produced very large volume (>200 km³) low aspect ratio lavas, vast (∼1000 km³) well-sorted, intensely welded ignimbrites and lava-like ignimbrites, and regionally widespread ashfall layers with little pumice. They are the youngest and best-preserved example of this type of volcanism, but the SRP eruptive centers are concealed beneath basalt. They have geochemical affinities to A-type/P-type granites and are common in other plume-related silicic provinces throughout the world (e.g., Etendeka). Major issues include:

(1) Origin of the SRP rhyolites: dry crustal melting or fractional crystallization of mantle-derived basalt?

(2) What are the volumes of the rhyolitic eruptions? What is the periodicity and eruptive mass flux, and how does this vary with time as the hot spot tracks across changing lithosphere? Related to this, how much plume-derived mafic magma is required to produce the rhyolites (e.g., Nash et al 2006), and what does this tell us about total magma flux in the Snake River-Yellowstone plume system?

(3) Do the rhyolites associated with the older western province differ from those of central and eastern SRP? How does the plume-crust interaction vary across a heterogeneous cratonic margin?

The formation of A-type granitic melts as dry melts of continental crust requires an external heat source capable of transferring immense amounts of heat to the crust – sufficient to form large volumes of high silica rhyolite with liquidus temperatures of 850-1000ºC. Determining the heat budget associated with these melts will be critical to our understanding of plume-continent interaction. In addition, the large volumes of rhyolite preserve a record of magma chamber processes in the middle crust that cannot be seen in surface exposures, but which are critical to understanding the origin and nature of these unique magmas.

Figure 2. Topographic-relief map of southern Idaho showing location of the three drill sites (red stars), previous drill sites (white circles) and some of the features referred to in the text.
Proposed Work

We have recently completed 3 deep (1.8 to 1.93 km) core holes in the SRP (figure 2), producing over 5.5 km of core (Shervais et al 2013). Two of these are located in the central SRP (near Twin Falls, Idaho) and comprise an offset pair that together sample a nearly complete section through a major caldera complex and its overlying basalt cover. The third hole penetrates a thick section of Plio-Pleistocene lake sediments that are overlain and underlain by basalts in the western SRP. Major funding for this project has come from U.S. Department of Energy, the International Continental Drilling Program, the U.S. Air Force, and collaborating universities. This funding supported drilling and logging of core, hydrologic studies, and other energy related studies, but not funding for basic science investigations. It is critical in cases such as this (where other agencies support drilling operations and core recovery) that NSF support follow-up science investigations not supported by the other agencies. These studies would include petrologic and mineralogic studies, major and trace element analyses of core, radiogenic tracer isotope studies, and Ar-Ar age studies. These value-added studies represent a fraction of the cost of drilling, core logging, geophysical logging, and sample curation.

References

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Alpine Fault – Deep Fault Drilling Project (DFDP), New Zealand: current and future opportunities for active US participation in an international continental fault zone drilling project

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The Alpine Fault in the western South Island of New Zealand (Fig. 1) ruptures every 200-400 years in a magnitude ~7.9 earthquake, and is thought to have last ruptured in 1717 AD (Sutherland et al., 2007). The Alpine Fault is globally significant and similar in character to the San Andreas Fault in America or the North Anatolian Fault in Turkey. However, the Alpine Fault is distinct in that the elapsed time since the last large earthquake represents a substantial fraction of the average recurrence interval; in other words, the Alpine Fault is late in its earthquake cycle (Townend et al., 2009). Moreover, unlike these strike-slip dominant structures, where even locally transpressive motions are accommodated on separate suites of structures (e.g. Dickinson, 1966), the Alpine Fault accommodates oblique plate motions via strike and dip-slip on a single structure (Norris & Cooper, 2001). Consequent rapid hangingwall uplift has exhumed fault rocks from depth (e.g. Norris & Cooper, 2007), and uplift continues to restrict earthquake activity to depths that are shallower than normal (<8km; e.g. Leitner et al., 2001).

The DFDP project (http://www.icdp-online.org/front_content.php?idcat=1281) aims to drill, sample, and monitor the Alpine Fault at depth, to take advantage of excellent surface exposures and the relatively shallow depths of geological transitions, and hence to better understand fundamental processes of rock deformation, seismogenesis, and earthquake deformation. We are particularly excited that we have the opportunity to track fault rock evolution at different conditions within the seismogenic zone via staged drilling to progressively increasing target depths along an exhumation trajectory (Fig. 2). We also hope to determine the physical conditions at depth around a locked fault that is late in its earthquake cycle, and to measure changes in these conditions when the next major event occurs.
Fig. 2: Block diagram illustrating the SE-dipping Alpine Fault, slip vector (grey arrows on fault plane), and the concept of staged drilling to sample and instrument the fault at a series of depths along an exhumation trajectory.

The first phase of DFDP ("DFDP-1") was completed in February 2011 with the successful construction of two boreholes intersecting the inferred most recently active principal slip zone of the Alpine Fault at depths of ~90 and ~121m at Gaunt Creek, South Westland. Further details regarding DFDP-1 and links to published results can be found at https://wiki.gns.cri.nz/DFDP/DFDP-1_Gaunt_Creek. Planning is now underway for the next phase of drilling ("DFDP-2"), which is scheduled to start in early 2014. The costs of DFDP-2 are largely being met by the Royal Society of New Zealand’s Marsden Fund, and by the International Continental Scientific Drilling Program (ICDP).

The DFDP project is led in NZ by Rupert Sutherland (GNS Science), John Townend (Victoria University of Wellington) and Virginia Toy (University of Otago). We are also fortunate to collaborate with a diverse suite of international scientists, whose participation has allowed, and will continue to allow us to undertake the most cutting-edge investigations of the fault zone possible.
US researchers currently (or recently) involved in DFDP research with NSF support include:

1. Clifford Thurber (University of Wisconsin-Madison) and Steven Roecker (Rensselaer Polytechnic Institute), Collaborative Research: Seismic characterization of microearthquakes and crustal velocity structure around the Whataroa fault zone drilling site, Alpine Fault, New Zealand, 2011 to 2014.

2. Harold Tobin (University of Wisconsin-Madison), Demian Saffer (Pennsylvania State University), Chris Marone (Pennsylvania State University), Collaborative Research: Physical properties of the Alpine Fault, New Zealand: Mechanical and hydrological processes in the brittle fault core and surrounding damage zone.


Successful outcomes of the work to date include >10 manuscripts either published (e.g. Townend et al., 2009, Sutherland et al., 2012, Boulton et al., 2012), submitted, or in preparation, and numerous conference presentations, including a number within the 2012 Fall AGU meeting session T31: Theory and Practice in Studies of the Earthquake Cycle, convened by the project team.

References:


The waters exploited in power-producing geothermal systems in extensional western U.S. settings are dominantly meteoric consistent with heat mining via deep circulation. While systems are numerous, net energy outputs are modest and usually <100 MWe. However, geochemistry (especially noble gases such as $^3$He) often implies some magmatic input to such geothermal systems with a source presumably below the brittle-ductile transition. This suggests that high enthalpy volumes may be closely connected to some systems and these could represent next-generation resources providing a greater contribution to national energy needs.

Recent magnetotelluric (MT) investigations in the U.S. Great Basin are producing images that strongly suggest the presence of specific melt underplating or intrusion zones in the deep crust. Commonly these zones have steep, conductive slab-like structures extending toward the surface and connecting into high-temperature geothermal systems. The zones are interpreted to represent crustal scale fault zones joining the deep magmatic and shallower meteoric structural regimes and may locally have elevated brittle-ductile transitions. Dixie Valley, Nevada, perhaps the flagship extensional geothermal system of the Great Basin, is one example of such and also possesses elevated $^3$He values in wells. High-temperature fluids are brought near surface apparently in dilatent zones formed at intersections of NNE-SSW and NNW-SSE faulting trends.

To strengthen a conceptual model where magmatically sourced systems can be identified through deep geophysical structure, fluid geochemistry and conducive structural settings, the U.S. Dept. of Energy is supporting a new investigation of the McGinness Hills geothermal system in central Nevada (see accompanying graphics). Here is imaged a similar lower-crustal tabular conductor with connection to the system at surface. Structural mapping and modeling show permeability is created in an accommodation zone with NNE-SSW and NW-SE faulting trends. Well fluids were sampled for $^3$He in April 2013 and found to have elevated values of 0.35-0.54 Ra. Thus the confluence of crustal scale low resistivity, geologic structures favorable to dilatency, and magmatic fluid geochemistry confirm the means to identify magma-sourced geothermal systems. Dixie Valley was not an accident.

The exploitation of deeper (>3 km) geothermal fluids at supercritical temperatures is a holy grail of this renewable energy field given the marked increase in enthalpy recovery possible under those conditions. It seems compelling to drill an example of these geophysical structures to see if such conditions pertain. Efforts to drill beyond the brittle regime and even to magma are underway in Japan and in Iceland. There are some uncertainties in geophysical properties that only drilling is likely to resolve. For one, conductivity is high and suggests very high salinity to keep porosity to reasonable levels. This is unlike the fluids typically produced from the upper levels of geothermal systems (1-2 wt % usually). It may imply a geochemical disconnection between the upper brittle regime and the ductile domain below by a zone of sealing. A positive drilling outcome will advance understanding of magmatic-hydrothermal transitions and the prospects for deep geothermal resources.
Magmatic Underplating and High-Enthalpy Geothermal Resources

P. Wannamaker (UU/EGI), J. Faulds (UNR), B. M. Kennedy (LBNL), B. Delwiche (Ormat Inc.)

- Recon MT surveying revealed likely deep magmatism, connections to systems.
- Deep magmatic input supported at Dixie Valley by $^3\text{He}/^4\text{He}$ (Ra) ratios, $\text{CO}_2$ flux.
- Systems form in zones of active structural dilatency.
- Can we verify these concepts with another system; test at new McGinness Hills?

U.S. DOE contract DE-EE0005514
McGinness Hills Geothermal System – Natural Lab for Deep Sources

- Structural setting as accommodation zone
- Deep magmatic connection from elevated Ra
- CO₂ flux anom. along Nly NW fault zone (first data)

![Map of accommodation zone with fault systems](image)

- 3D MT confirms 2D recon
- Connection of prod. to depth
- NW-SE trends at multi-scale

![3D MT resistivity plan views](image)

- Ra = 0.35 - 0.54
- Purging sample port on well 36-10 for He sampling (L. Owens, Ormat)

![Purging sample port](image)

3D MT Resistivity Plan Views
B is production, A is deep regional

U.S. DOE contract DE-EE0005514
Appendix C: PreProposal Documents (White Papers)

INVESTIGATING ULTRA HIGH-ENTHALPY GEOTHERMAL SYSTEMS: A COLLABORATIVE INITIATIVE TO PROMOTE SCIENTIFIC OPPORTUNITIES

OCTOBER 13-16, 2013
LAKE ARROWHEAD, CALIFORNIA
Conveners: W. A. ELDERS, D. NIELSON, P. SCHIFFMAN, AND A. SCHRIENER JR
Professor Rosalind Archer holds the Mighty River Power Chair in Geothermal Reservoir Engineering at the University of Auckland. She is also the director of the University’s Geothermal Institute. Rosalind’s expertise is in numerical modelling of fluid and solid mechanics relevant to geothermal reservoirs at a range of scale – her team have worked on models from pore to models with an areal extent of many square kilometres. The reservoir engineering group at the University of Auckland have a significant interest in the high enthalpy systems and have made modifications to their local version of the TOUGH2 code to accommodate supercritical flows.

Rosalind will present the combined work on many researchers at the University, including staff such as Professor Mike O’Sullivan in the Department of Engineering Science and Professor Peter Malin at the University’s Institute for Earth Science and Engineering. Professor Malin and his team have developed novel geophysical techniques for mapping permeability at depth via seismic arrays over reservoirs in production. Reservoir pressure changes lead a range of seismic emissions including microearthquake which lead to understand of the nature of natural fractures in the reservoir at depths of up to 20,000. This in turn can be used an input to fluid flow modelling codes to predict the future performance of such systems.
A challenge to develop EGS reservoirs beyond the brittle-ductile transition zones.
-outline of the Japan Beyond-Brittle Project (JBBP)-

H. Asanuma, H. Muraoka, N. Tsuchiya, H. Ito

Development using Engineered Geothermal System (EGS) technologies is considered to be the best solution to the problems of the localized distribution of geothermal resources and the risks of “dry wells”. However, it is considered that a number of problems, including low water recovery rate, difficulty in design of the reservoir, and induced earthquake, would appear in Japanese EGS. These problems in the development of EGS reservoirs cannot be readily solved in Japan because they are intrinsically related to the physical characteristics and tectonic setting of the brittle rock mass. Therefore, we have initiated the Japan Beyond-Brittle Project (JBBP), which will take a multidisciplinary scientific approach, including geology, geochemistry, geophysics, water–rock interactions, rock mechanics, seismology, drilling technology, well-logging technology, reservoir engineering, and environmental science.

The science and technology required for the creation and control of geothermal reservoirs in superheated rocks in the ductile zone is at the frontier of modern research in most of the related disciplines. Solutions to the associated problems will not easily be found without international collaboration among researchers and engineers. For this reason, in March, 2013 we held a five-day ICDP-supported workshop in Japan to review and discuss various scientific and technological issues related to the JBBP.

Throughout the discussions at the workshop on characteristics of the beyond-brittle rock mass and creation and control of EGS reservoirs in the ductile zone, it has concluded that there are two end-member reservoir models that should be considered (Fig. 1). The JBBP reservoir type-1 would be created near the top of the brittle–ductile transition (BDT) and connected to pre-existing hydrothermal systems, which would increase productivity and provide sustainability. The JBBP reservoir type-2 would be hydraulically or thermally created beyond the BDT, where pre-existing fractures are less permeable, and would be hydraulically isolated from the hydrothermal system.

Discussions on exploration/monitoring of the BDT rock mass and JBBP reservoirs, and engineering development have been also made in the workshop. We finally identified scientific/technological challenges for the JBBP and established roadmap and implementation plan. The workshop report is available at http://jbbp.kankyo.tohoku.ac.jp/jbbp
Dr. Ted Bertrand
Proposal to attend CSD Workshop  
13-16 Oct 2013
Lake Arrowhead, California, USA

Attn: Dr. Wilfred Eldred

I am an early career geophysicist employed at GNS Science, New Zealand, as a Magnetotelluric (MT) Scientist. Since arriving at GNS Science in early 2010, I have worked with Grant Caldwell to lead our MT team’s geothermal research program, which is presently focussed on understanding the constraints and mechanisms that control the flow of fluids and heat at 3-7 km depth beneath the Taupo Volcanic Zone (TVZ). The TVZ is a rifted arc, supporting 23 high-temperature geothermal systems, many developed to a maximum of 3 km depth, providing NZ with ~14% of its electricity demand. However, to maintain, or to increase this level of geothermal energy in the long-term, is likely to require production from depths >3km where temperatures may approach or exceed 400°C.

In 2008, the government of NZ funded an integrated research project, Hotter-and-Deeper Exploration Science (HADES) to guide future deep exploration in the TVZ. HADES included components of structural geology, experimental geochemistry, passive seismology and magnetotellurics. For this project, an array of 220 MT sites (2 km spacing) was collected in the Taupo-Reporoa Basin (NZ’s most intense area of deep-seated thermal activity) to provide a comprehensive picture of the 3-D conductivity structure down to the brittle-ductile transition (~7 km depth). Models of these MT data (in 2-D and 3-D) show the first-ever images of narrow, vertical low-resistivity zones beneath the shallow geothermal systems that are interpreted to be convection plumes of hot-fluids rising from a deeper magmatic heat source. Tomographic velocity models from the coincident HADES passive-seismic survey are complementary to the MT resistivity models, and are being used to compare and increase constraints on model interpretations. The experimental geochemistry and geological research is, in part, advancing understanding of the physical and chemical nature of the deep fluids, their flow paths, and important water-rock interactions.

NZ is a member of the IPGT and also the ICDP, with whom it has lodged a preliminary proposal seeking assistance to drill a deep well in the TVZ. I am interested to attend the CSD Workshop to present our HADES research, but also to learn of progress regarding the similar IDDP-like program under consideration in the United States.

Sincerely

Dr. Edward (Ted) Bertrand
Rare Earth Elements as Fluid Pathway Tracers in High Enthalpy Geothermal Systems.

Andrew Fowler¹, Robert Zierenberg¹, and Peter Schiffman¹
¹University of California, Davis Department of Geology.

1. Interest and Expertise

Please accept this document as my application for attendance at the Lake Arrowhead workshop. I am a Ph.D. candidate in geochemistry at the University of California – Davis, supervised by professor Robert Zierenberg. I study high temperature alteration in Iceland Deep Drilling Project (IDDP) test cores from the Reykjanes geothermal field. To date, I have focused on fluid inclusion microthermometry, the strontium isotope content of epidote, and the major element chemistry of various high-temperature alteration products. I am committed to research of geochemistry in high-enthalpy geothermal systems. I believe that students should be involved in future high-enthalpy geothermal research projects to learn how continue and build on the outstanding research of the current generation of researchers in the field. My expertise is further outlined in an abridged version of my CV (attached).

My research goal is to utilize trace element geochemistry to understand geothermal processes occurring in active, high-enthalpy geothermal systems. My approach involves studying the behavior of rare earth elements in geothermal fluids, minerals, and rocks during hydrothermal alteration. This can be achieved by comparing high-temperature alteration assemblages with unaltered protolith. I focus on drill core samples form Iceland Deep Drilling Project (IDDP) test cores drilled from depths >2km in the Reykjanes Geothermal System, Iceland.

2. Proposed Topic for Presentation

The Reykjanes geothermal system is located in southwest Iceland, and is the location of the next IDDP drilling attempt (Friðleifsson, Elders and Albertson, 2013 [in press]). The Reykjanes geothermal fluid is seawater, chemically modified through boiling and fluid/rock interaction (Arnórsson, 1978). The RN-17B and RN-19 drill cores were recovered from Reykjanes to test the IDDP deep coring apparatus. The ~10 m long RN-17B drill core was recovered from a down-hole depth of 2,798.5 m to 2,807.8 m at an in-situ temperature of 340°C (Friðleifsson and Richter, 2010). The RN-17B core contains pervasively altered hyaloclastite, lithic (basaltic) breccia, and volcanic sand, with minor areas including chloritized fine-grained basalt flow lobes. The degree of textural preservation is superb, despite the matrix and many of the clasts having been pervasively altered to amphibole accompanied by epidote, hydrothermal plagioclase, and minor chlorite. The ~3 m long RN-19 drill core was recovered from a down-hole depth of ~2245 m at an in-situ temperature of 250-260°C (Friðleifsson and Richter, 2010). The RN-19 drill consists of unaltered dolerite.
The whole rock rare earth element (REE) patterns of unaltered, subaerially erupted basalt samples show two main basalt end members on the Reykjanes Peninsula. Tholeiitic basalt is enriched in light REE (LREE; La through Sm) compared to heavy REE (HREE; Gd through Lu) with a prominent positive Eu anomaly. Olivine tholeiite is depleted in LREE relative to HREE and has a slight positive Eu anomaly.

REE in whole rock samples from various lithologies in the RN-17B core are much more variable. Units in the RN-17B core with a crystalline protolith (lithic breccia, volcanic sand, and basalt flow lobes) typically contain significantly more chlorite and are altered to a lesser degree than hyaloclastite units. Wholerock REE patterns in units with a crystalline protolith appear to have little modification. Wholerock REE patterns in volcanic sand and basalt flow lobes in RN-17B neatly match unaltered, subaerially erupted tholeiite. Wholerock patterns in lithic breccia from RN-17B neatly match unaltered, subaerially erupted olivine tholeiite. Work by Ottolini and others (2012) show that RN-19 dolerite also neatly matches unaltered, subaerially erupted olivine tholeiite.

Wholerock REE patterns in in the hyaloclastite units do not match either category. Hyaloclastite REE patterns are depleted in LREE, have significant negative Eu anomalies, yet have HREE consistent with a tholeiite protolith. The REE patterns of the hyaloclastite units are remarkably similar to REE patterns in individual hydrothermal hornblende crystals in the RN-17B core measured by laser ablation (LA-ICP-MS).

Previous studies have indicated that pH is the main factor influencing REE content of hydrothermal fluids (i.e. Michard, 1989). While pH is certainly a major factor influencing REE mobility in hydrothermal fluids, our results indicate that the REE content of hydrothermal fluids may also be influenced by additional factors including the nature of the protolith (glass versus crystalline rock) and the degree of alteration (i.e. almost complete disappearance of chlorite in favor of hydrothermal hornblende and plagioclase). An ongoing part of our study promises to reveal the role of temperature and ligand complexing of REE as potential agents for mobilizing REE from high enthalpy reservoir rocks.

This type of study shows great promise for the Salton Sea Geothermal Field, considering the variety sedimentary lithologies present. A comparison of the REE content of altered lithologies compared to the unaltered protolith in the Salton Sea Geothermal Field, coupled with existing REE data from Salton Sea Geothermal Fluids, may provide insight into preferential flow paths for high enthalpy hydrothermal fluids.

3. References


Andrew Fowler apfowler@ucdavis.edu

**Education**

**University of California - Davis (Fall 2012 to Present)**
Ph.D. Candidate, Geology, geothermal geochemistry focus

**University of California - Davis (Fall 2010 to Fall 2012)**
Master of Science, Geology, geochemistry focus (awarded Sep. 2012)

**California State University East Bay (2009-2010)**
Certificate in Geographical Information Systems (GIS)

**University of Otago, New Zealand (2000-2003)**
Bachelor of Science, Geology (awarded 2003)

**University of British Columbia, Vancouver, Canada (2002-2003)**
Geology department exchange student

**Kungsängskolan, Sala, Sweden (1998-1999)**
AFS high school exchange student for one year

**Academic Activities**

**Presenter Iceland Deep Drilling Project-2 (IDDP) Workshop, Svartsengi, Iceland**  
*September 2012*  
Presented research on the mineralogy and geochemistry of drill cores from the Reykjanes Peninsula, Iceland, the location for the next IDDP well attempt.

**Presenter Joint NZ-US Geothermal Forum, Rotorua, New Zealand**  
*April 2012*  
Received National Science Foundation grant funds to present geochemical and 3D computer modeling data of geothermal systems. The goal of the workshop was to share and discuss geothermal research and ideas from the heat source to the surface, i.e. lithospheric heat and mass transfer, and provide a venue for industry and researchers to discuss their needs and the challenges of characterizing, monitoring, and managing hydrothermal reservoirs.

**Hydrothermal Systems and Energy, University of Iceland, Nesjavellir, Iceland**  
*August 2011*  
Attended 10-day NORDVULK geothermal resources course in Nesjavellir, Iceland. Poster presented based on thesis work for the geothermal system at Reykjanes, Iceland.

**Winning Team: National Geothermal Student Competition (NGSC)**  
*February 2011 – June 2011*  
UC Davis team lead for the 1st United States NGSC competition. The team focused on Valles Caldera, New Mexico. The project involved creating an interactive 3-Dimensional “virtual reality” model of the Valles Caldera
geothermal system.

**Geology of Geothermal Resources, University of California - Davis**
*February 2011 – June 2011*
Semester long class focused on the geothermal system at Long Valley Caldera, California.

**Work Experience**

**Ph.D. Candidate, University of California - Davis**
*September 2010 to Present*
The Iceland Deep Drilling Project (IDDP) is an initiative that aims harness energy from supercritical geothermal resources for the first time. I study samples retrieved by the IDDP. My research goal is to understand geothermal processes occurring at previously unexplored depths in active geothermal systems by studying the behavior of trace elements in geothermal fluids, minerals and rocks during hydrothermal alteration. My primary field area is the Reykjanes Peninsula, Iceland.

**Graduate Researcher for the Surprise Valley Geothermal System, CA, California Geothermal Energy Collaborative (CGEC), Davis, California**
*April 2013 – September 2013*
Evaluated historical geothermal fluid samples to understand the fluid sources, fluid pathways and heat sources in the Surprise Valley Geothermal System, CA. Utilized geochemical modeling techniques (Geochemist’s Workbench software). Identified data gaps, and compiled a CGEC report outlining anticipated sampling efforts to fill existing knowledge gaps.

**Geothermal Geochemistry Intern, GeothermEX a Schlumberger Company, Richmond CA**
*August 2012 – September 2012*
Primarily worked on a research project focused on evaluating various isotope and chemical fluid geothermometers for geothermal systems. Additionally, I performed evaluations of geothermal fluid samples.

**Graduate Researcher, Iceland Deep Drilling Project (IDDP), University of California - Davis**
*January 2011 – September 2011*
Logged IDDP geothermal well cores RN-30 and RN-17B from Reykjanes, Iceland. Analyzed hydrothermal minerals using: laser ablation ICP-MS for strontium isotopes, electron microprobe for major element concentrations, and fluid inclusion micro-thermometry measurements in epidote.
Teaching Assistant, University of California - Davis

- Summerfield Volcanology: Summer 2013
- Summerfield Structural Field Mapping: Summer 2012
- Geology of Ore Deposits: Spring 2012
- Sedimentology: Winter 2012, Winter 2013
- Optical Mineralogy: Fall 2011, Fall 2012
- Mineralogy: Fall 2010, Fall 2013

Geologist, Environmental Remediation Department, URS Corporation, Oakland, CA

July 2005 – July 2010 (leave from August 2007 to July 2008 to volunteer abroad)

Lead geologist for site contamination investigations in California and internationally in Angola, Africa. Managed geological investigation tasks, supervised subcontractors, and managed site health and safety. Interacted with regulatory agencies and clients. Developed geological and hydrogeological investigation work-plans. Performed fieldwork including: soil and rock logging, groundwater and soil vapor sampling. Evaluated field data, and wrote technical reports.

Geologist, Environmental Remediation Department, TRC Solutions, Concord, CA

July 2004 – June 2005

Supervised and managed drilling subcontractors, sampled soil and groundwater, logged drill cuttings, designed groundwater monitoring wells, operated a groundwater sampling truck, evaluated field data, and compiled reports. Worked with a variety of drilling technologies.

Awards

- Geothermal Resources Council “Best Presentation Award”
  Collaboration with Scott Bennet, Maya Wildgoose, and Carolyn Cantwell for the Resource Assessment 2 section at the annual 2012 GRC meeting in Reno, Nevada (2012)

- Geothermal Resources Council “Best Speaker Presentation Award”
  Geology/ Exploration 11 section at the annual 2011 GRC meeting in San Diego, California (2011)

- Winning team 2011, National Geothermal Student Competition
  Competition run by the National Renewable Energy Laboratory (NREL)

- URS “Outstanding Services in the Field” award (2010)
  Annual award for outstanding achievement by employees in an office of ~ 350 people

- URS “Outstanding Achievement” award for project work in Angola, Africa (2007)
  Quarterly award for outstanding achievement by employees in an office of ~ 350 people
**Presentations:**


Fowler, Andrew P.G., Wildgoose, M., Bennett, S., Cantwell, C., and Barnes, L., (2011), A unique approach to managing complex geothermal datasets: An integrated multidisciplinary re-evaluation of the geothermal system at Valles Caldera, New Mexico, using an immersive three-dimensional (3D) visualization environment. Oral presentation at: 1st National Geothermal Student Competition, Santa Fe, New Mexico. 23 June.


**Publications:**


Fowler, Andrew P.G., Zierenberg, R. A., Schiffman, P., Marks, N. E., and Fridleifsson,
The Los Humeros geothermal field, México. A high enthalpy geothermal system.

Georgina Izquierdo Montalvo, Alfonso Aragón Aguilar, Víctor Arellano Gómez and Siomara López Blanco
Instituto de Investigaciones Eléctricas, Reforma 113, Col. Palmira, Cuernavaca Morelos, CP 62490.
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Abstract

A summary of the main geologic, geochemical and production characteristics of the Los Humeros Geothermal Field (LHGF) is presented.

The LHGF is one of the four geothermal fields under exploitation in Mexico. The Los Humeros reservoir is hosted in a volcanic caldera; located in the central-eastern portion of the country, within the Mexican Volcanic Belt, near the limit of this province with the Sierra Madre Oriental province. Most of the wells produce high-enthalpy fluids with low liquid fraction. Well H-1 was the only well that produced the higher fraction of water; at present the well declined.

The LHGF is a vapor dominated system, characterized by high enthalpy fluids, low recharge and low rock permeability. The static temperature profiles determined in the wells are in the range between 300 and 360 °C.

Hydrothermal alteration in the Los Humeros reservoir has been studied extensively; it is characteristic of the interaction of the rocks and neutral to alkaline pH fluids. Evidence of the presence of acidic fluids is accelerated corrosion which occurs in the production pipes mainly in wells located in de Colapso Central sector; however in the reservoir rocks there are not typical minerals formed by the interaction of the rock with low pH fluids.

Because of its high temperature, low permeability and low recharge LHGF could be a suitable place for an alternative energy generation.

Key words: Los Humeros geothermal field, high enthalpy.
Proposal to attend the
“DOSECC Workshop to Promote a Collaborative Initiative to Develop Higher Enthalpy Geothermal Systems in the USA”, October 13-15 2013, Lake Arrowhead, CA

Marie D. Jackson
Research Engineer, Department of Civil and Environmental Engineering
University of California at Berkeley, 760 Davis Hall, Berkeley, CA, 94720-1710
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https://www.researchgate.net/profile/Marie_Jackson/

I would very much like to participate in this workshop, and am very interested in generating mutually advantageous collaborations with representatives from the geothermal industry, other academics, and researchers from Federal and State Agencies as regards the mineralogical analysis of samples of hydrothermally-altered tephra from drill cores of wells in higher enthalpy geothermal systems. These samples could yield additional information of great interest to geoscientists and engineers investigating Al-tobermorite and zeolite mineral assemblages in environmentally-sustainable Pozzolanic cementitious systems. They have the potential to inform the very long term durability of high performance concretes formulated with volcanic ash pozzolans. I am particularly interested in advancing the research on this mineral assemblage that was initiated by the innovative study of the 1979 drill core of Surtsey Tuff, Iceland, by S. Jakobsson and J. G. Moore (1).

Over the past several years I have been investigating the material properties and mineralogical characteristics of the cementitious phases of ancient Roman seawater concrete, in collaboration with civil engineers (Professor P. J. M. Monteiro, and his graduate students) and mineralogists (Professor H.-R. Wenk, Dr. S. Mulcahy) at UC Berkeley, and beamline scientists at the Advanced Light Source of Lawrence Berkeley Laboratories (Dr. M. Kunz, Dr. N. Tamura) (2–6). These 2000-year-old pozzolanic concretes, produced with volcanic ash, lime, and seawater, are some of the most durable cementitious materials on the planet; they have a much smaller carbon footprint than modern Portland cement concretes. The principal crystalline cementitious phase of concrete cores drilled from eleven Roman harbors throughout the Mediterranean basin is aluminous tobermorite ([Ca₄(Si₅.₅Al₁₀.₅O₁₇H₂)]Ca₀.₂ ·Na₀.₁ ·₄H₂O) (7), a hydrothermal mineral that forms in basaltic tephra (1, 7–10), and has cation exchange properties that sequester monovalent and divalent radionucleides and heavy metals (11, 12). Although the Al-tobermorite structure forms the model basis of poorly crystalline calcium-aluminum-silicate-hydrate (C-A-S-H), the cementitious binder of a new class of environmentally sustainable concretes containing aluminous supplemental pozzolanic materials (13, 14), crystalline Al-tobermorite does not occur in conventional concretes.

Recent analyses of 11 Å Al-tobermorite from a drill core of a massive Roman concrete breakwater in Pozzuoli Bay, Italy, with synchrotron radiation applications shows the double-layered crystal that is associated with cation-exchange properties (4, 5, 11, 12). An adiabatic thermal model of the Baianus Sinus concrete structure suggests that heat evolved through hydration of lime and formation of C-A-S-H produced maximum temperatures of ~85 to 100 ºC in the breakwater (4, 5). These elevated temperatures are mainly less than those of laboratory syntheses (11, 12, 15, 16), and the Al-tobermorite that developed in 1963-1964 basaltic tephra erupted from Surtsey volcano, Iceland, which was sampled by the 1979 drill core (1, 3, 4) (Fig. 1). The mineralizing effects of seawater, alkali-and alumina-rich palagonitic volcanic ash, and
elevated temperatures appear to be critical to Al-tobermorite crystallization in both environments. In the HSDP 2 Phase 1 drill core of Mauna Loa, Hawaii, however, calcium-silicate-hydrates formed at 15 °C in palagonite deposits at 1.4 km depth (17). All three environments contain authigenic phillipsite (Fig. 1), a zeolite with cation-exchange properties that clogs pores in concrete waste repositories (18).

The topic that I would like to present for discussion is “Crystallization and stability of Al-tobermorite and phillipsite in geothermally-altered volcanic ash analogs of ancient Roman pozzolanic seawater concrete”. My presentation would focus on how future samples of drill core materials from higher enthalpy geothermal systems could provide a valuable geologic context to improve syntheses of these minerals in innovative concretes with advanced properties, including concrete waste repositories, using volcanic pozzolans.

Figure 1. Al-tobermorite and phillipsite in the cementitious matrix of the volcanic ash-hydrated lime mortar of the 2000-year-old *Baianus Sinus* concrete breakwater, Pozzuoli Bay, Italy (a, b, c) and the 12-year-old Surtsey Tuff, Iceland (d, image courtesy of J. G. Moore). (a) Pilatus 1M area detector and Debye rings diffracted by the crystalline phases in monochromatic (10K eV) X-ray micro-diffraction experiments, ALS beamline 12.3.2. (b) associated d-spacings and intensities of the Al-tobermorite, phillipsite, and calcite phases. SEM-SE images showing (c) a phillipsite rosette that has crystallized on a platy Al-tobermorite crystal, and (d) phillipsite and Al-tobermorite in the submarine Surtsey tuff, Iceland, that crystallized at about 150 °C in a 1979 drill core. After Jackson et al. 2013, *Journal of the American Ceramic Society* (4). For more information on the similiarites of the young Surtsey Tuff and the ancient Roman seawater concrete, see Jackson et al. 2012, AGU Fall Meeting (3).
References Cited


16 Shaw, S., Clark, S. M. and Henderson, C. M. B. (2000) Hydrothermal formation of the calcium silicate hydrates, tobermorite \((\text{Ca}_6\text{Si}_6\text{O}_{16}\text{(OH)}_2 \cdot 4\text{(H}_2\text{O})\) and xonolite \((\text{Ca}_6\text{Si}_6\text{O}_{17}\text{(OH)}_2):\) an in situ synchrotron study. *Chemical Geology*, 167, 129–140.


**Curriculum Vitae**

**Marie Dolores Jackson, Ph. D.**

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[http://ucberkeley.academia.edu/MarieJackson](http://ucberkeley.academia.edu/MarieJackson)  
[https://www.researchgate.net/profile/Marie_Jackson/](https://www.researchgate.net/profile/Marie_Jackson/)

**EDUCATION**

Ph. D., Earth Sciences, Johns Hopkins University, 1987  
Doctorat d’Université, Géologie Structurale, Université de Nantes, France, 1979  
Bachelor of Science, Earth Sciences, University of California at Santa Cruz, 1976

**PROFESSIONAL EXPERIENCE**

**Visiting Research Engineer**, Department of Civil and Environmental Engineering, UC Berkeley  
(August 2011 to present)

Investigations of ancient Roman seawater concretes and the concretes of the monuments of ancient Rome and the diverse microstructures and compositions of their cementitious phases, with applications to volcanic ash pozzolans in modern concretes, in collaboration with Professor P. Monteiro and Professor H.-R. Wenk and their graduate students. Analytical methods include petrographic microscopy, Scanning Electron Microscopy, Scanning X-ray Transmission Microscopy, High Pressure X-ray Diffraction experiments with Synchrotron Radiation, and X-ray Microdiffraction studies at beamlines 5.3.1, 5.3.2, 12.2.2., and 12.3.2 of the Advanced Light Source, Lawrence Berkeley Laboratories.

**Adjunct Faculty Member**, History Department, Northern Arizona University (2005-present)  
**Visiting Scientist**, School of Civil and Environmental Engineering, Cornell University  
(July to August 2010)


Investigations of the volcanic building stone and concrete masonry of ancient Roman monuments and maritime harbor concretes. Research includes petrographic and geochemical studies of Roman volcanic tuffs, concrete aggregates, and pozzolanic cements; experimental tests of strength and durability of these materials; the chronology of use of building stone and concrete in Roman construction; and analyses of ancient texts (e.g. *De Architectura*) to describe scientifically the expertise of Roman builders and assess the durability of ancient masonry in Rome.

1987 to 1995; GS 12 and 13 (1992)
Investigation of late Quaternary earthquake-ground ruptures along the Hat Creek fault near Lassen Volcano, California, 1991-1995. Developed innovative methods to make detailed, 1:1,000 scale geologic maps of segments of ground breakage along the 11-km long, Hat Creek fault scarp. Investigated processes of earthquake rupture on this young, well-developed normal fault and evaluated its earthquake potential.

Structural study of the seismically active Ka‘oiki fault zone and its recent earthquake ground ruptures, Mauna Loa volcano, Hawaii, 1988-1990. Published results include innovative geologic mapping, analysis of geodetic and seismic data, and mechanical analysis of faulting to clarify the ground-rupture process for one of the most seismically active areas in Hawaii.

**Visiting Scholar, Stanford University, Stanford, CA**
1984 to 1986
Collaborated with professors and students of the Geomechanics Group at Stanford on geological, geophysical, and geomechanical research towards Ph. D. dissertation.

**Graduate Assistant, Johns Hopkins University, Baltimore, MD**
1980 to 1986
Investigation of the deformation of host rocks over three igneous domes in the Southern Henry Mountains, Utah using geological mapping, geophysical methods and mechanical analysis. Published results are considered classic field studies in understanding how host rocks deform to accomodate near-surface accumulations of magmas. Ph. D. Dissertation: Deformation of Host Rocks during Growth of Igneous Domes, Southern Henry Mountains, Utah.

**Graduate Student, Université de Nantes, France**
1977 to 1979

**SCIENTIFIC PUBLICATIONS**

* denotes ten publications of greatest importance


**Editor’s choice, Highlights and Breakthroughs article 2013.**


**Editor’s choice, Featured article 2013.**


Jackson, M., G. Vola, D., J. Oleson, B. Scheetz, C. Brandon, R. Hohlfelder, 2012, Cement microstructures and durability in ancient Roman seawater concretes: 


Marra, F., D. Deocampo, M. Jackson, G. Ventura, 2011, The Alban Hills and Monti Sabatini volcanic products used in ancient Roman masonry (Italy): An integrated stratigraphic, archaeological, environmental and geochemical approach: 

**Earth Science Reviews**, doi:10.1016/j.earscirev.2011.06.005

Bianchi, E, R. Meneghini, M. Jackson, P. Brune, F. Marra, 2011, Archaeological, structural, and compositional observations of the concrete architecture of the Basilica Ulpia and Trajan’s Forum: 


Jackson, M. D., P. Ciancio Rossetto, C. K. Kosso, M. Buonfiglio, F. Marra, 2011, Building materials of the Theater of Marcellus, Rome: 

**Archaeometry**, v. 4, n. 4, p. 728-742. doi: 10.1111/j.1475-4754.2010.00570.x

*Editor’s choice, 25 best articles in 25 years, 2010.*

Jackson, M., F. Marra, 2010, Calcestruzi della volte del Foro di Traiano, Appendice I: Nuovi dati sulle volute in calcestruzzo della Basilica Ulpia e del Foro di Traiano, E. Bianchi and R. Meneghini: 

**Bollettino della Commissione Archeologica Comunale di Roma**, p. 111-140.


**Scienze dell’Antichità**, v. 16, p. 403-417.


**Proceedings of Structures Congress 2010**, Concrete and Masonry Structures, p. 1938-1948, American Society of Civil Engineers. doi 10.1061/ 41130(369)176


doi: 10.1086/628637


**ABSTRACTS AND PRESENTATIONS AT MEETINGS AND CONFERENCES**


Jackson, M. D., The role of pyroclastic rock in the durability of ancient Roman concretes: Why Imperial Age monuments have remained intact for 2000 years: *Invited lecture*, Department of Geological and Environmental Sciences, Stanford University, May 9, 2011.

Jackson, M. D., Rapid and innovative developments in concrete technologies by late Republican builders in Rome, *1st Annual BAIR Conference*, UC Berkeley Classics Department, October 9, 2010.


Jackson, M. D., 1980, The deformational history of alpine peridotite massifs as recorded by their internal mafic and ultramafic dikes (abs.): *Geological Society of America, Abstracts with Programs*, v. 12, n. 7, p. 454.

**POPULAR PUBLICATIONS**


**PROFESSIONAL MEMBERSHIPS**
SYNERGISTIC ACTIVITIES

UC Berkeley and LBL press releases describing our recent research on Al-tobermorite in ancient Roman seawater concrete, have attracted a great deal of positive attention in popular news articles, including No. 1 on Reddit (June 4, 2013) and No. 1 on Futurity.com (June 5, 2013)

To improve concrete, do as the Romans did
http://newscenter.berkeley.edu/2013/06/04/roman-concrete/

Roman Seawater Concrete Holds the Secret to Cutting Carbon Emissions
http://newscenter.lbl.gov/?p=28432&preview=true

American Mineralogist editors selected “Unlocking the secrets of Al-tobermorite in Roman seawater concrete” as a Highlights and Breakthroughs article in 2013.

Journal of the American Ceramic Society editors selected “Material and elastic properties of Al-tobermorite in ancient Roman seawater concrete” as a featured article in 2013.

Geoarchaeology editors selected “Mid-Pleistocene Volcanic Ash in Ancient Roman Concretes”, as one of the top 25 articles published in the past 25 years. http://www.wiley.com/bw/wiley_vi.asp?ref=0883-6353&site=1

An article in Earth Magazine, “Why Roman Concrete Stands the Test of Time” (April 2010, v. 55 p. 8-9) describes our current research on the material characteristics of ancient pozzolanic mortars

A 2010 National Geographic documentary film features our recent geological and archaeological research in Rome

A multidisciplinary analytical and testing program with Professor A. Ingraffea at Cornell University, Dr. P. Brune at DuPont Engineering, and archaeologists of Sovraintendenza ai Beni Culturale del Comune di Roma investigates the pozzolanic cements and fracture behavior of historically accurate imperial age Pozzolane Rosse ash-hydrated lime mortars, and 20 cm diameter drill cores of the walls of the Great Hall, Markets of Trajan, and will apply findings to alkali-activated pozzolanic systems in modern concretes

Reviews manuscripts for Archaeometry, Journal of Archaeological Science, Journal of the American Ceramic Society, University of California Press, and other academic journals


Commissioner, 2003-2009, City of Flagstaff Open Spaces Commission, Natural Sciences Advisor

Speaks fluent French and highly conversant Italian.

FUNDING FOR ARCHAEOLOGICAL RESEARCH

September 2011 - 2013 Principal Investigator, with Professor P. J. M. Monteiro and Professor H.-R. Wenk, UC Berkeley, Advanced Light Source, Lawrence Berkeley National
March 2010
Contributing investigator, with Professor John Oleson, University of Victoria: Loeb Classical Library Foundation “Roman Maritime Concrete Study: Analysis of Cores”, $22,353

In Kind Laboratory Contributions

October 2009 – present
Professor Anthony Ingraffea, Winter Laboratory, Cornell Fracture Group, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York: Innovative fracture testing and computer modelling of historically accurate laboratory reproductions of Imperial Roman pozzolanic mortars.

September 2009 – present
Dr Emmanuele Gotti, Dr. Gabriele Vola, CTG Italceimenti, Bergamo, Italy: A collaboration with CTG Italceimenti in Bergamo, Italy and the ROMACONS group on drill cores of seawater concretes from the Portus Cosa, Santa Liberata, Portus Claudius, Portus Traianus, and Portus Neronis harbors, and a 2004 reproduction of maritime concrete at Brindisi, provides chemical, XRD, and SEM-EDS studies of Roman maritime concretes.

October 2008 – 2010
Professor Barry Scheetz, Materials Research Laboratory, Pennsylvania State University, State College, Pennsylvania: SEM-EDS and XRD studies of Roman mortar and mortar reproductions: volcanic aggregates and pozzolanic cements

June 2008
Professor Daniel Deocampo, Geochemistry Laboratory, Department of Geology, Georgia State University, Atlanta, Georgia: XRF and XRD analyses of Roman volcanic ash and Roman pozzolanic mortars

September 2005
Professor David Veblen, Electron Microbeam Laboratory, Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland: SEM-EDS and TEM analyses of pozzolanic cements in Roman mortars

2003 – 2010
Professor Thomas Hoisch, Metamorphic Petrology Laboratory, Department of Geology, Northern Arizona University, Flagstaff, Arizona: Petrographic photomicrographs of Roman volcanic tuffs, volcanic ash, pozzolanic mortars

2000 – 2009
Professor Carl Cawood (retired), Testing Laboratory, Department of Civil and Environmental Engineering, Northern Arizona University, Flagstaff, Arizona: ASTM C97-96 tests of Roman building stones and pozzolanic mortars, and ASTM C170-90 uniaxial compressive strengths of Roman building stones

December 2000 – 2006
Professor Richard Hay (deceased), Limnology Laboratory (Professor A. Cohen), University of Arizona, Tucson, Arizona: Petrographic and micromorphological studies of Roman volcanic tuffs, volcanic ash, and pozzolanic mortars

July 1998
Professor Erhard Winkler (deceased), Rock Testing Laboratory, Department of Geology, University of Notre Dame, South Bend, Indiana: Modified Modulus of Rupture Tests, Roman volcanic tuffs and travertine building stones

June 1997 – 2010
Dr Fabrizio Marra, Istituto Nazionale di Geo fisica e Vulcanologia, Rome, Italy: Collaboration has provided support for work in quarries, outcrops, and monuments as well as petrographic, geochemical, mineralogical, and geochronological analyses, and shipping of rock samples and archaeological specimens

(SEM-EDS: scanning electron microscopy and energy dispersive spectrometry; XRD: X-ray diffraction analyses; XRF: X-ray fluorescence geochemistry; TEM: Transmission electron microscopy)
PH. D. COMMITTEE MEMBERSHIPS

Jennifer Wehby, “Compositions of Pozzolanic Mortars and Construction History of Concrete Masonry at Ostia Antica”, Department of Archaeology, Oxford University, United Kingdom, Ph. D. expected Spring 2013, external co-supervisor (with Professors Mark Pollard and Janet DeLaine at Oxford University)

Phillip Brune, “The Mechanics of Imperial Roman Concrete and Designed Vaulted Monuments”, Department of Mechanical Engineering, University of Rochester, New York, Ph. D. January 2011 (with Professors R. Perucchio (chair), J. Lambropoulos, E. Colantoni at University of Rochester, and Professor A. Ingraffea at Cornell University)

REFERENCES

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Barney and Estelle Morris Professor of Earth Science
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http://en.mercatiditraiano.it/museo/editoriale
Preproposal

I graduated with a PhD in Energy Resources Engineering from Stanford University this summer and I'm currently working for Ísor (Iceland GeoSurvey) on a project regarding the deep roots of geothermal systems. I've been working on modeling magmatic intrusions in geothermal reservoirs as an affiliate at Lawrence Berkeley National Laboratory since the beginning of August. I've so far been doing a literature review and I've started modeling supercritical geothermal systems using AUTOUGH2 as well as HYDROTHERM.

I'm very interested in higher enthalpy geothermal systems and know that this workshop would be a great opportunity for me. I would like to discuss the challenges associated with modeling higher enthalpy systems and magmatic intrusions. The heat sources in numerical models are often assumed to be below the model’s range and only incorporated into the model by choosing appropriate boundary conditions. Wells drilled into very hot formations (or magma) in higher enthalpy systems indicate that the heat sources extend up to shallower depth. Thus, it is of interest to improve current field scale numerical models by incorporating magmatic intrusions and the entire water circulation into the modeling scheme. Such model would improve the ability to answer many questions related to the field management of magmatic geothermal systems.

Sincerely,
Lilja Magnusdottir
Proposal from Jim McClain
High Enthalpy Geothermal System Workshop

The “Workshop to Promote a Collaborative Initiative to Develop Higher Enthalpy Geothermal Systems in the USA” sounds like an outstanding effort, and I would like to be involved at its initial stages. I think the approach, to develop collaborations with industry and government, fits in well with programs in which we at U.C. Davis are already investing time and effort. I am actively involved in geophysical research in low temperature systems in Long Valley, CA, and Surprise Valley, CA. I also have been peripherally involved with the EGS experiment at Newberry Caldera, OR. Because of my interest in high temperature systems I participated in the earliest meetings of the IDDP. I have not yet participated in the project that grew out of the meeting because I have not escaped my administrative post at UCD. However, as I transition out of my position and back to the faculty (10 years will be quite enough), I hope to become involved in later phases of the Reykjanes experiment, and participation in a comparable U.S. experiment would be quite exciting.

I am a seismologist by training, and a magnetotelluric (MT) person by the demands of converting to studies of continental systems. For both seismology and magnetotelluric studies the critical issue is that of anisotropic media, and the implications that anisotropy for crustal fractures and faults that may control some (brittle) hydrothermal systems. I hope to apply new techniques to examine anisotropy. These include ambient noise seismic tomography, seismic attenuation anisotropy, and MT inversion in anisotropic media. While these tools do not require high enthalpy systems for their development, they could be quite useful in characterizing a system regardless of its temperature.
My interest in higher enthalpy geothermal systems has involved research into igneous heat sources, depths of fluid circulation and creation of EGS reservoirs in explored high-temperature geothermal systems. I have been involved in scientific drilling of active geothermal systems for many years and currently serve on the advisory board (SAGA) of the Iceland Deep Drilling Project (IDDP).

Although geothermal power production is a mature technology, the industry suffers from high reservoir risk in the financial markets. Critical parameters of temperature, permeability and fluid availability can be difficult to assess even with high-cost drilling. There are a number of examples where drilling has intersected the brittle-ductile (B-D) transition and at least two holes have penetrated magma. The zone beneath the B-D transition represents a development frontier: it contains most of the thermal energy of a hydrothermal-magmatic system. However, there is no scientific, drilling, and reservoir engineering infrastructure to guide development of these higher enthalpy zones. As exemplified by IDDP, the first high enthalpy projects will take place through deep drilling at known geothermal systems. This approach can mitigate risk because of reservoir knowledge and existing power generation infrastructure. Power generation scenarios will involve deep injection to stimulate fracture formation thorough thermal contraction and to mitigate corrosive fluids. Permeability connection with the overlying brittle reservoir can serve as thermal recharge.
Project Summary for Water-Enthalpy-Life (WEL)
T.C. Onstott - Princeton University
E. Boyd, Montana State University
T. Kieft – New Mexico Institute of Technology
L. Murdoch – Clemson University
D. Moser – DRI

Intellectual Merit:

One of the frontiers in biogeoscience is the subsurface ecosystem of the Earth’s upper crust. The depth to which the subsurface biosphere reaches depends largely upon the temperature and upon the energy flux. Hyperthermophiles, microorganisms capable of living upwards of 80 to 122°C are known to exist in hydrothermal vents and hot springs, but their occurrence in the subsurface at those in situ temperatures has never been reported primarily because of the lack of opportunities to sample such subsurface environments. The proposed research focuses on the subsurface ecosystems of fractured, crystalline rock, which comprises 80% of the continental crust, in this temperature regime. The fundamental hydromechanical, geochemical, and microbial interactions of fractured, crystalline rock are just beginning to be revealed by the research we have carried out in 1-4 km deep mines of South Africa where the ambient temperatures attain a maximum of only 60°C due to the low geothermal gradient. The hypothesis to be tested is that the convectively driven fluid and gas flow in a pre-existing fracture network responds to the local stress field, thereby controlling the nutrient flux in the crust and, hence, the microbial abundance, diversity and activity. The microbial activity, in turn, causes mineral dissolution and precipitation, which can alter the hydromechanical properties of the fracture network. Results will be compared to that obtained by us in the much less dynamic South African crust. The research approach is to deduce the system’s responses over time scales ranging from seconds (e.g., hydraulic fracturing) to geologic time (e.g., hot spot migration) and to characterize the system’s state (stress, fractures, hydrology, geochemistry, and microbiology) over the following length scales:

1. **Grain Scale** \((10^{-4}-10^{-1} \text{ m})\): Fracture surfaces obtained by coring will be examined with electron microscopy (SEM and EMPA) and Fluorescence In Situ Hybridization (FISH) to document the sessile microbial community and its spatial relationship to fractured mineral surfaces. Porosity and pore water chemistry of the matrix rock proximal to the fractures will be measured to determine nutrient availability.

2. **Fracture scale** \((10^{-1}-10^{2} \text{ m})\): Individual fractures will be isolated by straddle packers, and the aqueous, gaseous, isotopic and microbial composition of fracture fluids will be determined. The fracture hydraulic conductivity and response to hydromechanical stresses will be measured to determine ambient conditions and how the fracture system responds hydromechanically to transient stresses. Small hydraulic fractures will be created to characterize the stress state, and to generate fresh fracture surface. Changes in the fluid and microbial composition due to hydraulic fracturing will also be measured using metagenomics, transcriptomics and proteomics, to determine how newly formed or re-opened fractures release nutrients to the microbial community and whether the community responds on the time scale of minutes to days. Intrafracture variability will be examined over the meter scale by sub-parallel coring that intersects the same fracture.

3. **Groundwater-flow-system scale** \((10^{2}-10^{3} \text{ m})\): Hydrogeologic flow systems will be studied over a range of depths from the ground surface down to ~200°C. This will involve mapping the geology, fracture system along with characterizing the distribution of hydraulic head, stress state, groundwater age, temperature and composition. Shallow boreholes will provide estimates of gas flux into the biosphere and atmosphere and samples for isotopic determination of its source (e.g. biogenic CH₄). Maps of the fracture systems will be used to integrate the measurements of interfracture variability in geochemistry, fracture fluid age and microbial abundance, diversity and activity. These data will be used to parameterize a hydromechanical, thermal, geochemical, microbial, fluid flow model that will serve as a tool for exploring important interactions between these coupled processes.

The research goals would also include the isolation of hyperthermophiles and the determination of their physiological response to high pressure to see how this enhances their enzyme kinetics and cardinal growth properties. The research plan requires closely integrated activities of a team with expertise in rock mechanics, hydrology, geochemistry and microbiology. For example, the team will develop the
modifications required to perform hydraulic fracturing and hydromechanical testing of fractures and fracture connectivity without contaminating the indigenous microbial community. Members of the research team have been collaborating for several years to more than a decade.

**Broader Impacts:**
The broader impacts and potential high returns include: (i) determining the extent of the continental subsurface biosphere; (ii) establishing a paradigm for the dynamic microbial ecosystem of upper crust; (iii) understanding the net flux of geogases and biogenic gases from the upper crust to the biosphere and atmosphere; (iv) advancing understanding of the coupled processes (bio, hydro, thermal, chemical, mechanical, etc.) over multiples spatial and temporal scales; (v) developing a new generation of future scientists in multidisciplinary research; and (vi) extending knowledge of subsurface ecosystems through education and outreach programs. These research pursuits are both academic and applied in their focus and have a significant potential to extend our understanding of the role of the upper crust in global biogeochemical cycling, evolutionary dynamics, energy exploration, and biological corrosion of geothermal power infrastructure.
Preproposal by Flavio Poletto

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My interest is the application of borehole methods, in particular while-drilling borehole geophysics, to develop Higher Enthalpy Geothermal Systems. The interest is in the use of the drill-bit as a seismic while drilling (SWD) source of reverse vertical seismic profiles (RVSP), also with very high temperatures. The proposer and his institute have a multyear demonstrated experience gained in cooperation with hydrocarbon industry during drilling of medium and medium-deep oil and gas [1] and also geothermal wells (case history of Nevada) [2]. Recently, our geophysical research has been focused also on the seismic rheological model and reflection coefficients of the brittle-ductile transition (BDT), including simulation of the seismic waves at the Earth mantle [3].

The topic we would like to present for discussion is related to SWD for high-enthalpy purposes, where conventional borehole tools have difficult acquisition conditions, considering the possibility: 1) to integrate innovative high-temperature downhole recording technology with the existing drill-bit SWD method, technology and experience, 2) to use SWD to evaluate scenarios for seismic investigations of BDT, 3) to provide subsurface velocity models to support also other geophysical and geo-mechanical methods and investigations, such as passive crack monitoring and mapping in high enthalpy areas. The BDT wave propagation analysis can be extended also to other seismic scenarios.


Lake Arrowhead high-H geothermal workshop

Mark H Reed, Professor of Geological Sciences
University of Oregon
USA

As a hydrothermal system geologist and geochemist, I have studied fossil and active hydrothermal systems for more than 30 years, specializing in the chemical relationship between fluid composition and mineral assemblages. The minerals are those in geothermal scale, hydrothermally altered rock, and in veins, many of which contain ore minerals. A key part of my work consists of thermodynamic modeling using programs (SOLVEQ-xpt, CHIM-xpt) written by my students and me, which, with funding from the IDDP project, we adapted for work up to 600°C and 500 MPa.

High enthalpy geothermal fluids form where magma heats formation waters at great depth, for example beneath mid-ocean ridges or beneath stratovolcanoes in a continental setting. Aside from engineering issues, the biggest challenge to obtaining a significant flux of high-enthalpy fluids is in forming or finding a volume of fractured rock with large permeability near magma. The fluids would need to be hydrostatically pressured and the fractures must remain open despite precipitation of quartz and despite hydrothermal alteration of the wall rock. The figure below shows one approach to producing high-enthalpy fluids, as proposed in the Japanese Beyond Brittle Project. In the Arrowhead meeting, I would address settings for fluid extraction based on knowledge of porphyry copper deposits and deep ocean ridge hot springs.

An approach to heat extraction at hydrostatic pressure from an initially lithostatically-pressured magma margin by fracturing and cooling ductile rock. (From Reed report to the Japanese Beyond Brittle Project workshop, 2013.)
Pre-proposal for “Workshop to Promote a Collaborative Initiative to develop Higher Enthalpy Geothermal Systems in the USA”

Peter Schiffman
Department of Geology
University of California, Davis

1. Expertise and interest

I am a mineralogist/petrologist whose expertise on hydrothermal alteration in active and fossil hydrothermal systems. I have been studying and publishing on these systems for over 30 years. My expertise on active geothermal systems dates back to the early 1980’s when I was part of the UC Riverside group which was using a multi-disciplinary approach to understand fluid flow and fluid-rock interactions within the Cerro Prieto geothermal system. Subsequently, I have conducted similar studies on cuttings and core materials from geothermal systems in California, Hawaii, and Iceland. Most recently, I have participated - as a member of the United States’ scientific team – on petrologic studies of samples from the Reykjanes and Krafla geothermal systems as part of the Iceland Deep Drilling Project (IDDP).

My interests in participating in this workshop are both scientific – as described above – as well as organizational. I am currently the P.I. on a Planning Grant from the National Science Foundation to work towards establishing an Industry/University Cooperative Research Center for Geothermal Resources with sites at UC Davis and UN Reno. Since the proposed center entails extensive collaboration with the geothermal industry, I feel that it is important for me to attend this workshop.

2. Proposed topic for discussion at the workshop

One of the major findings of work on drill cuttings from the IDDP-1 was the recognition of a thin conductive boundary layer (CDL) between the rhyolite magma and the overlying, conventional hydrothermal system above. Cuttings from this <<30 m zone are compromised of granoblastically recrystallized mafic rocks which record peak temperatures in the range of 800-950°C, essentially that of the immediately underlying rhyolite magma. In the search for high enthalpy systems, this CDL would be the zone through which the magmatic heat source would be “mined”. The topic for discussion would focus on the physical and chemical properties of the CDL and how we could recognize this zone during drilling, prior to encountering the magmatic source itself.
A new strategy for geothermal exploration drilling based on using of an electromagnetic sounding data

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Electrical resistivity of rocks could serve as a convenient proxy parameter to be used for indirect estimation of the temperature, porosity, permeability and water saturation of rocks from the electromagnetic (EM) sounding data (Spichak and Manzella, 2008). In particular, the deep temperature estimation in the geothermal areas could be based on the recently developed indirect EM geothermometer (Spichak et al., 2007; Spichak and Zakharova, 2008). It could be used for the temperature assessment in the locations where the resistivity data are available (in particular, revealed from the magnetotelluric (MT) sounding data (Spichak, 2007a,b; 2011)). Unlike other indirect geothermometers it enables the temperature estimation in the given locations in the earth (in particular, at large depths), which makes it an indispensable tool in geothermal exploration of high enthalpy geothermal systems.

Optimal methodologies for calibration of the indirect electromagnetic geothermometer in different geological environments are developed (Spichak et al., 2011). It is shown that the temperature estimation by means of the EM geothermometer calibrated by 5-6 temperature logs results in 12% average relative error. Prior knowledge of the geology and hydrological conditions in the region under study can help to correctly locate the EM sensors with respect to the points where the temperature is to be predicted and thereby reduce the estimation errors additionally up to 10%.

Special attention was paid to the application of indirect EM geothermometer to the temperature extrapolation in depth (Spichak and Zakharova, 2009). The results obtained in the Tien Shan geothermal area (Spichak et al., 2011) indicate that the temperature extrapolation accuracy essentially depends on the ratio between the well length and the extrapolation depth. For example, when extrapolating to a depth twice as large as the well depth the relative error is 5-6%, and if the extrapolation depth is three times as large, the error is about 20%. This result makes it possible to increase significantly the deepness of indirect temperature estimation in the earth’s interior based on the available temperature logs. This, in particular, opens up the opportunity to use available temperature logs for estimating the temperatures at large depths without extra drilling.

The indirect EM geothermometer was used for the deep temperature estimations in the Soultz-sous-Forêts geothermal area (France) using MT sounding data (Spichak et al., 2010). The
vertical temperature cross-section was built up to the depth 5000m and used for determining the dominant heat transfer mechanism at large depths and constraining the location of the new geothermal well planned to be drilled in the area.

Using of the available MT and TDEM sounding data enabled constructing of the 3D temperature model of the Hengill geothermal area up to the depth 20km (Spichak et al., 2013). The temperature accuracy estimations indicate that at the lower boundary of the model the average relative errors are equal to 26.5%. Joint analysis of the temperature and resistivity models together with the gravity data enabled to reveal the heat sources and discriminate the locations of relict and active parts of the volcanic geothermal complex.

Thus, practical application of indirect electromagnetic geothermometer enables the most correct temperature interpolation in the interwell space; temperature logs’ extrapolation to large depths; constraining the locations for borehole drilling; determining the heat sources and heat transfer dominating mechanisms (Spichak, Zakharova, 2012, 2013). These properties give an impetus to propose a new strategy for geothermal exploration drilling based on the indirect estimation of the temperature and other relevant parameters from the electromagnetic sounding data and available logs. Its main elements are as follows:

- drilling of 5-6 relatively short boreholes (say, up to the depth of 1km) instead of one superdeep well;
- electromagnetic (MT/CSMT/AMT/TDEM) sounding of the study area;
- building of the 3D resistivity model up to the required depth;
- calibration and testing by core samples and logs available while drilling;
- building of 3D models of the temperature, porosity, permeability and water saturation up to the target depth.

This strategy has the following advantages in comparison with the common one used presently:

- the temperature and other relevant parameters are estimated in the volume bounded by the target depth and boundaries of the study area (instead of the length and vicinity of the drilled borehole, accordingly);
- the required parameters are estimated more reliably and with higher accuracy than in the case of a single well logs;
- joint analysis of the resistivity and temperature models enables to infer about the location of the heat sources, fluid circulation parts and water saturation;
- the drilling cost is greatly reduced since drilling of a few wells to a relatively small depth is much less expensive than drilling of a single one of the same total length (EM sounding expenses are two orders less than drilling costs and could be neglected).
References


Utilization of geothermal supercritical water systems

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Utilization of supercritical water from high enthalpy geothermal systems offers many opportunities for efficient energy production and chemical processing. For example, high conversion efficiencies result for co-generation of electricity and thermal energy in fully integrated cascaded systems. In addition, municipal and food waste treatment using supercritical oxidation processes and other industrial applications requiring thermal energy at high temperatures provide collateral benefits that would have a substantive positive impact towards achieving sustainable development. Furthermore, the presence of high temperatures provides advantages for advanced hydrothermal jet drilling processes that are under investigation in our research group at Cornell.
To whom it may interest,

I am Luca Urpi, a PhD candidate, currently involved in the GFZ-German Research Centre for Geoscience (Potsdam) in the Reservoir Technologies section/International Centre for Geothermal Research (4.1), with focus on induced seismicity during geothermal reservoir stimulation treatment.

My last research activity was performed in the framework of the European project GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs), a re-evaluation of geothermal drilling and stimulation treatment performed at different sites in various environment (Europe, Iceland, Central and North/Central America).

Induced seismicity monitoring and mitigation involves a wide range of topics, I am especially interested in the workshop offered because of the importance of the subject for future research projects. I will be in the US for the annual Geothermal Research Council meeting (Las Vegas), therefore I will require very limited travel allowance (if available).

A meaningful characterization of geothermal reservoir behavior requires a detailed knowledge of the in situ condition, the drilling itself being fundamental to obtain information about deep lithology, stress regime, fault/fracture presence and decisive in planning consequent logging and monitoring. For example, stress orientation in the well may change due to the tectonic setting and/or due to the relatively cold drilling fluid used, special well completion may help in planning subsequent surveys or monitoring experiences.

Drilling into high temperature rock presents the challenging topic of operating into rock that have a transitional deformation behaviour between brittle and ductile, too. Even solving the drilling challenges, how permeability can be present and/or increased in this rock is a challenging task, if the final goal is to exploit the geothermal resource, I think the theme needs to be addressed from the very beginning.

Thanks a lot in advance for your consideration,

Best regards.
Magmatic-Hydrothermal Transitions in Active Extensional Regimes of the Western U.S.

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The waters exploited in power-producing geothermal systems in extensional western U.S. settings are dominantly meteoric consistent with heat mining via deep circulation. While systems are numerous, net energy outputs are modest and almost always <100 MWe. However, geochemistry (especially noble gases such as \(^{3}\)He) often implies some magmatic input to such geothermal systems with a source presumably below the brittle-ductile transition. This suggests that high enthalpy volumes may be closely connected to some systems and these could represent next-generation resources providing a greater contribution to national energy needs.

Recent magnetotelluric (MT) investigations in the U.S. Great Basin are producing images that strongly suggest the presence of specific melt underplating or intrusion zones in the deep crust. Commonly these zones have steep, conductive slab-like structures extending toward the surface and connecting into high-temperature geothermal systems. The zones are interpreted to represent crustal scale fault zones joining the deep magmatic and shallower meteoric structural regimes and may locally have elevated brittle-ductile transitions. Dixie Valley, Nevada, perhaps the flagship extensional geothermal system of the Great Basin, is one example of such and also possesses elevated \(^{3}\)He values in wells. High-temperature fluids are brought near surface apparently in dilatent zones formed at intersections of NNE-SSW and NNW-SSE faulting trends.

To strengthen a conceptual model where magmatically sourced systems can be identified through deep geophysical structure, fluid geochemistry and conducive structural settings, the U.S. Dept. of Energy is supporting a new investigation of the McGinness Hills geothermal system in central Nevada (see accompanying graphics). Here is imaged a similar lower-crustal tabular conductor with connection to the system at surface. Structural mapping and modeling show permeability is created in an accommodation zone with NNE-SSW and NW-SE faulting trends. Well fluids were sampled for \(^{3}\)He in April 2013 and found to have elevated values of 0.35-0.57 Ra. Thus the confluence of crustal scale low resistivity, geologic structures favorable to dilatency, and magmatic fluid geochemistry confirm the means to identify magma-sourced geothermal systems. Dixie Valley was not an accident. Numerous other such geophysical structures are seen in the Great Basin, and around the margins of the Snake River Plain.

The exploitation of deeper (>3 km) geothermal fluids at supercritical temperatures is a holy grail of this renewable energy field given the marked increase in enthalpy recovery possible under those conditions. It seems compelling to drill an example of these geophysical structures to see if such conditions pertain. Efforts to drill beyond the brittle regime and even to magma are underway in Japan and in Iceland. There are some uncertainties in geophysical properties that only drilling is likely to resolve. For one, conductivity is high and suggests very high salinity to keep porosity to reasonable levels. This is unlike the fluids typically produced from the upper levels of geothermal systems (1-2 wt % usually). It may imply a geochemical disconnection between the upper brittle regime and the ductile domain below by a zone of sealing. A positive drilling outcome will advance understanding of magmatic-hydrothermal transitions and the prospects for deep geothermal resources.
Appendix D:
Workshop Notes (including workshop breakout sessions, an inventory of current community cyberinfrastructure resources and the results from the online community survey)

CYBERINFRASTRUCTURE FOR PALEOGEOOSCIENCE

FEBRUARY 4-6, 2013,
MINNEAPOLIS, MN
Conveners: ANDERS NOREN, JULIE BRIGHAM-GRETTE, KERSTIN LEHNERT, SHANAN PETERS, JACK WILLIAMS, EMI ITO, DAVE ANDERSON, ERIC GRIMM
Appendix B: Breakout Group Notes / Breakout 1: Scientific Drivers/Goals

Group 1

1 Times of significant change, include marine-terrestrial data
   i. Ecological data, animal and plant data
   ii. Geomorphic data
   iii. Tectonic data if time scale requires
      a We know subdecadal shifts occur for some organisms such as aquatic organisms
      b Need to look at ecosystem – integrate specific data –
         i. connect availability of food to geographic distribution of animals, etc
      c What gets included in the integration?
      d Data comparison needs cyberinfrastructure
      e Space and time
      f Deeper time climate change, e.g., Plio-Pleistocene – sensitivity of species, climate,
      g Look at extremes, e.g., PETM?
         i. Existing data about PETM etc., are not comprehensive
      h Are there systematic patterns to species response to changes?
      i. Chronology – How to anchor data?
      j. “Transitions” – see SGP workshop report;
      k. Evolution – what triggers rapid evolutionary episodes?
      l. Cyclic events
      m. Paleoclimate sensitivity – over the Cenozoic?
      n. Hyper global taxa mapper - visualization of biogeographical information for various paleo data from different areas for a chosen time slice; data linkage

2 Invasive species & species migration under climate change scenario. Look for past examples? Immigration followed by extinction of prior population
   a. Biology – paleontology connection; pre-European settlement of North America
   b. Connect to modern data (VertNet)
   c. Neoeconomists need paleoecology data to test their ideas and theories – (Anson McKay is working on a report from Paleo50 Workshop)

(Miscellaneous ideas below)

3 EarthScope-type questions: roles of tectonics vs. other factors in ecological changes
4 Global warming and changes in hydrologic cycles (intensifications predicted)
5 Seafloor data – sed core color record being compiled; good coordinates, major changes in colors – time correlation?
6 Linking datasets; some are more readily linkable than others
7 Phylogeography (involves DNA work – is this within GEO purvue?)

Group 2

Practical Justifications: for Earth Cube
- Not to duplicate data sets where not needed, but also to compare with data sets to cross validate reconstructions.
- Reviving older data sets – repurposed data to produce new information
Appendix B: Breakout Group Notes / Breakout 1: Scientific Drivers/Goals

- Improvement of Age models to get at rates, fluxes and events.
- Education and Policy choices driven by an acceptance of science data.
- To Challenge anti-science movement with real data bases
- Making science accessible to improve science literacy.
- Teaching of Earth as a system at youngest ages.
- Data bases to protect Scientific integrity and protecting academic freedoms.

ACROSS DISCIPLINES WITHIN GEOSCIENCES

- Geohazards -- with earthquake hazards and tsunami coastal hazards.
- Natural Resource management
- What is the sensitivity of the Earth system to CO2.
- What can the data tell us about scales and rates
- PETM context and how can we learn about rates and magnitude of changes.
- What is the sensitivity of the cryosphere to warming
- Testing assumptions of feedbacks and triggers for feedbacks in the system and tipping points. (eg. SST, if above 28 deg C, we get hurricanes forming every day).
- What critical climatic reconstructions are important to our current Economic models.
- Understanding Extinction Risk – biological and ecological databases and Deep Time
- Understanding local changes in global scales.
- Predictive models of change with synoptic scale changes.
- Climate change –and environmental change
- Ecosystem processes (and resilience).
- Synergistic efforts to look at regional to global earth system.
- System level responses to change
- How do we tease out changes in seasonality and
- Scalability of Ecosystem and Climate processes – moving to continental scale changes.
- Global to local scaling on hundreds to 1000s of years, 200 yrs
- Human influences on the Earth system.
- Are there early warning indicators in climate transitions and tipping points?
- Example of deeper time food webs that inform us about today. This connect us with the biological community.

ACROSS DISCIPLINES OUTSIDE GEOSCIENCES

- Planetary studies of life in extreme environments -- astrobiology
- Biogeography of Diseases and Human Health.
- Threat multipliers in stability of societies—water, food production etc.
- National security issues of these changes.
- Influence of Climate change on human diaspora.
- What drives speciation and extinction in life history traits? Integrating geological data and that of a highly managed landscape. What is ecosystem or individual species resilience to change.
- Anthropogenic impacts of resource use and sustainability.
- Risk assessment and insurance industry

Group 3
summary statement
The challenge is to understand future change in the coupled earth system and particularly to understand biological change. Improved understanding of the biological response to change, from the organism level to population level (including extinctions), has value beyond our field, for example conservation biology and sustainability. Paleo adds to understanding the current state, because the current conditions are already perturbed. Also, paleo is needed for the successful modeling of the coupled system. (the observations at the system level are inadequate, too sparse in time and space). An integrated archive can help reduce uncertainty and noise with a multiproxy, multi site network, improving over our current tendency to analyze single sites and single proxies.

other points
Much data can be gleaned via OCR of documents, in addition to analyzing tables of data. Collaboration tools can accelerate the development of process models integrating software tools and data allows reconstruction from raw to be improved an integrated archive is more valuable for education, teaching Earth as a system

1 what is the biotic response to change cannot get this by looking at the modern its perturbed, this was made by conservation biology documents
2 (see detelon documents)
   a there are three values in paleo, one is that its better than the current state, or different, the second is that its needed for models, the third is that some processes occur too slowly, another is that only in the past are the driving changes large enough to see cause and effect. Furthermore, multiproxy views are a way to beat down noise and uncertainty.
   b with cyber we can turn the crank from raw to reconstruction many times.
   c there is educational value in bringing these data sets together. Education means teaching systems thinking.

Group 4

OVERARCHING GOALS:

A 4-D framework for life and its environment.
● Everything else we want to do emerges from this overarching objective.
● Across all time scales, regions, taxa, physical & geochemical properties, etc.
● Extract from this the state of system at a spatiotemporal moment of interest and the rate of change
● Fundamental geoinformatics issue of time - estimating it, relative vs. absolute time, accommodating continuously improving age models, etc.

EXAMPLES:
PALEOBIOLOGY:
4-D visualizations of species distributions in space and time. Globally – across all time scales, taxa, regions.
Abstract from this information about species richness and beta diversity
Cross-linking of those distributions with climate/environmental changes.
Appendix B: Breakout Group Notes / Breakout 1: Scientific Drivers/Goals

EVOLUTIONARY TREES
Cross-linking those 4D species distributions volumes to an evolutionary/phylogeographic and “phylochronologic” structure.

PALEOCLIMATE
Characterizing modes and patterns of climate variables and variability across space and time. Thermohaline circulation, ENSO, ocean biogeochemistry, etc. Rates of change.

WAYS THAT WE COULD SUBORGANIZE WITHIN THIS BROAD 4-D FRAMEWORK
   By scale of science and synthesis: individual PI labs vs. multiple labs working on common materials (e.g. cores) vs. large-scale data-data and data-model syntheses
   By timescale:

Educational Challenges & Opportunities
Caution: Challenge of all-virtual education. Still want students to go out the field!
Opportunity: Changing the way we teach. Making it more data-problem solving as opposed to observational/field work.
Environmental literacy.
Creating virtual on-line packages for teachers.
Make it easier for students and students to find/search/get data. Access to model and emblematic datasets.
Give students access to data – standard exercises using core data. Give them a starting point and a guided inquiry?
Tie products to national standards.
EdGCM. Enable paleoclimatic data-model syntheses.
Storytelling. Stories about how science is done. Linking personal bios and field expeditions to online datasets.
Thermohaline circulation. Discovered by soundings of oceanographic observations.
Evolution of climate system over time - ENSO over time.

Question about ethics: ok to put digitized data in database? Yes.

Policy Connections
Tipping points and rates of change.
Climate variability.
Climate adaptation

What Group 4 considered to come up with ideas
Who outside the field uses our data?
Geophysicists — accessed Paleobiology database so that they could constrain marine sediments/distribution in past.
Climate modelers — data/model comparison. How does our model work? Sensitivity experiments with models.
Ice sheet modelers
Ecosystem modelers (e.g. Paleon, tree-ring)
Ocean modelers
Evolutionary biologists – Classically molecular clock & divergence data. Now also Matching it up to isotope data and records of earth history.
Biogeographers – patterns and drivers of species diversity, species range size, genetic diversity, etc.
Proxy calibrators - people using modern calibration datasets and proxy records to make empirical estimates of past temperature, CO2, etc.
Geochronology: Constrained optimization & fossil groups – age modeling. Using biostratigraphies, isotope stratigraphies, paleomagnetism. This is an internal/feedback loop.
CO2 uptake & Global carbon cycle. Can we trust ecosystem and climate models to make predictions for future? A lot of hindcasting

How representative are two sites? Is Coral/Cave/Core X representative?
Is absence in fossil record diagnostic of absence of species?
Optimized site selection? Where do we core next? Analog in seismology and station placement.
Avoid repeating of coring at same place. More efficient uses of resources. Right now its all word of mouth. Lots of unused cores waiting to be analyzed.
Extreme events
Legacies - how systems are shaped by past events?

Notes - Frank Rack’s overview
Goal: regional and global syntheses of data
Bridging of disciplines – linking to ecosystems.
Shanan: Material fluxes in and out of crust. Be able to excise real estate from crust and characterize it – biological properties, geochemical properties, age distribution of sediments, interpretative ability.
Climate change – biological diversity, global carbon cycle – transparency and repeatability
Scientific Questions aren’t new – ability to answer them is new.
Challenges: Ease of access.
Providing collections with explanations for educators. Make implicit & expert knowledge available.
Metadata. cores
Updating datasets as e.g. new age models become available.
Citing data. Giving credit to data creators. Impact factors.
Group 1:

DATA ISSUES:
1. Availability or discovery of Legacy data
2. How do you find “right” repository for different data sets.
3. Unpublished data -
   a. Community Standards- Peer Review
4. Repository & Databases… --Continuity/ Persistence/ Maintenance/Sanctioned
5. Individual Expertise and Persistence essential in building reliable Databases. Automation and "crowdsourcing" don't work.
6. Issue of misuse of publicly available data.
7. Adoption and application of standards for data formats across disciplines
8. Integration of data and metadata
9. Inter-comparisons of datasets
10. Descriptive Field Data-- eg..Paleogeographic maps, stratigraphic sections, thin sections, etc., are not in databases
11. Concerns about making data easily available without "context' or "expertise" --

TOOLS:
1. Conversion of data formats (multiple formats for same types of data, e.g., tree ring data)
2. Visualization tools -- time and spatial scales, age models, integration.
3. New Level of Tools for Educators… eg...SERC…

EDUCATION:
1. How to create Education "products"
2. Data vaults or archives are not built for education …

SOCIAL POLICY :
1. Support, Time, Credit, Reward…
2. Time spend on researching data vs… time spent on contributing data.

GROUP 2

• Incentives for participation – citation of data; engage publishing outlets (incentivize them rather than get them mandated)
• Incorporating legacy data
• Dealing with calibration of data
• Dealing with shifting standards (age) or opinions (taxonomy) – tracking primary data
• Having a group responsible for producing and distributing data product, particularly outside communities (both research and education/policy)
• Cost
• Change in culture to working within a cyberinfrastructure
Group 3

Inside the Geosciences

1. Gaps in creating the databases or a lack of a place where to put data for “your proxy”.
2. We can put data into a database but we can’t get it out.
   a. Egs is the NOAA database Paleoclimate for corals. It’s a flat database for quick filing of data for access. But it would be nice if the data are also updated (maintained) and also incorporated into a searchable structured database (igsn fabric).
   b. Need a place for flat files and also databases for structured data.
3. Does the right interface exist and people don’t know about it or do they not exist.
   a. The Chronomid workers have not organized within Neotoma.
4. We need a standard template for inputs for non-programmers to submit data. The system can’t be too fancy because there are no staff to support that. But these data could be sent in parallel to both flat file and structure systems where it serves a purpose.
5. Long time maintenance of funding is the big elephant in the room. Yet there are Twin elephants. We also need the interface that links data for searching. Need meta data to provide the links. Currently we are funding undergraduates to log in data in chunks. EarthCube will help change the culture about data and data funding.
6. Need good visualization and storage tools that reap rewards for the scientists.
   a. If you would like to have all of your proxy data electronically prepared for a database. How does this person get funded for that purpose, because it’s the first thing that gets cut from the budget. Universities have techs for this but you have to pay in to get their time and they are not specialists in what the data means. THIS IS A COMMON PROBLEM.
7. Need Geo Identifiers that follow the data no matter what so there is no anxiety about sharing! Some users will acknowledge the data base source but not the original researcher. So this inhibits sharing.

We need to rethink the moratoriums on cores and data. And there should be a means of accessing all of the data completed on that core via the repository. Making the link between what has already been done on the core materials and what is not published should assist. How to enter into a database that a sample was taken but analyses are still ongoing.

8. We need mechanism for citation index of data sets and data products.

OUTSide the Geosciences

1. How do we make the data accessible for non-specialists to do novel new things.
   a. We want people to make novel new discoveries – and new data products.
   b. There is Taxamapper in Neotoma, so you can map a taxon over time and . If you were a researcher you have to look at the dots and the data but a map gives a visual means of
accessing the results of existing databases. This is an education tool and a research tool. Conservation biologists are using Faunmap.

c Isomap data products are routinely used by ecologists, forensic scientists in ways not originally envisioned.

d Space Science and Engineering needs to make searches of data easier to use for the media or educators people can find maps ear

2 In biology, everyone puts their data in GENBank because there is the community recognition for the value for having all of your data in one place. All sequences are giving identifier with the citation information. In the Encyclopedia of Life, it required all sorts of layers of attribution.

Group 4

- Museum collections (physical samples) lacking geospatial data – sample location described but not lat and long; a large time sink searching through old maps, field notes, lithology, archaeological site, etc. Level of precision shifts with time of sample collection.

- Funds have to be available to convert legacy collections so they can go into databases; targeted data rescue projects – funded projects. How to prioritize? If people don’t know these samples exist, they don’t know what questions can be asked; we don’t know questions that future researchers might ask - importance of sample archiving. Poll disciplinary society members for suggested priorities? Cost of analysis is high, to reacquire samples and repeat analysis is very costly. This cost is not readily understood by people outside the immediate discipline and this needs to be advertised.

- Legacy data – time sink; needed support for bodies; community buy-in needed not just for legacy data but to enter data. Feedbacks from community, more immediate the better.

- Individual labs data management – time sink populating information needed to upload data. Time needed for data entry is generally not included in proposals; NSF has not really come to grips with this cost. Large projects such as NEON and CZO have requirement for Data Manager, but smaller projects can’t.

- Provide carrot: access to other data from the region, etc.

- More education: start early (students) with IGSN, etc.

- Free data access implies data are not valuable - difficulty obtaining appropriate support, reward

- Data storage is becoming expensive. Institutional servers are asking for monthly fees – new development. Data storage required, but cost of that is generally not taken into account initially. Commercial enterprise can support data storage for a cost. Government enterprise such as EarthCube is underfunded. Purpose of EarthCube vs availability of cyberinfrastructure. The needed cost vs. benefit arising from that cost.

- “Management” needs to be told about cyber infrastructure impediments (not technology but funds to hire programmers).

- Community of paleogeoscientists needs to organize better and become less territorial. Can EarthCube help broker breaking down of fences? These artificial fences exist within funding agencies, also. Importance of 4D coordinates; Some culture shift may occur naturally with new generation who take sharing as normal MO. Target date for RCN proposal is very soon, but if this group decided to go for it, this exercise will help start the process of breaking down barriers (Quaternary, deep time, sample and data types).
Appendix B: Breakout Group Notes / Breakout 2: Impediments

- Governance – who speaks for us?
- International collaboration – who plays leadership role?
- RCN can address this.
- Cross discipline fields - where funding sits and where researchers sit.
- Climate modelers don’t have to worry about data sharing because the organization such as NCAR takes care of it.
Working Group 1 - Needs

Highlights

Technical Needs

  Leveraging Existing Capabilities
  EarthCube as platform for package development

User Needs

  4D data capabilities specific to Paleo-geoscience
  Diversity of data set & research areas within Paleo
  Need to allow flexibility for future needs that we can’t predict

Milestones & Metrics

  Getting live as quickly as possible (skeletal version)
  Targeting low-hanging fruit for quick return on investment

Technical Needs

  Build on existing efforts rather than start over from scratch (Federated approach)
  Challenge and Opportunity of the diverse research areas within paleo-geoscience
  Get databases linked
  Knowledge transfer between DBs for construction, integration, and brokering

1. Resource Evaluation – need for RCN on this
   a. Reduce redundancy
   b. IDing data types
   c. Resource state - Funded and growing? Stagnant?
   d. Data format
   e. Metadata documentation?
   f. Identify gaps
   g. Evaluate data types
   h. Determine methods for integration

2. Technical Evaluation
   a. Dependent on Step 1
   b. Open source tools v. proprietary tools evaluation
   c. Exposing resources in a way that is decoupled from resources
   d. Web-service output standards to allow for integration (Exposure)
      i. Space-time
      ii. Taxonomic
   e. User-cases

3. Technical Implementation
   a. Develop middleware – handshaking between resources
   b. User Interface
   c. Queries

- Age Model component needed for Earthcube – spatial context relatively easy, time component more challenging and subject to change (more interpretation involved)
- Result focused (knowledge) queries over inventory focused (prevent data overload)
- Knowledge level allows greater horizontal integration – works for research & integration
- Allow flexibility for users to identify future needs that aren’t necessarily part of the original design
- Identifying derived products for paleocommunity
- Package development by experts – coordination of workshops to develop educational products within the EarthCube platform – Google Maps as an analogy or R
  - Creates governance issues (Apple v. Android models)
  - Develops community aspect of project
  - Work to lower bar to entry
  - Requires outreach to different communities (educators, etc…)
  - Means we don’t need to identify all the needs up-front

Service oriented architecture
Identification of standards of basic data types (time series, … )

User Needs
Emphasis on Space – Time (4D) as the primary goal/target for Paleo-geoscience community
Want to make maps in time and combine info on them
  - Basic mapping capability
  - Animations in time (for education and on-line journals)

Simpler User interface than is available from some commercial software (i.e. ArcGIS)
Code Library – many already available
  - MatLab code
  - R code

Simplify data submission/acquisition process
Analytical capacity
  - Correlation analysis
  - Time series analysis

Ability to keep the data living as age models, interpretations, etc… evolve over time
Some sort of referencing system for code development and/or data for tenure negotiations etc…
Basic minimum meta-data standards with optional refinements possible
Need for collective resources in order to discuss system-level processes

Milestones & Metrics
Goals list for defining success of project
  - How much effort to devote to dark data
  - How much effort to harvesting info from structural geo maps, etc…

See Evaluations above (assign timetable) 1 yr? 18 months?
Development of central code hub early on
Get live with something as quickly as possible by leveraging resources we already have
  - Generates community involvement quickly

Data Acquisition & Submission efforts
  - improve outreach
  - reduce barriers
  - educate stakeholders

Dark data recovery as secondary step

Strategies for RCN & motivation
EarthCube Cyberinfrastructure for Paleogeoscience Workshop Report
Appendix B: Breakout Group Notes / Breakout 4: Needs

Link to Bioscience directorate
Emphasize 4D
Emphasize Climate
“How History of Life and Environment”
Links to Natural Resource Management & Geohazards

breakout four, needs prioritized
started with Anne describing how data conservancy preserves the long tail, all those little data efforts and individual PI data empires. Randall- data conserv could be a back room part of earthcube.

what about tools and models. from the user perspective. discussed personas.

how do we help the non computer literate person outside our field to explore the history of the earth
-you need products, similar to the droughtmap produced by operational center, the products need to be high level, refined, self explanatory
-assume some computer literacy

mark says we dont need the communications products like info about the sixth greatest extinction

mark says the super savvy want the lowest level data level zero, because they will write their own software

Lets concentrate on the tools to get the data out. Consider tapping all the levels of the data (raw, level 2, level 3). Beware the IODP experience, so hard to get the data out. the data are easiest if you only need to go to one location, or provide a hub,

design for what is coming out two years from now, not what is available now.

reduce the impact of the number of portals, so that its not such mess that you do not know where to start. There might even be more portals, but the key is, this does not get in the way or make it harder. Further, people like their own portals, for example the chemist outside our field, uses his favorite portal to access the history of the earth data

we dont have consistency of formats yet, once we have this it will attract the software people and engender greater use.

All these data are time series. We need to build off the corewall idea to show time series as a general application. And it should be flexible with a search capability. And really, we need four D tools that show lat, lon, elevation, and time

Lets catalog our efforts. lets implement sample numbers throughout the paleogeosciences lets push the journals to implement archiving expectations and standards, this has additional advantages, incorporates a level of quality control, casts an international net, increases visibility of the data
mark- does NSF need credit for past efforts, like the pliocene and esh projects that ended

mark- tools to see a portfolio of your own data, projects data- how often is it used,

dave- we need to produce the data that calibrates and tests and validates process-based models of the coupled earth system

paleobiology database has strong mapping capabilities, the big thing is combining time to extending existing products to show changes through time.

julie wishes we could see in a window above tilia an image of the forest, like a picture of the forest, changing through time as the cursor moves downward on the graph in Tilia. Mark says animation is phenomenally difficult. So we need movies of the earth changing through time. they can be animated or pictures, but they need to be movies that are visual and impactful

the easy low hanging fruit on the road to buy in is to get people people credit, first for their one thing in the database, and the second is to include citations of all data as supplemental information, in such a way that it gets into the citation index

randall says there may be different solutions for different things to cite. each data set gets a unique identifier

anne says publishing data is good because it fits into the existing system, lisa says it would work for alot of people, mark says it stops the dark data path by getting things out there, randall says their are problems if you republish stuff, chop it up, it also gets more data out there, for better or worse

Summary
First thing we expose the long tail with a vigorous catalog and outreach effort, and then everyone knows about all the great stuff going on. Use increases.
Then we implement the sample identifier IGSN broadly, leading to more credit for paleogeoscientists, broader use of our physical samples, a deterrent to hoarding. The IGSN implementation extends emerging catalog interoperability down to the sample level.
Catalog interoperability is established. Many portals exist but they do not hinder you. Our data goes out to portals in other fields, for example a chemist using his favorite portal finds information about changing earth chemistry thru time.
'What Doug said' leads to an distributed database of observations of past earth climate, environment, and biotic exchange. Individual databases remain, their schemas intact, and ontologies translate among them so that all the data can be used together. Plenty of funding ensures these individual databases improve in quality and impact.
Methods to analyze, visualize, and display time series grow and become more powerful. Products (high level, not needing specialized knowledge) are developed, communicating the history of earth change to those outside our field. The data become rich enough and a four D capability to slice and dice and interpret in four dimensions (latitude, longitude, elevation, time) is developed and linked to the new software tools developed within and outside our field. A movie capability is developed, becoming the
premier way that our scientific results are understood by a non-scientist audience. As an early example, one sees the cursor moving down a tilia style pollen graph as a movie or animation of the changing forest, pictures of trees, plays above.

Working Group 2 - Needs

within your discipline

- Data semantics: established standards; geological ontology that cut across all concepts
  - geologic time, location, lithology
  - mapping between terms; build background knowledge base, subset of; part of; nuanced relationships
  - Age models tied to samples and data
    - Tools for tracking interpretations by users
    - Tools for updating for new calibrations and new time scales
    - Tools for indicating age uncertainty (which needs to be defined)

- Data availability: minimum community requirements for uploading structured data (e.g., GenBank)

- Database stability: Decision on centralization of data repositories to ensure their long-term viability
  - Prioritize which should be centralized physically and others that are accessible through central web resource
    - Concern about continued support/accessibility of distributed databases

- Curation: Lack of direct funding to manage research/legacy and “private” collections
  - Need a funding line independent of host institutions
    - Build more unified geoscience constituency to push for funding
    - Identify broad community benefits (predictive climate/biological models depend on deep-time perspectives)
      - First get funding to create metadata
      - Funds for curation/cataloging

- Tool: Project management software for small labs to create tools for tracking and uploading samples (e.g., CoreWall)
  - Facilitates collaboration of small groups
  - Saves time creating

- Workshops, education training for best practices

- Tool: Taxonomic/identification software aids to improve scientific reproducibility
  - Improve stability of concepts through image libraries, descriptions
  - Community updatable

- Programming applications: central repository for programming code, open source code

- Organization of geoscience disciplines under umbrella groupings where there data of mutual interest
  - Group the database lists under geoscience subdisciplines

- Visualization tools:
  - GeoWall imaging of data plots tied to archive sediments vs. sampled sediment, individual samples
    - Data distribution/availability spatially and with time
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Appendix B: Breakout Group Notes / Breakout 4: Needs

- Modeling: link geospatial data with GPlates
- Modeling: Process based niche models that link organism distributions, paleoclimate reconstructions using empirical data

Measurements of success
- Cultural changes; % compliance with uploads
- Success with data miners discovering dark data (by date)
- Rate at which new data discovered levels out
- User-based success particularly for non-specialists
- Teachers using search results in lessons
  - Number of datasets cited in individual papers
  - Reproducibility of results from published analyses
- Taxonomic studies difficult to assess
  - Number of community workshops, students trained
- Coursework on data management, informatics approaches in geosciences as a requirement for student graduation

§ Need better metrics to track

Working Group 3 - Needs

Community Global Ecosystem/Biogeochemical Model (to complement global climate and ocean models)

Community Gridded Climate Data (finely enough gridded to pick up elevation data) – Neotoma calibration purposes – gridding and contouring tools (PICKLE – grids that and it becomes accessible to R and Python)

Data on data sets available around a particular research (data mining tools to build this?) – searchable set of databases

Age modeling – dynamic updating?

Database of databases – Where to reposit? Where to obtain data? Searchable, thesaurus

High-resolution geologic maps, organism distributions, interpreted values (e.g., summer temperature, etc.), plate reconstructions

Archive services? – part of publication process – updating latest image is much more important than state-of-the-art in the past

Archiving software; archeological reconstruction for existing data repositories

Physical data and sample repositories
Semantics requirements? – taxonomy (GNRD – taxonomic name finder) – tied to images? – stratigraphic semantics

Automatic updates of data products

Standards for metadata

Availability of educational/outreach products

Sustained access to databases through their lifetimes

**Working Group 4 - Needs**

**Highest Priority**
- Central place for data discovery
- Searchable catalog of resources

**Data Discovery & access**
- Access/archive all materials used for a publication for reproducibility
- Discovery of ‘near-by’ datasets
- Sample repositories
- Standards for metadata in data reporting

**Data products**
- Global biogeochemical model
- Gridded climate data for calibration purposes
- Faster and automated update of data products such as models and maps
- Age models, new calibration standards, store parameters for age models, re-generate age models automatically after new calibration is published
- High-resolution maps with integrated data (e.g. distribution of species)
- Educational products and modules

**Other Needs**
- Structure/mechanisms to ensure sustained accessibility of databases that are discontinued
- Semantics: History of taxonomy, organism names, parameters, stratigraphy (Chronos, EarthTime?)
USE CASES PALEOBIOLOGY

A data product – a global 3-D Wheeler diagram with all data populating the framework available

Identifying hotspots of information and gaps in information

Accessibility at hand (e.g., in the field)

Link fossil data to tree life

Use case: mammals and tectonism

Experimental framework requires reproducibility – in historical terms, comparison of recurrent similar/comparable events

Paleo brings time to the table – a framework that allows causal hypotheses to be tested and relationships to be recognized/visualized

Derived products are what we use from others in our own research

Dynamic syntheses and dynamic calibrations – data products on the fly rather than static standards

Multiple scales in space and time

Preservation of current state in rock record – inversion of fossil to state at a moment

Role of models in forecasting – an ideal Earth history framework provides the basis for comparative studies, but also incorporates model outcomes as well as direct measurements of the world

Brief Title: A Community Earth-Life System Model

Scenario Goal: A community-based Earth-Life system model that dynamically generates a data product synthesizing environment and biology in a temporal and spatial framework (4D). The model uses data assimilation to dynamically update products and allows access to the underlying primary data.

Utility of Scenario: Such a framework would highlight data hotspots as well as baldspots for future data collection effort. A comprehensive framework would allow comparative studies that are the basis for testing causal hypotheses in historical science. The critical societal need is a model that can forecast Earth-Life system response at multiple scales into the future.

Bulleted List of Needs:
Appendix B: Breakout Group Notes / Breakout 5: Scientific Scenarios/Use Cases

- Access to existing data
- On the fly assimilation of data/data product
- Expert knowledge base and training

Bulleted List of Results/Deliverables:
- Extinction prediction
- Climate/Sea level prediction
- Reference/context of a point observation
- Accessibility of knowledge
- Accessibility of methodology (alternative)
- Intuitive result-focused visualization tools (research and education)
- Accessibility to data and experts who generated it

Graphic:

Paleoclima
Gabe Bowen, Mark Chandler, Josh Feinberg, Ben Hardt, Brian Huber, Xiaoming Liu, Jessica Whiteside, Jack Williams

Specific Use Case:

Limnology example:
Project Planning: EarthCube allows you to determine an optimal site: where in a region no one has cored before, or where models have an ambiguity in time or space.
You upload your data to relevant EarthCube repositories as it is collected in the field and in the lab. The PI has the option to not make the data available to the general public (to embargo the data until it is published).
You have a chance to compare your data to other nearby cores and GCMs that have been run for similar time periods.
Secondary software, hosted by EarthCube allows you to use pollen data from your core allows to reconstruct paleo-vegetation distributions through time with uncertainties for statistical analysis. Age models and their uncertainties would also be included, and would use the most up-to-date timescales and standards. This allows times-slices to be rapidly created using standardized data.
Modelers can be automatically alerted to your new data, and incorporate it into their models (once it is released by the PI).

Fundamental Idea:

Seamless movement between data and models…
Integrated Earth systems models (interlinked atmosphere, ocean, biosphere) that are built up iteratively to fit available data that is assimilated continuously from multiple data networks.
By incorporating long-term feedbacks, and transient processes that occur on timescales of 100s to 10,000s of years, we be able to reasonably constrain and forecast the effects of the current carbon cycle perturbation on changes over the coming decades and centuries to temperature, sea level, precipitation, storm frequency around the globe.

- Standardization of paleoclimate data (e.g., units, uncertainty) to allow for rapid incorporation into Earth System models.
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Appendix B: Breakout Group Notes / Breakout 5: Scientific Scenarios/Use Cases

- Translation of data proxies to actual environmental parameters (more comprehensive, consistent metadata to allow integration of information from experimentalists into Earth Systems models, and vice versa). E.g., inclusion of isotopic tracers or regionally important pollen into the Earth System models.
- We’ve done short-term modeling of short-term feedbacks (decades or less) Try to capture transient phenomena (100s to 10,000s of years processes, e.g., dynamic vegetation, carbon cycle events)
- Focus on the important transition zones that capture dramatic events (last deglaciation, PETRM)
- Low-effort derived data products – e.g., sea level curves, temperature models

**EarthCube’s role is**

- Organizing standardized data from relevant communities.
- Creating feedback loops that allow communities to fill gaps in temporal and geographic data.
- Fostering tiers of data products
  - 0th order tier: paper
  - 1st order tier: database of similar papers
  - 2nd order tier: derived parameter from previous database to be fed to Earth system models
- Translating data from a variety of communities into a format that is directly related to a specific paleoclimate question.
- Establishing doors for collaborations between modelers and experimentalists.

SynTrace model – 22,000 years

Data Model Simulations – Pick among models that achieve agreement with existing data. (Iterative Ensembles)

Models should initially use boundary conditions derived from data, but ultimately

**Service to Larger Community**

Climate science relevant to policy
Resource management
Education
Strategic science planning

Breakout session 5 - CURATION USE CASES

(K/T, Younger Dryas)

1. POC:

2. Major Earth-Life Transitions

3. The goal is to facilitate research and education that increases the understanding of the Earth system’s response to major transitions in Earth history at all time scales from decades to millions of years. This comprises investigations that synthesize data and samples from the ecological, biological, geological, and oceanographic Earth record.
4. Enable predictive science, policy decisions, funding prioritization, training new workforce, applied resource management

5. What is needed:
   - Global Access to Global Collections: establish repositories for all samples, establish network of all collections, link samples and data (IGSN)
   - Digitize all physical collection and make them accessible through searchable catalogs that contain comprehensive metadata and link to data
   - Develop 3D visualization tools of cores and other samples (visualization of sample, thin sections, smear slides, etc.) that allow to
   - Access to collectors for questions, social networking
   - Access to all sample-based data

6. Set new work into context of existing
   - Fully digitize
   - Enables serendipitous discovery of patterns
   - Adds on to existing data
   - Mobilize inaccessible data and samples

**EarthCube Scenarios: Paleoceanography**

1. Point of Contact (POC) for the scenario, institutional/group affiliation, and POC contact information (i.e., email, phone, URL, etc.): Some graduate research team.

2. Brief title Reconstructions of Global Ocean Circulation (4-D) during every Interglacial of the past 4 million years: Scenarios for the future.

3. Scenario goal: The goal of this research is to develop very high-resolution accurate data and animations of every interglacial on a global scale. This work will inform policy and management to narrow uncertainties about the warming world. Also to optimize future economic and social planning (reach consensus quicker and at global to regional scales). The real question is how much resource should be used to tackle the problems of global change.

4. 2-3 sentences on why the Scenario is useful to your science and/or the broader geoscience community. These data would allow us to narrow uncertainties in global scale resources to better achieve sustainability - healthy, well-balanced economies and societies.

5. Bulleted list of data, observations, tools, utilities, models, etc. required to accomplish the work, with a note indicating those that are not currently available or that are not accessible to you and why.
   - Use existing data set to determine spatial gaps in core and or data acquisition.
Use EarthCube data to expose sections of data that don’t fit into prevailing consensus – highlight what the anomalies are, where they are and what they are telling us.

- Strong geochronology perhaps based on Paleomag, Oxygen Isotopic ratios, tephra etc needed to inform us of rates and age uncertainties
- Biomarker of various types that provide SSTs and sea ice distribution
- Ocean chemistry data – improved proxies (sediment redox/color and mineralogy with other isotopes)
  - Sea water carbonate chemistry – Mg/Ca and Boron/Ca isotopes,
  - Models of gateway changes and influence in ocean circulation
  - Hydrologic proxies - Process models of P-E. (including monsoon changes, lake level changes over time)
  - Improved use and understanding of scanned data – XRF for example.
- Models of ocean circulation – have to be transient models changing through time.
- Atmospheric CO2 proxies
- Improved model/data iterations – rapid model evaluations

6. Bulleted list of the expected results/deliverables (i.e., conclusions, models, studies, data products, conclusions, etc.) Ultimately! -- Develop products that allow scientists to get to the answer quicker. How does oceanography work!

- Derive a better understanding of the global system machinery with the interglacial changes as levers that help us understand climate dynamics and vulnerabilities.
- High resolution reconstructions of paleoceanographic changes that converged on synthesis
- SST production, Fluxes, pCO2 estimated and averaged
- Aggregation of available data on each of the interglacials

Scales matter so we have to trust proxy calibrations to input data into models

7. Graphic illustrating project workflow, a model of what you are studying, or some other visualization that might help us understand your Scenario or its products (optional).

StoryCore Elevator Story….
Young woman at UMN and she has a busy day, she visits a core site and does work for a class and uses cyber network to work on her thesis with a Title Too Little Water: Climate and Changing Hydrology. At night she is giving a talk at the library. She collects her data in the field, assigns her IGSN’s to the samples on her iPhone. Within minutes her data is available on Corewall and modelers everywhere know about the data. She contacts modelers who produce her animation ##.

The earth as a system of wheels and levers to show how data flow creates these product that inform policy and management.

Other NOTES:

This has to be a story that we can tell in 30 seconds in the elevator so you can visual.
## Appendix C: Paleo Community Cyberinfrastructure Resource Inventory

This inventory was populated by the steering committee, online survey, and workshop participants during Breakout Session 4. Participants agreed that this list represents only the most commonly-used subset of available resources, and does not fully characterize these resources. Conducting a full inventory of resources, and a detailed characterization (from both scientific and IT perspectives) of the data types, formats, and their methods of exposure was identified as one of the primary next steps required as the paleo community moves forward with efforts to link these disparate data.

<table>
<thead>
<tr>
<th>Resource Name</th>
<th>Resource Type</th>
<th>Data/services offered</th>
<th>Communities served</th>
<th>URL</th>
<th>Contact</th>
<th>Comment/Relation to other resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlgaeBase</td>
<td>database</td>
<td>terrestrial, marine, freshwater algae image library and information</td>
<td>evolutionary biology, paleoclimatology</td>
<td><a href="http://www.algebase.org/">http://www.algebase.org/</a></td>
<td>John Wehmiller</td>
<td></td>
</tr>
<tr>
<td>Aminostratigraphy database</td>
<td>database</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animal Diversity Web</td>
<td>database</td>
<td>basic zoological and taxonomic data</td>
<td>evolutionary biology, general public</td>
<td><a href="http://animaldiversity.ummz.umich.edu/">http://animaldiversity.ummz.umich.edu/</a></td>
<td>Peter Gell</td>
<td></td>
</tr>
<tr>
<td>AQUA-IPACs</td>
<td>database</td>
<td>multiproxy paleodata for Australia</td>
<td>paleoecologists</td>
<td>playstudio.com/aqua1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BugCEP Coleopteran Ecology Package</td>
<td>database</td>
<td>research and teaching aid, data and tools</td>
<td>paleoentomology, entomology and ecology</td>
<td><a href="http://www.bugcep.com">www.bugcep.com</a></td>
<td>Doug Fils</td>
<td></td>
</tr>
<tr>
<td>CHRONOS</td>
<td>database</td>
<td>Foram, forams, foraminifera</td>
<td></td>
<td><a href="http://www.chronos.org">www.chronos.org</a></td>
<td>Doug Fils</td>
<td></td>
</tr>
<tr>
<td>Chronos Neptune</td>
<td>database</td>
<td>microfossil age /geography distributions + deep sea (OSDP, GDP, JODI core ages</td>
<td>all deep sea research communities</td>
<td>portal.chronos.org/gridspire/gridspire/fc/desearches</td>
<td>Doug Fils</td>
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<tr>
<td>Chronos Taxon Atlas</td>
<td>database</td>
<td>taxonomic atlas for planktic foraminifera</td>
<td>biostratigraphers, paleoceanographers, paleontologists</td>
<td>portal.chronos.org/gridspire/gridspire/fc/desearches</td>
<td>Brian Huber</td>
<td></td>
</tr>
<tr>
<td>Climate Explorer</td>
<td>database</td>
<td>KNMI Climate Explorer. Serves meteorological and 20th/21st-century climate data</td>
<td></td>
<td>dmlenw.knmi.nl</td>
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<tr>
<td>CMIP5 (Coupled Model Intercomparison Project)</td>
<td>database</td>
<td>promotes a standard set of model simulations</td>
<td>WCRP etc</td>
<td><a href="http://cmip-pcmdi.llnl.gov/cmip5/">http://cmip-pcmdi.llnl.gov/cmip5/</a></td>
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<tr>
<td>CoCoRaHS</td>
<td>database</td>
<td>precipitation monitoring</td>
<td>citizen science</td>
<td><a href="http://www.cocorahs.org/">http://www.cocorahs.org/</a></td>
<td>Mike Benton/Phil Donoghue</td>
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</tr>
<tr>
<td>Date A Clade</td>
<td>database</td>
<td>static and dynamic databases of fossil calibrations for molecular divergence</td>
<td>evolutionary biology, paleoentomology</td>
<td><a href="http://www.fossilsr.cn/dataclade/index.html">http://www.fossilsr.cn/dataclade/index.html</a></td>
<td></td>
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<tr>
<td>DsEBED</td>
<td>database</td>
<td>Global seafloor materials and mesoscale features</td>
<td>geosciences, biosciences, engineering, conservation resources</td>
<td><a href="http://instaar.colorado.edu/~jenkins/dssea">http://instaar.colorado.edu/~jenkins/dssea</a> bed/</td>
<td>Chris Jenkins</td>
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<td>Diatom Paleolimnology Data Cooperative</td>
<td>database</td>
<td>diatom identification</td>
<td>paleolimnology</td>
<td>diatom.aniso.org</td>
<td>Don Charles</td>
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<tr>
<td>EarthBase</td>
<td>database</td>
<td>RESTful access to a variety of geological data</td>
<td>geology</td>
<td>earth-base.org</td>
<td>S. Peters</td>
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<tr>
<td>EarthChem / SedDB</td>
<td>database</td>
<td>geochemical data for sediments, age models, integration with rock data</td>
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<tr>
<td>EDNA Fossil Insect Database</td>
<td>database</td>
<td></td>
<td></td>
<td>edna.palass-hosting.org</td>
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<tr>
<td>EODC</td>
<td>database</td>
<td>images from satellites and space station</td>
<td>geos and planetary science</td>
<td><a href="http://earthdata.nasa.gov/">http://earthdata.nasa.gov/</a></td>
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<td>EPA</td>
<td>database</td>
<td>various natural resource inventories</td>
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<td>ESRF paleoentomological microtomographic database</td>
<td>database</td>
<td>collection of training sets</td>
<td>paleoentomologists</td>
<td>craticula.ncl.ac.uk/Eddi/jsp</td>
<td>Steve Juggins</td>
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<tr>
<td>European Diatom Database</td>
<td>database</td>
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</tr>
<tr>
<td>FishBase</td>
<td>database</td>
<td>all info about fish (all of it)</td>
<td>ichthyology, biodiversity, conservation</td>
<td>Fishbase.org</td>
<td></td>
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<tr>
<td>Foreign Natural Resources National Agencies (various)</td>
<td>database</td>
<td>varies</td>
<td>geoscience</td>
<td></td>
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<tr>
<td>Fossil record electronic database (FRED)</td>
<td>database</td>
<td>Paleobiological research database for NZ and nearby regions</td>
<td></td>
<td>fred.org.nz</td>
<td></td>
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<tr>
<td>Fossil Calibration Database (forthcoming)</td>
<td>database</td>
<td>fossil calibrations for divergence dating; data include fossil specimens, geochronology, phylogeny, etc</td>
<td>paleontology, evolutionary biology, molecular biology, geochronology</td>
<td><a href="http://www.nescent.org/science/awards_summary.php?id=259">www.nescent.org/science/awards_summary.php?id=259</a></td>
<td>James Parham/Daniel Kaspka</td>
<td>will eventually be associated with the electronic open access journal Palaeontologia Electronica</td>
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<td>GBIF (Global Biodiversity Information Facility)</td>
<td>database</td>
<td>species occurrences</td>
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<td>gbif.org</td>
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<td>Resource Name</td>
<td>Resource Type</td>
<td>Data/services offered</td>
<td>Communities served</td>
<td>URL</td>
<td>Contact</td>
<td>Comment/Relation to other resources</td>
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<tr>
<td>GeoChron</td>
<td>database</td>
<td>database for geochronology, workflow support</td>
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<tr>
<td>Seedstratsys</td>
<td>database</td>
<td>Repository for modern species collections, aggregated from various sources. Also has some fossil collections.</td>
<td></td>
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<td>Global Biodiversity Information Facility (GBIF)</td>
<td>database</td>
<td>satellite imagery</td>
<td>GIS</td>
<td><a href="http://landcover.org">http://landcover.org</a></td>
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<td>Global Land Cover Facility</td>
<td>database</td>
<td>first palefire database</td>
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<tr>
<td>Global Paleofire Database</td>
<td>database</td>
<td>modern water isotope data, access and download</td>
<td>paleoclimate, hydrology</td>
<td><a href="http://gwpw.org">http://gwpw.org</a></td>
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<tr>
<td>IAEA GNP database (Global Network of Isotopes in Precipitation)</td>
<td>database</td>
<td>modern water isotope data, access and download</td>
<td>paleoclimate, hydrology</td>
<td><a href="http://gwpw.org">http://gwpw.org</a></td>
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<tr>
<td>IAEA GNP database (Global Network of Isotopes in Rivers)</td>
<td>database</td>
<td>modern water isotope data, access and download</td>
<td>paleoclimate, hydrology</td>
<td><a href="http://gwpw.org">http://gwpw.org</a></td>
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<tr>
<td>IAEA-MIBA (Moisture Isotopes in the Biosphere and Atmosphere)</td>
<td>database</td>
<td>modern water isotope data, access and download</td>
<td>scientific drilling, CSD, IODP, IODP-ECORD</td>
<td><a href="http://www.icdp-online.org">http://www.icdp-online.org</a></td>
<td>Ronald Conze</td>
<td></td>
</tr>
<tr>
<td>CDP CurationDIS</td>
<td>database</td>
<td>data capture during initial core description and archiving</td>
<td>CDP, IODP-ECORD</td>
<td><a href="http://www.icdp-online.org">http://www.icdp-online.org</a></td>
<td></td>
<td>Ronald Conze</td>
</tr>
<tr>
<td>ICDP ExpeditionDIS</td>
<td>database</td>
<td>data capture during drilling</td>
<td>CDP, IODP-ECORD</td>
<td><a href="http://www.icdp-online.org">http://www.icdp-online.org</a></td>
<td></td>
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<tr>
<td>DigBio</td>
<td>database</td>
<td>database of physical samples - modern and paleo, fossil and physical.</td>
<td></td>
<td><a href="http://www.idigbio.org">www.idigbio.org</a></td>
<td>Bruce McFadden</td>
<td></td>
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<tr>
<td>IGOR Integrated core and log Database</td>
<td>database</td>
<td>Search for geophysical logs or geologic samples</td>
<td>sedimentary geology, petroleum geology</td>
<td><a href="http://egor.reg.utexas.edu/crc/">http://egor.reg.utexas.edu/crc/</a></td>
<td>Daniel Ortmann</td>
<td></td>
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<tr>
<td>International Fossil Algae Association</td>
<td>database</td>
<td>fossil algae collections catalog and image library</td>
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<td>International Multi-proxy Paleo Fire Database</td>
<td>database</td>
<td>taxonomic atlas of Mesozoic radiolaria data and micropaleo communities</td>
<td>paleoceanographic and micropaleo communities</td>
<td><a href="http://www2.unet.ch/interraad">http://www2.unet.ch/interraad</a></td>
<td>Peter Baumgartner</td>
<td></td>
</tr>
<tr>
<td>INTERRAD Mesozoic Radiolaria Database</td>
<td>database</td>
<td>Tree-ring data</td>
<td>Geoscience, Ecology, Forestry</td>
<td><a href="http://www.ncdc.noaa.gov/paleo/treeing.html">http://www.ncdc.noaa.gov/paleo/treeing.html</a></td>
<td><a href="mailto:paleo@noaa.gov">paleo@noaa.gov</a></td>
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<tr>
<td>JODP JANUS / UMS</td>
<td>database</td>
<td>RESTful access to macrostratigraphic database</td>
<td>paleobiology, sedimentary geology, geodynamics</td>
<td>macrostrat.org</td>
<td>S. Peters</td>
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<tr>
<td>R/V VENDO</td>
<td>database</td>
<td>Climate data library. Proxy data and model runs.</td>
<td></td>
<td>rvl3ide.columbia.edu</td>
<td></td>
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<td>JTDB Data Bank</td>
<td>database</td>
<td>Tree-ring data</td>
<td></td>
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<tr>
<td>Macrostrat</td>
<td>database</td>
<td>RESTful access to macrostratigraphic database</td>
<td>paleobiology, sedimentary geology, geodynamics</td>
<td>macrostrat.org</td>
<td>S. Peters</td>
<td></td>
</tr>
<tr>
<td>MagIC</td>
<td>database</td>
<td>global database of paleomagnetic data from published studies</td>
<td>geophysics, tectonics, sedimentary geology, paleoclimate, marine geology</td>
<td><a href="http://earthref.org/MAGIC/">http://earthref.org/MAGIC/</a></td>
<td>Lisa Tauge, Cathy Constable</td>
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<tr>
<td>Marine Geoscience Data System</td>
<td>database</td>
<td>marine geology and geophysics database</td>
<td></td>
<td></td>
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<td>MIO MAP</td>
<td>database</td>
<td>Published records of latest Oligocene to end Miocene mammal fossils from the continental USA.</td>
<td>Mammal paleontologists</td>
<td><a href="http://www.ucmp.berkeley.edu/miomap/">www.ucmp.berkeley.edu/miomap/</a></td>
<td>Edward Davis</td>
<td>In NeoMap</td>
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<tr>
<td>Nanotax Atlas</td>
<td>database</td>
<td>calcium carbonate fossil, paleoceanography</td>
<td>calcareous nanofossil, paleoceanography</td>
<td>nanotax.org</td>
<td>Paul Bown</td>
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<tr>
<td>NANODe (North American Non-Marine Ostracode Database Project)</td>
<td>database</td>
<td>calcium carbonate fossil, paleoceanography</td>
<td>calcareous nanofossil, paleoceanography</td>
<td>nanotax.org</td>
<td>Paul Bown</td>
<td></td>
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<td>Neotoma Paleoecology Database</td>
<td>database</td>
<td>paleoclimate, data download and visualization</td>
<td>citizen science</td>
<td><a href="http://www.usanpn.org/">http://www.usanpn.org/</a></td>
<td>Allison Smith</td>
<td>part of this is in Neotoma, but not all</td>
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<tr>
<td>Neotropical Pollen Database</td>
<td>database</td>
<td>On-line visual reference library for neotropical pollen types</td>
<td>citizen science, paleoecology</td>
<td>research.fit.edu/paleob/pollen.php</td>
<td>Mark Bush</td>
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<td>NGDC Index to Marine and Lacustrine Geological Samples</td>
<td>database</td>
<td>global marine and lacustrine geological sample inventory and basic datasets derived from the samples</td>
<td>marine geology, limnology/paleolimnology</td>
<td><a href="http://www.seabedsamples.org">www.seabedsamples.org</a></td>
<td>Carla Moore</td>
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<tr>
<td>NMFTA Neogene Marine Biota of Tropical America</td>
<td>database</td>
<td>global marine and lacustrine geological sample inventory and basic datasets derived from the samples</td>
<td>marine geology, limnology/paleolimnology</td>
<td><a href="http://www.seabedsamples.org">www.seabedsamples.org</a></td>
<td>Carla Moore</td>
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<td>Resource Name</td>
<td>Resource Type</td>
<td>Data/services offered</td>
<td>Communities served</td>
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<td>Comment/Relation to other resources</td>
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<td>NSIDC</td>
<td>database</td>
<td>Cryosphere data, ice core data, some analysis tools</td>
<td>all paleo climate at least</td>
<td>nsidc.org</td>
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<td>OBIS</td>
<td>database</td>
<td>marine species occurrences</td>
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<td>Paleobiology Database (PBDB)</td>
<td>database</td>
<td>RESTful access to extinct and extinct taxonomic and fossil occurrence data</td>
<td>paleobiology, sedimentary geology, geodynamics</td>
<td>paleobdb.org</td>
<td>J. Alroy, S. Peters</td>
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<tr>
<td>Paleontological Data Portal</td>
<td>database</td>
<td>paleontological specimen data aggregated from various individual museum databases</td>
<td>paleontology, geology, organismal biology</td>
<td><a href="http://www.paleportal.org/">http://www.paleportal.org/</a></td>
<td>Lisa White/Suddy Scotchmoor</td>
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<tr>
<td>PALEOSTRAT</td>
<td>database</td>
<td>sedimentary geology data archive, visualization</td>
<td></td>
<td><a href="http://www.paleostrat.org">www.paleostrat.org</a></td>
<td>Walt Snyder</td>
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<td>Peabody Paleo Portal (Yale)</td>
<td>database</td>
<td>digitized museum data holdings</td>
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<td>peabody.yale.edu/collections</td>
<td>Derek Briggs</td>
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<td>Physiological Society of America</td>
<td>database</td>
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<td>PMIP (Paleoclimate Modelling Intercomparison</td>
<td>database</td>
<td>Archive for paleoclimatic model simulations run under standard PMIP</td>
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<td><a href="http://www.pmaalgae.org">www.pmaalgae.org</a></td>
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<td>Project)</td>
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<td>experimental protocols</td>
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<td>Polar Data Catalogue</td>
<td>database</td>
<td>polar scientific data archive</td>
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<td>Polar Information Commons</td>
<td>database</td>
<td>polar scientific data archive</td>
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<td>R2R</td>
<td>database</td>
<td>shipborne sensor data archive</td>
<td>oceanography, paleoceanography, paleoclimatology</td>
<td><a href="http://www.rvdata.us/">http://www.rvdata.us/</a></td>
<td>Bob Arko</td>
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<td>Radiolarians.org</td>
<td>database</td>
<td>images, stratigraphic data and taxonomic data on radiolarians</td>
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<td>radiolarias.org</td>
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<td>Rudist Bivalve Database</td>
<td>database</td>
<td>taxonomy, regional and stratigraphical distribution of rudist bivalves</td>
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<td><a href="http://www.paleotax.de/rudists/intro.htm">http://www.paleotax.de/rudists/intro.htm</a></td>
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<td>SEAL Stratigraphic Environmental Archaeology</td>
<td>database</td>
<td>biological and chemical, physical data derived from soil samples from archaeological</td>
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<tr>
<td>Database</td>
<td></td>
<td>and natural deposits</td>
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<td>Siliac Secchi Disk</td>
<td>database</td>
<td>online reference key for paleoecologists - diatoms, chrysophytes, algae</td>
<td></td>
<td>siliacsecchidisk.conncoll.edu/Main_Menu_Frameset.html</td>
<td>Peter Siver</td>
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<td>Smithsonian National History</td>
<td>database</td>
<td>metadata and images for specimens and samples accession by</td>
<td>paleontological, biological, and sedimentology</td>
<td>paleobiology.si.edu/collections/paleocollectors.html</td>
<td>Brian Huber</td>
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<td>Paleontology and Sediment collections</td>
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<td>Smithsonian and NMNH</td>
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<td>Southern Louisiana Paleo Database</td>
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<td>biostatigraphy.com</td>
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<td>Swedish Lifewatch</td>
<td>database</td>
<td>biodiversity and taxonomic data</td>
<td></td>
<td><a href="http://www.slu.se/lifewatch">http://www.slu.se/lifewatch</a></td>
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<td>TDAR</td>
<td>database</td>
<td>archaeology, faunal remains, data as it generated</td>
<td>archaeology</td>
<td><a href="http://www.tdar.org">www.tdar.org</a></td>
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<tr>
<td>TimeTree</td>
<td>database</td>
<td>static database of molecular divergence estimates for various evolutionary groups</td>
<td>evolutionology, paleontology</td>
<td><a href="http://www.timetree.org/">http://www.timetree.org/</a></td>
<td>Blair Hedges</td>
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<td>UCMP Database (University of California Museum</td>
<td>database</td>
<td>paleontological specimen data</td>
<td>paleontology, geology, organismal biology</td>
<td>ucmpdb.berkeley.edu</td>
<td>Mark Goodwin</td>
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<tr>
<td>of Paleontology)</td>
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<tr>
<td>University of Minnesota Mineral Database</td>
<td>database</td>
<td>Search for mineral samples and images within the University of Minnesota collection</td>
<td>Mineralogy, petrology, geochemistry, geophysics</td>
<td>mineral.esi.umn.edu</td>
<td>Joshua Feinberg</td>
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<td>US State natural resource agencies (various)</td>
<td>database</td>
<td>observational data for lakes, rivers, and other natural resources</td>
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<td>USDA-Natural Resources Conservation Service</td>
<td>database</td>
<td>soil data and information produced by the National Cooperative Soil Survey</td>
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<td><a href="http://websoilsurvey.nrcs.usda.gov/app/HaMapPage.htm">http://websoilsurvey.nrcs.usda.gov/app/HaMapPage.htm</a></td>
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<td>Web Soil Survey</td>
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<tr>
<td>USGS CMG Infobank</td>
<td>database</td>
<td>Metadata guide to all past USGS marine and coastal surveys</td>
<td>geoscientists, coastal sedimentologists</td>
<td>walrus.wr.usgs.gov/infobank/</td>
<td>Infobank staff</td>
<td></td>
</tr>
<tr>
<td>USGS Geologic Maps</td>
<td>database</td>
<td>GIS maps, Google Earth maps</td>
<td>geoscience</td>
<td>ngmdb.usgs.gov/gmna/</td>
<td></td>
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</tr>
<tr>
<td>USGS Log DB</td>
<td>database</td>
<td>down hole logs for ocean drilling</td>
<td></td>
<td>org.ldeo.columbia.edu/logdb/</td>
<td>Bob Arko</td>
<td></td>
</tr>
<tr>
<td>VIBRANT</td>
<td>database</td>
<td>biodiversity research facilitator website</td>
<td>straitshap is part of VIBRANT</td>
<td>vbrant.eu/</td>
<td>Robert J. Hijmans, Susan Cameron, and Juan Parra</td>
<td></td>
</tr>
<tr>
<td>WorldClim</td>
<td>database</td>
<td>global gridded climate data</td>
<td>ecological modeling, GIS</td>
<td><a href="http://www.worldclim.org">www.worldclim.org</a></td>
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</tr>
<tr>
<td>RESAR/IGSN</td>
<td>database/registry</td>
<td>unique identifiers for samples; sample metadata catalog</td>
<td>sample collectors; repositories and collections</td>
<td><a href="http://www.staff.ncl.ac.uk/staff/stephen_juggins/software.htm">http://www.staff.ncl.ac.uk/staff/stephen_juggins/software.htm</a></td>
<td>Steve Juggins</td>
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<td>Resource Name</td>
<td>Resource Type</td>
<td>Data/services offered</td>
<td>Communities served</td>
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<td>Comment/Relation to other resources</td>
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<tr>
<td>Zoobank</td>
<td>database/registry</td>
<td>official registry for zoological taxonomic names</td>
<td>paleontology, evolutionary biology</td>
<td><a href="http://zoobank.org/">http://zoobank.org/</a></td>
<td></td>
<td>required by ICZN for valid publication of new taxonomic names in electronic-only journals</td>
</tr>
<tr>
<td>Diatoms of the United States</td>
<td>image library</td>
<td>diatom identification</td>
<td>diatomists</td>
<td><a href="http://westerndiatoms.colorado.edu/">http://westerndiatoms.colorado.edu/</a></td>
<td>Sarah A. Spaulding</td>
<td></td>
</tr>
<tr>
<td>TMI / Tool for Microscopic Identification</td>
<td>image library</td>
<td>Images and tools for visual identification in smear slides</td>
<td></td>
<td><a href="http://tmi.lacroire.unr.edu">http://tmi.lacroire.unr.edu</a></td>
<td>Amy Myrbo</td>
<td></td>
</tr>
<tr>
<td>CoreWall / CoreRef</td>
<td>portal</td>
<td>visualization</td>
<td></td>
<td></td>
<td>Josh Reed, Frank Rack</td>
<td></td>
</tr>
<tr>
<td>EarthTime</td>
<td>portal</td>
<td>organized, community-based international scientific initiative</td>
<td></td>
<td><a href="http://www.earth-time.org/">http://www.earth-time.org/</a></td>
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<tr>
<td>NEOMAP</td>
<td>portal</td>
<td>federated data portal for paleomammalogy. Serves FAUNMAP II and MKMAP. Will link to Neotoma with API.</td>
<td>neotoma</td>
<td><a href="http://www.ucmp.berkeley.edu/neomap/">http://www.ucmp.berkeley.edu/neomap/</a></td>
<td>Edward Davis</td>
<td>linked to MKMAP, FAUNMAP II, will link to NEOTOMA</td>
</tr>
<tr>
<td>OneGeology</td>
<td>portal</td>
<td>geological map data</td>
<td>all geosciences</td>
<td><a href="http://www.onegeology.org/">http://www.onegeology.org/</a></td>
<td><a href="mailto:OneGeology@bgs.ac.uk">OneGeology@bgs.ac.uk</a></td>
<td></td>
</tr>
<tr>
<td>Antarctic Marine Geology Research Facility, Florida State University</td>
<td>repository</td>
<td></td>
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</tr>
<tr>
<td>Biodiversity Heritage Library</td>
<td>repository</td>
<td>scanned and OCR'd biodiversity text including extinct species</td>
<td>paleontology, taxonomy</td>
<td>biodiversitylibrary.org</td>
<td></td>
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</tr>
<tr>
<td>Data Conservancy</td>
<td>repository</td>
<td>data preservation for reuse</td>
<td>life, earth and social science and astronomy</td>
<td>dataconservancy.org</td>
<td>Anne Thessen</td>
<td></td>
</tr>
<tr>
<td>Digimorph</td>
<td>repository</td>
<td>x-ray CT data of objects (mostly paleo/bio, but also petrological/mineralogical)</td>
<td>paleontology, organismal biology, petrology, mineralogy</td>
<td><a href="http://www.digimorph.org">www.digimorph.org</a></td>
<td>Tim Rowe, Rich Ketcham, Jesse Maiano, Matthew Colbert</td>
<td></td>
</tr>
<tr>
<td>DRYAD</td>
<td>repository</td>
<td>data sets from evolution and ecology literature. Mostly unstructured data library</td>
<td>evolution, ecology, biodiversity, biology</td>
<td>datadryad.org</td>
<td></td>
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<tr>
<td>Ellis and Messina catalogues</td>
<td>repository</td>
<td>taxonomic data for microfossils</td>
<td></td>
<td><a href="http://www.micropress.org/e_m.html">http://www.micropress.org/e_m.html</a></td>
<td></td>
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<tr>
<td>Ice Core Storage Facility, Byrd Polar Research Center, Ohio State University</td>
<td>repository</td>
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<tr>
<td>ODP core repositories (BCR/GCR/KCR)</td>
<td>repository</td>
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<tr>
<td>ITIS (Integrated Taxonomic Information System)</td>
<td>repository</td>
<td></td>
<td></td>
<td><a href="http://www.itis.gov">www.itis.gov</a></td>
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<tr>
<td>Laboratory of Tree-Ring Research, University of Arizona</td>
<td>repository</td>
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<tr>
<td>LacCore/National Lacustrine Core Facility, University of Minnesota</td>
<td>repository</td>
<td>paleolimnological core samples and associated data</td>
<td>paleolimnology, paleoclimatology</td>
<td>laccore.org</td>
<td>Emi Ito</td>
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<tr>
<td>Lamont-Doherty Core Repository, Columbia University</td>
<td>repository</td>
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<tr>
<td>Marine Geological Samples Laboratory, University of Rhode Island</td>
<td>repository</td>
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<tr>
<td>Marine Geology Repository, Oregon State University</td>
<td>repository</td>
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<tr>
<td>Morphobank</td>
<td>repository</td>
<td>morphological data - that is phylogenetic characters and matrices, images of morphology, histological data, etc.</td>
<td>paleontology, organismal biology</td>
<td><a href="http://www.morphobank.org">www.morphobank.org</a></td>
<td>Nancy Simmons</td>
<td></td>
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<tr>
<td>Museum collections databases (various)</td>
<td>repository</td>
<td>various</td>
<td></td>
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<tr>
<td>NCDC</td>
<td>repository</td>
<td>Modern and Paleo-Climate data on scales from hourly to millennial; searchable via GoogleEarth</td>
<td>meteorologist, paleoclimatologist, paleoecology</td>
<td><a href="http://www.ncdc.noaa.gov/">http://www.ncdc.noaa.gov/</a></td>
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<tr>
<td>PANGAEA</td>
<td>repository</td>
<td>earth and environmental science</td>
<td></td>
<td><a href="http://www.pangaea.de">www.pangaea.de</a></td>
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<td>Polar Rock Repository, Byrd Polar Research Center, Ohio State University</td>
<td>repository</td>
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<td>Rutgers Core Repository, Rutgers University</td>
<td>repository</td>
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<td>Resource Name</td>
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<td>Scripps Institution of Oceanography Geological Samples Repository, UCSD</td>
<td>repository</td>
<td>Information about higher level taxa and phylogenies</td>
<td>evolution, phylogenetics</td>
<td><a href="https://biodiversity.ucsd.edu">https://biodiversity.ucsd.edu</a></td>
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<tr>
<td>USGS (Tree of Life)</td>
<td>repository</td>
<td>phylogenetic (evolutionary) trees</td>
<td>paleontology, evolutionary biology</td>
<td><a href="http://www.usgs.gov">www.usgs.gov</a></td>
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<tr>
<td>US Geological surveys (various)</td>
<td>repository</td>
<td>State-level geological mapping agency. Has lots of drill cores warehoused. Many other state agencies have cores.</td>
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<tr>
<td>USGS Denver Core Research Center</td>
<td>repository</td>
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<tr>
<td>USGS-Monte Carlo Marine Geology Sample Repository</td>
<td>repository</td>
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<tr>
<td>USGS-National Ice Core Laboratory</td>
<td>repository</td>
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<tr>
<td>USGS-Woods Hole East Coast Geological Sample Repository</td>
<td>repository</td>
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<tr>
<td>Waterisotopes.org</td>
<td>repository</td>
<td>GIS data sets</td>
<td>isotope geoscience</td>
<td><a href="http://www.waterisotopes.org">www.waterisotopes.org</a></td>
<td>Gabe Bowen</td>
<td></td>
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<tr>
<td>Woods Hole Oceanographic Institution Seafloor Samples Laboratory</td>
<td>repository</td>
<td></td>
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<tr>
<td>Analyses</td>
<td>software/tool</td>
<td>time series analysis</td>
<td>paleoecologist, paleoclimate</td>
<td><a href="http://www.lsce.ipsl.fr/logiciels/index.php">http://www.lsce.ipsl.fr/logiciels/index.php</a></td>
<td>Didier Paillard</td>
<td></td>
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<tr>
<td>Arand</td>
<td>software/tool</td>
<td>time series analysis</td>
<td>paleoenvironment, paleoclimate</td>
<td><a href="http://www.ncdc.noaa.gov/paleo/sedib/arand">http://www.ncdc.noaa.gov/paleo/sedib/arand</a></td>
<td>Phil Powell</td>
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<tr>
<td>BACON</td>
<td>software/tool</td>
<td>Age modelling in R</td>
<td>geoscience, paleoecology, paleoclimates</td>
<td><a href="http://chrono.qub.ac.uk/blaaub/bacon.html">http://chrono.qub.ac.uk/blaaub/bacon.html</a></td>
<td>Maarten Blaaub</td>
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<tr>
<td>C2</td>
<td>software/tool</td>
<td>Paleoenvironmental transfer functions from paleodata</td>
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<tr>
<td>CHRONOS-Age-Depth Plot (ADP)</td>
<td>software/tool</td>
<td>reads paleontological age-depth data from the Neptune database or from local files, plots those data, and allows interactive fitting of a line of correlation or age model</td>
<td>geology, planetary science, paleontology, archaeology, neoclimates</td>
<td><a href="http://portal.chronos.org/gridpoints/gridpoints/cdi-1cdm,adp">http://portal.chronos.org/gridpoints/gridpoints/cdi-1cdm,adp</a></td>
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<tr>
<td>CoreWall / Corelyzer</td>
<td>software/tool</td>
<td>visualization</td>
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<td>CoreWall / Correlator</td>
<td>software/tool</td>
<td>core-borehole, core-core correlation</td>
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<tr>
<td>CoreWall / PSCAT</td>
<td>software/tool</td>
<td>lithologic description</td>
<td></td>
<td></td>
<td>Josh Reed, Frank Rack</td>
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<tr>
<td>DjR</td>
<td>software/tool</td>
<td>Tree-ring data analysis in R</td>
<td>Geoscience, Ecology, Forestry</td>
<td><a href="http://cran.r-project.org/web/packages/djR/index.html">http://cran.r-project.org/web/packages/djR/index.html</a></td>
<td>Andy Burn</td>
<td></td>
</tr>
<tr>
<td>EdGCM: Educational Global Climate Model</td>
<td>software/tool</td>
<td>Climate modeling tool, post-processing software, and visualization for climate model output</td>
<td>paleoclimate and climate modeling</td>
<td>edgcm.columbia.edu</td>
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<td>Encyclopedia of Life</td>
<td>software/tool</td>
<td>aggregates information about species, including extinct species</td>
<td>broad, citizen science</td>
<td><a href="http://www.eol.org">www.eol.org</a></td>
<td>Mark Chandler</td>
<td>Value added through the EOS curator network and communities</td>
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<tr>
<td>Figshare</td>
<td>software/tool</td>
<td>store data sets and assign citable identifier</td>
<td>any community that produces data</td>
<td><a href="http://www.figshare.org">www.figshare.org</a></td>
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<td>GeoMapApp</td>
<td>software/tool</td>
<td>Images</td>
<td>Geoscience</td>
<td><a href="http://www.geomapapp.org">www.geomapapp.org</a></td>
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<td>Gigapan</td>
<td>software/tool</td>
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<td></td>
<td><a href="http://gigapan.com/gigapan/tags=geology">http://gigapan.com/gigapan/tags=geology</a></td>
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<tr>
<td>GNRL</td>
<td>software/tool</td>
<td>algorithm for automated extracting scientific species names from data files and text</td>
<td>biodiversity</td>
<td>gnrd.globalnames.org</td>
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<td>NLP and machine learning application</td>
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<td>Google Fusion Tables</td>
<td>software/tool</td>
<td>tool for integrating and normalizing tabular data</td>
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<td>Resource Name</td>
<td>Resource Type</td>
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<td>Communities served</td>
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<td>Comment/Relation to other resources</td>
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<td>GPlates</td>
<td>software/tool</td>
<td>software to rotate plates to provide paleogeographic orientations and reconstructions</td>
<td>paleoclimatology, hydrology</td>
<td>gplates.org</td>
<td>Mike Gumis</td>
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<tr>
<td>IAEA WISER (Water Isotope System for Data Analysis, Visualization and Electronic Retrieval)</td>
<td>software/tool</td>
<td>identify and visualize modern water isotope data</td>
<td>paleoclimatology, hydrology</td>
<td>ias121.iaea.org</td>
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<td>IsoMap</td>
<td>software/tool</td>
<td>identify, analyze, visualize modern water isotope data</td>
<td>paleoclimatology, hydrology</td>
<td>isomap.org</td>
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<tr>
<td>Kepler</td>
<td>software/tool</td>
<td>maintains provenance and workflow information</td>
<td></td>
<td></td>
<td>not sure if this will work for paleo</td>
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<tr>
<td>Kingdom Suite</td>
<td>software/tool</td>
<td>seismic survey data visualization</td>
<td></td>
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<tr>
<td>Match</td>
<td>software/tool</td>
<td>time series analysis</td>
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<td>Mesquite</td>
<td>software/tool</td>
<td>for visualization, manipulation, and analysis of phylogenetic (evolutionary) trees</td>
<td>evolutionary biology, paleontology</td>
<td><a href="http://mesquiteproject.org/">http://mesquiteproject.org/</a></td>
<td>WP Maddison</td>
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<tr>
<td>Ocean Data View</td>
<td>software/tool</td>
<td>visualizations for oceanographic data</td>
<td>oceanography</td>
<td>adv.awi.de</td>
<td></td>
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<tr>
<td>Paleomap</td>
<td>software/tool</td>
<td>global maps of continental positions over Earth History; includes GIS (S)</td>
<td>Geoscience</td>
<td><a href="http://www.scotese.com/earth.htm">www.scotese.com/earth.htm</a></td>
<td>Christopher Scotese</td>
<td></td>
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<tr>
<td>R-analogue</td>
<td>software/tool</td>
<td>R package for paleoenvironmental transfer functions</td>
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<td>R-rioja</td>
<td>software/tool</td>
<td>R package for paleoenvironmental analysis &amp; visualization</td>
<td>paleocology</td>
<td><a href="http://www.staff.ncl.ac.uk/staff/stephen.juggins/analysis.htm">www.staff.ncl.ac.uk/staff/stephen.juggins/analysis.htm</a></td>
<td>Stephen Juggins</td>
<td></td>
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<tr>
<td>Scratchpads</td>
<td>software/tool</td>
<td>data management</td>
<td>biodiversity</td>
<td>scratchpads.eu</td>
<td>Sandy Knapp</td>
<td></td>
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<tr>
<td>Specify</td>
<td>software/tool</td>
<td>software for sample curation</td>
<td>museum &amp; herbarium curators</td>
<td><a href="http://specifysoftware.org">http://specifysoftware.org</a></td>
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<tr>
<td>USGS MTM Toolkit</td>
<td>software/tool</td>
<td>time series analysis</td>
<td>paleoecorecord community</td>
<td><a href="http://www.atmos.ucla.edu/tod/ssa/">http://www.atmos.ucla.edu/tod/ssa/</a></td>
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<tr>
<td>Stratigraph</td>
<td>software/tool</td>
<td>R package/toolkit for the plotting and analysis of stratigraphic data</td>
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<tr>
<td>Tila</td>
<td>software/tool</td>
<td>data entry, graphics, analysis</td>
<td>invertebrates, stratigraphic data</td>
<td></td>
<td>Eric Grimm</td>
<td></td>
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<tr>
<td>Time Scale Creator</td>
<td>software/tool</td>
<td>provides the data for biozones and time scale age boundaries for the entire geologic time scale. Also visualization tools for presenting multiple fields of information (magnetic chron, sea level, isotopes, etc.)</td>
<td>all geosciences</td>
<td>engineering.purdue.edu/Stratigraphy/tscreator/index/index.php</td>
<td>Jim Ogg</td>
<td></td>
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<tr>
<td>TRICYCLE</td>
<td>software/tool</td>
<td>Format conversion for tree-ring data</td>
<td>Geoscience, Ecology, Forestry</td>
<td><a href="http://www.trides.org/tricycle/">http://www.trides.org/tricycle/</a></td>
<td><a href="mailto:Info@trides.org">Info@trides.org</a></td>
<td>Example of how to avoid a single data standard</td>
</tr>
<tr>
<td>Zone</td>
<td>software/tool</td>
<td>MS-OOS program for constrained clustering of stratigraphic data</td>
<td></td>
<td><a href="http://www.staff.ncl.ac.uk/staff/stephen.juggins/software/ZoneHome.htm">www.staff.ncl.ac.uk/staff/stephen.juggins/software/ZoneHome.htm</a></td>
<td>Steve Juggins</td>
<td></td>
</tr>
</tbody>
</table>
# EarthCube Cyberinfrastructure for Paleogeoscience Community Survey

**1. Are you male or female?**

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>58.0%</td>
<td>51</td>
</tr>
<tr>
<td>Female</td>
<td>42.0%</td>
<td>37</td>
</tr>
</tbody>
</table>

answered question 88
skipped question 0

**2. Indicate years of experience within your professional disciplinary affiliation, including graduate study.**

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>under 5 years</td>
<td>3.4%</td>
<td>3</td>
</tr>
<tr>
<td>5-10 years</td>
<td>22.7%</td>
<td>20</td>
</tr>
<tr>
<td>11-20 years</td>
<td>33.0%</td>
<td>29</td>
</tr>
<tr>
<td>over 20 years</td>
<td>40.9%</td>
<td>36</td>
</tr>
</tbody>
</table>

answered question 88
skipped question 0
<table>
<thead>
<tr>
<th>Response</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>81.8%</td>
<td>72</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>19.3%</td>
<td>17</td>
</tr>
</tbody>
</table>

answered question 88
skipped question 0
<table>
<thead>
<tr>
<th>Institutional Affiliation</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education – University or 4-Year College</td>
<td>87.5%</td>
<td>77</td>
</tr>
<tr>
<td>Education – Community College</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Education – K-12</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Government – Federal Agency</td>
<td>3.4%</td>
<td>3</td>
</tr>
<tr>
<td>Government – State or Local Agency</td>
<td>3.4%</td>
<td>3</td>
</tr>
<tr>
<td>Industry – Small company (less than 50 employees)</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Industry – Medium company (50-500 employees)</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Industry – Large company (over 500 employees)</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Museum</td>
<td>4.5%</td>
<td>4</td>
</tr>
<tr>
<td>Other – National Laboratory or Federally Funded Research and Development Center (FFRDC)</td>
<td>1.1%</td>
<td>1</td>
</tr>
<tr>
<td>Other – Supercomputing Facility</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Other – Not-for-profit/Non-Governmental Organization (NGO)</td>
<td>2.3%</td>
<td>2</td>
</tr>
<tr>
<td>Other – Professional Society or Scientific Community Governance Organization</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Other – Citizen Scientist</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>1.1%</td>
<td>1</td>
</tr>
</tbody>
</table>

**5. How would you describe your specific area of expertise?**

<table>
<thead>
<tr>
<th>Response</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>84</td>
</tr>
</tbody>
</table>

- answered question 88
- skipped question 0
### 6. What are the primary disciplines of your research or work? Select all that apply.

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>paleobiology/paleoecology</td>
<td>54.1%</td>
<td>46</td>
</tr>
<tr>
<td>paleoclimatology</td>
<td>64.7%</td>
<td>55</td>
</tr>
<tr>
<td>paleoceanography</td>
<td>29.4%</td>
<td>25</td>
</tr>
<tr>
<td>paleolimnology</td>
<td>27.1%</td>
<td>23</td>
</tr>
<tr>
<td>paleohydrology</td>
<td>15.3%</td>
<td>13</td>
</tr>
<tr>
<td>paleomagnetism</td>
<td>11.8%</td>
<td>10</td>
</tr>
<tr>
<td>paleontology</td>
<td>23.5%</td>
<td>20</td>
</tr>
<tr>
<td>paleoglaciology</td>
<td>5.9%</td>
<td>5</td>
</tr>
<tr>
<td>geochronology</td>
<td>22.4%</td>
<td>19</td>
</tr>
<tr>
<td>modeling (please specify below)</td>
<td>7.1%</td>
<td>6</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>22.4%</td>
<td>19</td>
</tr>
</tbody>
</table>

answered question 85

skipped question 3
7. Within the discipline(s) identified above, what are your primary topics of focus? Select all that apply.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>sedimentology/lithostratigraphy</td>
<td>44.2%</td>
<td>38</td>
</tr>
<tr>
<td>microfossils (pollen, diatoms, ostracodes, foraminifera, or others; specify below)</td>
<td>37.2%</td>
<td>32</td>
</tr>
<tr>
<td>macrofossils (insects, plants, molluscs, vertebrates, or others; specify below)</td>
<td>27.9%</td>
<td>24</td>
</tr>
<tr>
<td>organic geochemistry (bulk or compound-specific; specify below)</td>
<td>24.4%</td>
<td>21</td>
</tr>
<tr>
<td>inorganic geochemistry (specify below)</td>
<td>41.9%</td>
<td>36</td>
</tr>
<tr>
<td>ancient DNA</td>
<td>2.3%</td>
<td>2</td>
</tr>
<tr>
<td>glaciology</td>
<td>5.8%</td>
<td>5</td>
</tr>
<tr>
<td>dendrochronology/dendroclimatology</td>
<td>5.8%</td>
<td>5</td>
</tr>
<tr>
<td>atmospheric circulation</td>
<td>3.5%</td>
<td>3</td>
</tr>
<tr>
<td>other / please specify</td>
<td>44.2%</td>
<td>38</td>
</tr>
</tbody>
</table>

answered question 86

skipped question 2
8. Is your research focus primarily on marine or terrestrial systems?

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>marine</td>
<td>41.2%</td>
<td>35</td>
</tr>
<tr>
<td>terrestrial</td>
<td>67.1%</td>
<td>57</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>7.1%</td>
<td>6</td>
</tr>
</tbody>
</table>

answered question 85
skipped question 3
9. What natural archives are used in your research? Select all that apply.

<table>
<thead>
<tr>
<th>Natural Archive</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>outcrops</td>
<td>44.8%</td>
<td>39</td>
</tr>
<tr>
<td>marine sediments</td>
<td>41.4%</td>
<td>36</td>
</tr>
<tr>
<td>lacustrine sediments</td>
<td>51.7%</td>
<td>45</td>
</tr>
<tr>
<td>speleothems</td>
<td>13.8%</td>
<td>12</td>
</tr>
<tr>
<td>corals</td>
<td>10.3%</td>
<td>9</td>
</tr>
<tr>
<td>tree rings</td>
<td>4.6%</td>
<td>4</td>
</tr>
<tr>
<td>soils</td>
<td>24.1%</td>
<td>21</td>
</tr>
<tr>
<td>peat</td>
<td>14.9%</td>
<td>13</td>
</tr>
<tr>
<td>loess</td>
<td>10.3%</td>
<td>9</td>
</tr>
<tr>
<td>glacial ice</td>
<td>9.2%</td>
<td>8</td>
</tr>
<tr>
<td>borehole data</td>
<td>26.4%</td>
<td>23</td>
</tr>
<tr>
<td>packrat middens</td>
<td>4.6%</td>
<td>4</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>17.2%</td>
<td>15</td>
</tr>
</tbody>
</table>

answered question 87

skipped question 1
10. How do you curate or archive the physical samples generated in your research? Select all that apply.

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>central repository: Antarctic Marine Geology Research Facility, Florida State University</td>
<td>2.3%</td>
<td>2</td>
</tr>
<tr>
<td>central repository: LacCore/National Lacustrine Core Facility, University of Minnesota</td>
<td>15.1%</td>
<td>13</td>
</tr>
<tr>
<td>central repository: Lamont-Doherty Core Repository, Columbia University</td>
<td>7.0%</td>
<td>6</td>
</tr>
<tr>
<td>central repository: Marine Geology Repository, Oregon State University</td>
<td>1.2%</td>
<td>1</td>
</tr>
<tr>
<td>central repository: Marine Geological Samples Laboratory, University of Rhode Island</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>central repository: Rutgers Core Repository, Rutgers University</td>
<td>2.3%</td>
<td>2</td>
</tr>
<tr>
<td>central repository: Scripps Institution of Oceanography Geological Samples Repository, UCSD</td>
<td>3.5%</td>
<td>3</td>
</tr>
<tr>
<td>central repository: Woods Hole Oceanographic Institution Seafloor Samples Laboratory</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Central Repository</td>
<td>Percentage</td>
<td>Count</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>USGS-Denver Core Research Center</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>USGS-Menlo Park Marine Geology Sample Repository</td>
<td>1.2%</td>
<td>1</td>
</tr>
<tr>
<td>USGS-National Ice Core Laboratory</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>USGS-Woods Hole East Coast Geological Sample Repository</td>
<td>1.2%</td>
<td>1</td>
</tr>
<tr>
<td>IODP core repositories (BCR/GCR/KCR)</td>
<td>7.0%</td>
<td>6</td>
</tr>
<tr>
<td>Polar Rock Repository, Byrd Polar Research Center, Ohio State University</td>
<td>1.2%</td>
<td>1</td>
</tr>
<tr>
<td>Ice Core Storage Facility, Byrd Polar Research Center, Ohio State University</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>Laboratory of Tree-Ring Research, University of Arizona</td>
<td>1.2%</td>
<td>1</td>
</tr>
<tr>
<td>Museum (please specify below)</td>
<td>23.3%</td>
<td>20</td>
</tr>
<tr>
<td>On your own</td>
<td>65.1%</td>
<td>56</td>
</tr>
<tr>
<td>Samples are discarded after a period of time</td>
<td>12.8%</td>
<td>11</td>
</tr>
<tr>
<td>Other / Comment (please specify)</td>
<td>36.0%</td>
<td>31</td>
</tr>
</tbody>
</table>
11. If you curate samples on your own, please describe in a few words how the samples are stored and cataloged.

<table>
<thead>
<tr>
<th>Response</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>43</td>
</tr>
</tbody>
</table>

12. If you curate samples on your own, are metadata for the samples made available for discovery through any central resource?

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>28.3%</td>
<td>13</td>
</tr>
<tr>
<td>No</td>
<td>71.7%</td>
<td>33</td>
</tr>
</tbody>
</table>

If yes, please describe.

<table>
<thead>
<tr>
<th>Answered question</th>
<th>46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skipped question</td>
<td>42</td>
</tr>
</tbody>
</table>
13. If you curate samples on your own, please specify the reason(s). Select all that apply.

<table>
<thead>
<tr>
<th>Reason</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>convenience for future examining, subsampling, or other use</td>
<td>84.8%</td>
<td>39</td>
</tr>
<tr>
<td>no suitable repository</td>
<td>52.2%</td>
<td>24</td>
</tr>
<tr>
<td>no requirement to archive centrally</td>
<td>52.2%</td>
<td>24</td>
</tr>
<tr>
<td>difficulty of organizing samples and metadata for submission (time, expense, etc.)</td>
<td>26.1%</td>
<td>12</td>
</tr>
<tr>
<td>concern about sample ownership / use</td>
<td>26.1%</td>
<td>12</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>17.4%</td>
<td>8</td>
</tr>
<tr>
<td>answered question</td>
<td></td>
<td>46</td>
</tr>
<tr>
<td>skipped question</td>
<td></td>
<td>42</td>
</tr>
</tbody>
</table>
14. If you curate samples on your own, do you have a plan for long-term curation when you retire or depart from your current position? Please describe.

<table>
<thead>
<tr>
<th>Response Count</th>
<th>Answered Question</th>
<th>Skipped Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td></td>
<td>51</td>
</tr>
</tbody>
</table>

15. What data types are generated in your research? Consider both primary data (e.g., seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, etc.) as well as interpretations (e.g., temperature, moisture, floods, etc.). Please list all types.

<table>
<thead>
<tr>
<th>Response Count</th>
<th>Answered Question</th>
<th>Skipped Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td></td>
<td>21</td>
</tr>
</tbody>
</table>
16. What file formats do you use for data generated in your research? Select all that apply.

<table>
<thead>
<tr>
<th>File Format</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>spreadsheet / CSV / other forms of “flat files” with delimited data</td>
<td>97.3%</td>
<td>71</td>
</tr>
<tr>
<td>relational databases (Access, SQL, Paradox, etc.)</td>
<td>32.9%</td>
<td>24</td>
</tr>
<tr>
<td>multidimensional data arrays (NetCDF, HDF5, etc.)</td>
<td>8.2%</td>
<td>6</td>
</tr>
<tr>
<td>images and rasters (TIFF, BMP, JPEG, PNG, etc.)</td>
<td>72.6%</td>
<td>53</td>
</tr>
<tr>
<td>vector-based geospatial data (shapefiles, WMS/WCS/WFS, KML/KMZ, etc.)</td>
<td>27.4%</td>
<td>20</td>
</tr>
<tr>
<td>text (descriptions, characterizations, journal logs, etc.)</td>
<td>69.9%</td>
<td>51</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

answered question 73

skipped question 15
17. What is the typical size of datasets generated (and/or used) in your research? Select all that apply.

<table>
<thead>
<tr>
<th>Dataset Size</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>kilobytes (KB)</td>
<td>47.4%</td>
<td>36</td>
</tr>
<tr>
<td>megabytes (MB)</td>
<td>73.7%</td>
<td>56</td>
</tr>
<tr>
<td>gigabytes (GB)</td>
<td>38.2%</td>
<td>29</td>
</tr>
<tr>
<td>terabytes (TB)</td>
<td>9.2%</td>
<td>7</td>
</tr>
<tr>
<td>petabytes (PB)</td>
<td>0.0%</td>
<td>0</td>
</tr>
</tbody>
</table>

**Total responses:** 76

**Skipped question:** 12
18. What resource(s) have you used to archive your data? Select all that apply.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Response Percent</th>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA Paleoclimatology</td>
<td>31.6%</td>
<td>24</td>
</tr>
<tr>
<td>Other NOAA (NCDC / NGDC / NODC) (please specify below)</td>
<td>17.1%</td>
<td>13</td>
</tr>
<tr>
<td>PANGAEA</td>
<td>7.9%</td>
<td>6</td>
</tr>
<tr>
<td>PALEOSTRAT</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>CHRONOS</td>
<td>3.9%</td>
<td>3</td>
</tr>
<tr>
<td>Paleobiology Database</td>
<td>10.5%</td>
<td>8</td>
</tr>
<tr>
<td>IODP JANUS / LIMS</td>
<td>9.2%</td>
<td>7</td>
</tr>
<tr>
<td>FAUNMAP</td>
<td>2.6%</td>
<td>2</td>
</tr>
<tr>
<td>MIOMAP</td>
<td>1.3%</td>
<td>1</td>
</tr>
<tr>
<td>R2R</td>
<td>1.3%</td>
<td>1</td>
</tr>
<tr>
<td>Marine Geoscience Data System (MGDS)</td>
<td>2.6%</td>
<td>2</td>
</tr>
<tr>
<td>System for Earth Sample Registration (SESAR)</td>
<td>1.3%</td>
<td>1</td>
</tr>
<tr>
<td>Macrostrat</td>
<td>1.3%</td>
<td>1</td>
</tr>
<tr>
<td>EarthBase</td>
<td>1.3%</td>
<td>1</td>
</tr>
<tr>
<td>EarthChem / SedDB</td>
<td>1.3%</td>
<td>1</td>
</tr>
<tr>
<td>Database</td>
<td>Response</td>
<td>Percentage</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>----------</td>
<td>------------</td>
</tr>
<tr>
<td>EarthTime</td>
<td></td>
<td>1.3%</td>
</tr>
<tr>
<td>GeoSysStrat</td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>GeoChron</td>
<td></td>
<td>1.3%</td>
</tr>
<tr>
<td>MagIC</td>
<td></td>
<td>5.3%</td>
</tr>
<tr>
<td>Neotoma Paleoecology Database</td>
<td></td>
<td>6.6%</td>
</tr>
<tr>
<td>North American Pollen Database</td>
<td></td>
<td>6.6%</td>
</tr>
<tr>
<td>ICDP website and/or DIS</td>
<td></td>
<td>1.3%</td>
</tr>
<tr>
<td><strong>On your own</strong></td>
<td></td>
<td><strong>61.8%</strong></td>
</tr>
<tr>
<td>Other (please specify)</td>
<td></td>
<td><strong>22.4%</strong></td>
</tr>
</tbody>
</table>

**answered question** 76  
**skipped question** 12
19. If you answered "On your own" to the previous question, please indicate reason(s). Select all that apply.

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<th>Response Count</th>
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<td>22</td>
</tr>
<tr>
<td>no requirement to archive centrally</td>
<td>55.3%</td>
<td>26</td>
</tr>
<tr>
<td>difficulty of organizing data and metadata for submission</td>
<td>38.3%</td>
<td>18</td>
</tr>
<tr>
<td>concern about data ownership / use</td>
<td>25.5%</td>
<td>12</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>29.8%</td>
<td>14</td>
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<tr>
<td>answered question</td>
<td></td>
<td>47</td>
</tr>
<tr>
<td>skipped question</td>
<td></td>
<td>41</td>
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</table>
20. Where have you looked for previously-generated data to accomplish your research goals? Select all that apply.

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<th>Response Count</th>
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<td>42</td>
</tr>
<tr>
<td>Other NOAA (NCDC / NGDC / NODC)</td>
<td>32.4%</td>
<td>23</td>
</tr>
<tr>
<td>PANGAEA</td>
<td>31.0%</td>
<td>22</td>
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<tr>
<td>PALEOSTRAT</td>
<td>1.4%</td>
<td>1</td>
</tr>
<tr>
<td>CHRONOS</td>
<td>12.7%</td>
<td>9</td>
</tr>
<tr>
<td>Paleobiology Database (PBDB)</td>
<td>21.1%</td>
<td>15</td>
</tr>
<tr>
<td>IODP JANUS / LIMS</td>
<td>22.5%</td>
<td>16</td>
</tr>
<tr>
<td>FAUNMAP</td>
<td>9.9%</td>
<td>7</td>
</tr>
<tr>
<td>MIOMAP</td>
<td>4.2%</td>
<td>3</td>
</tr>
<tr>
<td>Macrostrat</td>
<td>5.6%</td>
<td>4</td>
</tr>
<tr>
<td>EarthBase</td>
<td>2.8%</td>
<td>2</td>
</tr>
<tr>
<td>EarthChem / SedDB</td>
<td>8.5%</td>
<td>6</td>
</tr>
<tr>
<td>Marine Geoscience Data System (MGDS)</td>
<td>5.6%</td>
<td>4</td>
</tr>
<tr>
<td>System for Earth Sample Registration (SESAR)</td>
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</tr>
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<td>EarthTime</td>
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<td>Source</td>
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<tr>
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<td>GeoChron</td>
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<td>MagIC</td>
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<td>3</td>
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<tr>
<td>Neotoma Paleoeology Database</td>
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</tr>
<tr>
<td>North American Pollen Database</td>
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</tr>
<tr>
<td>ICDP website and/or DIS</td>
<td>4.2%</td>
<td>3</td>
</tr>
<tr>
<td>KMNI Climate Explorer</td>
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<td>2</td>
</tr>
<tr>
<td>IRI/LDEO Climate Data Library</td>
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</tr>
<tr>
<td>Industry, including public release of industry data (please specify below)</td>
<td>1.4%</td>
<td>1</td>
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<tr>
<td>Colleagues (direct request)</td>
<td>42.3%</td>
<td>30</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td>16.9%</td>
<td>12</td>
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</table>

**Answered question**: 71

**Skipped question**: 17
21. What other resources for data archiving in the paleogeoscience community are not shown above? Please list (even if you do not use them in your own research).

<table>
<thead>
<tr>
<th>Response</th>
<th>Count</th>
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<tbody>
<tr>
<td></td>
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22. How EASY is it for you to find, access, and/or use previously-generated data in your research?

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<th>Count</th>
<th>Rating Count</th>
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<tr>
<td>2</td>
<td>10.7% (8)</td>
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<td>3</td>
<td>10.7% (8)</td>
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<td>4</td>
<td>18.7% (14)</td>
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<td>5</td>
<td>16.0% (12)</td>
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<td>6</td>
<td>16.0% (12)</td>
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<td>7</td>
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<td>8</td>
<td>10.7% (8)</td>
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</tr>
<tr>
<td>9</td>
<td>1.3% (1)</td>
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<table>
<thead>
<tr>
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<th>Comment</th>
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<td>5.05</td>
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| answered question | 75 |
| skipped question | 13 |
23. How IMPORTANT is it for you to find, access, and/or use previously-generated data in your research?

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<tr>
<td>2</td>
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<td>3</td>
<td>6.7% (5)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.7% (5)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>18.7% (14)</td>
<td></td>
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<tr>
<td>6</td>
<td>21.3% (16)</td>
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<tr>
<td>7</td>
<td>37.3% (28)</td>
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<tr>
<td>8</td>
<td>8.43</td>
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<tr>
<td>9</td>
<td>75</td>
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</tbody>
</table>

Comment

answered question

skipped question

24. Large collections of data and/or samples remain undigitized and only available through analog media, by contacting individual researchers, or through manual searches of repository holdings. How much would your research benefit if such "dark data" were digitized?

<table>
<thead>
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<th>Rating</th>
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<tbody>
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<td>0.0% (0)</td>
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<td>1.4% (1)</td>
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<tr>
<td>4</td>
<td>9.6% (7)</td>
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<td>5</td>
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<td>6</td>
<td>16.4% (12)</td>
<td></td>
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<tr>
<td>7</td>
<td>24.7% (18)</td>
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<tr>
<td>8</td>
<td>8.2% (6)</td>
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<tr>
<td>9</td>
<td>27.4% (20)</td>
<td></td>
</tr>
<tr>
<td>10: transformative benefit</td>
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Comment

answered question

skipped question
25. What generic software packages do you currently use in your research for data management and visualization? Consider all data generated from the project initiation, through primary data collection and/or gathering previously-collected data, interpretation, and publishing. Select all that apply.

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<th>Software</th>
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</thead>
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<td>Google Earth</td>
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<tr>
<td>Online maps (Google, Bing, etc.)</td>
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<td>48.0%</td>
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<tr>
<td>Microsoft Excel</td>
<td>72</td>
<td>96.0%</td>
</tr>
<tr>
<td>Adobe Photoshop/Illustrator</td>
<td>58</td>
<td>77.3%</td>
</tr>
<tr>
<td>CorelDraw/PhotoPaint</td>
<td>10</td>
<td>13.3%</td>
</tr>
<tr>
<td>Origin / Origin Pro</td>
<td>4</td>
<td>5.3%</td>
</tr>
<tr>
<td>Cricket Graph</td>
<td>4</td>
<td>5.3%</td>
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<tr>
<td>Delta Graph</td>
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<td>8.0%</td>
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<tr>
<td>SigmaPlot</td>
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<td>20.0%</td>
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<tr>
<td>MATLAB</td>
<td>27</td>
<td>36.0%</td>
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<tr>
<td>R</td>
<td>30</td>
<td>40.0%</td>
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<tr>
<td>IDL (Interactive Development Language)</td>
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<td>1.3%</td>
</tr>
<tr>
<td>NCAR Command Language / Graphics</td>
<td>1</td>
<td>1.3%</td>
</tr>
<tr>
<td>Python</td>
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<td>6.7%</td>
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<td>Database Type</td>
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<tr>
<td>Kepler</td>
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<td>ArcGIS</td>
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<td>OpenLayers</td>
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<tr>
<td>Other (please specify)</td>
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</table>

**Answered Question:** 75

**Skipped Question:** 13
26. What geoscience-specific software packages do you currently use in your research for data management and visualization? Consider all data generated from the project initiation, through primary data collection and/or gathering previously-collected data, interpretation, and publishing. Select all that apply.

<table>
<thead>
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<th>Software Package</th>
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<td>Tilia</td>
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<td>6</td>
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<tr>
<td>CoreWall / Corelyzer</td>
<td>17.4%</td>
<td>8</td>
</tr>
<tr>
<td>CoreWall / Correlator</td>
<td>10.9%</td>
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<tr>
<td>CoreWall / PSICAT</td>
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<td>6</td>
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<tr>
<td>CoreWall / CoreRef</td>
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<td>3</td>
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<tr>
<td>ICDP DIS</td>
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<td>Other (please specify)</td>
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</tbody>
</table>

answered question 46
skipped question 42
27. What other geoscience-specific software packages for data management and visualization are not shown above? Please list (even if you do not use them in your research).

<table>
<thead>
<tr>
<th>Response Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
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</tbody>
</table>

28. Please list important science drivers and scientific challenges you would like to tackle (or tackle more easily) within a 5 to 15 year time frame: a. within your discipline b. across disciplines within the geosciences (if possible, rank the geoscience disciplines by priority) c. across disciplines outside the geosciences (if possible, rank the disciplines by priority)

<table>
<thead>
<tr>
<th>Response Count</th>
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</thead>
<tbody>
<tr>
<td>58</td>
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</table>
29. Please list what is preventing you, at present, from being able to pursue your research and education goals, regarding data discovery and access, data integration, modeling, differences in scale in terms of time, space, or data density/abundance, difference in types or structure of datasets/databases, user interfaces, shared workspaces, etc. Any examples to illustrate the problem(s) would be helpful. 

<table>
<thead>
<tr>
<th>a. within your discipline</th>
<th>b. across disciplines within the geosciences from which you want to access data/models/tools, etc.</th>
<th>c. across disciplines outside the geosciences from which you want to access data/models/tools, etc.</th>
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</thead>
<tbody>
<tr>
<td>Response Count</td>
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<td></td>
</tr>
</tbody>
</table>

Answered question 27

Skipped question 61

30. Please list and describe any tools, databases, modeling capabilities, etc. that you feel should be developed/created/improved/simplified to allow you (or others in your community) to pursue the research and education goals indicated above. 

<table>
<thead>
<tr>
<th>a. within your discipline</th>
<th>b. across disciplines within the geosciences from which you want to access data/models/tools, etc.</th>
<th>c. across disciplines outside the geosciences from which you want to access data/models/tools, etc.</th>
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<tbody>
<tr>
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Answered question 24

Skipped question 64
31. (Optional) Provide your contact information if you wish to be associated with your survey responses. You may also indicate interest in attending the workshop (February 4-6, 2013, Minneapolis), or fill out the application separately at: www.surveymonkey.com/s/earthcubecyberforpaleoapplication

<table>
<thead>
<tr>
<th></th>
<th>Response Percent</th>
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<tr>
<td>City/Town</td>
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<tr>
<td>State/Province</td>
<td></td>
<td>88.6% 31</td>
</tr>
<tr>
<td>Country</td>
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<td>94.3% 33</td>
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<tr>
<td>Email Address</td>
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<td>97.1% 34</td>
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<tr>
<td>Interested in Participating?</td>
<td></td>
<td>91.4% 32</td>
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</table>

answered question 35
skipped question 53
32. Thank you for taking this survey. Your responses help ensure that the paleo community is well-represented in EarthCube cyberinfrastructure development efforts. If you have any additional comments, please note them here.

<table>
<thead>
<tr>
<th>Response Count</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>answered question</td>
<td>13</td>
</tr>
<tr>
<td>skipped question</td>
<td>75</td>
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</tbody>
</table>
### Page 1, Q3. What is the national affiliation of your institution?

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<tr>
<td>2</td>
<td>UK</td>
<td>Dec 15, 2012 7:57 AM</td>
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<tr>
<td>3</td>
<td>Canada</td>
<td>Dec 14, 2012 6:18 PM</td>
</tr>
<tr>
<td>4</td>
<td>Argentina</td>
<td>Dec 14, 2012 9:02 AM</td>
</tr>
<tr>
<td>5</td>
<td>Italy</td>
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<tr>
<td>6</td>
<td>Denmark</td>
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</tr>
<tr>
<td>7</td>
<td>UK</td>
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</tr>
<tr>
<td>8</td>
<td>Europe</td>
<td>Dec 13, 2012 10:28 AM</td>
</tr>
<tr>
<td>9</td>
<td>UK</td>
<td>Dec 13, 2012 4:27 AM</td>
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<tr>
<td>10</td>
<td>German</td>
<td>Dec 13, 2012 1:41 AM</td>
</tr>
<tr>
<td>11</td>
<td>Frostback (canadian)</td>
<td>Dec 12, 2012 5:25 PM</td>
</tr>
<tr>
<td>12</td>
<td>Canada</td>
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<tr>
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<td>Canada</td>
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<td>Australia</td>
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<td>Canada</td>
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</tr>
<tr>
<td>16</td>
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</tr>
<tr>
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<td>lkjlkkj</td>
<td>Nov 27, 2012 11:09 AM</td>
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### Page 1, Q4. Institutional affiliation (please indicate your primary affiliation):

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<tr>
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## Page 1, Q5. How would you describe your specific area of expertise?

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<th></th>
<th>Description</th>
<th>Date/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Palynology, Paleoecology, Paleobotany</td>
<td>Jan 31, 2013 10:20 AM</td>
</tr>
<tr>
<td>2</td>
<td>Carbonate stratigraphy, invertebrate taphonomy, quantitative stratigraphy</td>
<td>Jan 28, 2013 4:14 PM</td>
</tr>
<tr>
<td>3</td>
<td>Research geologist, curator of foraminifera</td>
<td>Jan 24, 2013 1:35 PM</td>
</tr>
<tr>
<td>4</td>
<td>Stable Isotope paleoecology</td>
<td>Jan 23, 2013 1:51 PM</td>
</tr>
<tr>
<td>5</td>
<td>Quaternary geochronology and stratigraphy</td>
<td>Jan 17, 2013 9:18 AM</td>
</tr>
<tr>
<td>6</td>
<td>Glacial stratigraphy, surficial mapping of glacial deposits Paleolimnology</td>
<td>Jan 16, 2013 3:31 AM</td>
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<tr>
<td>7</td>
<td>fossil marine mammals</td>
<td>Jan 15, 2013 10:06 AM</td>
</tr>
<tr>
<td>8</td>
<td>professor of geology, specialty in Quaternary studies &amp; micropaleontology</td>
<td>Jan 14, 2013 8:41 PM</td>
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<tr>
<td>9</td>
<td>Quaternary vertebrate paleoecologist</td>
<td>Jan 11, 2013 8:41 PM</td>
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<tr>
<td>10</td>
<td>paleopedology: the study of past landscapes, climate and atmospheric chemistry based on fossil soils, or what are known as &quot;paleosols&quot;</td>
<td>Jan 10, 2013 1:19 PM</td>
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<td>11</td>
<td>Late Paleozoic invert. paleontology &amp; stratigraphy</td>
<td>Jan 9, 2013 9:37 PM</td>
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<tr>
<td>12</td>
<td>Stratigraphic Paleobiology</td>
<td>Jan 8, 2013 5:08 PM</td>
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<tr>
<td>13</td>
<td>Palynology, quantitative paleontology</td>
<td>Jan 7, 2013 2:39 PM</td>
</tr>
<tr>
<td>14</td>
<td>curator of sediment cores and oversee/operate lab and machines to process samples from cores</td>
<td>Jan 7, 2013 12:53 PM</td>
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<td>15</td>
<td>I am a broadly trained geoscientist specializing in the use of organic molecules (biomarkers) and their isotopic composition to unravel the physical and geochemical signatures (temperature, water column stratification, salinity, redox potential, carbon and nutrient cycling) associated with climatic change, particularly CO2 forcing. My research program is driven by fundamental questions related to the spatio-temporal dynamics and processes of climate change and biotic extinction, from deep time to the future.</td>
<td>Jan 4, 2013 2:53 PM</td>
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<tr>
<td>16</td>
<td>biotic and environmental change of terrestrial ecosystems in deep time</td>
<td>Jan 4, 2013 2:15 PM</td>
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<td>17</td>
<td>micropaleontologist</td>
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<td>18</td>
<td>biomarker-based plant paleoecology</td>
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<td>20</td>
<td>climate science</td>
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<td>21</td>
<td>Pliocene and Quaternary history of the Arctic; New England Climate change.</td>
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<td>22</td>
<td>sedimentary geology and paleobiology</td>
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<td>23</td>
<td>R1 university Earth Sciences professor specializing in paleontology and isotope geochemistry</td>
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<td>24</td>
<td>paleomagnetism</td>
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<td>25</td>
<td>Sediment Magnetism</td>
<td>Dec 16, 2012 3:06 PM</td>
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<td>26</td>
<td>Vertebrate paleontology - evolution, dinosaurs</td>
<td>Dec 16, 2012 1:16 PM</td>
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<tr>
<td>27</td>
<td>Tropical ecosystem dynamics</td>
<td>Dec 15, 2012 7:57 AM</td>
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<tr>
<td>28</td>
<td>Paleoceanography, paleoclimatology</td>
<td>Dec 14, 2012 6:18 PM</td>
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<tr>
<td>29</td>
<td>Development and application of organism-derived transfer functions</td>
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<td>31</td>
<td>pollen analysis, carbon dynamics, Holocene, climate change, peatlands, lakes</td>
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<tr>
<td>32</td>
<td>Marine Geology, Geophysics, and Geomagnetism</td>
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<tr>
<td>33</td>
<td>Paleomagnetism with application in paleoclimatic and paleosecular and paleointensity of the Earth magnetic field variations</td>
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<td>34</td>
<td>Paleo and rock-magnetism</td>
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<td>35</td>
<td>Quaternary paleoecology</td>
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<td>36</td>
<td>Palaeogene timescales</td>
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<td>Page 1, Q5. How would you describe your specific area of expertise?</td>
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<td>37</td>
<td>Glacial geology, paleoclimatology</td>
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<td>38</td>
<td>Abrupt climate change across the Quaternary, deglacial climate events, proxy development and refinement. Mainly using foraminifera.</td>
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<td>lake sediment geochemistry and environmental reconstructions</td>
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<td>40</td>
<td>Global change and paleobiology</td>
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<td>41</td>
<td>Paleoecology of NE N America</td>
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<td>42</td>
<td>Paleoclimate, paleodiet, light isotopes, ancient DNA</td>
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<td>paleoecology</td>
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<td>44</td>
<td>paleoclimatology, with an emphasis on lake sediments</td>
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<td>Isotopic Geoscience</td>
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<td>46</td>
<td>Limnogeology, Sedimentology, Paleoclimate, Magnetostratigraphy, Geochemistry, Physical Geography</td>
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<td>47</td>
<td>paleolimnology, geochemistry</td>
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<td>palaeoenvironmental reconstruction, paleohydrology</td>
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<td>49</td>
<td>Lateglacial and Holocene pollen analysis in Minnesota and Java, Indonesia</td>
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<td>organic geochemistry, stable isotope geochemistry, paleoclimate</td>
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<td>52</td>
<td>desert geomorphology sand dunes</td>
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<td>53</td>
<td>paleoceanography</td>
<td>Dec 12, 2012 6:34 PM</td>
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<tr>
<td>54</td>
<td>Paleoceanography, Marine geology, Paleobiology</td>
<td>Dec 12, 2012 6:12 PM</td>
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<td>55</td>
<td>Paleobiogeoscience</td>
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<td>56</td>
<td>goechnology</td>
<td>Dec 12, 2012 5:10 PM</td>
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<tr>
<td>57</td>
<td>information science, data modeling, currently interested in semantics</td>
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<tr>
<td>58</td>
<td>Ground- and surface water chemistry</td>
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<tr>
<td>59</td>
<td>biogeochemistry including linking biological evolution and earth surface evolution</td>
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<tr>
<td>60</td>
<td>tropical paleoclimatology: observations and modeling.</td>
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<td>61</td>
<td>I am a coastal geomorphologist and marine sedimentologist.</td>
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<tr>
<td>62</td>
<td>Marine geochemistry/paleoceanography</td>
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<tr>
<td>63</td>
<td>U/Th dating and controls on speleothem stable isotope composition</td>
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<td>Quaternary geology</td>
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<tr>
<td>65</td>
<td>freshwater paleoecology, paleolimnology</td>
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<tr>
<td>66</td>
<td>Evolution and Ecology of Insects</td>
<td>Dec 12, 2012 2:31 PM</td>
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<tr>
<td>67</td>
<td>I apply geochemical proxies to the skeletal archives of marine organisms in an effort to reconstruct paleoclimate and oceanography.</td>
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<tr>
<td>68</td>
<td>geochemist and paleoclimatologist</td>
<td>Dec 12, 2012 2:19 PM</td>
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<tr>
<td>69</td>
<td>IT Manager for ANDRILL</td>
<td>Dec 12, 2012 2:17 PM</td>
</tr>
<tr>
<td>70</td>
<td>high-res paleoclimate</td>
<td>Dec 12, 2012 2:06 PM</td>
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<tr>
<td>71</td>
<td>Rock magnetism and paleomagnetism.</td>
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<tr>
<td>72</td>
<td>Much of my work focuses on the history of pluvial lake basins and their inflowing streams within the Great Basin of the western U.S.</td>
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<tr>
<td>73</td>
<td>compilations and statistical analysis of paleoclimate time series (especially ocean cores) on orbital timescales</td>
<td>Dec 10, 2012 12:13 PM</td>
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<tr>
<td></td>
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<td>Date and Time</td>
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<tr>
<td>74</td>
<td>Laboratory manager and sample curator, safety and environmental officer and</td>
<td>Dec 7, 2012 2:23 PM</td>
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<tr>
<td></td>
<td>at one time seafloor mapper and research marine geologist.</td>
<td></td>
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<tr>
<td>75</td>
<td>Coral paleoclimatology</td>
<td>Dec 6, 2012 6:29 PM</td>
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<tr>
<td>76</td>
<td>Reconstructing terrestrial and freshwater Quaternary paleoenvironments</td>
<td>Dec 5, 2012 9:29 AM</td>
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<td>using lake and wetland sediment archives</td>
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<tr>
<td>77</td>
<td>Soils, Geomorphology, and database analysis</td>
<td>Nov 30, 2012 2:59 PM</td>
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<td>78</td>
<td>Palaeoclimate modelling.</td>
<td>Nov 27, 2012 8:09 PM</td>
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<tr>
<td>79</td>
<td>Image analysis, sediments, physical properties, geochemical properties,</td>
<td>Nov 27, 2012 3:16 PM</td>
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<tr>
<td></td>
<td>paleoclimatic. limnogeology</td>
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<tr>
<td>80</td>
<td>Limnogeology, stable isotope and solute geochemistry, and lake system</td>
<td>Nov 27, 2012 2:26 PM</td>
</tr>
<tr>
<td></td>
<td>modeling.</td>
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<td>81</td>
<td>quaternary</td>
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<td>82</td>
<td>paleoanthropology</td>
<td>Nov 27, 2012 11:22 AM</td>
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<tr>
<td>83</td>
<td>ñhhihhoig</td>
<td>Nov 27, 2012 11:09 AM</td>
</tr>
<tr>
<td>84</td>
<td>Polar geology</td>
<td>Nov 27, 2012 10:45 AM</td>
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Page 1, Q6. What are the primary disciplines of your research or work? Select all that apply.

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<tr>
<th></th>
<th>Disciplines</th>
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<tbody>
<tr>
<td>1</td>
<td>paleopedology</td>
<td>Jan 10, 2013 1:19 PM</td>
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<tr>
<td>2</td>
<td>Models of competition in high-diversity ecological communities as well as postmortem age distribution of biogenic material in sedimentary systems.</td>
<td>Jan 8, 2013 5:08 PM</td>
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<tr>
<td>3</td>
<td>we send samples to researchers involved in most of the areas above but do not participate in any directly</td>
<td>Jan 7, 2013 12:53 PM</td>
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<tr>
<td>4</td>
<td>quantitative stratigraphy</td>
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<tr>
<td>5</td>
<td>ecosystem modelling</td>
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<tr>
<td>6</td>
<td>Forensics</td>
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<td>7</td>
<td>geomorphology</td>
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<td>8</td>
<td>bitterness</td>
<td>Dec 12, 2012 5:25 PM</td>
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<tr>
<td>9</td>
<td>geoarchaeology, Quaternary geology, archaeological science</td>
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<tr>
<td>10</td>
<td>computer/information science</td>
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<td>11</td>
<td>biogeochemistry</td>
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<td>12</td>
<td>proxy system modeling</td>
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<tr>
<td>13</td>
<td>taxonomy and systematics</td>
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<tr>
<td>14</td>
<td>curation of paleontological collections and global digitization efforts</td>
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<tr>
<td>15</td>
<td>software development and support</td>
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<tr>
<td>16</td>
<td>Laboratory manager and sample curator, safety and environmental officer and at one time seafloor mapper and research marine geologist.</td>
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<td>17</td>
<td>soil geochemistry</td>
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<td>18</td>
<td>Coupled atmosphere-ocean general circulation modelling</td>
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<td>19</td>
<td>stable isotope and solute modeling of lake systems</td>
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<tr>
<td>1</td>
<td>pollen, plants, cuticle</td>
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<td>2</td>
<td>stable isotopes</td>
<td>Jan 24, 2013 1:35 PM</td>
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<tr>
<td>3</td>
<td>Aminostratigraphy and aminoacid geochronology of coastal and marine deposits</td>
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<td>4</td>
<td>stable isotopes and trace elements in biogenic carbonates</td>
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<tr>
<td>5</td>
<td>micromorphology of soils and paleosols; stable isotopes of organic matter and carbonates; bulk geochemistry of paleosols</td>
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<td>we provide core descriptions (micro/macro fossil identification, stratigraphy) as well as process samples for researchers for grain size (coarse and fine fractions), density (wet and dry bulk), magnetic susceptibility, acoustic travel time, coulometry (total inorganic carbon), microfossil slide preparation (diatoms)</td>
<td>Jan 7, 2013 12:53 PM</td>
</tr>
<tr>
<td>7</td>
<td>U-Pb zircon geochronology; organic stable isotopes</td>
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<td>stable isotopes</td>
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<tr>
<td>9</td>
<td>Carbon cycle, ionic chemistry and authigenic mineralogy</td>
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<tr>
<td>11</td>
<td>mammals, paleosol carbonates, paleosol organic matter (bulk and compound specific)</td>
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<td>12</td>
<td>past geomagnetic field</td>
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<tr>
<td>13</td>
<td>vertebrates, dinosaurs, evolution</td>
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<tr>
<td>14</td>
<td>incorporating historical data into models</td>
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<tr>
<td>15</td>
<td>Ostracodes, chironomids, testate amoebae</td>
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<td>isotope geochemistry</td>
<td>Dec 14, 2012 10:43 AM</td>
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<td>17</td>
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<td>pollen</td>
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<tr>
<td>20</td>
<td>XRF, XRD, ICP, CNS, and other standard methods</td>
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<td>21</td>
<td>elemental and stable isotope geochemistry</td>
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<td>pollen and pteridophyte spores</td>
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<td>landforms</td>
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<td>boron isotopes, trace metals</td>
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<td>light stable isotopes, elemental chemistry using XRF</td>
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<td>hominin evolution, archaeology, cosmic radiation, ESR dating, sedimentary geochemistry</td>
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<td>I would be looking for use cases for semantic needs, such as for heterogeneous terms between data sets.</td>
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<td>isotope geochemistry</td>
<td>Dec 12, 2012 3:37 PM</td>
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<tr>
<td>30</td>
<td>pigments, isotopes, organics, nutrients, metals</td>
<td>Dec 12, 2012 2:32 PM</td>
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<td>31</td>
<td>stable/radiogenic isotopes and minor/trace element ratios in marine biominerals</td>
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<td>visualization and data management</td>
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<td>corals and caves</td>
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<td>soil geochemistry</td>
<td>Nov 30, 2012 2:59 PM</td>
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<tr>
<td>36</td>
<td>Modes of interannual and interdecadal climate variability; sensitivity to external forcings</td>
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<tr>
<td>37</td>
<td>solute evolution and lake mass balance</td>
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Page 1, Q7. Within the discipline(s) identified above, what are your primary topics of focus? Select all that apply.

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<th></th>
<th>Topic</th>
<th>Date</th>
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<tbody>
<tr>
<td>38</td>
<td>vertebrate macrofossils, isotopes in vertebrate teeth</td>
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Page 1, Q8. Is your research focus primarily on marine or terrestrial systems?

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<tr>
<th></th>
<th>Response</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fossil material from coastal units</td>
<td>Jan 17, 2013 9:18 AM</td>
</tr>
<tr>
<td>2</td>
<td>both</td>
<td>Dec 14, 2012 4:01 AM</td>
</tr>
<tr>
<td>3</td>
<td>freshwater</td>
<td>Dec 13, 2012 10:28 AM</td>
</tr>
<tr>
<td>4</td>
<td>It doesn't matter.</td>
<td>Dec 12, 2012 4:57 PM</td>
</tr>
<tr>
<td>5</td>
<td>freshwater</td>
<td>Dec 12, 2012 2:32 PM</td>
</tr>
<tr>
<td>6</td>
<td>Both, plus the atmosphere and cryosphere.</td>
<td>Nov 27, 2012 8:09 PM</td>
</tr>
<tr>
<td></td>
<td>Natural Archives</td>
<td>Date</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>1</td>
<td>Shallow marine and estuarine deposits from coastal regions</td>
<td>Jan 17, 2013 9:18 AM</td>
</tr>
<tr>
<td>2</td>
<td>all terrestrial deposits with vertebrate fossils but especially caves</td>
<td>Jan 11, 2013 12:00 PM</td>
</tr>
<tr>
<td>3</td>
<td>paleosols (buried soils)</td>
<td>Jan 10, 2013 1:19 PM</td>
</tr>
<tr>
<td>4</td>
<td>museum specimens</td>
<td>Jan 4, 2013 2:19 PM</td>
</tr>
<tr>
<td>5</td>
<td>terrestrial sediments, macrofossils</td>
<td>Jan 3, 2013 6:39 PM</td>
</tr>
<tr>
<td>6</td>
<td>vertebrate fossils</td>
<td>Dec 18, 2012 2:27 PM</td>
</tr>
<tr>
<td>7</td>
<td>vertebrate and invertebrate fossils</td>
<td>Dec 13, 2012 8:04 AM</td>
</tr>
<tr>
<td>8</td>
<td>Water</td>
<td>Dec 13, 2012 4:27 AM</td>
</tr>
<tr>
<td>9</td>
<td>spring deposits</td>
<td>Dec 12, 2012 10:56 PM</td>
</tr>
<tr>
<td>10</td>
<td>sand dunes</td>
<td>Dec 12, 2012 6:46 PM</td>
</tr>
<tr>
<td>11</td>
<td>Groudwater</td>
<td>Dec 12, 2012 4:06 PM</td>
</tr>
<tr>
<td>12</td>
<td>amber</td>
<td>Dec 12, 2012 2:31 PM</td>
</tr>
<tr>
<td>13</td>
<td>sclerosponges, molluscs</td>
<td>Dec 12, 2012 2:21 PM</td>
</tr>
<tr>
<td>14</td>
<td>marine sediments</td>
<td>Dec 12, 2012 2:19 PM</td>
</tr>
<tr>
<td>15</td>
<td>till</td>
<td>Nov 27, 2012 11:33 AM</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Date</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>1</td>
<td>Smithsonian Micropaleontological Reference Center</td>
<td>Jan 24, 2013 1:35 PM</td>
</tr>
<tr>
<td>2</td>
<td>Bell Museum of Natural History</td>
<td>Jan 23, 2013 1:51 PM</td>
</tr>
<tr>
<td>3</td>
<td>I currently maintain my collection at my university, but I am in the process of distributing most of the collection to one or more museums: LA County Museum of Natural History; Paleo Research Institute (Ithaca); Academy of Natural Sciences (Philadelphia); Florida Museum of Natural History</td>
<td>Jan 17, 2013 9:18 AM</td>
</tr>
<tr>
<td>4</td>
<td>At the core repository at the Illinois State Geological Survey; some cores that I have examined are stored at the Illinois State Museum</td>
<td>Jan 16, 2013 3:31 PM</td>
</tr>
<tr>
<td>5</td>
<td>US National Museum</td>
<td>Jan 15, 2013 10:06 AM</td>
</tr>
<tr>
<td>6</td>
<td>Smithsonian</td>
<td>Jan 14, 2013 8:41 PM</td>
</tr>
<tr>
<td>7</td>
<td>Earth and Mineral Sciences Museum &amp; Art Gallery, The Pennsylvania State University</td>
<td>Jan 11, 2013 12:00 PM</td>
</tr>
<tr>
<td>8</td>
<td>Florida Museum of Natural History</td>
<td>Jan 9, 2013 8:28 PM</td>
</tr>
<tr>
<td>9</td>
<td>Smithsonian Institution, Texas Bureau of Economic Geology</td>
<td>Jan 8, 2013 5:08 PM</td>
</tr>
<tr>
<td>10</td>
<td>All samples we send out are cataloged in SESAR</td>
<td>Jan 7, 2013 12:53 PM</td>
</tr>
<tr>
<td>11</td>
<td>A number of museums (depending on specific permit requirements), but based at Natural History Museum of Utah</td>
<td>Jan 4, 2013 2:15 PM</td>
</tr>
<tr>
<td>12</td>
<td>Varies depending on geographic area of collection</td>
<td>Jan 4, 2013 11:15 PM</td>
</tr>
<tr>
<td>13</td>
<td>MARUM, Bremen</td>
<td>Jan 2, 2013 11:39 AM</td>
</tr>
<tr>
<td>14</td>
<td>University of Wisconsin Museum of Geology</td>
<td>Dec 20, 2012 8:35 PM</td>
</tr>
<tr>
<td>15</td>
<td>Most fossils sampled are curated in museums</td>
<td>Dec 18, 2012 2:27 PM</td>
</tr>
<tr>
<td>16</td>
<td>With collaborators that have their own storage facilities</td>
<td>Dec 16, 2012 3:06 PM</td>
</tr>
<tr>
<td>17</td>
<td>In laboratory not listed above</td>
<td>Dec 14, 2012 6:18 PM</td>
</tr>
<tr>
<td>18</td>
<td>Will hold our lake sediment cores for a few years then send them to the Limnological Research Center. Physical samples</td>
<td>Dec 14, 2012 5:29 PM</td>
</tr>
</tbody>
</table>
### Page 1, Q10. How do you curate or archive the physical samples generated in your research? Select all that apply.

<table>
<thead>
<tr>
<th>Number</th>
<th>Response</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>all the fossils have been archived in the UCMP the primary genetic material (eg aDNA extracts) are archived in the lab</td>
<td>Dec 13, 2012 11:06 PM</td>
</tr>
<tr>
<td>20</td>
<td>Oregon State University repository</td>
<td>Dec 13, 2012 11:05 AM</td>
</tr>
<tr>
<td>21</td>
<td>UCMP</td>
<td>Dec 13, 2012 10:15 AM</td>
</tr>
<tr>
<td>22</td>
<td>Smithsonian, Peabody (Harvard), MCZ (Harvard)</td>
<td>Dec 13, 2012 8:04 AM</td>
</tr>
<tr>
<td>23</td>
<td>Some cores went to MARUM (Multiple PIs)</td>
<td>Dec 12, 2012 10:56 PM</td>
</tr>
<tr>
<td>24</td>
<td>institutional storage</td>
<td>Dec 12, 2012 6:46 PM</td>
</tr>
<tr>
<td>25</td>
<td>Science Museum of MN</td>
<td>Dec 12, 2012 2:32 PM</td>
</tr>
<tr>
<td>26</td>
<td>CU Museum of Natural History, University of California Museum of Paleontology, National Museum of Natural History - depends on where specimens were collected, permits and repository agreements.</td>
<td>Dec 12, 2012 2:31 PM</td>
</tr>
<tr>
<td>27</td>
<td>Smithsonian Tropical Research Institute and Florida Museum of Natural History</td>
<td>Dec 12, 2012 2:21 PM</td>
</tr>
<tr>
<td>28</td>
<td>N/A I don't collect physical samples</td>
<td>Dec 10, 2012 12:13 PM</td>
</tr>
<tr>
<td>29</td>
<td>They are kept in our lab</td>
<td>Dec 6, 2012 6:29 PM</td>
</tr>
<tr>
<td>30</td>
<td>WDC Paleo: which should be in the above list, as this is the PRIMARY international archive for our discipline.</td>
<td>Nov 27, 2012 8:09 PM</td>
</tr>
<tr>
<td>31</td>
<td>I have accessioned materials to LacCore and sponged off of LacCore for extended temporary storage of unaccessioned materials when convenient for me, while we also maintain a collection at my home institution.</td>
<td>Nov 27, 2012 2:26 PM</td>
</tr>
</tbody>
</table>
If you curate samples on your own, please describe in a few words how the samples are stored and cataloged.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Date/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I don't have a large amount of primary material. Most material is held by collaborators. Within the lab, lake sediments are labelled and stored at 4 deg C in a dedicated cold room. Hard rock material is labeled and stored in cabinets. Pollen residues in oils and glycerine are labelled and stored in vials at room temperature out of sunlight, organized by project. Slides are stored in labeled slide boxes. Pollen residue in water or fresh is stored at at 4 deg C. Fresh pollen samples for DNA analysis are stored in dedicated freezers. Teaching material is stored separately.</td>
<td>Jan 31, 2013 10:29 AM</td>
</tr>
<tr>
<td>2</td>
<td>Lane cabinets with locality/formation names</td>
<td>Jan 28, 2013 4:15 PM</td>
</tr>
<tr>
<td>3</td>
<td>Individual sample bags, numbered chronologically in order of collection, stored in standard size cardboard boxes (6x8x24&quot;) and cataloged in an MS Access database, linked to collection sites.</td>
<td>Jan 17, 2013 9:22 AM</td>
</tr>
<tr>
<td>4</td>
<td>If it is done correctly, there is an American Petroleum Institute number assigned to the boring or outcrop. This is standard practice at the ISGS. This gives, at least, geographic coordinates, either PLSS, or lat-long. Descriptions of the core are stored on line through the Geologic Records Unit. Samples are stored at the core library, but there isn't much room left. If I pick samples for ostracodes and plant macrofossils, I keep them in my office or in the local refrigerator.</td>
<td>Jan 16, 2013 3:36 PM</td>
</tr>
<tr>
<td>5</td>
<td>Microfossils are stored on micropaleo slides, set in slide trays, and stored flat in cabinets.</td>
<td>Jan 14, 2013 8:43 PM</td>
</tr>
<tr>
<td>6</td>
<td>Samples are boxed and indexed to Excel spread sheets and stored in Carlile Geology Research Building on the Baylor University campus</td>
<td>Jan 10, 2013 1:22 PM</td>
</tr>
<tr>
<td>7</td>
<td>We primarily work with material that has been collected in collaboration with other research groups. These groups are primarily responsible for the long-term storage of these material. These materials are stored in a variety of facilities, from museums/federal research facilities to industry.</td>
<td>Jan 7, 2013 2:44 PM</td>
</tr>
<tr>
<td>8</td>
<td>Samples are housed in cases in a shared department space. Rock and fossil samples are stored in Lane cases; other samples are stored in labelled, binned containers.</td>
<td>Jan 3, 2013 6:42 PM</td>
</tr>
<tr>
<td>9</td>
<td>In cold room; cataloged by PI project</td>
<td>Dec 27, 2012 8:26 PM</td>
</tr>
<tr>
<td>10</td>
<td>Any samples in my care are in a 4 deg C cold room.</td>
<td>Dec 27, 2012 8:20 PM</td>
</tr>
<tr>
<td>11</td>
<td>Stored in cabinets and cataloged by physical labels and notebooks</td>
<td>Dec 20, 2012 8:36 PM</td>
</tr>
<tr>
<td>12</td>
<td>Specimens are stored in rock cabinets and sample lists are maintained in spreadsheets</td>
<td>Dec 18, 2012 2:28 PM</td>
</tr>
<tr>
<td>13</td>
<td>Samples are stored by project but with no overall catalog.</td>
<td>Dec 18, 2012 10:35 AM</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td></td>
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<tr>
<td>---</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>cold store located by site</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Pollen slides are put in slide boxes with name of site, name of analyst, and year collected on the outside. Pollen preps are kept in vials that are stored in cardboard boxes. We have excel spreadsheets listing all samples collected from each core, and keep both electronic and physical copies of these spreadsheets. The physical copies are kept in a binder, with one binder for each site.</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>in walk-in cold room, but no systematic catalog for cores (identified by sites/cores/investigators)</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>The samples are stored at 4°C until the measurements. The samples are cataloged: Short name of the lake- name of the core - number of the sample</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>samples are stored in a -80 degree freezer, identified with unique identifiers, and I have a FileMakerPro database to organize them, as well as the original lab sheets.</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Stored in cold room and toher storage facilities (shelves/drawers) on campus. Cataloguing in spreadsheets.</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>extracts at -80</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>sediment cores stored in labeled tubes in cold room on campus</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Spare room, uncatalogued</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>stored sealed in darkness at 4°C excel sheet for entire working group</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Archival cored sediments are stored in a cooler at the university. Cores are cataloged in the Paleoclimate lab.</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Kept at 4 deg C either as whole or split cores or as subsamples in vials.</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>student: follow professor standards (which vary)</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>stored in my office. Data on my computer and stored at ncdc.noaa.gov</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>freeze-dried and excel.</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>in labelled boxes in our basements</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Box, shelf</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td>---</td>
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<td></td>
</tr>
<tr>
<td>31</td>
<td>frozen</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Haphazardly in labeled cardboard boxes and using spreadsheets.</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Maintain a sample inventory in Excel with location information. All samples are labeled and stored in plastic bins</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Government &quot;core library&quot; servicing industry and government geologists. Generally cold storage, boxed, shelved and catalogued.</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>They are stored in boxes labelled by expedition (for unprocessed stuff) or by publication (for processed/dated stuff). We have no central database inventory, but are working on something for the speleothem collection (corals to follow).</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Samples are stored in my office or home, with sample numbers in field notebooks and labeled on bags.</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>They are kept in our lab, in labelled boxes.</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Cold storage, organized by research site. Labelling includes site/core name, dates of sub-sampling, analyst name.</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Model output is archived on a tape store.</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Cold room</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Stored in a dedicated, well-maintained cold room and in-lab dry storage, but cataloged in an admittedly ad hoc collection of lab notes and spreadsheets. I'm working on improving it.</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Government lab archive</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>teeth are stored in museums. The isotope data is stored in excel files, and sometimes published.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Date</td>
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<td>------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>1</td>
<td>The only public announcement of these materials is through publication.</td>
<td>Jan 31, 2013 10:29 AM</td>
</tr>
<tr>
<td>2</td>
<td>Some data and metadata are now being stored at our NOAA/WDC amino acid racemization (AAR) site. Much more information remains to be uploaded to WDC!</td>
<td>Jan 17, 2013 9:22 AM</td>
</tr>
<tr>
<td>3</td>
<td>See above... any site can be accessed through its API number which is assigned and stored (electronically) at the Geological Records Unit.</td>
<td>Jan 16, 2013 3:36 PM</td>
</tr>
<tr>
<td>4</td>
<td><a href="http://www.neotomadb.org">www.neotomadb.org</a></td>
<td>Jan 14, 2013 8:43 PM</td>
</tr>
<tr>
<td>5</td>
<td>Metadata is only available through publications.</td>
<td>Jan 7, 2013 2:44 PM</td>
</tr>
<tr>
<td>6</td>
<td>NOAA WDC-A for Paleoclimatology</td>
<td>Dec 27, 2012 8:26 PM</td>
</tr>
<tr>
<td>7</td>
<td>Any finished projects -- we send all data to NGDC and PANGEA</td>
<td>Dec 27, 2012 8:20 PM</td>
</tr>
<tr>
<td>8</td>
<td>Metadata for some collections are stored in MagIC</td>
<td>Dec 18, 2012 10:35 AM</td>
</tr>
<tr>
<td>9</td>
<td>for aDNA samples, metadata and sequences are submitted to GenBank</td>
<td>Dec 13, 2012 11:10 PM</td>
</tr>
<tr>
<td>10</td>
<td>NOAA paleo server for published data</td>
<td>Dec 13, 2012 6:43 AM</td>
</tr>
<tr>
<td>11</td>
<td>NOAA paleoclimatology</td>
<td>Dec 12, 2012 7:05 PM</td>
</tr>
<tr>
<td>12</td>
<td>ncdc.noaa.gov</td>
<td>Dec 12, 2012 6:37 PM</td>
</tr>
<tr>
<td>13</td>
<td>published records</td>
<td>Dec 12, 2012 5:12 PM</td>
</tr>
<tr>
<td>14</td>
<td>But I'd love to have them available for such an activity!</td>
<td>Dec 12, 2012 2:08 PM</td>
</tr>
<tr>
<td>15</td>
<td>Metadata files are created in excel and posted either on my lab webpage or a central data portal (e.g., Arctic data portal)</td>
<td>Dec 5, 2012 9:30 AM</td>
</tr>
<tr>
<td></td>
<td>Reason</td>
<td>Date</td>
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<td>---</td>
<td>-------------------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>1</td>
<td>As a young lab, all of my material is in active use. I have not made long term plans for the curation of my original material.</td>
<td>Jan 31, 2013 10:29 AM</td>
</tr>
<tr>
<td>2</td>
<td>If I curate samples myself, there is intent to do future analyses or to take pictures with a digital camera mounted to a trinocular dissecting scope.</td>
<td>Jan 16, 2013 3:36 PM</td>
</tr>
<tr>
<td>3</td>
<td>I also have a collection of over 1000 soil and paleosol thin sections and it is not apparent how they should/could be archived. They are used extensively in my teaching.</td>
<td>Jan 10, 2013 1:22 PM</td>
</tr>
<tr>
<td>4</td>
<td>No clear community standards for how we archive our materials. Most colleagues curate their own samples/cold rooms.</td>
<td>Jan 7, 2013 2:44 PM</td>
</tr>
<tr>
<td>5</td>
<td>didn't know about other options</td>
<td>Dec 12, 2012 7:05 PM</td>
</tr>
<tr>
<td>6</td>
<td>need to keep so when new techniques come up I can smoke the competition</td>
<td>Dec 12, 2012 5:26 PM</td>
</tr>
<tr>
<td>7</td>
<td>may not comply with government permits</td>
<td>Dec 12, 2012 5:12 PM</td>
</tr>
<tr>
<td>8</td>
<td>The volume of data that I curate is much too large for any central repository: more than 20 terabytes!</td>
<td>Nov 27, 2012 8:12 PM</td>
</tr>
<tr>
<td></td>
<td>Response</td>
<td>Date/Time</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>1</td>
<td>As a young lab, I have not made long term plans for the curation of my original material. At the moment, my priority is publication and tenure.</td>
<td>Jan 31, 2013 10:29 AM</td>
</tr>
<tr>
<td>2</td>
<td>I do not have a plan at this point.</td>
<td>Jan 28, 2013 4:15 PM</td>
</tr>
<tr>
<td>3</td>
<td>As above - I have just retired and am spending quite a bit of my time organizing samples for distribution to three or four museums. This will take at least six months.</td>
<td>Jan 17, 2013 9:22 AM</td>
</tr>
<tr>
<td>4</td>
<td>NO</td>
<td>Jan 16, 2013 3:36 PM</td>
</tr>
<tr>
<td>5</td>
<td>yes. Collection goes to Smithsonian</td>
<td>Jan 14, 2013 8:43 PM</td>
</tr>
<tr>
<td>6</td>
<td>I have made no such plans (unfortunately).</td>
<td>Jan 10, 2013 1:22 PM</td>
</tr>
<tr>
<td>7</td>
<td>At the moment - no. Since I am decades away from retirement, most of the material will move with me if I leave my current position.</td>
<td>Jan 7, 2013 2:44 PM</td>
</tr>
<tr>
<td>8</td>
<td>Depends on the sample. Fossils and sediments will probably continue to be housed. Other samples (plants) will probably be discarded.</td>
<td>Jan 3, 2013 6:42 PM</td>
</tr>
<tr>
<td>9</td>
<td>no</td>
<td>Dec 27, 2012 8:26 PM</td>
</tr>
<tr>
<td>10</td>
<td>not currently</td>
<td>Dec 20, 2012 8:36 PM</td>
</tr>
<tr>
<td>11</td>
<td>Not yet, lots of time until then!</td>
<td>Dec 18, 2012 2:28 PM</td>
</tr>
<tr>
<td>12</td>
<td>No</td>
<td>Dec 18, 2012 10:35 AM</td>
</tr>
<tr>
<td>13</td>
<td>no plan</td>
<td>Dec 15, 2012 7:58 AM</td>
</tr>
<tr>
<td>14</td>
<td>Ultimately, I'm hoping that Minnesota LacCore or other repository will take up the job of curating pollen and charcoal samples.</td>
<td>Dec 14, 2012 5:33 PM</td>
</tr>
<tr>
<td>15</td>
<td>No</td>
<td>Dec 14, 2012 10:45 AM</td>
</tr>
<tr>
<td>16</td>
<td>No</td>
<td>Dec 14, 2012 9:05 AM</td>
</tr>
</tbody>
</table>
Page 2, Q14. If you curate samples on your own, do you have a plan for long-term curation when you retire or depart from your current position? Please describe.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>I'm not sure what the standards are here for genetic data. In some cases, all of the primary material is used up, and otherwise the extracts probably have a natural lifetime and may not be suitable for long-term curation. So no, I don't currently have a plan for long-term curation, though this is something good to think about since I'm now setting up my own lab (previous comments are relevant to my dissertation lab).</td>
<td>Dec 13, 2012 11:10 PM</td>
</tr>
<tr>
<td>18</td>
<td>Not yet</td>
<td>Dec 13, 2012 12:24 PM</td>
</tr>
<tr>
<td>19</td>
<td>No, and it is a worry for many of us.</td>
<td>Dec 13, 2012 8:05 AM</td>
</tr>
<tr>
<td>20</td>
<td>no</td>
<td>Dec 13, 2012 7:17 AM</td>
</tr>
<tr>
<td>21</td>
<td>We think about contacting the IODP BCR for storage of material we are not working on anymore.</td>
<td>Dec 13, 2012 1:44 AM</td>
</tr>
<tr>
<td>22</td>
<td>I will see if they can be curated at LacCore or they will be disposed.</td>
<td>Dec 12, 2012 9:24 PM</td>
</tr>
<tr>
<td>23</td>
<td>Remaining cores and subsamples, with existing data, will be transferred to the LacCore facility.</td>
<td>Dec 12, 2012 9:12 PM</td>
</tr>
<tr>
<td>24</td>
<td>up to professors</td>
<td>Dec 12, 2012 7:05 PM</td>
</tr>
<tr>
<td>25</td>
<td>no</td>
<td>Dec 12, 2012 6:37 PM</td>
</tr>
<tr>
<td>26</td>
<td>Offer to former graduate students</td>
<td>Dec 12, 2012 5:26 PM</td>
</tr>
<tr>
<td>27</td>
<td>no at the moment</td>
<td>Dec 12, 2012 5:12 PM</td>
</tr>
<tr>
<td>28</td>
<td>No; early career scientist</td>
<td>Dec 12, 2012 4:07 PM</td>
</tr>
<tr>
<td>29</td>
<td>not applicable</td>
<td>Dec 12, 2012 3:42 PM</td>
</tr>
<tr>
<td>30</td>
<td>Send to suitable national repository when analysis of samples are complete.</td>
<td>Dec 12, 2012 3:39 PM</td>
</tr>
<tr>
<td>31</td>
<td>no current plans</td>
<td>Dec 12, 2012 2:51 PM</td>
</tr>
<tr>
<td>32</td>
<td>Samples belong to Geological Survey and will be kept for as long as deemed necessary.</td>
<td>Dec 12, 2012 2:49 PM</td>
</tr>
<tr>
<td>33</td>
<td>no, but I have many years to figure this out, thankfully. although I'm sure that's what everyone says.</td>
<td>Dec 12, 2012 2:08 PM</td>
</tr>
<tr>
<td></td>
<td>Response</td>
<td>Date</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>34</td>
<td>I wouldn't think that many people would be interested in my samples, so they will probably be thrown out.</td>
<td>Dec 10, 2012 3:13 PM</td>
</tr>
<tr>
<td>35</td>
<td>No</td>
<td>Dec 5, 2012 9:30 AM</td>
</tr>
<tr>
<td>36</td>
<td>I am working with others on the expansion of WDC Paleo to host climate model output.</td>
<td>Nov 27, 2012 8:12 PM</td>
</tr>
<tr>
<td>37</td>
<td>No plan in place.</td>
<td>Nov 27, 2012 2:35 PM</td>
</tr>
</tbody>
</table>
Page 3, Q15. What data types are generated in your research? Consider both primary data (e.g., seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, etc.) as well as interpretations (e.g., temperature, moisture, floods, etc.). Please list all types.

|   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Date and Time                          |
|---|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | Pollen and charcoal counts, potentially other associated chemical data Images                                                                                                                                                                                                                                                                                                                                                                                                         | Jan 31, 2013 10:35 AM                 |
| 2 | sedimentary rock type and depositional environment, bed/facies/cycle thickness and composition (lithology/depositional environment)                                                                                                                                                                                                                                                                                                               | Jan 28, 2013 4:20 PM                  |
| 3 | foraminifer abundance counts, oxygen and carbon isotope data, strontium isotope data                                                                                                                                                                                                                                                                                                                                          | Jan 24, 2013 1:41 PM                  |
| 4 | Primary data type is Amino acid racemization (extent of racemization of amino acids). This includes locality, collection history, analytical history, etc. Additional results include Sr-isotope data, 14C data, U-Th data, and physical or microscopic properties of analyzed samples.                                                                                                                                                                    | Jan 17, 2013 9:29 AM                  |
| 5 | Geologic maps, stratigraphic columns/interpretations of cores, gamma ray logs, Ostracode counts, geochemical analyses results Sediment analyses (grain-size data, X-ray diffraction data, color (L *a *b))                                                                                                                                                                                  | Jan 16, 2013 3:43 PM                  |
| 6 | fossil occurrences, taxonomic data                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Jan 15, 2013 10:09 AM                 |
| 7 | microfossil counts and taxonomic identification interpretations-water chemistry, temperature, salinity, recharge/discharge hydrology                                                                                                                                                                                                                                                                                                   | Jan 14, 2013 8:50 PM                  |
| 8 | Fossil bones and teeth, counts of specimens, descriptions, geographic data, geological and absolute time Fossils are used for paleoecology, paleoenvironmental reconstructions, biogeography, evolutionary biology, aDNA                                                                                                                                                                                                                     | Jan 11, 2013 12:06 PM                 |
| 9 | Sediment/soil/rock lithology; thin-sections and micrographs; XRF and ICP elemental data, stable C and O isotopes of soil organic matter (C) and pedogenic carbonate (O): all are used for paleoenvironmental reconstructions of terrestrial (soil) systems.                                                                                                                                                                      | Jan 10, 2013 1:28 PM                  |
| 10| biodiversity, taxonomic, biostratigraphic and geochronologic data.                                                                                                                                                                                                                                                                                                                                                                                                                          | Jan 9, 2013 8:36 PM                   |
| 11| sediment/rock lithology, fossil assemblage lists, fossils                                                                                                                                                                                                                                                                                                                                                                                                                                      | Jan 8, 2013 5:11 PM                   |
| 12| Pollen counts, geochemical proxy data, radiocarbon dates, magnetic susceptibility data, potentially other proxy data (diatoms, chironomids, charcoal, etc.). Images.                                                                                                                                                                                                                                                                   | Jan 7, 2013 2:58 PM                   |
| 13| wet and dry bulk density, magnetic susceptibility, acoustic travel time, coarse and fine (Sedigraph) fraction grain sizes, coulometry (total inorganic carbon), sediment core images, line scan (RGB) data, sediment core descriptions                                                                                                                                                                                                                          | Jan 7, 2013 1:05 PM                   |
**Page 3, Q15. What data types are generated in your research? Consider both primary data (e.g., seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, etc.) as well as interpretations (e.g., temperature, moisture, floods, etc.). Please list all types.**

<table>
<thead>
<tr>
<th></th>
<th>Data Types</th>
<th>Date/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Stratigraphic sections, XRD, fossil specimens, radiogenic isotope data, stable isotope data, biomarker data</td>
<td>Jan 4, 2013 3:47 PM</td>
</tr>
<tr>
<td>15</td>
<td>Outcrop photos, stratigraphic logs, XRD, QEMSCAN, fossil specimens, phylogenetic datasets, specimen photos, CT scans, 3D surface scans, stable isotope values (mostly d13C), radiogenic isotope values (U-Pb zircon principally)</td>
<td>Jan 4, 2013 2:24 PM</td>
</tr>
<tr>
<td>16</td>
<td>Lithic type, onshore-offshore gradient</td>
<td>Jan 4, 2013 11:26 AM</td>
</tr>
<tr>
<td>17</td>
<td>Biomarker abundances and stable isotope compositions, ecological interpretations</td>
<td>Jan 3, 2013 6:45 PM</td>
</tr>
<tr>
<td>18</td>
<td>Seismic survey lines, magnetic susceptibility, sediment/rock lithology, ostracode and diatom counts, XRF elemental counts, stable isotope data, temperature, moisture, floods, wind</td>
<td>Jan 2, 2013 11:49 AM</td>
</tr>
<tr>
<td>19</td>
<td>MSCL logger data, images, XRF, LOI and/or coulometry, TS, TN, sometimes paleobiological data including phytoliths, pollen, diatoms, d13C of organics and carbonates</td>
<td>Dec 29, 2012 6:41 PM</td>
</tr>
<tr>
<td>20</td>
<td>All physical properties data, pollen counts, biome data, lithology, XRF, X-rays, color spectrometry, gamma ray density etc</td>
<td>Dec 27, 2012 8:27 PM</td>
</tr>
<tr>
<td>21</td>
<td>Stable carbon and oxygen isotopes, point count petrographic data, fossil abundance</td>
<td>Dec 20, 2012 8:39 PM</td>
</tr>
<tr>
<td>22</td>
<td>Stable isotopic and elemental composition, petrographic images, GIS databases</td>
<td>Dec 18, 2012 2:33 PM</td>
</tr>
<tr>
<td>23</td>
<td>Paleomagnetic, rock magnetic, magnetic anomaly, mineralogy, geochemical data, petrofabric data, geochronology data</td>
<td>Dec 18, 2012 10:44 AM</td>
</tr>
<tr>
<td>24</td>
<td>U-channel paleomagnetic data and rock magnetic data, MST data (magnetic susceptibility, gra density, p-wave), line scan images, CT scans, XRF, physical grain-size, color</td>
<td>Dec 16, 2012 3:14 PM</td>
</tr>
<tr>
<td>25</td>
<td>Lithology, vertebrate and invertebrate fossils, interpretations of depositional environments and paleoecology</td>
<td>Dec 16, 2012 1:20 PM</td>
</tr>
<tr>
<td>26</td>
<td>Pollen counts, isotopic data stable isotopes charcoal counts fungal spore counts phytolith counts</td>
<td>Dec 15, 2012 8:01 AM</td>
</tr>
</tbody>
</table>
|27 | PRIMARY DATA (from lakes and mires) Pollen & spore counts Macroscopic charcoal Loss-on-ignition Radiocarbon dates (sending samples out to third-party labs) Stable isotopes (sending samples out to third-party labs) XRF (sending cores out to third-party labs) OTHER RESOURCES USED & SYNTHESIZED Paleoclimatic simulations from general circulation models 21st-century climate projections from general circulation models Neotoma Paleoecology Database Paleoclimatic data from NOAA NCDC DERIVED INTERPRETATIONS Continental maps of fossil pollen distributions in space and time Temperature reconstructions Species distribution models | Dec 14, 2012 5:44 PM
Q15. What data types are generated in your research? Consider both primary data (e.g., seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, etc.) as well as interpretations (e.g., temperature, moisture, floods, etc.). Please list all types.

| 28 | pollen counts, macrofossil counts, LOI results, radiocarbon dating results, bulk density measurements, C accumulation rates |
| 29 | Magnetic remanence data (natural and artificial), susceptibility, color reflectance, and natural gamma radiation counts for studies of geomagnetic field variability, plate and hotspot motions, chronology, and environmental change. |
| 30 | Directional and rock magnetic measurements |
| 31 | seismics, petrophysics, XRF scanning |
| 32 | magnetic properties |
| 33 | primary data: count data (e.g., abundances of different taxa), measurements (e.g., tooth length), genetic sequences interpretations: biome type, species ID, haplotype. |
| 34 | XRF element counts, Stable isotope data. Temperature, carbonate content, |
| 35 | Lab sediment analysis, geochronological data, numerical model output, digital and paper maps |
| 36 | Elemental ratios generated from ICP-MS, foraminiferal faunal abundance counts, XRF elemental counts, stable isotope data, |
| 37 | Vertebrate fossils, isotope data, morphometric data |
| 38 | pollen counts, diatom counts, GPR transects, temperature, moisture |
| 39 | light isotopes, DNA sequence (which is curated in Genbank) |
| 40 | time series of microfossil abundance, particle size, stable isotopes of carbon, nitrogen (bulk), XRF elemental counts. |
| 41 | Light Isotopes |
| 42 | seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, digital images, color analyses, XRD, ICP, grain sizes, diatoms, ostracods, alkanes, stable isotopes, other magnetic measurements (NRM, ARM, hysteresis loops, etc.), OSL, radiocarbon, CNS, density, etc. |
Page 3, Q15. What data types are generated in your research? Consider both primary data (e.g., seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, etc.) as well as interpretations (e.g., temperature, moisture, floods, etc.). Please list all types.

<table>
<thead>
<tr>
<th></th>
<th>Data Types</th>
<th>Date and Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>Sediment lithology, loss on ignition, pollen counts, plant macrofossils, age via 14C.</td>
<td>Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>44</td>
<td>GEOTEK, XRF scan, XRD, Aquatic invertebrate species assemblage and abundance data, grain size analysis, mineral magnetic data, stable isotope and ICP-MS analysis; paleohydrochemistry and paleohydrology, lacustrine environment,</td>
<td>Dec 12, 2012 11:05 PM</td>
</tr>
<tr>
<td>45</td>
<td>Primary data- MS, lithology, grain size, ICPMS, XRD, pollen, diatoms, charcoal, macro fossils interpretations-temperature, moisture, erosional episodes, aquatic versus terrestrial inputs, C3 versus C4</td>
<td>Dec 12, 2012 9:34 PM</td>
</tr>
<tr>
<td>46</td>
<td>radiocarbon and Pb ages, stable isotope, LOI, %C, %N, compound-specific concentrations, Average chain length, carbon preference index, alkenone inferred temperature, gdgt (branched and tex86) inferred temperature</td>
<td>Dec 12, 2012 7:32 PM</td>
</tr>
<tr>
<td>47</td>
<td>sediment size and mineralogy; OSL ages; periods of dune sand accumulation and stability</td>
<td>Dec 12, 2012 7:04 PM</td>
</tr>
<tr>
<td>48</td>
<td>isotope and trace metal analyses on marine carbonates for pH and temperature reconstructions, as well as isotope stratigraphy</td>
<td>Dec 12, 2012 6:42 PM</td>
</tr>
<tr>
<td>49</td>
<td>Data: lithology, XRF, stable isotopes of foraminifera, microfossil abundance counts, seismic data, X-rays, sediment geochemistry, sedimentary petrology Interpretations: paleoclimate records (temperature, deep water age, oxygen levels, growth rates), orbital chronologies, paleoproductivity, biological community organization, evolutionary histories</td>
<td>Dec 12, 2012 6:19 PM</td>
</tr>
<tr>
<td>50</td>
<td>Lots. Over 120 papers worth.</td>
<td>Dec 12, 2012 5:30 PM</td>
</tr>
<tr>
<td>51</td>
<td>Temperature, paleohydroclimate data</td>
<td>Dec 12, 2012 4:10 PM</td>
</tr>
<tr>
<td>52</td>
<td>ground-penetrating radar survey lines, magnetic gradiometer surveys, topographic sections (e.g., beach profiles and dune topography); bulk chemistry (e.g., TOC, TIC, major &amp; trace element abundances); particle size distribution; magnetic susceptibility; XRD mineralogy; foraminiferal abundances; plant macrofossil types; mollusc shell abundances; radiocarbon age; stable oxygen and carbon isotopic compositions; Interpretations include: paleo-sea level; paleo-shoreline; seawater paleosalinity and paleotemperature; paleotempestology (storms).</td>
<td>Dec 12, 2012 3:48 PM</td>
</tr>
<tr>
<td>53</td>
<td>location images (scanned materials) isotopic composition ring width</td>
<td>Dec 12, 2012 3:43 PM</td>
</tr>
<tr>
<td>54</td>
<td>stable isotopes, U/Th ages, trace metal ratios (Sr/Ca, Mg/Ca, etc...), water isotopes, drip counts, calcite growth rates, pCO2, cave maps</td>
<td>Dec 12, 2012 2:57 PM</td>
</tr>
<tr>
<td>55</td>
<td>Opal, CaCO3, Corg, U, Th-series isotopes, trace metals, 230Th-normalized fluxes</td>
<td>Dec 12, 2012 2:57 PM</td>
</tr>
</tbody>
</table>
Page 3, Q15. What data types are generated in your research? Consider both primary data (e.g., seismic survey lines, magnetic susceptibility, sediment/rock lithology, pollen counts, XRF elemental counts, etc.) as well as interpretations (e.g., temperature, moisture, floods, etc.). Please list all types.

<table>
<thead>
<tr>
<th>No.</th>
<th>Data Types</th>
<th>Date/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>organismal diversity data (occurrence, abundance distributions, similarity indices), sampling curves, paleoclimate proxies (temperature, precipitation, salinity), paleoelevation. Insect feeding identifications and counts, preservation quality scores, body size distributions and other morphometric data, geographic ranges, XRD and SEM, etc...</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>57</td>
<td>sediment/rock lithology, high resolution core imagery</td>
<td>Dec 12, 2012 2:19 PM</td>
</tr>
<tr>
<td>58</td>
<td>primarily timeseries of oxygen isotopes, although our chronologies are getting increasingly complex. we also generate tons of images of samples (microscopic and macroscopic).</td>
<td>Dec 12, 2012 2:13 PM</td>
</tr>
<tr>
<td>59</td>
<td>magnetic susceptibility, magnetic remanence, magnetic anisotropy, temperature dependent magnetic properties, hysteresis loops, first order reversal curves, microscopy images.</td>
<td>Dec 12, 2012 10:06 AM</td>
</tr>
<tr>
<td>60</td>
<td>Sediment and stratigraphic descriptions Radiocarbon ages Tephra samples and correlations</td>
<td>Dec 10, 2012 3:17 PM</td>
</tr>
<tr>
<td>61</td>
<td>seismic survey lines, sediment/rock lithology, MSCL core logging data, core x-ray, formainiferal</td>
<td>Dec 7, 2012 2:27 PM</td>
</tr>
<tr>
<td>62</td>
<td>Peat: depth and stratigraphy, major elemental composition, pollen counts, macrofossil counts, testate amoeba counts, activity of radioisotopes 210Pb and 14C, peat humification estimated spectrophotometrically. Interpretations: depth to water table reconstructions, temperature and precipitation reconstructions Lake sediments: stratigraphy, magnetic susceptibility, pollen counts, siliceous microfossil counts (diatoms, chrysophyte cysts and scales, sponge spicules), chronologies (14C and 210Pb dating, Ambrosia pollen rises and other biostratigraphic chronological markers), biogenic silica content, organic matter and carbonate content estimated by loss on ignition. Interpretations: pH and nutrient reconstructions, temperature and precipitation reconstructions</td>
<td>Dec 5, 2012 9:41 AM</td>
</tr>
<tr>
<td>63</td>
<td>XRF and ICP-MS data, paleo-temperature, paleo-precipitation</td>
<td>Nov 30, 2012 3:02 PM</td>
</tr>
<tr>
<td>64</td>
<td>Climate model output.</td>
<td>Nov 27, 2012 8:15 PM</td>
</tr>
<tr>
<td>65</td>
<td>magnetic susceptibility, sediment/rock lithology, XRF elemental counts, CT-Scans, SEM images, Grain-size, CNS, lamination thickness, temperature, paleodischarge</td>
<td>Nov 27, 2012 3:22 PM</td>
</tr>
<tr>
<td>66</td>
<td>sediment lithology, isotopic composition of carbonate minerals and bulk OM, xrd scans, xrf output (third-party), carbon concentrations, basic magnetic susceptibility, aqueous chemistry (isotopes and solutes), core scans (third-party), lake bathymetry, locational data</td>
<td>Nov 27, 2012 2:55 PM</td>
</tr>
<tr>
<td>67</td>
<td>seismic survey lines, till composition, till clast dispersal patterns, till geochemistry, glacial history</td>
<td>Nov 27, 2012 11:37 AM</td>
</tr>
</tbody>
</table>
Page 3, Q16. What file formats do you use for data generated in your research? Select all that apply.

<table>
<thead>
<tr>
<th></th>
<th>File Format</th>
<th>Date/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Neotoma database</td>
<td>Jan 11, 2013 12:06 PM</td>
</tr>
<tr>
<td>2</td>
<td>note that relational databases can include &quot;vector-based&quot; geospatial data. e.g., PostGIS</td>
<td>Dec 20, 2012 8:39 PM</td>
</tr>
<tr>
<td>3</td>
<td>OPJ (OriginLab Proyect)</td>
<td>Dec 14, 2012 9:09 AM</td>
</tr>
<tr>
<td>4</td>
<td>matlab workspaces (.mat)</td>
<td>Dec 12, 2012 3:43 PM</td>
</tr>
<tr>
<td>5</td>
<td>we try to archive in matlab files, but supported by excel sheets and text files, for those who find those more accessible.</td>
<td>Dec 12, 2012 2:13 PM</td>
</tr>
<tr>
<td>6</td>
<td>netCDF</td>
<td>Nov 27, 2012 8:15 PM</td>
</tr>
<tr>
<td></td>
<td>Resource Description</td>
<td>Date</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>1</td>
<td>NANODE, NACODE</td>
<td>Jan 16, 2013 3:43 PM</td>
</tr>
<tr>
<td>2</td>
<td>NANODe  <a href="http://www.kent.edu/nanode">www.kent.edu/nanode</a></td>
<td>Jan 14, 2013 8:50 PM</td>
</tr>
<tr>
<td>3</td>
<td>NGDC has records of all our sediment core holdings including descriptions and photographs</td>
<td>Jan 7, 2013 1:05 PM</td>
</tr>
<tr>
<td>4</td>
<td>DigiMorph, Morphobank, DRYAD. Fossil Calibration Database (forthcoming NESCENT initiative)</td>
<td>Jan 4, 2013 2:24 PM</td>
</tr>
<tr>
<td>5</td>
<td>morphobank, morphbank</td>
<td>Dec 16, 2012 1:20 PM</td>
</tr>
<tr>
<td>6</td>
<td>Global Paleofire Database</td>
<td>Dec 14, 2012 5:44 PM</td>
</tr>
<tr>
<td>7</td>
<td>The UCMP database; supplemental info of the papers, GenBank</td>
<td>Dec 13, 2012 11:14 PM</td>
</tr>
<tr>
<td>8</td>
<td>Data sheets and descriptions organized in site-specific notebooks.</td>
<td>Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>9</td>
<td>data published in manuscript supplements</td>
<td>Dec 12, 2012 6:42 PM</td>
</tr>
<tr>
<td>10</td>
<td>NGDC</td>
<td>Dec 12, 2012 3:48 PM</td>
</tr>
<tr>
<td>11</td>
<td>Journal supplementary info</td>
<td>Dec 12, 2012 2:57 PM</td>
</tr>
<tr>
<td>12</td>
<td>GBIF, DRYAD, Own Database in MS Access</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>13</td>
<td>NCDC</td>
<td>Dec 10, 2012 12:20 PM</td>
</tr>
<tr>
<td>14</td>
<td>USGS InfoBank</td>
<td>Dec 7, 2012 2:27 PM</td>
</tr>
<tr>
<td>15</td>
<td>Polar Data Catalogue</td>
<td>Dec 5, 2012 9:41 AM</td>
</tr>
<tr>
<td>16</td>
<td>Varve working group metadata (in construction)</td>
<td>Nov 27, 2012 3:22 PM</td>
</tr>
<tr>
<td>17</td>
<td>Project-specific database developed by and shared among interinstitutional collaborators</td>
<td>Nov 27, 2012 2:55 PM</td>
</tr>
<tr>
<td></td>
<td>Reason</td>
<td>Date/Time</td>
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<tr>
<td>---</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Ignorance of what is available</td>
<td>Jan 31, 2013 10:35 AM</td>
</tr>
<tr>
<td>2</td>
<td>unaware of potential databases and format necessary for submission</td>
<td>Jan 28, 2013 4:20 PM</td>
</tr>
<tr>
<td>3</td>
<td>Simply because our lab (and other AAR labs) have been slow to get started with &quot;public&quot; data preservation efforts!</td>
<td>Jan 17, 2013 9:29 AM</td>
</tr>
<tr>
<td>4</td>
<td>NACODE should be uploaded into Neotoma; we should make plans to do so</td>
<td>Jan 16, 2013 3:43 PM</td>
</tr>
<tr>
<td>5</td>
<td>Issues with data ownership of collaborative research; currently, there are no suitable archives for large image data.</td>
<td>Jan 7, 2013 2:58 PM</td>
</tr>
<tr>
<td>6</td>
<td>most of the data generated is for researchers outside our lab and we leave it up to them to archive the data properly</td>
<td>Jan 7, 2013 1:05 PM</td>
</tr>
<tr>
<td>7</td>
<td>submission fees</td>
<td>Jan 2, 2013 11:49 AM</td>
</tr>
<tr>
<td>8</td>
<td>time consuming and unpaid</td>
<td>Dec 14, 2012 8:16 AM</td>
</tr>
<tr>
<td>9</td>
<td>Inertia. The data are publicly available via supplemental info and I plan to put them into Neotoma, but I haven’t had the time to do so.</td>
<td>Dec 13, 2012 11:14 PM</td>
</tr>
<tr>
<td>10</td>
<td>The concept of &quot;archiving data&quot; is mysterious. Who defines &quot;data,&quot; and how should errors be indicated?</td>
<td>Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>11</td>
<td>replicate of NOAA/Paleoclimatology archives, just easier to read/analyze the data.</td>
<td>Dec 12, 2012 3:43 PM</td>
</tr>
<tr>
<td>12</td>
<td>Have been trying to integrate with the most appropriate DB above, but there have been difficulties with the person overseeing the database.</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>13</td>
<td>The Institute for Rock Magnetism maintains the world's largest database of rock magnetic data (IRM Database).</td>
<td>Dec 12, 2012 10:06 AM</td>
</tr>
<tr>
<td>14</td>
<td>Differing perspectives among collaborators concerning centralized archiving of data and samples</td>
<td>Nov 27, 2012 2:55 PM</td>
</tr>
</tbody>
</table>
### Page 3, Q20. Where have you looked for previously-generated data to accomplish your research goals? Select all that apply.

<table>
<thead>
<tr>
<th></th>
<th>Source</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NANODe, NACODe, Denis Delorme's database (pre-NACODe)</td>
<td>Jan 16, 2013 3:43 PM</td>
</tr>
<tr>
<td>2</td>
<td>USDA-NRCS soils database</td>
<td>Jan 10, 2013 1:28 PM</td>
</tr>
<tr>
<td>3</td>
<td>NGDC. use data repositories when trying to fill in gaps in core metadata or when trying to find published works using our material</td>
<td>Jan 7, 2013 1:05 PM</td>
</tr>
<tr>
<td>4</td>
<td>DigiMorph, Morphobank, DRYAD</td>
<td>Jan 4, 2013 2:24 PM</td>
</tr>
<tr>
<td>5</td>
<td>IAEA</td>
<td>Dec 13, 2012 8:07 AM</td>
</tr>
<tr>
<td>6</td>
<td>Published research papers, of course.</td>
<td>Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>7</td>
<td>journal article supplementary data or from journal articles</td>
<td>Dec 12, 2012 11:05 PM</td>
</tr>
<tr>
<td>8</td>
<td>GNIP database, isoscapes.org</td>
<td>Dec 12, 2012 7:32 PM</td>
</tr>
<tr>
<td>9</td>
<td>published data sets</td>
<td>Dec 12, 2012 7:04 PM</td>
</tr>
<tr>
<td>10</td>
<td>State climatology offices, state water quality agencies</td>
<td>Dec 12, 2012 6:38 PM</td>
</tr>
<tr>
<td>11</td>
<td>ITIS, GBIF, EDNA (Europe), ToL, PaleoPortal, International Databases that are taxon specific (many funded through NSF AToL), others...</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>12</td>
<td>CMIP5 archive, which could use some improvement!!!!</td>
<td>Dec 12, 2012 2:13 PM</td>
</tr>
<tr>
<td></td>
<td>Resource</td>
<td>Date</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>1</td>
<td>published articles, student theses</td>
<td>Jan 28, 2013 4:20 PM</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>Jan 17, 2013 9:29 AM</td>
</tr>
<tr>
<td>3</td>
<td>USDA-NRCS soils database with soil characterization data and some whole-soil geochemical data.</td>
<td>Jan 10, 2013 1:28 PM</td>
</tr>
<tr>
<td>4</td>
<td>GBIF.org, WorldClim.org</td>
<td>Jan 7, 2013 2:58 PM</td>
</tr>
<tr>
<td>5</td>
<td>DigiMorph, Morphobank, DRYAD. Fossil Calibration Database (forthcoming NESCENT initiative)</td>
<td>Jan 4, 2013 2:24 PM</td>
</tr>
<tr>
<td>6</td>
<td>morphobank, morphbank</td>
<td>Dec 16, 2012 1:20 PM</td>
</tr>
<tr>
<td>7</td>
<td>International Tree Ring Database Global Paleofire Database PMIP (climate models, but they also do data syntheses)</td>
<td>Dec 14, 2012 5:44 PM</td>
</tr>
<tr>
<td>8</td>
<td>Journal supplementary data are highly important.</td>
<td>Dec 14, 2012 10:30 AM</td>
</tr>
<tr>
<td>9</td>
<td>--</td>
<td>Dec 14, 2012 9:09 AM</td>
</tr>
<tr>
<td>10</td>
<td>GeoMapApp</td>
<td>Dec 14, 2012 8:16 AM</td>
</tr>
<tr>
<td>11</td>
<td>I feel like museum collections are a good resource that aren't on the list above. Many museums have electronic, publicly available databases.</td>
<td>Dec 13, 2012 11:14 PM</td>
</tr>
<tr>
<td>12</td>
<td>Museum collections databases</td>
<td>Dec 13, 2012 10:23 AM</td>
</tr>
<tr>
<td>13</td>
<td>Published research papers. Are they not considered to be data archives?</td>
<td>Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>14</td>
<td>GNIP database, isoscapes.org</td>
<td>Dec 12, 2012 7:32 PM</td>
</tr>
<tr>
<td>16</td>
<td>fishbase</td>
<td>Dec 12, 2012 6:19 PM</td>
</tr>
<tr>
<td>17</td>
<td>amino acid researchers are creating their own site for data storage (run by John Wehmiller at least until he retires this year)</td>
<td>Dec 12, 2012 5:18 PM</td>
</tr>
<tr>
<td>18</td>
<td>There are so many - mostly through biological initiatives related to taxonomic data, aggregation and distribution of</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
</tbody>
</table>
Page 3, Q21. What other resources for data archiving in the paleogeoscience community are not shown above? Please list (even if you do not use them in your own research).

<table>
<thead>
<tr>
<th></th>
<th>museum data and those related to geospatial data (biogeomancer comes to mind).</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Again, more and more of us are using the CMIP-type archives.</td>
</tr>
<tr>
<td>21</td>
<td>GSC geoscan of publications, government open files</td>
</tr>
</tbody>
</table>

Dec 12, 2012 2:13 PM
Dec 5, 2012 9:41 AM
Nov 27, 2012 11:37 AM
<table>
<thead>
<tr>
<th>Comment</th>
<th>Date and Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>It is hard to find data that has been updated with new/better age interpretations.</td>
<td>Jan 24, 2013 1:41 PM</td>
</tr>
<tr>
<td>My concern about accessing other data has arisen from my need (desire) to know about existing collections (or data) from areas where our collections and results exist.</td>
<td>Jan 17, 2013 9:29 AM</td>
</tr>
<tr>
<td>time consuming-searching, translating to useful form</td>
<td>Jan 14, 2013 8:50 PM</td>
</tr>
<tr>
<td>It is a pain to hunt down authors to secure their data if not journal-archived.</td>
<td>Jan 10, 2013 1:28 PM</td>
</tr>
<tr>
<td>many times cores are not identified properly or at all in research papers</td>
<td>Jan 7, 2013 1:05 PM</td>
</tr>
<tr>
<td>Depends on the type of data, who generated it, and how long ago it was generated. The increasing requirements of journals that data be archived in places like DRYAD has helped immensely.</td>
<td>Jan 4, 2013 2:24 PM</td>
</tr>
<tr>
<td>I am too impatient....</td>
<td>Jan 2, 2013 11:49 AM</td>
</tr>
<tr>
<td>I usually ask my graduate students to access because I am not familiar with formats etc.</td>
<td>Dec 27, 2012 8:27 PM</td>
</tr>
<tr>
<td>Some modern climate data are very difficult to find and are often not in easy to use formats</td>
<td>Dec 18, 2012 2:33 PM</td>
</tr>
<tr>
<td>Easy if pollen data has been submitted to Neotoma; hard otherwise</td>
<td>Dec 14, 2012 5:44 PM</td>
</tr>
<tr>
<td>Data is often in some format I can't use (Paradox, etc.) &amp; it is often difficult to select what I want.</td>
<td>Dec 13, 2012 8:45 AM</td>
</tr>
<tr>
<td>depends on data and research question</td>
<td>Dec 13, 2012 1:53 AM</td>
</tr>
<tr>
<td>climate model results seem the most difficult to obtain</td>
<td>Dec 12, 2012 2:57 PM</td>
</tr>
<tr>
<td>But it could be much easier!</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>After about a decade in the field and after supervising 10 graduate students, the volume of data and number of people involved is making data archiving more challenging.</td>
<td>Dec 5, 2012 9:41 AM</td>
</tr>
<tr>
<td>It was easy until the Canadian conservatives closed the government library, limiting access to anything not yet digitized......</td>
<td>Nov 27, 2012 11:37 AM</td>
</tr>
<tr>
<td></td>
<td>Response</td>
</tr>
<tr>
<td>---</td>
<td>----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Especially important for data synthesis studies</td>
</tr>
<tr>
<td>2</td>
<td>if it were easier, it would become critically important</td>
</tr>
<tr>
<td>3</td>
<td>documented use of our cores is vital to renewal of our grant</td>
</tr>
<tr>
<td>4</td>
<td>will become more important....</td>
</tr>
<tr>
<td>5</td>
<td>I am just learning how important this is now.</td>
</tr>
<tr>
<td>6</td>
<td>depends on data and research question</td>
</tr>
<tr>
<td>7</td>
<td>I only work with people who share, and I share with those with whom I work</td>
</tr>
<tr>
<td>8</td>
<td>Sometimes more so than others.</td>
</tr>
</tbody>
</table>
Large collections of data and/or samples remain undigitized and only available through analog media, by contacting individual researchers, or through manual searches of repository holdings. How much would your research benefit if such "dark data" were digitized?

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>For my research, I have access to the largest ostracode autecological database for North America, but so far, no one else has access to it. Jan 16, 2013 3:43 PM</td>
</tr>
<tr>
<td>2</td>
<td>if it can be searchable, and translated into formats that can be easily accessed Jan 14, 2013 8:50 PM</td>
</tr>
<tr>
<td>3</td>
<td>We did not consider it. We contacted authors directly for data Dec 27, 2012 8:27 PM</td>
</tr>
<tr>
<td>4</td>
<td>Lack of access and data friction are <em>the</em> primary bottleneck in my research. Dec 14, 2012 5:44 PM</td>
</tr>
<tr>
<td>5</td>
<td>I see 50% of data as obsolete Dec 14, 2012 8:16 AM</td>
</tr>
<tr>
<td>6</td>
<td>Their value would depend on the purpose and judgment of the digitizer. Lousy data are still lousy when digitized. Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>7</td>
<td>not sure Dec 12, 2012 9:34 PM</td>
</tr>
<tr>
<td>8</td>
<td>Maybe, a lot of it is crap though. If I know the quality, maybe. Dec 12, 2012 5:30 PM</td>
</tr>
<tr>
<td>9</td>
<td>uncertain at the moment Dec 12, 2012 5:18 PM</td>
</tr>
<tr>
<td>10</td>
<td>not sure Dec 12, 2012 2:57 PM</td>
</tr>
<tr>
<td>11</td>
<td>This is huge and completely necessary! Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>12</td>
<td>Not sure of the benefit, because I really don't know what is out there. Dec 10, 2012 3:17 PM</td>
</tr>
<tr>
<td>13</td>
<td>Many older datasets are at lower resolution and not as well dated. Nevertheless, I have sought and used many of them, particularly from remote areas were there are few records. Dec 5, 2012 9:41 AM</td>
</tr>
</tbody>
</table>
What generic software packages do you currently use in your research for data management and visualization? Consider all data generated from the project initiation, through primary data collection and/or gathering previously-collected data, interpretation, and publishing. Select all that apply.

<table>
<thead>
<tr>
<th></th>
<th>Software Package(s)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Photoshop, SYSTAT</td>
<td>Jan 16, 2013 3:43 PM</td>
</tr>
<tr>
<td>2</td>
<td>post GIS software (e.g., cartoDB)</td>
<td>Jan 9, 2013 8:36 PM</td>
</tr>
<tr>
<td>3</td>
<td>ImageJ and Mesquite</td>
<td>Jan 4, 2013 3:47 PM</td>
</tr>
<tr>
<td>4</td>
<td>Mesquite, ImageJ</td>
<td>Jan 4, 2013 2:24 PM</td>
</tr>
<tr>
<td>5</td>
<td>Stata</td>
<td>Jan 3, 2013 6:45 PM</td>
</tr>
<tr>
<td>6</td>
<td>grapher</td>
<td>Dec 27, 2012 8:29 PM</td>
</tr>
<tr>
<td>7</td>
<td>KaliedaGraph</td>
<td>Dec 16, 2012 3:14 PM</td>
</tr>
<tr>
<td>8</td>
<td>GRASS</td>
<td>Dec 15, 2012 8:01 AM</td>
</tr>
<tr>
<td>9</td>
<td>kaleidagraph</td>
<td>Dec 14, 2012 6:24 PM</td>
</tr>
<tr>
<td>10</td>
<td>GRADS, FERRET (specialized for visualizing climate model output).</td>
<td>Dec 14, 2012 5:44 PM</td>
</tr>
<tr>
<td>11</td>
<td>GMT, FINK (compilers and more), KaleidaGraph, Endnote, SuperDuper (backups!), TextWrangler, Dropbox</td>
<td>Dec 14, 2012 10:30 AM</td>
</tr>
<tr>
<td>12</td>
<td>Sequencher, ImageJ</td>
<td>Dec 13, 2012 11:14 AM</td>
</tr>
<tr>
<td>13</td>
<td>Kaleidagraph</td>
<td>Dec 13, 2012 11:08 AM</td>
</tr>
<tr>
<td>14</td>
<td>Grapher, Surfer</td>
<td>Dec 13, 2012 8:45 AM</td>
</tr>
<tr>
<td>15</td>
<td>DrDepth, Sufer</td>
<td>Dec 13, 2012 1:53 AM</td>
</tr>
<tr>
<td>16</td>
<td>kaleidagraph</td>
<td>Dec 12, 2012 7:32 PM</td>
</tr>
<tr>
<td>17</td>
<td>various programs we have created ourselves or created for our specific interests by suppliers</td>
<td>Dec 12, 2012 5:18 PM</td>
</tr>
<tr>
<td>18</td>
<td>Kaleidagraph</td>
<td>Dec 12, 2012 3:48 PM</td>
</tr>
<tr>
<td>19</td>
<td>Kaleidagraph</td>
<td>Dec 12, 2012 3:45 PM</td>
</tr>
</tbody>
</table>
# Question 25

What generic software packages do you currently use in your research for data management and visualization? Consider all data generated from the project initiation, through primary data collection and/or gathering previously-collected data, interpretation, and publishing. Select all that apply.

<table>
<thead>
<tr>
<th></th>
<th>Software Packages</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>ocean data view, datagraph</td>
<td>Dec 12, 2012 2:57 PM</td>
</tr>
<tr>
<td>21</td>
<td>JMP statistical package (through SAS), EstimateS, EcoSim</td>
<td>Dec 12, 2012 2:45 PM</td>
</tr>
<tr>
<td>22</td>
<td>Mathematica</td>
<td>Dec 12, 2012 10:06 AM</td>
</tr>
<tr>
<td>23</td>
<td>Ferret</td>
<td>Nov 27, 2012 8:15 PM</td>
</tr>
<tr>
<td>24</td>
<td>Kaleidagraph</td>
<td>Nov 27, 2012 3:22 PM</td>
</tr>
</tbody>
</table>
Page 3, Q26. What geoscience-specific software packages do you currently use in your research for data management and visualization? Consider all data generated from the project initiation, through primary data collection and/or gathering previously-collected data, interpretation, and publishing. Select all t...

<table>
<thead>
<tr>
<th></th>
<th>Software Package</th>
<th>Date and Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C2</td>
<td>Jan 31, 2013 10:35 AM</td>
</tr>
<tr>
<td>2</td>
<td>Map and data files for our work are currently being developed on <a href="http://www.arcgis.com">www.arcgis.com</a></td>
<td>Jan 17, 2013 9:29 AM</td>
</tr>
<tr>
<td>3</td>
<td>SYSTAT</td>
<td>Jan 16, 2013 3:43 PM</td>
</tr>
<tr>
<td>4</td>
<td>Neotoma taxa mapper</td>
<td>Jan 11, 2013 12:06 PM</td>
</tr>
<tr>
<td>5</td>
<td><a href="http://www.staff.ncl.ac.uk/staff/stephen.juggins/software/C2Home.htm">http://www.staff.ncl.ac.uk/staff/stephen.juggins/software/C2Home.htm</a></td>
<td>Jan 7, 2013 2:58 PM</td>
</tr>
<tr>
<td>6</td>
<td>we will be using corewall products in the near future as part of a hyperwall we are building</td>
<td>Jan 7, 2013 1:05 PM</td>
</tr>
<tr>
<td>7</td>
<td>GMT, MBSYSTEM</td>
<td>Dec 18, 2012 10:44 AM</td>
</tr>
<tr>
<td>8</td>
<td>GMT, FORCIT, ZPLOTIT, FINK packages, MacMirone, PMAGPY, Match</td>
<td>Dec 14, 2012 10:30 AM</td>
</tr>
<tr>
<td>9</td>
<td>IAPD</td>
<td>Dec 14, 2012 9:09 AM</td>
</tr>
<tr>
<td>10</td>
<td>Ocean Data View</td>
<td>Dec 13, 2012 11:08 AM</td>
</tr>
<tr>
<td>11</td>
<td>ISE</td>
<td>Dec 13, 2012 1:53 AM</td>
</tr>
<tr>
<td>12</td>
<td>Personal software (PollenCount and Psidium) for acquiring and analyzing pollen stratigraphy.</td>
<td>Dec 12, 2012 11:14 PM</td>
</tr>
<tr>
<td>13</td>
<td>specific software written by comp programmers at our univeristy</td>
<td>Dec 12, 2012 7:32 PM</td>
</tr>
<tr>
<td>14</td>
<td>C2</td>
<td>Dec 12, 2012 6:38 PM</td>
</tr>
<tr>
<td>15</td>
<td>Canoco-Canodraw and other stuff for stats nerds</td>
<td>Dec 12, 2012 5:30 PM</td>
</tr>
<tr>
<td>16</td>
<td>grapher</td>
<td>Dec 12, 2012 5:18 PM</td>
</tr>
<tr>
<td>17</td>
<td>Match (Lisiecki and Lisiecki, 2002)</td>
<td>Dec 10, 2012 12:20 PM</td>
</tr>
<tr>
<td>18</td>
<td>C2, paleo packages for R</td>
<td>Dec 5, 2012 9:41 AM</td>
</tr>
</tbody>
</table>
Page 3, Q27. What other geoscience-specific software packages for data management and visualization are not shown above? Please list (even if you do not use them in your research).

<table>
<thead>
<tr>
<th></th>
<th>Software Package</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Age-depth profiler (Chronos), Time Scale Creator</td>
<td>Jan 24, 2013 1:41 PM</td>
</tr>
<tr>
<td>2</td>
<td>Not familiar enough with the field to be able to answer!</td>
<td>Jan 17, 2013 9:29 AM</td>
</tr>
<tr>
<td>3</td>
<td>Neotoma taxa mapper</td>
<td>Jan 11, 2013 12:06 PM</td>
</tr>
<tr>
<td>4</td>
<td>cartoDB</td>
<td>Jan 9, 2013 8:36 PM</td>
</tr>
<tr>
<td>5</td>
<td>GMT, MBSYSTEM, Fledermaus</td>
<td>Dec 18, 2012 10:44 AM</td>
</tr>
<tr>
<td>6</td>
<td>ODV</td>
<td>Dec 14, 2012 6:24 PM</td>
</tr>
<tr>
<td>7</td>
<td>GMT, FORCIT, ZPLOTIT, FINK packages, MacMirone  What would be nice is a GUI for viewing SEGY files. There is really no high quality program. GMT has a subroutine that can plot some SEGY files but not most. Geophysics firms charge too much for their software to make it viable for those of us who only occasionally use SEGY files</td>
<td>Dec 14, 2012 10:30 AM</td>
</tr>
<tr>
<td>8</td>
<td>--</td>
<td>Dec 14, 2012 9:09 AM</td>
</tr>
<tr>
<td>9</td>
<td>There are geoscience-specific packages within R, such as ‘analogue’ and ‘rioja’, to name two.</td>
<td>Dec 13, 2012 11:14 PM</td>
</tr>
<tr>
<td>10</td>
<td>OceanDataView</td>
<td>Dec 13, 2012 11:08 AM</td>
</tr>
<tr>
<td>11</td>
<td>C2</td>
<td>Dec 12, 2012 6:38 PM</td>
</tr>
<tr>
<td>12</td>
<td>Gigawiz Aabel Statistics and Visualization software; Surfer.</td>
<td>Dec 12, 2012 3:48 PM</td>
</tr>
<tr>
<td>13</td>
<td>Match (Lisiecki and Lisiecki, 2002)</td>
<td>Dec 10, 2012 12:20 PM</td>
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<td>14</td>
<td>Surfer</td>
<td>Dec 5, 2012 9:41 AM</td>
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<td>15</td>
<td>SAS, JMP</td>
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Page 4, Q28. Please list important science drivers and scientific challenges you would like to tackle (or tackle more easily) within a 5 to 15 year time frame:

- **a. within your discipline**
- **b. across disciplines within the geosciences (if possible, rank the geoscience disciplines by priority)**
- **c. across disciplines (computer science, applied mathematics, optics, plant biology - morphology and development) would be involved.**

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<tr>
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<th>Challenge Description</th>
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<tr>
<td>1</td>
<td>Increase the rate and quality of data collection; generalize our image analysis methods to other micro, meso, and macrofossils; attempt large spatial and temporal analyses of turnover in plant communities. This would apply to paleo disciplines, as well as across geo disciplines (e.g., stratigraphy, climatology). Other disciplines (computer science, applied mathematics, optics, plant biology - morphology and development) would be involved.</td>
<td>Jan 31, 2013 1:19 PM</td>
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<tr>
<td>2</td>
<td>a. Paleoceanography/Paleoclimatology: 1. Reconstruction of global marine temperatures through time using all available proxy data. 2. Reconstruction of paleo-CCD through time in different ocean basins. b. 1. Global map of marine sediment types and ages in 3D</td>
<td>Jan 24, 2013 1:58 PM</td>
</tr>
<tr>
<td>3</td>
<td>a. I would like to update NACODe, collaborating with others to add data in areas where we currently lack data (e.g., Canadian arctic: Joan Bunbery, Alaska: Rick Forester and others at USGS; Florida: numbers of people, etc.) b. I would be happy to contribute, but will need funding. c. As above</td>
<td>Jan 16, 2013 3:56 PM</td>
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<td>4</td>
<td>a) Community reorganization in response to environmental change, shifts in composition and space of biogeographic provinces, changes in morphology in response to environmental change. b) Community reorganization in response to environmental change, shifts in composition and space of biogeographic provinces, changes in morphology in response to environmental change. c) Community reorganization in response to environmental change, shifts in composition and space of biogeographic provinces, changes in morphology in response to environmental change.</td>
<td>Jan 11, 2013 12:12 PM</td>
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<td>5</td>
<td>a. Collating temporal data for specific events in the last 4 million years. Finding the original references to the temporal data for proper citation finding meta data and also value added data for specific sites. b. Paleomagnetics data by site with citations geochronology data by site climate reconstructions or model runs for the time periods I am interested in. c. Public communications about science outcomes as a template for how we might be more effective as communicating our science.</td>
<td>Dec 27, 2012 8:37 PM</td>
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<td>6</td>
<td>I would like to have a complete physical and chemical characterization of the upper crust with a spatial resolution as great or greater than Macrostrat. This dataset would allow us to address an incredibly large range of questions, ranging from biogeochemical cycling and climate change to the tectonic evolution of the continent.</td>
<td>Dec 20, 2012 8:42 PM</td>
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<td>7</td>
<td>Document variations in geomagnetic field over time. Investigate links between observables of the geomagnetic field (e.g., intensity, reversal rate, scatter) and geodynamo models and deep earth processes. Use seafloor records of geomagnetic field to better understand ridge crest processes.</td>
<td>Dec 19, 2012 9:57 AM</td>
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</table>
Page 4, Q28. Please list important science drivers and scientific challenges you would like to tackle (or tackle more easily) within a 5 to 15 year time frame:

a. within your discipline
b. across disciplines within the geosciences (if possible, rank the geoscience disciplines by priority)
c. across discipl...

|   | 8 | a - Precise stratigraphic placement of all dinosaur specimens ever collected (the ideal result, obviously challenging to impossible). Preferably this database would be linked to all radiometric dates ever collected for Mesozoic formations. This would enable detailed studies of the evolutionary relationships of dinosaur taxa over time, so we can analyze the patterns and processes of dinosaur evolution including the frequency of cladogenic splits vs anagenetic lineages, diversity (number of lineages alive at each time slice), extinction rates, etc. | Dec 16, 2012 1:38 PM |
|   | 9 | link palaeoecological perspectives to historical / remotely sensing perspectives on ecosystem dynamics to be able to characterise useful ecosystem services / soci-ecological interconnections so that palaeo can have a more applied rationale | Dec 15, 2012 8:05 AM |
|   | 10 | 1. use of molecular tools in paleoecology 2. integrating paleoecology with management and policy | Dec 14, 2012 6:44 PM |
|   | 11 | Assimilating paleoecological data into terrestrial ecosystem models in order to improve models' representation of decadal-to-centennial processes. Comprehensive biodiversity surveys at global scale across all fossil types across glacial-interglacial cycles. Global vegetation mapping for for purposes of reconstructing terrestrial carbon sequestration, surface-atmosphere feedbacks, etc. Full integration of all available paleoclimatic proxies and paleoecological proxies in order to study environmental drives of ecological and evolutionary dynamics. | Dec 14, 2012 5:57 PM |
|   | 12 | Mapping the global geomagnetic field on a millennial scale for the past 1 m.y. Improving plate reconstructions for constraining geodynamic questions about mantle flow and hotspot motions. Determining the links between climate change and a myriad of other potential forcing factors including those with geodynamic, atmospheric, geomagnetic, oceanographic, and extraterrestrial origins. Locating, mapping, and assessing the extent of future energy and mineral resources. | Dec 14, 2012 11:09 AM |
|   | 13 | I believe that it is important for paleoscience to develop new approaches and strategies to facilitate synergy and coupling of empirical data and process modeling, especially at global scale. For that purpose, the data need to be synthesized in formats that can be systematically and meaningfully used by modelers. The challenges would be to develop these new approaches and methodologies. One example that we have worked on in my lab is to synthesize all peatland carbon accumulation data at global scale and work with global climate-carbon cycle modelers to incorporate these data into global models. Also, paleoscience is in a position to expand and extend the time scales of neoscience, such as Eddy flux measurements of ecosystem carbon balance. So I see two science drivers and related challenges: (1) global data synthesis and modeling, and (2) importance of timescales in driving ecological and other processes. | Dec 14, 2012 11:04 AM |
|   | 14 | I am interested in refining and quantifying issues with Mg/Ca paleothermometry and also addressing ocean/atmosphere interactions associated with abrupt climate change across MIS3. | Dec 13, 2012 11:15 AM |
Page 4, Q28. Please list important science drivers and scientific challenges you would like to tackle (or tackle more easily) within a 5 to 15 year time frame:

a. within your discipline  
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c. across disciplines...

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| 15 | a. mechanistic control of organic nitrogen and oxygen isotopes  
    |   | b. preservation and fidelity of ancient biomolecules, with the development of rigorous pipeline to aid in assessments. | Dec 13, 2012 8:12 AM |
| 16 | Should I live so long, with mental faculties unimpaired, then:  
    |   | b. and c. I am not sure where the limits of "the geosciences" are, but the projects listed in (a) all involve plant biology, taxonomy, and ecology, and my interests and abilities are in there somewhere. | Dec 12, 2012 11:48 PM |
| 17 | Geography, environmental science, biology | Geography, environmental science, biology | Dec 12, 2012 9:41 PM |
| 18 | a. orbital scale monsoon variability and causes causes of climate variability in the Arctic, and how this influences past and future changes in ice sheets, glaciers, permafrost, etc  
    |   | b. compare paleoclimate outputs with model output, tune models for better performance in future predictions  
    |   | c. inform public about our findings | Dec 12, 2012 7:36 PM |
| 19 | (A) within discipline  
    |   | • What are the boundary conditions for sand sea development and how have they changed through time?  
    |   | • What are the patterns of dunes in sand seas and how have they developed in response to boundary conditions and dunefield dynamics?  
    |   | • How is the sedimentary record of Quaternary sand seas developed?  
    |   | • How do aeolian systems respond to changes in boundary conditions?  
    |   | (B) across disciplines (within earth sciences)  
    |   | • Understand the chronology of dune system development in relation to changes in sediment supply, availability, and mobility as forced by Quaternary changes in climate, sea level, and tectonics  
    |   | (C) outside geosciences  
    |   | • develop scientific data mining approaches | Dec 12, 2012 7:04 PM |
| 20 | Challenge: I would like to know if Earth has long-period cycles in biological productivity and biodiversity; I would also like to reconstruct global patterns of biodiversity in the modern oceans, trends in biodiversity over the recent past (last 1000 years), and the long-period dynamics of assembly and disassembly of biological communities. | Challenge: I would like to know if Earth has long-period cycles in biological productivity and biodiversity; I would also like to reconstruct global patterns of biodiversity in the modern oceans, trends in biodiversity over the recent past (last 1000 years), and the long-period dynamics of assembly and disassembly of biological communities. | Dec 12, 2012 6:44 PM |
| 21 | My science is driven by funding and the Canadian government is bushist and thinks science is an inconvenience so I will likely be out of science unless I can move to Germany or China, where there is still hard cash for science. Biggest global change questions are geopolitical and socio-economic, not scientific. I think proteomics and paleogenomics will be the biggest challenges for data storage, not pollen/diatom counts that no one, especially not govs that fund us, really care about. | My science is driven by funding and the Canadian government is bushist and thinks science is an inconvenience so I will likely be out of science unless I can move to Germany or China, where there is still hard cash for science. Biggest global change questions are geopolitical and socio-economic, not scientific. I think proteomics and paleogenomics will be the biggest challenges for data storage, not pollen/diatom counts that no one, especially not govs that fund us, really care about. | Dec 12, 2012 5:35 PM |
Page 4, Q28. Please list important science drivers and scientific challenges you would like to tackle (or tackle more easily) within a 5 to 15 year time frame:

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c. across discipl...

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<td>22</td>
<td>I would like to take the domain specific answers to this question as use cases for work in the semantic area. I'm assuming paleogeologists would state specific data problems here that need to be solved. These problems would likely have a semantic component regarding finding, understanding, and integrating data. I'd like to work on some of the semantic problems myself and also be a go-between with others involved in semantic technology.</td>
<td>Dec 12, 2012 5:34 PM</td>
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<td>23</td>
<td>Pray tell what is a &quot;science driver&quot;? What do you want to ask in this question? It is not at all clear! Good English and no government speak would help here.</td>
<td>Dec 12, 2012 5:21 PM</td>
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<td>24</td>
<td>Global groundwater dataset</td>
<td>Dec 12, 2012 4:12 PM</td>
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| 25 | a. Sea-level rise and coastal response: marine/coastal sedimentology  
b. Sea-level rise and coastal response: geodesy, glaciology, physical oceanography, atmospheric circulation, geophysics, remote sensing.  
c. Sea-level rise and coastal response: sociology, socioeconomic adaptation; alternative energy technology; economics; marketing; communication.  | Dec 12, 2012 3:53 PM |
<p>| 26 | a) improved age model development tools  | Dec 12, 2012 2:59 PM |
| 27 | data-model intercomparisons multi-proxy data synthesis representation of uncertainties in proxy data (in the time and &quot;response&quot; dimensions)  | Dec 12, 2012 2:19 PM |
| 28 | To reconstruct and understand global climate variability and change over the past 2,000 years.  | Nov 27, 2012 8:17 PM |
| 29 | I'd like to establish a clearer and more productive common collaborative language between myself (as limnogeologist/paleoenvironmental analyst), geomorphologists concerned with lake basin genesis, and landscape ecologists speaking the nebulous jargon of 'connectivity' in ecosystem functions.  | Nov 27, 2012 3:29 PM |
| 30 | Collaboration is key, and requires communication between parties (uni, government, industry) as to who is working where, so all data can be collected and kept together - I believe shared workspaces and shared, open, free data is the key to future work. This is part of why I work in government - so data collected is publically available. I, however, have no idea where to start looking for past data from university projects. Topics: paleoglaciology of Canada, ice-flow, cold-based/warm-based ice, glacial landform generation/modification/preservation mechanisms  | Nov 27, 2012 11:41 AM |</p>
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<td>1</td>
<td>Developing collaborations across disciplines takes time, which makes initiating these collaborative projects difficult and initially not very rewarding. For example, I engaged in collaborative research very early on, but it took ~2 years for the collaborations to gel and publications to result. Although now my publication rate has increased, it meant that for several years, I had poor departmental reviews. Although data storage costs are going down, it is still very expensive to store many TB of data. It is significantly more expensive to make that data available on servers. Long-term maintenance of databases, support for users who may be using software or images we generate, developing UI - these are all tasks that need external technical support. IT support is good - but limited - at my university.</td>
<td>Jan 31, 2013 1:19 PM</td>
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<td>2</td>
<td>a&amp;b: Lack of age model information for deep sea sites is a real handicap to users of deep sea core material; for some sites there is no information beyond what was published in the initial results volume, which is very low resolution and often not very reliable. But much information has been published but has not been captured for accessibility through database searches.</td>
<td>Jan 24, 2013 1:58 PM</td>
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<td>3</td>
<td>I am quite new to the effort of “global” data management, and my specific focus in this arena has arisen from my experience of being unable to locate information about existing collections from Quaternary coastal sites in the US where geochronological data might exist. Ideally, there would be on-line maps that show collection sites, with references to published data or links to contact individuals, museums, etc. I am in the process of doing this for our own work (and related work from others) but, ideally, this effort should be part of some larger database platform. The AAR community has, in th past two years, begun to upload data to the NOAA WDC site, so hopefully we will be able to build a set of maps that can serve the purposes described. On a broader scale, these maps should include information about all sorts of studies: stratigraphy, geochronology, paleoclimatology, paleontology, etc.</td>
<td>Jan 17, 2013 9:38 AM</td>
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<td>4</td>
<td>a. I need time and education in using modern analogs. I have the datasets of fossil material, and data for moderns, but not the skill set to meaningfully access and use a modern analog program. I am aware of Juggin’s C++, and will probably be trying to learn this soon. This would be used primarily to model paleohydrology, with some emphasis on paleoclimate as well. b. Across disciplines, I would be happy to collaborate. c. As above. I'm too old and long in the tooth to learn other systems at this point, unless someone wants to train me. I have a feeling that that is the standing of many researchers who are nearing retirement.</td>
<td>Jan 16, 2013 3:56 PM</td>
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<td>5</td>
<td>c) comparable databases in the other disciplines, although vertnet is quite useful</td>
<td>Jan 11, 2013 12:12 PM</td>
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<td>6</td>
<td>a. I am at the starting point of making our data available. so I don't have problems yet.</td>
<td>Dec 27, 2012 8:37 PM</td>
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<td>7</td>
<td>The above ambition is a monumental task. However, it is frustratingly realizable. It just requires an infrastructure and the collaborative involvement of geoscientists who have the knowledge at hand for their regions/time intervals.</td>
<td>Dec 20, 2012 8:42 PM</td>
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8. For many types of paleomagnetic studies, access to original data is required and these data typically are not available. While the MagIC database provides a mechanism for archiving data, a mechanism to encourage/require data submission will be needed. For marine geophysical studies, access to U.S. generated data is adequate though this could be significantly improved by merging data from various archives to provide a single repository.

9. a - Stratigraphic information published with dinosaur specimen descriptions is generally limited, hindering detailed studies that need to know the precise stratigraphic ages of different specimens (on a scale of 100,000 years or less) to analyze the gradual changes in morphology over time and connect the evolutionary relationships of different taxa (i.e., 3 different closely related species living at the same time, or are they 3 members of a gradually evolving lineage?). Ways to improve this: 1) All new research should measure AND publish the precise stratigraphic position of new specimens, and include their stratigraphic age relative to other closely related specimens. 2) Past research may have collected important stratigraphic data that was not published. This data may be hidden in old field notes, research notes, or individual museum databases. If this "lost" data could be digitized and accumulated in a multi-institutional database, it would greatly benefit future research. 3) Incomplete or lost data may require significant effort to complete and make useful. Example: paleontologists a century ago generally only included vague locality descriptions (50 miles southwest of Town X) that can only be correlated to a formation or general part of formation. However, if they took a photograph of the site, a dedicated modern researcher can search the entire area for archaeological evidence of an old quarry and match the site to the outcrops in the photograph. Yes, a lot of work, but the stratigraphic data that results is extremely important.

10. Time - and methods - these are ongoing within our lab and I expect to make good progress in the 3-8 year time frame.

11. 1. Lack of taxonomic harmonization tools (i.e. trying to determine what was being ID'd by others)

12. (sorry, ran out of time - figured it was better to turn in an incomplete survey than none at all)

13. Limiting factors are (1) insufficient funding (2) lack of data analysis software for specific research needs, which the requires that I spend much of my time as a software developer rather than interpreting the geoscience data, e.g., (a) geomagnetic field modeling ← only relatively rudimentary software is available. The methods are published but the user has to write the software or adapt complex software for advance to be made. (b) viewing and processing seismic data (SEGY files) ← these exist but are too expensive for academic use (c) plate reconstruction and their uncertainties ← Methods are published but one must create the software. (3) insufficient sampling of thick sedimentary units with high temporal resolution and global distribution (4) lack of access to seismic reflection data (in many cases, the data exist but are owned by exploration firms and are not accessible) (5) lack of a global marine magnetic data set in which the data are collected at or below sea surface, with high density and good spatial distribution.

14. Data availability (lack of records, and lack of access).
Page 4, Q29. Please list what is preventing you, at present, from being able to pursue your research and education goals, regarding data discovery and access, data integration, modeling, differences in scale in terms of time, space, or data density/abundance, difference in types or structure of datasets/databases...

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<td>15</td>
<td>Lately, I have been reading a lot of older papers regarding carbonate dissolution in the Atlantic Ocean (mainly from the 1960's and 1970's), and it is very difficult to access the data from these papers, and the only good way to plot it is to type in all of the data by hand into excel. I find this to be my main frustration. Dec 13, 2012 11:15 AM</td>
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<td>16</td>
<td>Generally, there are a serious lack of isotopic databases. There are a few exception (IAEA), but investigator attempts have proven lacking or insufficient. In the field of ancient DNA, many geoscience journals do not require submission of data to Genbank. This should be changed immediately. Dec 13, 2012 8:12 AM</td>
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<td>17</td>
<td>a. Workspace and facilities are kindly being provided to me by the Department of Ecology, Evolution and Behavior, my former employer. The chief limits to attaining my goals are (1) my impaired mental and physical capabilities, (2) increasing demands from my family, and (3) the necessity to keep up with technological changes--e.g., computer programs that fail to run on newer machines. b. and c. If I were starting over again, no doubt I would have a very different background and set of skills. But I have plenty to think about now, old-fashioned as I am, that still seems to have some value. Dec 12, 2012 11:48 PM</td>
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<tr>
<td>18</td>
<td>a. difficulty in obtaining data, especially those that are not publicly available and are generated by individuals not funded by the US NSF (and therefore have no 'obligation' to provide us with their data, and in fact, have refused outright to provide published data) b. education to access models c. outreach skills to educate public Dec 12, 2012 7:36 PM</td>
</tr>
<tr>
<td>19</td>
<td>a) resources (funding, people) (b) lack of expertise in database creation and management (c) lack of expertise in data mining Dec 12, 2012 7:04 PM</td>
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<tr>
<td>20</td>
<td>NASA and NOAA have beautiful animations of different parameters (storm tracks and predictions, aerosols etc.) but those are no easily accessible for teaching purposes Dec 12, 2012 6:45 PM</td>
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<td>21</td>
<td>Present barriers include the difficulty in accessing high quality chronologies for sediment cores in a common framework, or for constructing chronologies because chronological marker data and sediment geochemistry data are often scattered through the literature. For example, I recently attempted to reconstruct the history of the carbonate compensation depth using the archive of DSDP, ODP and IODP cores. This required determining the subsidence histories of various cores, identifying cores that have sediments indicative of a position near the CCD, and determining which cores have sediments of what age. I did this largely through revisiting the publications form the initial reports and scientific reports volumes, but a more searchable online database and on-line tools for calculating subsidence histories (and sediment unloading) would be very useful. Indeed the &quot;CCD community&quot; recently held a workshop in which we discussed creation of such a database. Another example, is that I have long been interested in using sediment trap data of species abundance for microfossils and comparing these data against physical oceanographic compilation data (such as form the World Ocean Circulation Experiment (WOCE). However, there is no common framework in which to assemble such an Dec 12, 2012 6:44 PM</td>
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Page 4, Q29. Please list what is preventing you, at present, from being able to pursue your research and education goals, regarding data discovery and access, data integration, modeling, differences in scale in terms of time, space, or data density/abundance, difference in types or structure of datasets/datab...

intercomparison, there are few tools to visualize data, and much of the sediment trap data is hidden in papers not in a central data base.

| 22 | Time. Too much email, too much computers, too many surveys, not enough time to think. I harken for the late 80's, when Tiligraph was exciting. | Dec 12, 2012 5:35 PM |
| 23 | Again, the answers to these questions by domain scientists would be great and would form use cases for work regarding the semantic aspects that could be worked on, which is my current area of interest. But, I also have a background in database systems, so I would be interested in other types of problems too. | Dec 12, 2012 5:34 PM |
| 24 | Time & paperwork | Dec 12, 2012 5:21 PM |
| 25 | I cannot access the CMIP5 data archive in an easy manner (it would take me several days head-banging to do it). also, students are not well-trained in managing/working with large datasets - we need training as a key component of any new "system" | Dec 12, 2012 2:19 PM |
| 26 | The lack of a central global repository for climate model output. | Nov 27, 2012 8:17 PM |
| 27 | a. Scaling (time and space) disjuncts between core-based data analysis and temporally restricted (modern ecosystem) and spatially distributed (geomorphic) concepts. b. Differing concepts of what constitutes useful modeling scale and structure a., b., c. Also my own time and organizational limitations. | Nov 27, 2012 3:29 PM |
Page 4, Q30. Please list and describe any tools, databases, modeling capabilities, etc. that you feel should be developed/created/improved/simplified to allow you (or others in your community) to pursue the research and education goals indicated above.

a. within your discipline  
b. across disciplines within ...

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<td>1</td>
<td>It would be good to have a common data portal for paleoecological, climatological, and other geophysical data. This includes metadata on the original samples as well as counts and other measurements, and images. I am interested in developing a shared imaging facility for the virtual scanning of samples/slides for archival and automated analyses.</td>
<td>Jan 31, 2013 1:19 PM</td>
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<td>2</td>
<td>a &amp; b: Chronos Neptune database needs to be restored and updated; Improvements to Chronos foram databases needed and both databases need to be accessible for queries by other databases. Visualization tools for distribution data on global paleogeographic reconstruction maps would be helpful.</td>
<td>Jan 24, 2013 1:58 PM</td>
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<td>3</td>
<td>As a newcomer to this effort, one of the issues I see is that there may already be a lot of databases and visualization tools &quot;out there&quot; - the challenge for all of us is to learn which might be best for the purposes of our community. However, if the different databases cannot talk with each other, then it may be difficult to develop the searching capabilities that we all desire. I hope to learn more about this issue in the near future.</td>
<td>Jan 17, 2013 9:38 AM</td>
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<td>4</td>
<td>a. A short course on how to input data into Neotoma. A more general tool would be to have an easily accessible and interpretable table of radiocarbon ages. b. database development of geomorphological data as it pertains to ice-sheet modeling (could be &quot;c&quot;).</td>
<td>Jan 16, 2013 3:56 PM</td>
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<td>5</td>
<td>continuation of Neotoma database</td>
<td>Jan 11, 2013 12:12 PM</td>
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<td>6</td>
<td>Keep the following up to date and moving forward.  psicat corewall and all programs. coreref ICDP DIS IODP equivalent DIS ANDRILL IODP call cores Marion Dufrane cores all cores collected on the Healy Ice breaker and stored at WHOI or Ohio State without notation</td>
<td>Dec 27, 2012 8:37 PM</td>
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<tr>
<td>7</td>
<td>Being able to access existing knowledge and datasets quickly and efficiently. Integration into a <strong>quantitative</strong> framework and NOT a laundry-list portal framework.</td>
<td>Dec 20, 2012 8:42 PM</td>
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<tr>
<td>8</td>
<td>a - Precise stratigraphic placement of all dinosaur specimens ever collected (the ideal result, obviously challenging to impossible). Preferably this database would be linked to all radiometric dates ever collected for Mesozoic formations. Initially this would be based on a compilation of published literature data. Filling in the gaps of missing data would require a significant effort from multiple researchers and institutions.</td>
<td>Dec 16, 2012 1:38 PM</td>
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<td>9</td>
<td>Databases that link the various material across a range of timescales and allow visualizations of data through 4 dimensions</td>
<td>Dec 15, 2012 8:05 AM</td>
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<tr>
<td>10</td>
<td>1. Taxonomic harmonization tools</td>
<td>Dec 14, 2012 6:44 PM</td>
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Page 4, Q30. Please list and describe any tools, databases, modeling capabilities, etc. that you feel should be developed/created/improved/simplified to allow you (or others in your community) to pursue the research and education goals indicated above.

a. within your discipline
b. across disciplines within ...

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<td>11</td>
<td>Would like to be able to cross-query existing databases so that I can search one data portal and access resources in other portals. One job is to get the existing repositories (Neotoma, PBDB, SESAR etc.) better integrated, and to create repositories for 'orphan' data types. Would like better informatics support for individual labs and PIs with good intentions to share data, but not the time and training to appropriately develop structured metadata. This could be in the form of better lab-level data-management software, better training in the use of existing resources. Might also consider consultants who could visit labs, help them with data management practices, and facilitate training and providing of data to central data repositories.</td>
</tr>
<tr>
<td>12</td>
<td>See above. One basic idea that could help across the geosciences would be to have a dedicated group of software developers that create and maintain critical software packages. One of the most used packages (GMT) is maintained by one very dedicated individual, but what happens once he retires. This is true of most geoscience software packages that fade once the developer moves to other topics and computer platforms change. If a facility was funded to produce and maintain software that was user friendly, cross platform, open access, and covered many critical topics, that would result in a huge savings and greatly enhance the odds for transformative science to be conducted. Just a few software packages that come to mind are: (1) User friendly GUI for GMT (2) Stratigraphic description and correlation software (currently maintained poorly by multiple organizations, with no real new development taking place) (3) Signal analysis software for analyzing stratigraphic data ...</td>
</tr>
<tr>
<td>13</td>
<td>For research the data availability is key issue, while modeling capacities and visualization are useful for education goals.</td>
</tr>
<tr>
<td>14</td>
<td>I would like to see large databases have good ways to filter out and flag bad data, and especially a listing of the methods used to create the data. This is a major issue in Mg/Ca paleothermometry with regards to cleaning procedures, exact types of species morphotypes analyzed, etc.</td>
</tr>
<tr>
<td>15</td>
<td>Modelers should be expected to contribute user friendly access to their models, just as data is (and should be) expected to be contributed to publicly available databases.</td>
</tr>
<tr>
<td>16</td>
<td>a. (1) Better coring equipment for sediments that is portable into roadless areas, takes continuous cores with minimal disturbance, and can handle both peat and lake sediments. (2) Better databases for identification of palynomorphs.</td>
</tr>
<tr>
<td>17</td>
<td>From a marine curators standpoint, we very much need a common database with google-like search functions. We also need a web form system for data entry into the database and a way that curators can check data quality and update...</td>
</tr>
<tr>
<td>Entry</td>
<td>Comment</td>
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<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>18</td>
<td>As long as we have access to Jim Hansen’s web-site with full data, and pre-prints, as long as we have NGDC-paleo, as long as we have genbank, we can stay afloat.</td>
</tr>
<tr>
<td>19</td>
<td>A goal of EarthCube is to create a cyberinfrastructure to help with various access and integration problems. The design of the cyberinfrastructure itself is an interesting research problem. Also, putting semantic components (e.g. ontologies, reasoners, mapping files, RDF, etc.) into the cyberinfrastructure is a research problem. I am interested in working in these areas.</td>
</tr>
<tr>
<td>20</td>
<td>Cut down the paperwork need for grant applications and reports.</td>
</tr>
<tr>
<td>21</td>
<td>It would be helpful if large datasets (this goes for observational data at CDC as well as paleodata at NCDC) could come in standard formats, so that one doesn’t have to spend forever building a toolbox just to access large observational or modeling datasets. *.nc is generally accessible. Whatever is decided, providing some public toolkits that can plug into different platforms (I use Matlab a lot) for getting the *.nc data on my computer would be helpful to those of us who are not modelers by trade. I hate it when data are archived with a billion subfolders, one for each month of the year. Data delivery should be flexible so that even the more basic users can get what they need. Right now, this whole issue represents a MAJOR speed bump in my research program.</td>
</tr>
<tr>
<td>22</td>
<td>There needs to be a central global repository for climate model output.</td>
</tr>
<tr>
<td>23</td>
<td>a,b. Landscape-evolution models that link sediment production, transport and delivery processes to ecosystem structure and function on one end and sediment flux and deposition on the other. I should say I don’t have the faintest idea how to do this.</td>
</tr>
<tr>
<td>24</td>
<td>All digital, all the time; more journals need the supplementary data attached, so duplication/improvement of results is possible.</td>
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<tr>
<td>---</td>
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</tr>
<tr>
<td>1</td>
<td>Sorry this is so late.</td>
</tr>
<tr>
<td>2</td>
<td>I allude to geomorphological databases above as they relate to ice-sheet modeling. I recently submitted an NSF proposal (with Tom Lowell) where we propose, among other things, to hold workshops that bring field people and ice-sheet modelers together. A very basic issue that we propose discussing are these databases, which are temporally and spatially heterogenous, with heterogeneous errors. The modelers NEED to know the errors. A challenging topic, to say the least.</td>
</tr>
<tr>
<td>3</td>
<td>We really need to do something regarding archiving and retrieval of data. Thanks for taking this initiative.</td>
</tr>
<tr>
<td>4</td>
<td>Thanks!</td>
</tr>
<tr>
<td>5</td>
<td>Good for you.</td>
</tr>
<tr>
<td>6</td>
<td>I was not aware that there are so many databases. Until now I only knew NOAA and Pagea. Are those linked to the other databases?</td>
</tr>
<tr>
<td>7</td>
<td>Currently developing digital atlas of chronometric data on periods of dune accumulation and stability see - <a href="http://inquadunesatlas.dri.edu/">http://inquadunesatlas.dri.edu/</a></td>
</tr>
<tr>
<td>8</td>
<td>As should be clear, I am not a domain scientist. Instead, my interests are in helping with data issues for domain scientists. My background is in computer science and broadly in various natural science domains.</td>
</tr>
<tr>
<td>9</td>
<td>Great initiative. This is a very worthwhile and exciting endeavor.</td>
</tr>
<tr>
<td>10</td>
<td>I'll come back and answer the last three question later.</td>
</tr>
<tr>
<td>11</td>
<td>Thanks for doing this all! It is an issue of critical importance.</td>
</tr>
<tr>
<td>12</td>
<td>This survey should be sent to the whole PCMSC Center as there are a multitude of scientists there than can better answer these questions than I. If you want please email this to <a href="mailto:pcmsc@octopus.wr.usgs.gov">pcmsc@octopus.wr.usgs.gov</a> and you will reach our researchers. Or if you would like I can. My email is <a href="mailto:mtorresan@usgs.gov">mtorresan@usgs.gov</a>. just let me know.</td>
</tr>
<tr>
<td>13</td>
<td>This is a really important effort for moving our discipline forward. I will complete the above questions soon and also submit an application to attend the workshop.</td>
</tr>
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Appendix E: PreProposal Documents (White Papers)

DRILLING, SAMPLING, AND IMAGING THE DEPTHS OF THE CRITICAL ZONE

OCTOBER 24–26, 2013, DENVER, CO
Conveners: CLIFFORD S. RIEBE, AND JON CHOROVER
Drilling Sampling and Imaging the Depths of the Critical Zone

List of Appendices

Appendix 1: Dear Colleague Workshop Advertisement.
Appendix 2: Workshop Schedule.
Appendix 3: Drilling and Sampling the Critical Zone.
Appendix 4: Beyond the Regolith: A Deep Critical Zone Drilling Perspective on Weathering Profiles, by Heather L. Buss and Oliver W. Moore.
Appendix 5: Resolving the structure and composition of water flow paths in the deep critical zone, by Jon Chorover.
Appendix 7: Planning an International CZO Programme, by Steve Banwart, Jerome Gaillardet, Marty Goldhaber, Don Sparks, and Sue Trumbore.
Appendix 10: Dating Alteration and Exhumation in the Deep Critical Zone, by A. Joshua West and Pete Reiners.
Dear Colleagues:

Mark your calendars for the upcoming NSF Workshop “Drilling, Sampling, and Imaging the Depths of the Critical Zone”.

Timing: 24-26, October, 2013, immediately before the annual Geological Society of America meeting.
Location: Downtown Denver, Colorado (details to be determined).

Our goal in hosting this workshop is to build a community-wide consensus on strategies for investigating critical zone processes below the depths that are easily accessed with a shovel and hand auger. Our workshop will be highly informative, involving presentations by experts in drilling, sampling, and geophysical imaging of near-surface Earth materials. We also expect it to be highly productive, leading to research proposal development and a written commentary to be published in AGU Eos or similar outlet.

We expect attendance by scientists at all career levels, from students through senior professors. We also expect representation from diverse disciplines, including engineering, near-surface geophysics, geochemistry, geobiology, geomorphology, soil science, and hydrology.

A tentative schedule:

Thursday, 24 October 2013
Participants arrive in afternoon and early evening and attend icebreaker dinner and introductory presentation at workshop venue (to be determined).

Friday, 25 October 2013
All day workshop, with presentations by invited speakers and breakout groups

Saturday, 26 October 2013
More presentations by invited speakers and breakout groups, concluding mid to late afternoon.

Additional announcements about funding for travel and lodging are forthcoming. For now, mark your calendars and contact us if you are interested in attending.

Best Regards,

Cliff Riebe (criebe@uwyo.edu)
Jon Chorover (chorover@cals.arizona.edu)
NSF Workshop: Drilling, Sampling, and Imaging the Depths of the Critical Zone

Schedule

Thursday, October 24th
6:00 PM  Icebreaker dinner (provided by workshop)
7:00 PM  Bill Dietrich; 25 min + 5 min discussion
7:30 PM  Sue Brantley; 25 min + 5 min discussion

Friday, October 25th

Session 1 – Drilling and sampling
7:00 AM  Breakfast provided by workshop
8:00 AM  Introduction by session conveners
8:15 AM  Dennis Nielson – Drilling 101 (50 min + 10 min discussion)
9:15 AM  Brian Clarke; 15 min + 5 min discussion
9:35 AM  Heather Buss; 15 min + 5 min discussion
9:55 AM  Poster introductions; brief 2-min, 1 slide overviews of poster content; 10 posters = 20 min
10:15 AM Coffee break followed by poster session
10:50 AM Oliver Bour; 15 min + 5 min discussion
11:10 AM Bob Graham; 15 min + 5 min discussion
11:30 AM Suzanne Anderson; 15 min + 5 min discussion
11:50 AM Plenary discussion leading to breakout groups
12:15 PM Break for lunch (provided by workshop)
1:00 PM – 3:00 PM Breakout Group Discussions
(a) Drilling technology: core recovery in weathered rock
(b) Drilling technology: core recovery for robust geobiology
(c) Designing a timely, insightful drilling study (site selection & experimental design)
3:00 PM  Coffee break (posters are still up)
3:30 PM  Plenary synthesis. (Each breakout group presents outcomes, followed by group discussion.)
5:00 PM  Break for dinner (on your own)

Saturday, October 26th

Session 2 – Geophysical imaging
7:00 AM  Breakfast provided by workshop
8:00 AM  Introduction by session convener
8:05 AM  Lee Slater – Geophysics 101: 50 min + 10 min discussion
9:05 AM  Steve Holbrook; 30 min + 10 min discussion
9:45 AM  Coffee break (Posters are still up.)
10:00 AM Someone leads plenary discussion leading to breakout groups
10:15 – 12 PM Breakout Group Discussions
(a) Seismic refraction and waveform tomography
(b) Drilling and measurements to inform geophysics
(c) Resistivity, EM methods, NMR
12:15 PM Break for lunch (provided by workshop)
1:30 – 3:00 PM Session Syntheses Breakout Groups
(a) Drilling
(b) Sampling
(c) Imaging
The Critical Zone represents a unique environment that is not difficult to drill, but has challenges in terms of sample quality. For this discussion, we will consider maximum drilling depths of about 100 m. There are a number of drilling techniques that can be used to this depth including: rotary, sonic, augering and coring. The size of the drill rig is generally dependent on the depth objective, sampling system and the resulting weight of the drilling assembly. Of the above techniques, coring collects the highest quality lithologic sample and is preferred for most scientific drilling projects. The other techniques are often less expensive and may be used for the installation of ground water monitoring wells, but their sample quality is generally poor.

There are several coring methods that can be used depending on the sampling requirements and soil or rock character. Soft sediment and soils require methods that collect the core in liners. DES uses this methodology in our sampling of modern and ancient lake sediments. Our suite of soft sediment sampling tools collect core that is consistent with dimensions from ocean drilling and are therefore easily handled by research laboratories (66.3 mm diameter). The tool suite is wireline-deployable includes the following.

- **Hydraulic Piston Corer (HPC).** A beveled shoe is fired into unconsolidated, saturated sediment. Depth capability ~100 m in modern lake sediments.
- **Extended Nose (EXN).** A non-rotating shoe is pushed into unconsolidated sediments aided by a rotating outer bit.
- **Alien (ALN).** A rotating bit cuts semi- to consolidated sediments.
- **Non-sampling Assembly (NSA).** Used to advance the hole to a specified sampling interval.

Consolidated rocks are most effectively sampled using diamond coring, a technique commonly used in the mining industry. A diamond bit cuts a core from the rock and the sample is collected in a lined or unlined core barrel. Diamond core bits are available in established sizes (PQ, HQ, NQ). Alternatives that utilize liners are designated HQ3 or HQT (Triple Tube). Custom core catcher assemblies are effective in adapting these systems to collect core from unconsolidated rocks.

DES is currently working with Columbia University to adapt its soft sediment suite to sample unconsolidated aquifer sands using a freeze shoe technique. This freezes the bottom of the core sample and will allow the collection of aquifer sands in contact with pore water. The purpose of the system is an evaluation of high arsenic ground water in SE Asia. An ICDP project to test the technique in Illinois has been funded for 2014.
Drilling often requires the circulation of a drilling fluid, generically referred to as "mud". This may consist of anything from water to complex combinations of clays, polymers and chemical addatives. Mud has several purposes: lubricate and cool the bit, remove cuttings from the hole and condition and stabilize the hole. Although the success of a drilling program may depend on the efficiency of the mud program, it also serves as a source of contamination of the core and fluid samples. The references below include papers that discuss contamination and strategies for mitigation.

Scientific drilling projects range from shallow and simple ($10^4$) to deep and complex ($10^7$), and their development often takes time and a considerable amount of persistence (Cohen and Nielson, 2003). It is important to formulate drilling, sampling and logging objectives and then formulate a drilling plan to achieve those objectives. Costs can be predicted on the basis of the plan, and they often are in the range of $300/m to $400/m for shallow scientific holes. Local contractors can be used to do the work, but monitoring is generally required to achieve the desired results.

References


Geochemical changes with depth through a weathered or weathering material are known as weathering profiles and are commonly used in critical zone (CZ) studies. Regolith (here including mobile and in situ weathered material) weathering profiles record CZ processes over the timescale of regolith development. Weathering profiles are frequently represented in terms of the mass transfer coefficient, commonly known as tau (Brimhall and Dietrich, 1987; Anderson et al. 2002), which describes the amount of a specific component (element, isotope, mineral) mobilized during weathering by comparison to a parent material (e.g., bedrock) and have proven particularly useful in identifying weathering mechanisms and mineral-specific weathering rates (e.g., White and Buss, 2013).

A typical regolith weathering profile consists of component concentrations in either solute (pore water) or solid (<2 mm sieved regolith) fractions with depth. However, the entire belowground CZ also includes fractured bedrock and rock fragments and corestones of various sizes and stages of weathering (Fig. 1). The rock (>2 mm) components of the CZ are integral to the narrative of CZ development; they record geologic history and provide clues to the physical and chemical feedbacks in CZ formation. Therefore, as deep CZ drilling pushes our weathering profiles beyond the regolith and into the parent material, some adaptation of the regolith-centric model of weathering profiles is required.

Deriving meaningful information from tau profiles of CZ rocks as a function of depth in drilled boreholes is problematic: unless samples are highly weathered (e.g., saprock), it is likely that lithological variations will swamp out incipient weathering signals in many locations. For example, in the volcaniclastic Bisley watershed at the Luquillo Critical Zone Observatory (LCZO), mineral abundances in unweathered rock can vary by 30 wt% in a single borehole. However, borehole weathering profiles need not be defined on the m or cm scale as done for regolith. CZ boreholes containing corestones or fractured bedrock may contain multiple weathering fronts in the guise of mm’s thick rinds along fractures and corestone surfaces (Buss et al. 2013). Micro-scale weathering profiles extending from visibly unweathered rock into an attached rind record incipient weathering and regolith formation processes.

Micro-scale analysis of weathering profiles across rinds have documented dramatic mass losses and mineralogical transformations across core-rind boundaries in basaltic, andesitic volcaniclastic and granitic rocks (e.g., Navarre-Stitchler et al. 2011; Sak et al. 2010; Buss et al. 2008, 2013). Although weathering rinds make up a much smaller volume % of a watershed than regolith, they likely record the vast majority of mass transfer in most CZs. For example, in the Bisley watershed, ca. 40% of protolith Mg is lost over ca. 3 mm of weathering rind, reflecting significantly more and faster weathering than the final 20% of protolith Mg, which is lost over 8 m of regolith. Micro-profiles may also reflect differ-
ent weathering mechanisms as well as different weathering rates in that highly reactive phases will be present in weathering bedrock that are no longer present (or are inaccessible, e.g., shielded by oxides) in regolith. In Bisley borehole rocks, we find pyrite and other sulfide and sulfate phases associated with early weathering of silicate minerals, suggesting a weathering mechanism involving sulfuric acid, whereas regolith weathering is dominated by carbonic acid and, in surficial layers, organic acids (Fig. 2).

Micro-scale weathering profiles may prove to be more significant in terms of CZ development and weathering fluxes than regolith weathering profiles; recent work has suggested that most of a watershed’s weathering solute flux is sourced from bedrock fracture zones (Kurtz et al. 2011; Schopka and Derry, 2012). Furthermore, fracture spacing combined with mineral dissolution may largely control watershed topography in many watersheds (Fletcher and Brantley, 2010; Buss et al. 2013).

Deep CZ drilling provides unparalleled opportunities to study CZ formation processes in situ, however, these processes may operate in discrete zones such that micro-scale weathering profiles may be more appropriate and more informative than whole-borehole weathering profiles.

References

Buss HL et al., 2013 Probing the deep critical zone beneath the Luquillo Experimental Forest, Puerto Rico. ESPL. 38: 1170-1186.
Sak PB et al., 2010. Controls on rind thickness on basaltic andesite clasts weathering in Guadeloupe. Chem. Geol., 276: 129-143.
Resolving the structure and composition of water flow paths in the deep critical zone
Jon Chorover, Department of Soil, Water and Environmental Science, University of Arizona

Our CZO team has the goal of resolving the relation between the evolution of water biogeochemical composition during flow through the CZ subsurface and structure evolution of the CZ matrix itself. Results of our CZ research to date suggest an important role for deep (below soil, in fractured bedrock) CZ flow paths affecting water delivery to streams even in upland forested catchments, particularly in rhyolitic terrain of the Jemez River Basin Critical Zone Observatory (JRB-CZO). Aqueous geochemical data for stream discharges, analyzed using an end member mixing model analysis (EMMA), suggest that a large fraction of water discharged from these small forested catchments during the spring snowmelt pulse derives from deep groundwater reservoirs that are apparently displaced during pressure wave propagation through the subsurface (Figure 1). These waters have tritium ages of ca. 4-12 years. Meanwhile, geophysical (seismic) surveys indicate regolith depth extending meters deeper than the soils that we have excavated to date and wherein our sensor and sampler array is installed.

We have yet to conduct any deep drilling exercises in our CZO. Hence, although data indicate a strong influence of deep subsurface flow paths on stream water dynamics and, therefore, a deep subsurface rock weathering regime, we have not yet been able to observe this portion of the CZ directly. Drilling even a single borehole and effectively extracting the core for analysis is an expensive undertaking that must be done with careful planning. Given our strong interest in the coupled biological, physical and geochemical processes controlling CZ evolution, we need to employ geophysical imaging methods that can help to inform on where such drilling may provide the most useful information on deep GW flowpaths. Further, we seek methods that will enable us to best preserve intact cores for geochemical and microbial analysis while introducing the fewest artifacts. Finally, since our goal is to instrument the excavated boreholes with an appropriate sensor/sampler array that will enable follow-on time series measurements of fluid (both liquid and gas) composition and dynamics at depth, a key question pertains to the spatial distribution of boreholes when drilling only a few is possible, and how we can make the most beneficial and synergistic use of multiple borehole installations.

Figure 1. End member mixing analysis (EMMA) of stream water discharges based on geochemical parameters for three streams draining different aspects of Redondo Mountain in the Jemez River Basin CZO. All streams show the largest contribution from deep groundwater (GW) deriving from a portion of the CZO that has yet to be elucidated. (From Harpold et al., in revision).
Selecting Sites for Technical Exploration of the Deep Critical Zone
White Paper Author: Brad Goodfellow

This will be a learning experience for me with respect to how these workshops operate but more specifically to the types of techniques that are being used in probing the deep critical zone. One of my primary interests is controls and processes of regolith production (from a geomorphologist’s perspective) from the macro-scale (climate, tectonics) down to the granular-scale (weathering reactions, formation of connected porosity, etc). My experience of working in the deep critical zone has been through using road cuts and natural exposures excavated by streams and visible in wave-cut sea-cliffs. I have also used GPR (with some success) to measure depth to bedrock in in situ-produced periglacial regoliths in Arctic Scandinavia.

Given this background, my most useful contribution may be in highlighting some factors that could be considered when selecting sites for technical exploration of the deep critical zone (within and beyond the existing network of critical zone observatories). My perspective is that weathering does not generally follow a neat top-down decrease in intensity below the soil but rather displays a complex 3-D spatial pattern that reflects where water is accessing rock (according to joints, faults, fabric, hydrothermal alteration, etc). Clearly then, this 3-dimensionality of the deep critical zone poses both a technical challenge and a research opportunity. An additional technical challenge is posed by the extreme depths to which weathering can occur (10s to 100s of meters). Neither of these issues will likely surprise anyone at this workshop but I can perhaps offer some insight on how, or where, to constrain these depending on the research question at hand.

Key constraints on critical zone thickness include tectonic uplift rate (through its control on surface erosion rate) and climate (specifically long-term water balance). Assuming, firstly, a zero erosion rate to unravel the role of climate: Observations across steep rainfall gradients on ‘uneroded’ surfaces on Hawaii indicate that where the water balance is negative over regolith forming timescales (i.e. mean annual precipitation < potential evapotranspiration): (i) the critical zone is thin (<2 m); (ii) its base is perched above local base (stream incision) level, and; (iii) weathering is confined to water flow paths through the critical zone, leaving a high proportion of unweathered rock and a complex 3-D spatial distribution of weathering (see Scenario A in the figure). Conversely, where water balance is positive over regolith forming timescales (i.e. mean annual precipitation > potential evapotranspiration): (i) the critical zone is thick (many 10s of meters); its base corresponds with local base (stream incision) level, and (iii) much more of the rock is comprehensively weathered, which reduces the spatial variation of weathering intensity (see Scenario C in the figure). In transitional zones (where mean annual precipitation ~ potential evapotranspiration) the base of the critical zone correlates with local base level but the intensity of weathering is intermediate between positive and negative water balance sites (see scenario B in the figure).

This simple pattern is, however, disrupted where tectonic uplift and surface erosion occur. As rates of these processes increase, it is predicted that the critical zone will thin, become perched above local base (stream incision) level, and the intensity of weathering will decrease because less time for weathering has been available (see the Figure below). Qualitative observations, for example in the Santa Cruz Mountains, support this (speculative) conceptual model. Where uplift and erosion rates are high near Loma Prieta, a summit located on a lateral restraining bend in the San Andreas Fault, the critical zone appears in general to be relatively thin (~ 8 m deep) and is perched above local base level. However, further north past the focus of uplift at the restraining bend, erosion rates have decreased by about a factor of 6, the critical zone is 10s of meters thick and its base appears to correlate with local base level.
So what might all this mean for site selection? If we want to capture what governs the spatial distribution of weathering in the deep critical zone, or investigate incipient weathering processes, then select sites that experience a negative water balance and/or which are undergoing active tectonic uplift. Conversely, if we wish to investigate what ultimately constrains the thickness of the critical zone, then select sites in positive water balance locations. Of course, sites that have been subjected to a relatively consistent climate over regolith forming timescales are difficult to locate. In this regard, tropical sites might offer the best possibilities (less variation over Quaternary glacial-interglacial cycles). Because of the steep and persistent rainfall gradients, Hawaii is excellent, but the leaky basalts pose a hydrological headache. Qualitative observations indicate that the western flank of the Sierra Nevada, California, offers some promise perhaps because, while temperatures and precipitation magnitudes have varied over time, the relative drying with declining altitude has persisted! The region also has the advantage of containing lots of granite.

Figure: Conceptual model of water balance and tectonic uplift controls on the thickness of the critical zone and intensity and spatial distribution of weathering within it. The model is based primarily on observations of Kohala Peninsula, Hawaii, which has been subject to a steep rainfall gradient and minimal erosion of interfluvies. Rainfall rate declines from NE to SW and this directionality has persisted through glacial and interglacial periods. The ‘A’, ‘B’ and ‘C’ labels indicate the parts of the figure that illustrate some key features of critical zones developed where the long-term water balance is negative, transitional, and positive, respectively. MAP = mean annual precipitation, PET = potential evapotranspiration.
Planning an International CZO Programme
Steve Banwart, Jerome Gaillardet, Marty Goldhaber, Don Sparks, Sue Trumbore

Introduction
Recent advances in national programmes and funding for critical zone observatory (CZO) science provide a platform to establish a global network of advanced field research sites. This network will enable scientists around the world to work together – to achieve transformative basic science advances in knowledge of Earth’s surface and to create interdisciplinary solutions to the global challenges of adapting to rapid environmental change and food and water supply security.

International Call to Action
Earth’s Critical Zone (CZ), the thin planetary veneer extending from the top of vegetation to the bottom of aquifers that supports almost all human activity [1,2], is under intensive pressure from growth in human population and wealth. Critical Zone Observatories (CZOs), established during the past 5 years, intensively study the complex interactions of rock, soil, water, air and organisms that regulate CZ properties and their ability to provide life-sustaining resources.

CZOs are providing transformative advances in basic natural sciences with far greater, holistic understanding of how geophysical, geochemical, and biological processes integrate from the vegetation canopy, across the land surface through soil, to aquifers and the deeper biosphere [3,4]. CZOs have established scientific focal points that define major research questions, raise awareness of critical zone vulnerability, and interface with environmental policy. They have fostered the interdisciplinary research necessary to rapidly deliver solutions to the major societal challenges of land degradation, climate change, food security, biofuel production and a clean and plentiful water supply. International networks of CZOs offer enormous potential to globally integrate basic science with innovation in human adaptation to rapid and intensive environmental change [5].

Achieving this vision requires a transformation in the ambition and integration of CZO science agendas worldwide. Our goal in forming an International CZO Programme is to facilitate the integration and broad communication of knowledge gained from new and existing CZOs, with an aim towards understanding of the resilience and vulnerabilities of the Earth’s CZ and its inhabitants and to formulate interdisciplinary solutions to sustaining Earth’s CZ for future generations.

Programme Plan
An international workshop was convened 9th-11th November, 2011 at U. Delaware, USA to develop an international Critical Zone science agenda for the next 10 years [6]. Eighty-nine scientists from 25 countries representing around 60 CZOs and associated field sites around the world attended the meeting.

The workshop participants debated and refined six key science questions and developed these into research hypotheses and framework experimental designs, in order to drive this 10-year agenda forward. The science areas spanned basic science enquiry and challenge-driven research that delivers solutions. The six science questions were divided into time scales of environmental change. Long-term geo-biological evolution of Earth’s near-surface environment and short-term, rapid change driven by human activity.

Long-Term Processes and Impacts
1. How has the geological evolution and paleobiology of the CZ established ecosystem functions and the foundations for CZ sustainability?
2. How do molecular-scale interactions between CZ processes dictate the linkages in flows and transformations of energy, material and genetic information across the vertical extent of above ground vegetation, soils, aquatic systems and regolith - and influence the development of watersheds and aquifers as integrated ecological-geophysical units?
3. How can theory and data be combined from molecular- to global- scales in order to interpret past transformations of Earth’s surface and forecast CZ evolution and its planetary impact?
Short-Term Processes and Impacts

4. What controls the resilience, response and recovery of the CZ and its integrated geophysical-geochemical-ecological functions to perturbations such as climate and land use changes, and how can this be quantified by observations and predicted by mathematical modelling of the interconnected physical, chemical and biological processes and their interactions?

5. How can sensing technology, e-infrastructure and modelling be integrated for simulation and forecasting of essential terrestrial variables for water supplies, food production, biodiversity and other major benefits?

6. How can theory, data and mathematical models from the natural- and social- sciences, engineering, and technology, be integrated to simulate, value, and manage Critical Zone goods and services and their benefits to people?

A common feature of the experimental designs is the establishment of networks of CZOs located along planetary-scale gradients of environmental change, e.g. gradients of climate and intensity of land use.

The workshop prepared a 3-year plan to establish a coordinated international CZO programme. The report proposed to review progress and agree next steps 10 months later, during the CZO Geobiology conference, convened 5th-8th September, 2012 at the China University of Geosciences in Wuhan. An outcome of discussions with the participating scientists and national funders at the Wuhan meeting was the concept to develop an international steering committee, whose members are the authors of this white paper, in order to further develop and drive forward this project plan. The committee members are committed to the hard work and the necessary consultation and preparatory work with partners around the world, to enable this vision to be realised.

Initial Steps
To advance this global project requires a series of steps through 2013 and continuing into 2014:

1. Establishment of an international forum of CZO leaders to integrate with additional observatory networks, to broaden the disciplinary mix, and to debate, test and strengthen the programme of research,
2. Creation of a Critical Zone Science Joint Working Group of The International Union of Soil Science (IUSS), American Geophysical Union (AGU), and the Ecological Society of America (ESA);
3. Preparation and presentation of a proposal to develop and implement this CZ Science agenda within the interdisciplinary activities of the International Council for Science (ICSU);
4. Preparation of a bid with national funders for multilateral international funding with the Belmont Forum;
5. Coordinated advocacy and strategy development with national funders and research foundations; and
6. Continued development and implementation of this plan for a coordinated international programme of CZO research.

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Topographic stress and rock fracture: Probing the effects of landforms on bedrock structure in the shallow subsurface

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Summary
The development of landforms influences numerous processes on Earth’s surface, ranging from the routing of water and sediment to the distribution of species. Theory predicts that landforms should also perturb the state of stress in the underlying rock, potentially altering rock fracture patterns in the shallow subsurface and leading to long-term feedbacks between erosion and rock fracture. However, the extent of these effects is unknown, because there have been few attempts to compare calculated stresses with observed fracture patterns in specific landscapes. There is currently an opportunity to make rapid progress on this basic problem by adapting existing stress models and obtaining field data on subsurface rock structure. A field-tested model for predicting topographically induced rock fracture patterns would have applications in geomorphology, hydrology, seismology, and the design of near-surface infrastructure.

The Challenge
Theoretical calculations indicate that topographic stresses – gravitational stresses associated with the presence of landforms at Earth’s surface – can be large enough to fracture rocks [1-6]. These calculations typically have involved idealized, hypothetical topographic profiles [1-6], with few direct comparisons between predicted topographic stresses and observed fractures at specific field sites [7,8]. Images of shallow boreholes (Figure 1) reveal populations of fractures that are distinct from bedding planes and that vary spatially in abundance, but it is not clear whether these fracture patterns are correlated with topographic stresses. Thus, despite several decades of theoretical studies, it is unknown whether Earth’s surface topography significantly influences the distribution of bedrock fractures.

Significance
Fractures in the shallow subsurface affect bulk rock strength and permeability, which should in turn affect rock erodibility, slope stability, infiltration capacity, and groundwater flow [4,7,9]. These effects have implications for short-term land use as well as long-term landscape evolution. Over human timescales, an understanding of topographic effects on the distribution of bedrock fractures could help predict the location and frequency of landslides, patterns of runoff and streamflow, and the suitability of potential building sites for above- or below-ground infrastructure.

Figure 1. Borehole image log from a Pennsylvania shale. Planar features that intersect the borehole have sinusoidal traces in this unwrapped view of the borehole walls. Black arrows mark examples of bedding planes. White arrows mark examples of fractures.
Over longer timescales, topographically induced fracturing could lead to feedbacks between landscape evolution and rock fracture patterns. For example, several investigators have suggested that the incision of river valleys may induce topographic stresses that promote rock fracture beneath valley floors, which could in turn accelerate valley incision [1,4,6]. Fracturing is also an essential part of soil formation, a key mechanism in the development of the interface between the atmosphere and the lithosphere [10]. The factors controlling the population of fractures that arrives in the shallow subsurface as rock is exhumed by erosion are major uncertainties in the study of Earth’s surface.

**Opportunities**

Determining the extent to which these effects actually occur will require a detailed understanding of the mechanisms that generate stresses and fractures beneath real-world topography as well as an evaluation of field evidence for topographic fracture, including comparisons of observed rock fracture patterns with predicted topographic stresses. The basic theoretical groundwork for such comparisons has been laid over the past few decades. The elastic stresses induced by surface topography in a uniform two-dimensional half-space can be calculated analytically for certain idealized ridge and valley cross-sectional profiles that are amenable to analytical solutions [2,3]. These stress solutions have been compared with rock fracture criteria to predict spatial patterns of fracture mode and occurrence [4,6].

The main obstacle preventing a direct test of these predictions is that the analytical solutions for idealized topographic profiles across isolated ridges and valleys are too simple to be applied to field sites with irregular, asymmetric, three-dimensional topography that includes many adjacent ridges and valleys. Thus, the next steps toward assessing the effects of topographic stress on bedrock structure are to create models that can calculate stresses beneath complex topography and to compare the predicted fracture patterns with field measurements of shallow fracture patterns.

Four recent developments have made these steps possible, creating a new opportunity to test long-standing ideas about topographically induced fracturing. First, numerical methods for calculating stresses near geometrically irregular free boundaries have been adapted to Earth’s surface [5,11], making it possible to calculate stresses induced by arbitrary topographic profiles. Second, new technologies such as airborne laser altimetry have been used to acquire high-resolution digital maps of bare-earth topography, which are necessary inputs to the stress models. Third, new methods for mapping shallow bedrock structure have been developed and tested, including active-
source seismic surveys [12] and digital image logs of boreholes [13]. Fourth, advances in landscape evolution modeling [14] have provided a framework for exploring potential feedbacks between topography, erosion, and rock fracture. These recent developments have created a timely opportunity to compare theoretical predictions of topographic stresses with rock fracture patterns observed in the field.

Figures 2 and 3 illustrate the potential for such comparisons. In Figure 2, a boundary element model [15] has been adapted [5,11] to calculate the stresses induced by a topographic profile across a valley in the Shavers Creek watershed in central Pennsylvania, an experimental site maintained by Pennsylvania State University. In addition to the horizontal, vertical, and shear stresses (Fig. 2a,b,d), it is straightforward to calculate the orientations and magnitudes of the principal stresses (Fig. 2c), a widely used proxy for normalized differential stress (Fig. 2e), and the predicted modes and orientations of fractures for typical mechanical properties of shale (Fig. 2f). Four existing wells in the valley floor have been logged with an optical borehole imager (OBI), making it possible to compare trends of fracture abundance as a function of depth (Fig. 3b) with modeled proxies for shear failure (Figure 3a). Fig. 3 shows that fracture abundance and the modeled failure proxy decline similarly with depth beneath the valley floor, whereas a very different trend is predicted beneath ridgetops. This preliminary comparison suggests that fractures beneath the valley floor may have been influenced by topographic stresses, and illustrates the potential for a more thorough test through comparisons of modeled stresses with fractures in ridgetop boreholes.

**Research Needs**

An expanded effort to explore topographic effects on rock fracture would include several components:

1. **Creation of models capable of calculating topographic stresses and fracture patterns beneath arbitrary topographic surfaces.** Although the basic components of such models are in place [5,11,15; Fig. 2], additional refinements and extensions are necessary for a rigorous examination of topographic stresses in a wide range of landscapes. These include improving procedures for calculating induced stresses on and near boundaries; extending two-dimensional models of stresses beneath arbitrary profiles to three-dimensional models of stresses beneath arbitrary surfaces [16]; and incorporating recent theoretical and experimental insights into transitions between different modes of fracture [17].

2. **Better estimates of regional near-surface tectonic stresses.** The extent, mode, and orientation of fractures should be sensitive to the sign and magnitude of the regional tectonic stress. Regional estimates of tectonic stresses have been compiled from a variety of sources [18], but local measurements from hydrofracture or borehole deformation in the...
vicinity of study sites would complement these regional estimates and provide an additional constraint on stress models.

3. **Field measurements of subsurface fracture distributions.** Few measurements of fracture patterns in the shallow subsurface, where topographic effects are most pronounced, are currently available, because most efforts to characterize subsurface structure (for oil or gas exploration, for example) focus on depths deeper than a few tens of meters. Surveys of fracture mode, orientation and abundance in a variety of lithologic, topographic and tectonic settings will be critical for evaluating the extent to which topographic stresses control bedrock fracturing. Surveys of field sites could be conducted with complementary techniques such as optical imaging of shallow boreholes [13] and low-cost, active-source seismic surveys [12].

4. **Application of stress models to sites where high-resolution surface topography and subsurface fracture measurements are available.** This will provide a test of the hypothesis that topographically induced stresses can significantly influence subsurface fracturing, as well as a calibration of the relationship between modeled stresses and observed fractures that could potentially be applied to other landscapes where observations of subsurface fractures are not available. These efforts would leverage the growing availability of high-resolution laser altimetry.

5. **Exploration of feedbacks between rock fracture, erosion, and landscape evolution.** Comparisons of static stress models with present-day fracture patterns will provide a snapshot of two dynamic processes – landform evolution and bedrock deformation – that may be coupled if spatially variable fracture patterns influence spatial patterns of erosion. Incorporating topographic stresses and spatially variable rock fracture into models of landscape evolution will provide a framework for exploring the coevolution of topography and bedrock structure as erosion exhumes rock and shapes the land surface.

**Summary and Recommendations**

The influence of topography on bedrock fracture patterns is predicted by theory, but these predictions remain largely untested due to the generic nature of analytical stress models and the scarcity of fracture measurements in the shallow subsurface. If topographic stresses do indeed control bedrock fracture patterns, the implications and applications are numerous, and could include assessments of rock strength effects on infrastructure, predictions of reservoir characteristics, slope stability modeling, and characterization of near-surface seismic response. An improved understanding of topographic effects on rock fracture would also benefit basic research into Earth surface processes by revealing the influence of topographic stresses on soil development and landscape evolution.

Two steps that will make rapid progress on this topic are (1) producing models for calculating the three-dimensional topographic stresses generated by arbitrary topographic surfaces, and (2) collecting field measurements of fracture patterns in the shallow subsurface at field sites with varied topography and tectonic context. Recent technological advances have made both of these steps possible, creating an opportunity to shed light on decades-old questions. However, the lack of existing field data on topographically mediated rock fracture could lead some funding agencies to label new efforts to investigate this topic as “high-risk”. Given the ARO’s directive to support research that carries some risk but potentially yields large returns, an effort to generate new tools and datasets for investigating the largely untested hypothesis that Earth’s surface topography shapes bedrock fracture patterns would be consistent with the objectives of the ARO Geomorphology Program.
References

Weathering profiles in the Intensively-Managed Landscape Critical Zone Observatory, Illinois and Iowa

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The critical zone’s geologic materials in Illinois and Iowa house a 2 million year old legacy of deposition and erosion controlled primarily by the actions of glaciers, flowing water, and wind. Sixty to 130 meters of glacial, fluvial, lacustrine, and eolian sediments overly an eroded surface cut in Paleozoic bedrock. Within this thick package of unlithified sediments resides multiple weathering profiles formed as the landscape evolved between glacial episodes (Bettis, 1998). Weathering profiles in these deposits are recognized by pedologic features and structures, color and mottling patterns, fractures, and geochemical alterations such as leaching of primary carbonate minerals and/or accumulation of secondary minerals (Bettis, 2007).

The uppermost weathering profile in the area includes the postglacial or modern soil, a prairie soil (mollisol), or forest soil (alfisol). This weathering profile is most often formed in loess (Peoria Silt) or overconsolidated loamy glacial till, but along river valleys it may be formed in alluvium and glacial outwash (e.g., Figs. 1 and 2). The Peoria Silt includes variably thick deposits of windblown material deposited by dust storms that were common during the last glacial period (Bettis et al., 2003). Regionally across the IML-CZO, the thickness of loess varies from 7 m in Clear Creek Basin (CCB) to about 0.75 m in parts of the Upper Sangamon Basin (USRB). Loess typically thins downslope as a result of postglacial erosion, and the upper weathering profile is often developed through the thin loess and extends into underlying glacial till. In the CCB, the Peoria Silt buries Pre-Illinois Episode till (>500 ka) while in the USRB the Peoria Silt buries Wisconsin Episode till (c.a. 21 ka). Oxidation from the modern surface extends to a depth of at least 4 m and in some places beyond 8 m.

A second prominent weathering profile occurs beneath the thick loess in CCB (Fig. 2) and between deposits of the Wisconsin and Illinois Episodes at depths between 15 and 50 m below the present land surface in USRB (Fig. 1). This profile formed from a land surface that developed during the last interglacial period (c.a. 130-30 ka) in USB and between about 500 and 30 ka in CCB. The Sangamon Geosol formed during an extended period of climate warming (Follmer, 1979) that lasted from ~130,000–60,000 years ago (Curry et al., 2011) and forms the upper, pedogenically altered part of this weathering profile. The paleosol in the USRB is developed in a variety of materials including glacial diamicton, sand and gravel, and silt and fine sand of the Illinois Episode Glasford Formation, while in the CCB the geosol is in loamy glacial till of the pre-Illinois Episode Wolf Creek Formation (Figs. 1 and 2). The Sangamon Geosol often has well-developed Bt horizons with notable eluvial clay accumulations in the sand and gravel. Typically, only part of the Sangamon Geosol solum remains; the A and E horizons were truncated either by glacial erosion in USRB or by periglacial processes in CCB. Below the paleosol the weathering profile is recognized by either olive green (reduced) to dark brown (oxidized) fine-grained sediment and matrix-supported diamicton or yellowish brown- to reddish brown sand and gravel. The fine-grained sediments were deposited in flat areas or depressions that were poorly drained, the sand and gravel form elevated plains or fill paleovalleys and are well drained, and the diamicton is glacial till on slopes and elevated parts of uplands (cf. Jacobs, 1998). Typically, these sediments are leached of primary carbonate minerals, usually to a depth of 1.5–3 m below the paleo-land surface. Oxidation and mottling commonly extend much more deeply. The weathering profile extends along subvertical fractures into unaltered (unoxidized and unleached) dense glacial till.
Another weathering profile is buried beneath till of the Illinois Episode Vandalia Member in USB. Well-to moderately-drained facies of the Yarmouth Geosol occupy the upper part of this profile. In USRB this weathering profile is developed in pre-Illinois Episode tills that cover bedrock highlands or in valley fills in tributaries of the Mahomet Bedrock Valley (Fig. 1). Less frequently, the geosol is associated with a poorly expressed weathering profile. These profiles are only encountered in the Mahomet Bedrock Valley where pre-Illinois till was deposited on erosional hills on the valley bottom that are formed of bedrock or glacial sediment. To preserve these profiles in the till, the surfaces of these hills must have been above the maximum level of scour by glacial meltwater during the Illinois Episode glaciation. The weathering profile associated with well-drained facies of the Yarmouth Geosol is thicker and more oxidized than that associated with poorly drained facies of the geosol. Pedogenic alteration may extend 3–5 m into the till. In southern Illinois, mineralogical and magnetic measurements from these oxidized weathering profiles suggest that Yarmouth Geosol alteration and soil development was about triple the intensity as compared to alteration associated with the Sangamon Geosol (Grimley et al., 2003). Glacial erosion has truncated the upper soil horizons of this weathering profile in USRB.

Illinois Episode glaciation did not extend as far west as CCB where landscape evolution and weathering profile development continued uninterrupted through the Illinois Episode and into the Wisconsin Episode. Thus, the profile beneath the Peoria Silt in CCB represents weathering over the period encompassing development of the Yarmouth and Sangamon geosols in USRB. Almost without exception this thick weathering profile (usually 10-15 meters) is formed in loamy glacial diamicton of the upper Wolf Creek Formation and often extends into older, partially truncated weathering profiles formed in older Wolf Creek Formation glacial sediments (Fig. 2).

Other buried weathering profiles are present in the sequence of glacial sediments in CCB and USRB. These weathering profiles range from thin to thick and are associated with soils formed in deposits of sand, silt, clay, diamicton, or gravel that in some places contain organic matter. In the buried Mahomet Bedrock Valley (in USRB), a weathering profile extends into the underlying glacial outwash (Mahomet Sand Member of the Banner Formation) (Fig. 1) that was deposited during the first ice advance into Illinois (Stumpf and Dey, 2013). This glacial outwash comprises part of an aquifer (Mahomet aquifer) that is an important source of groundwater in the USRB. On the adjacent uplands, the weathering profile extends into the underlying till that Stumpf and Dey (2013) assigned to the West Lebanon Member. In west-central Indiana, this till is believed to have been deposited prior to the Matuyama-Brunhes magnetic reversal (Bleuer, 1976), which occurred 773.1 ±0.8 ka (Channell et al., 2010). A similar-age buried bedrock valley with a prominent weathering profile developed into its alluvial fill is present in the lower reaches of CCB near its junction with the Iowa River Valley (Bettis et al, 2010; Rovey et al, 2010; Fig. 2).

The lowermost weathering profile within the Quaternary section at USRB and CCB is encountered in various landscape positions (uplands and valleys), 60–100 m below the present land surface. The profiles are formed in variable thicknesses of sand, silt, gravel and rubbly diamicton, and lie directly on bedrock (Figs. 1 and 2). These sediments have a distinctive greenish gray to olive weathering color, may be leached, and generally contain distinctive clay mineral content and lower magnetic susceptibilities compared to the overlying glacial sediment. These sediments often contain some angular-shaped, oxidized and unoxidized clasts of the local bedrock.

In the USRB, the uppermost bedrock is Pennsylvanian and composed of alternating bands of shale, limestone, coal and underclay, with sandier lenses possible within the large shale bodies. Shale is the most volumetric lithology, and the most commonly encountered Pennsylvanian exposure surface when drilling. The shales may show a degree of lamination or stratification in the unweathered state, but this is obfuscated with weathering. Additionally, shales surfaces become soft and mushy. Consequently, material from the bedrock can be easily incorporated into the overlying un lithified sediments, making
distinguishing a precise surface of the bedrock difficult. In CCB the uppermost bedrock is variable and ranges from micaceous Pennsylvanian siltstone and sandstone to Devonian mudstone and limestone. Smears and clasts of local bedrock occur prominently in the oldest few tills of the Alburnett Formation and decrease in abundance up section.

The modern landscape in the IML-CZO is underlain by a variety of un lithified deposits altered to various degrees by several periods of weathering. Weathering profiles developed in bedrock are uncommon and, for the most part, the bedrock surface is a glacially scoured erosion surface. Initial materials in which the weathering profiles developed are dominantly wind-blown silt (the upper weathering profile) and dense, unoxidized matrix-dominated loamy glacial diamicton. Fracture networks in these materials provide preferential pathways for movement of water and colloids in these otherwise slowly permeable materials.

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Figure 1. The geological framework for the Upper Sangamon River Basin (USRB); from Stumpf and Dey (2013).

Figure 2. The geological framework for the Clear Creek Basin (CCB) in eastern Iowa.
Dating alteration and exhumation in the deep Critical Zone

White paper for NSF Workshop on Drilling, Sampling, and Imaging the Depths of the Critical Zone, Thursday October 24th – Saturday October 26th, 2013, Denver, CO

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Motivation: Why dates are likely to be important
There is wide agreement about the need to understand chemical reaction and rock alteration that takes place beneath the depth of identifiable soil. Drilling and other deep sample collection provide the opportunity to directly sample alteration at depth, and alteration minerals such as clays and oxides are likely to provide particularly valuable information about the chemical processes in recovered material (e.g. Buss et al., 2008). But clays and oxides in many rocks reflect processes that range widely in age, with some clays and oxides forming millions of years ago, or even earlier, and others forming as recently as the past decades (e.g. Vasconcelos et al., 1999). Moreover, there is little a priori information about when rock in the deep Critical Zone was exhumed to depths where alteration occurs. Properly understanding the geochemical records of drill cores or other samples from the deep Critical Zone, and accurately interpreting what they mean about the nature and rates of geochemical and biogeochemical reactions, will depend on determining both when rock was brought to the shallow crustal depths where alteration occurs, and when key alteration reactions actually took place. This brief white paper summarizes some ideas for adding age information about clays and oxides recovered from the deep Critical Zone, as well as constraining the timing and rate of shallow exhumation.

Dating by K/Ar, Ar-Ar, and Rb-Sr
Ar-Ar dating has been successfully applied to Mn-oxides (e.g., Vasconcelos, 1999), and K-Ar and Rb-Sr methods have proved useful in dating clay minerals (e.g. Gilg et al., 2003). The long half-lives of these systems generally have restricted their application to clays and oxides >100,000 years in age. This means that they are not well suited for the study of recent (Holocene or similar) alteration, which may be most relevant for understanding active Critical Zone processes. However, older alteration, which may be reflected in ancient oxides and other minerals, is important for setting the stage for more recent chemical reaction and shaping the physiochemical characteristics of the bedrock. Indeed, much remains to be understood about how the older history of rock alteration shapes present-day processes. Ar dating would be a potentially valuable tool for gaining older age information from alteration phases, although (U-Th)/He chronology, described below, may also provide valuable insights into the history of deep Critical Zone samples.

Dating by (U-Th)/He
Radiogenic He dating may be valuable for understanding deep CZ evolution for two reasons:
- First, (U-Th)/He thermochronology of common primary minerals can constrain the timing and rate of exhumation of bedrock into the shallow crust (1-2 km for apatite), where it is exposed to chemical alteration and the initiation of CZ processes (e.g. Reiners et al., 2005). Knowing the timing of the initiation of the CZ context would provide a valuable interpretive baseline. For example, as noted above, CZ processes occurring in a modern setting may be influenced by previous or ancient exposure episodes that initiated bedrock weathering.
- Second, ongoing studies show significant potential for this method to date the timing of formation of secondary oxides (e.g., hematite, goethite, Mn-oxides) in bedrock (e.g. Shuster et al., 2005). This is useful because it constrains the timing of flow of oxidized fluids in the uppermost crust and therefore the timing of chemical weathering in the deep CZ (e.g. Buss et al., 2008).
Dating by U-series disequilibrium

There are several ways in which the $^{238}$U-$^{234}$U-$^{230}$Th system can be used to date alteration processes. This system can cover a useful range from a few thousands of years to >350 ka. Perhaps the most robust use of this system is in dating of specific individual phases, and several alteration phases have been successfully dated this way, including:

- **Secondary carbonates and opal rinds**: These are obvious targets and there has been considerable use of this tool especially on carbonate rinds from soils in arid environments (e.g. Ludwig and Paces, 2002; Sharp et al., 2003).
- **Oxides**: Fe-oxides including goethite are datable; most applications have focused on concretions (Short et al., 1989; Augustinues et al., 1997; Bernal et al., 2006).
- **Clays**: Dequincey et al. (1999) dated the <0.2mm fraction of laterite soils, which they viewed as a clay fraction and which exhibited quasi-closed system behavior sufficient to yield a clay formation age at the bottom of the profile. This approach has not been widely used but may be promising.

If appropriate secondary phases can be recovered from samples from the deep Critical Zone, these kinds of phase-specific $^{238}$U-$^{234}$U-$^{230}$Th work have the potential to provide valuable age information.

There have also been many efforts to infer ages of initial alteration of bulk material (the “weathering timescale” of soils and sediments) using $^{238}$U-$^{234}$U-$^{230}$Th disequilibria. This includes isochron methods using co-genetic samples with varying detrital component (e.g. Rosholt, 1976), and modeling of leaching timescales (e.g. Vigier et al., 2001; Dossetto et al., 2008; Chabaux et al., 2013). These methods may often provide useful information, and they may be useful in application to deep CZ samples, but there are several uncertainties and the context of their application requires careful attention in order not to yield ages that may be biased, for example by complex leaching behavior (e.g. Keech et al., 2013).

Summary

U-series disequilibrium and (U-Th)/He geo- and thermochronology offer geochemical techniques that may be particularly useful in providing age information about alteration in the deep Critical Zone. Planning sample recovery with these techniques in mind will help to maximize the information gained from drilling and other recovery efforts, because understanding the age of alteration will be critical to interpreting other geochemical, geophysical, and geobiological information.

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The Deep Critical Zone (DCZ) need not go “Unmeasured”: Advancing Process-Based Geophysical Characterization and Monitoring

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Although the Deep Critical Zone (DCZ) has been nicknamed the “unmeasured zone” (Dietrich, 2010) it is actually highly accessible with well-established geophysical imaging technologies. This misrepresentation of the DCZ highlights a pressing need for more collaboration between near surface geophysicists and the hydrologists, geochemists and geomorphologists currently studying critical zone processes. Dramatic advances in near surface geophysical techniques have occurred over the last decade, resulting in improved spatiotemporal resolution of subsurface structure and processes. The information content of geophysical measurements with respect to hydrogeological and biogeochemical properties of the Earth has also increased through theory and observation. Geophysical imaging of the DCZ is not new: The current opportunity is to better perform geophysical imaging in a manner that helps to unravel how the DCZ structure regulates biogeochemical processes observed in the shallow critical zone and at the Earth surface. In a nutshell, near surface geophysicists need to better understand the significance of their trade with respect to advancing understanding of critical zone processes. This requires new thinking on geophysical sensors, instrumentation and petrophysical interpretation.

A new era of geophysical instrumentation: Geophysical characterization and monitoring of the DCZ should be better coupled with other sensors being used to understand critical zone processes. Such coupling of geophysical images to surface observations offers the solution to understanding how shallow CZO processes are linked to the DCZ. This strategy has already led to [1] improved understanding of hydrogeological controls on focused groundwater discharge into rivers, and [2] geological controls on peatland formation and carbon cycling within peatlands. This new era requires development of geophysical instrumentation that overcomes the inflexibility of instruments designed for traditional exploration geophysics. Instead geophysical sensors and monitoring systems that maximize the information content retrievable from the DCZ are needed. Integration of these geophysical sensors with instrumentation for monitoring shallow CZ processes must be considered. Autonomous geophysical monitoring platforms should ultimately be developed to provide invasive proxy measurements of chemical, physical, and biological processes operating in the DCZ over long time scales. For example, electrical geophysical monitoring systems have recently been deployed to determine the control of geological structure on surface water-groundwater interactions.

A new era of “petrophysical” research: Petrophysics is a petroleum geophysics term for the science defining the relations between geophysical properties measured with imaging and the physicochemical properties of the Earth. Existing petrophysical relations generally consider static systems i.e. they are parameterized with the physicochemical properties or rocks that are primarily determined by processes acting on geological timescales. However, the DCZ is dynamic in that biogeochemical transformations modify both the physicochemical and geophysical properties of earth materials on much shorter timescales. Recent studies have repeatedly demonstrated the sensitivity of geophysical techniques to biogeochemical processes and transformations occurring in the DCZ. Consequently, we foresee a need for research on time-variable petrophysics to develop robust relations that will improve the information content of geophysical signatures resulting from natural biogeochemical processes, and allow better quantitative coupling of deep CZO processes to the shallow zone.
Exploring Weathered Bedrock Characteristics: A Pedologic Approach

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Introduction

Weathered bedrock plays a critical role in the hydrologic cycle and directly influences ecosystem productivity (Graham et al., 2010). Its ability to store water is especially relevant in arid and semi-arid environments, yet equally important in the midst of climate uncertainty in humid regions. Remarkably, very little is known about the spatial variability of weathered bedrock characteristics. Geophysical investigations are promising, but alone do not provide information about ecologically important characteristics such as water and nutrient availability, propensity to accommodate roots, and carbon storage. On the other hand, deep coring provides direct point observations, but of limited spatial extent and questions of representative sample collection arise. In combination with geophysical techniques and deep drilling, pedological approaches can be applied to describe deep regolith characteristics across catchment scales.

In many landscapes, repeating patterns of soil forming factors (usually overlapping) give rise to predictable patterns in soil characteristics. This phenomenon and its application define a paradigm for mapping soils using field observations coupled with contextual data (aerial imagery, topographic maps, geologic maps, etc.) that are hypothesized to have a connection with active soil forming factors: time, topography, organisms, climate and parent material (Jenny, 1941 & 1980). The fairly recent digital implementation of this approach, supported by widely available, high-resolution spatial data coupled with statistical and mapping software, has resulted in effective quantification techniques that document soil variability and their influence on near surface processes (Moore et al., 1991; McBratney et al., 2003; Grunwald, 2009).

Most digital mapping studies focus on external “drivers” of soil formation (e.g. hillslope processes that affect the redistribution of water, sediment, and mineral weathering), with an inferred relationship to digital proxies for these drivers. This approach relies on fitting statistical models to soil and environmental covariates (i.e. proxies for soil forming factors), followed by prediction at un-sampled locations. Terrain-based attributes calculated from digital elevation models such as slope shape, exposure, and compound metrics describing flow (water or energy) or sediment accumulation are some of the common proxies used to describe soil forming processes (Moore et al., 1993).

Quantitative models that describe weathered bedrock characteristics are needed in order to understand critical zone processes operating at catchment and hillslope scales. We believe that digital soil mapping and other pedologic approaches should be included as part of the toolkit for deep CZ research. The following questions are examples of how the characteristics and spatial distribution of weathered bedrock might be addressed from a pedological perspective.
1. Do soil forming factors, (Time, Topography, Parent material, Organisms, and Climate) explain spatial variability of weathered bedrock characteristics? Are some factors more or less important?

2. To what degree do digital soil mapping techniques and their digital proxies (terrain attributes, airborne gamma ray mapping, remote sensing) explain weathered bedrock thickness and mineralogical, chemical, biological and physical characteristics?

3. To what extent does soil variability as documented by the Cooperative Soil Survey relate to spatial trends in weathered bedrock characteristics?

4. What other observational techniques are possible to sample and describe important characteristics of weathered bedrock?

5. Can traditional soil analyses be applied to deep regolith to help interpret their ecosystem and hydrologic functions?

6. How does the degree of soil development influence the nature and dynamics of processes in weathered bedrock?

7. Is there a fundamental scaling relationship between the depth of regolith, canopy height, and depth of chemical alteration of bedrock?

**Case Studies**

*Study 1:* Preliminary evidence at the Southern Sierra CZO suggests that a linkage exists between the degree of soil development and characteristics of weathered bedrock. Spatially explicit patterns of soil forming factors give rise soil sequences that correspond to an altitudinal gradient. This gradient imposes a weathering environment that is limited by moisture at low elevations and by low temperature at high elevations. A zone of high weathering intensity exists across the entire Sierra Nevada at mid elevations, between ~800 to 1600 m. This belt of intense soil development occurs in many parent materials throughout Sierra Nevada and reflects the combined influence of mild temperatures and high precipitation, predominantly as rain (Dahlgren et al., 1997; Rasmussen et al., 2007).

Weathered bedrock thickness coincides in part with the degree of soil development along the altitudinal gradient. Generally, weathered bedrock thickness is limited at low elevations because of a lack of water and at high elevations due to glaciation, which has limited the amount of time the material has been exposed to weathering processes. There is a greater elevation range of landscapes with deep regolith (~800-2000 m) compared to landscapes with highly weathered soils (~800-1600 m) (Figure 1.). Elevations between 1600-2000 m appear to have deep regolith, but relatively weakly developed soils. Additional factors that influence regolith thickness appear to be at play. For example, physical weathering plays a significant role in weathered bedrock thickness. Physical weathering in Sierran granitic materials is largely controlled by mica exfoliation. Hence, higher mica contents result in thicker weathered bedrock, if enough water is present and the terrain has not been glaciated.
Figure 1. Soil development and regolith thickness across an altitudinal gradient in the Sierra Nevada. The intensity of redness reflects the degree of soil development.

Study 2: Numerical and digital soil mapping models of soil properties in the Marshall Gulch catchment of the Santa Catalina Mountain CZO indicate clear relationships between terrain attributes (wetness index and annual solar radiation) and properties such as the depth of potentially mobile regolith (defined here as the depth of refusal when excavated by hand) and chemical depletion (Pelletier and Rasmussen, 2009; Holleran, 2013). The Marshall Gulch study area focused on a small 6 ha basin at ~2,200 m a.s.l. with a mixed conifer forest underlain by dominantly granitic parent materials, characterized by an assemblage of quartz, alkali and plagioclase feldspars, and muscovite.

Pelletier and Rasmussen (2009) used a mass transport numerical model that incorporates an exponential form of the “soil production function” (Heimsath et al., 1997) and a non-linear depth and slope dependent sediment transport function using 1-m resolution LiDAR data and an assumption of topographic steady-state to model the depth of the potentially mobile regolith with a reasonable degree of accuracy based on field observations (Fig. 2a). The modeled depth expresses strong correlation with topographic divergence and convergence as expected based on the sediment transport model.

Figure 2. Numerically modeled depth of mobile regolith (defined here as depth to refusal when excavated by hand) (a) indicates clear relationship between depth and topography, namely deep soils in convergent portions of the landscape (dark blue ~2 m depth) and shallow soils in divergent landscape positions (red and orange < 0.15 m depth). The second panel (b) overlays the LiDAR derived canopy...
height (green bars), modeled regolith depth (red-brown layer), and topography (all scaled to meters a.s.l.). Data from a 6 ha basin in Marshall Gulch SCM-CZO (Pelletier and Rasmussen, 2009).

Application of digital soil mapping techniques to the same basin similarly indicated strong statistical relationships between topographic wetness index and solar radiation to mobile regolith depth and degree of chemical denudation (Fig. 3) (Holleran, 2013). It is encouraging to note that two independent modeling techniques (a numerical mass transport approach and a statistically based digital soil mapping approach) yield very similar patterns in mobile regolith depth and degree of chemical alteration. However, the large scale difference and relative lack of spatial correlation in modeled and measured mobile regolith depth and LiDAR derived canopy height (Fig. 2b), suggests the mixed conifer forest must rely on water from depths much greater than those that can be excavated by hand. We suggest there may be a scaling relationship among terrain attributes, mobile regolith depth, canopy height, and depth of weathered bedrock that would facilitate coupling these techniques and data to model the depth of weathered bedrock.

Figure 3. Modeled mobile regolith depth (defined here as depth to refusal when excavated by hand) and Na mass loss for the 6 ha basin in Marshall Gulch SCM-CZO using statistically based digital soil mapping techniques (Holleran, 2013).

Summary

The opportunity to incorporate the pedologic method with other disciplines for deep, weathered bedrock CZ investigations appears promising. Soil landscape relationships such as those described here are commonly used in pedologic investigations. Moreover, these types of models serve as the foundation for how soil surveys are made. Thus, the possibility of using soil survey as an upscaling mechanism for weathered bedrock characteristics is conceivable. To fully understand the characteristics of weathered bedrock, and the processes it mediates, a joint-CZO effort is needed that involves a variety of disciplines.
References


