White Papers

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Drilling Active Tectonics and Magmatism

(Volcanics, Geoprisms, and Fault Zones Post-SAFOD)

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

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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.

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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, in review; 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 (> M_w 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_w7.0) 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_w7.5 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.

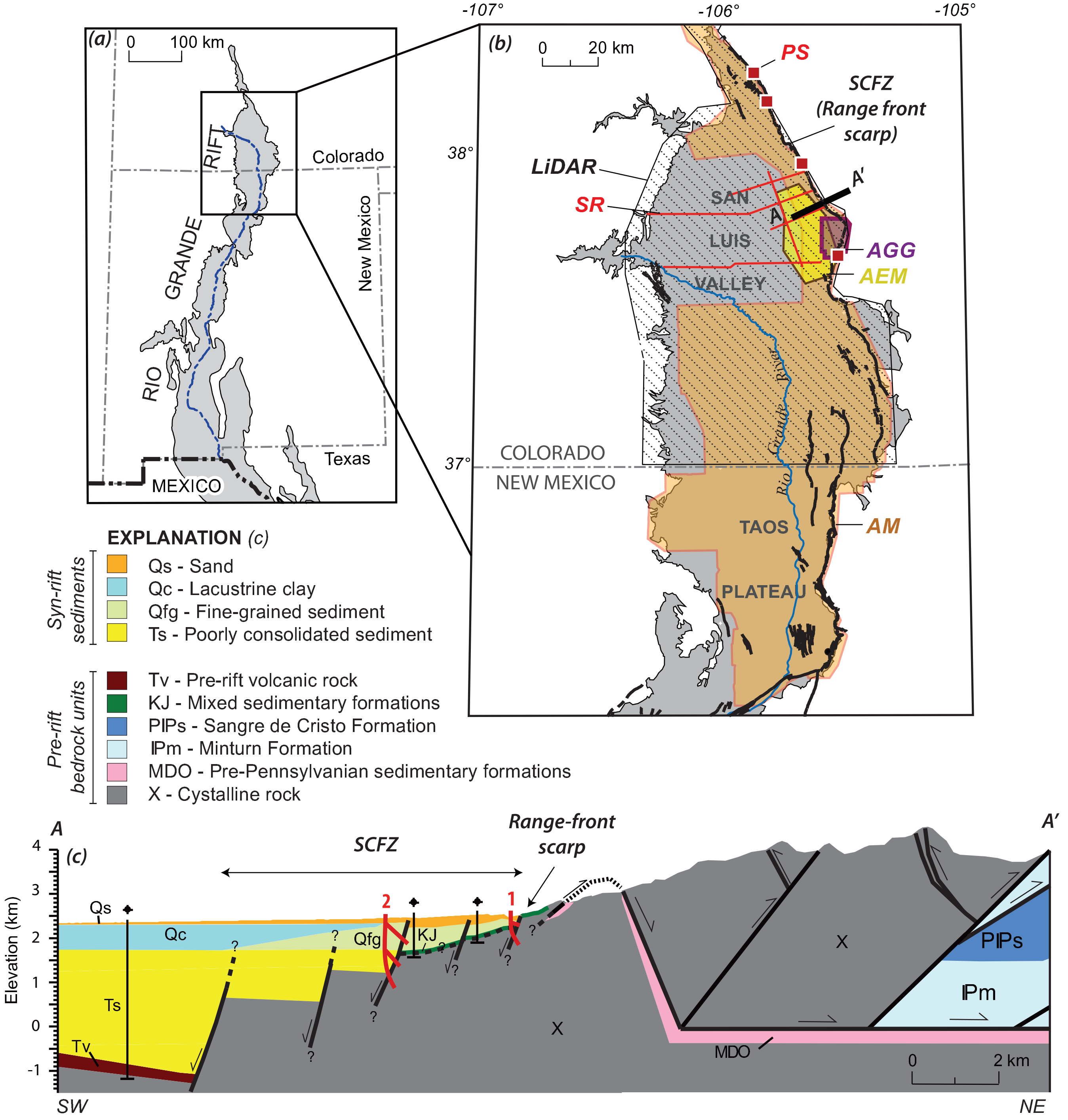

Figure 1. (a) Extensional basins associated with the Rio Grande Rift. (b) Distribution of selected datasets near the Sangre de Cristo fault zone (SCFZ) for the San Luis Valley (PS, paleoseismology; LiDAR, light-detection and ranging; SR, seismic reflection; AGG, airborne gravity gradiometry; AEM, airborne 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.

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Figure 1

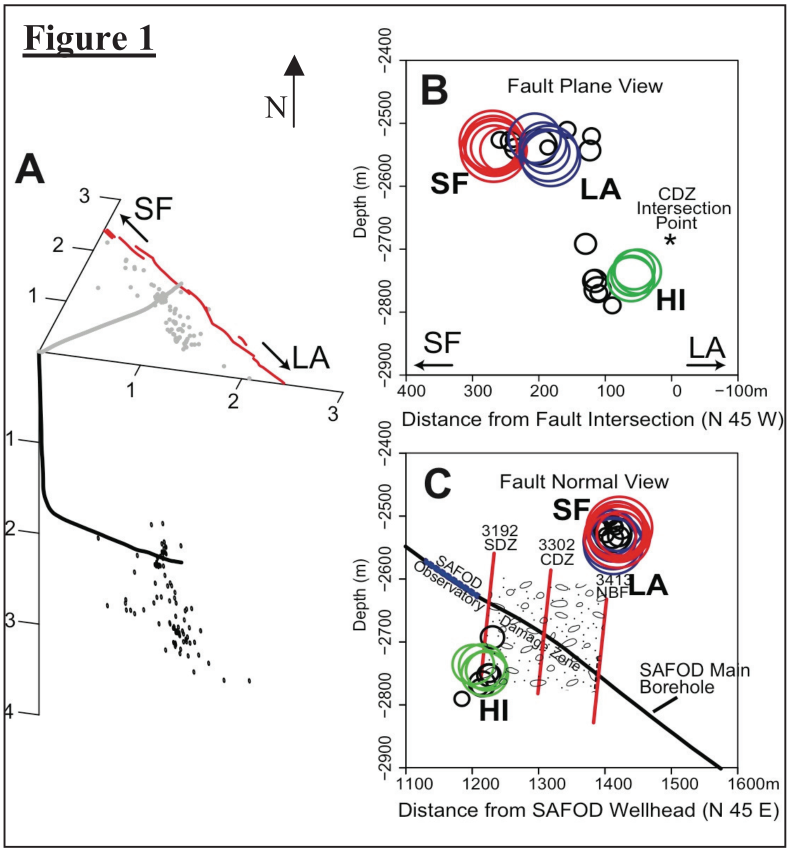

Figure 1: Repeating earthquake clusters in the SAFOD target zone. (A) Three-dimensional view of the volume surrounding the SAFOD borehole, with microearthquakes shown as black dots. Axes are in km. (B) Location of repeating microearthquakes within the plane of the SAF, showing the borehole intersection 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 micorearthquake 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 that an additional multilateral be drilled off the main SAFOD borehole to allow for coring, downhole measurements and monitoring directly within the HI cluster.***

Reconstructing an "A-type" Silicic Magma System along the track of the Yellowstone Hotspot, Central Snake River Plain, Idaho

Eric H Christiansen and the Hotspot Science Team

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 delta ^{18}O. 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 (850º-1000ºC) 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 km^3), low aspect ratio lavas, vast (≈1000 km^3) 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.

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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

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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).

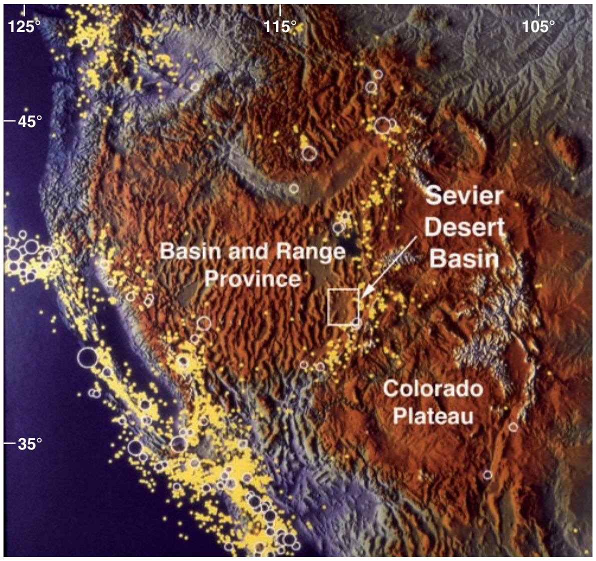

Figure 1. Regional physiography, seismicity, and location of the Sevier Desert basin in the western United States (from Simpson and Anders, 1992). White open circles are earthquakes greater than magnitude 6.0 from 1900 to 1975. Yellow dots are earthquakes greater than magnitude 2.5, occurring between 1970 and 1985. The north-trending band of seismicity adjacent to the Sevier Desert marks the eastern edge of the Basin and Range Province. Intense seismicity to the west and southwest, and including the western Basin and Range Province, corresponds with the diffuse transform plate boundary of which the San Andreas fault system is the most important element.

Interest in the Sevier Desert detachment (Fig. 3) relates to its large scale, geometric simplicity, severe misorientation with respect to σ_1, 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 scarps 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 scarps 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 (downdip) 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.

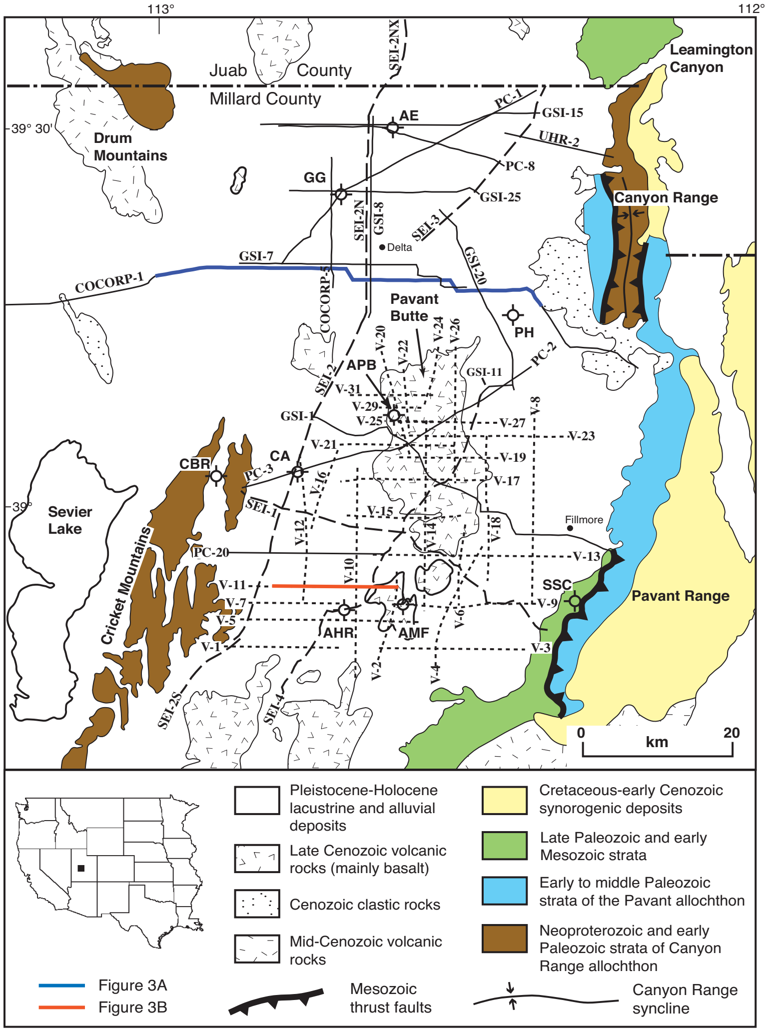

Figure 2. Generalized map of the Sevier Desert basin, west-central Utah, showing locations of wells and seismic reflection profiles (from Wills et al., 2005; see Fig. 1 for location). Wells: AE, Argonaut Energy Federal; AHR, ARCO Hole-in-Rock; AMF, ARCO Meadow Federal; APB, ARCO Pavant Butte; CA, Cominco American Federal; CBR, Chevron Black Rock; GG, Gulf Gronning; PH, Placid Henley; SSC, Shell Sunset Canyon. Solid, dashed, and dotted lines correspond with different seismic datasets. Part of Consortium for Continental Reflection Profiling (COCORP) Utah Line 1 (blue) is shown in Fig. 3A. A portion of Vastar Resources, Inc. Line V-11 (red) is shown in Fig. 3B. Thrust faults are the tightly folded Canyon Range thrust in the Canyon Range and the structurally lower Pavant thrust in the Pavant Range (teeth on upper plate). Inset map shows location relative to states in the western U.S.

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—are 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.

Acknowledgments

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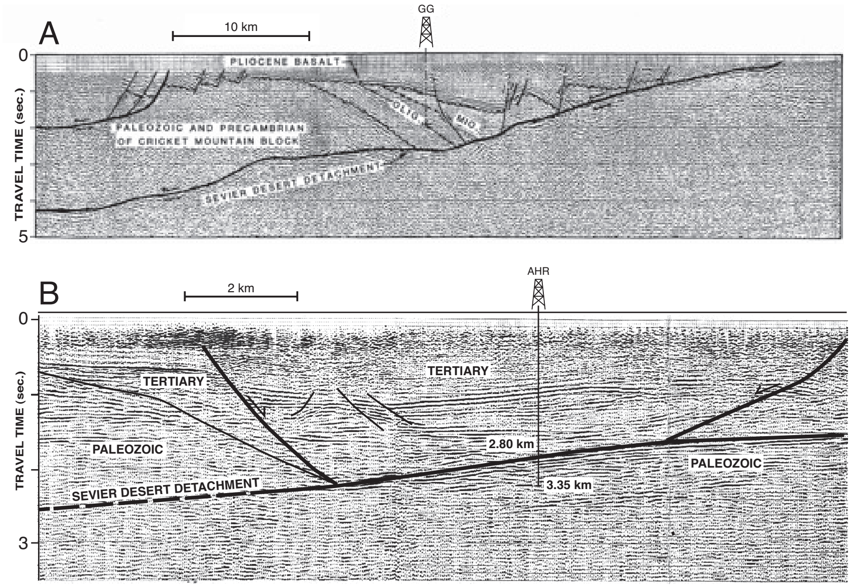

Figure 3. Examples of seismic reflection profiles from the Sevier Desert basin (see Fig. 2 for location). [A] Part of COCORP Utah Line 1, with interpretation of the Sevier Desert detachment from Von Tish et al. (1985). [B] A portion of Vastar Resources, Inc. Line V-11, with interpretation modified from Planke (1987). Projected wells: GG, Gulf Gronning; AHR, ARCO Hole-in-Rock. Line V-11, located ~3 km north of the Hole-in-Rock well, is the profile that best illustrates the geological structure in the vicinity of the well.

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

Zachary Frone, Southern Methodist University

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 km^2 and has a volume of approximately 450 km^3 (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 of 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 km^2 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.

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

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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.

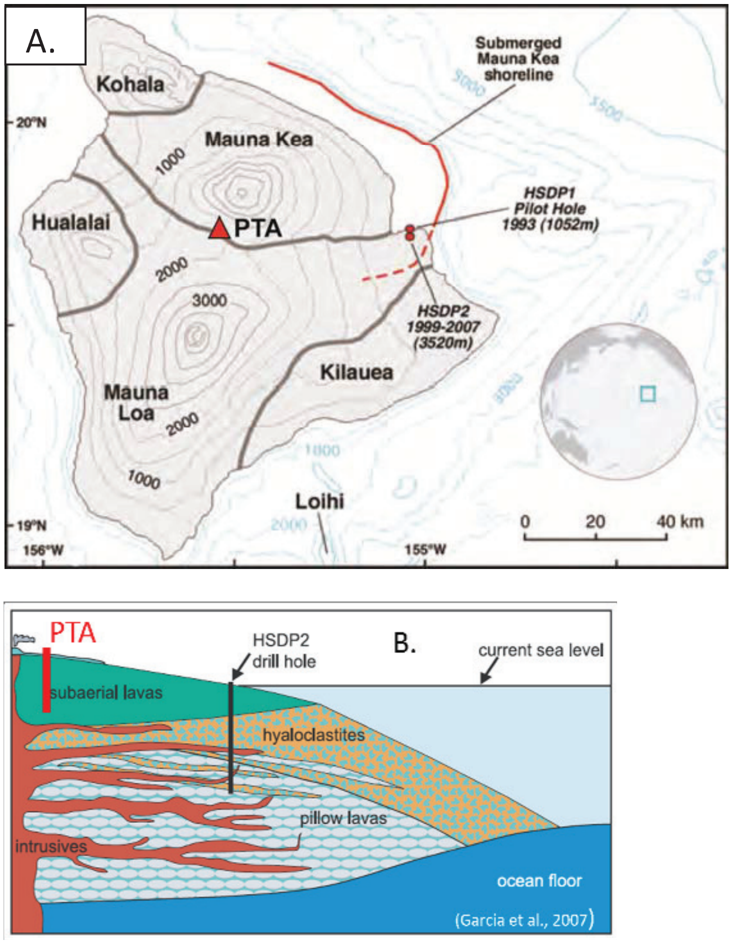

Figure 1. A. Map of the Island of Hawaii showing location of the Hawaiian Scientific Drilling 2), the new PTA drill site and the subaerial boundaries of the five volcanoes forming the island (after Stolper et al., 2009). **B.** Schematic cross section of Mauna Kea Volcano drawn from summit to deep ocean floor (after Garcia et al., 2007)

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 cycylic 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.

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Coring and studying clay gouges from mature active fault zones

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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

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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 Braile 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}He/^{4}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}He/^{4}He extends into the Miocene (≥8 Ma) SRP basalts and includes the Columbia River Basalt group *(Graham et al. 2009).* High ^{3}He/^{4}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}He/^{4}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 ∂^{18}O and ^{3}He/^{4}He signatures, and the lack of correlation between ^{87}Sr/^{86}Sr (or ∂^{18}O, ^{206}Pb/^{204}Pb, and ^{208}Pb/^{204}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-lithosphere 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 basaslts, 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 (M_l5.7, M_d5.0) 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 rhyolitic 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^o 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.

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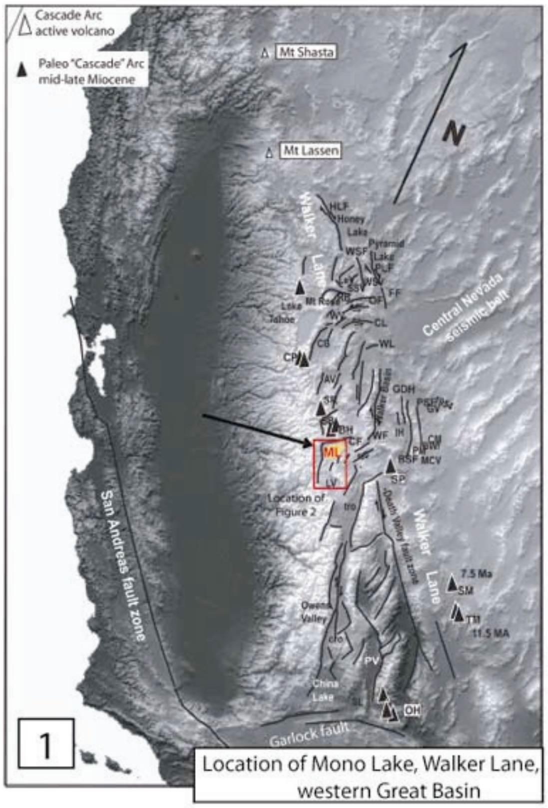
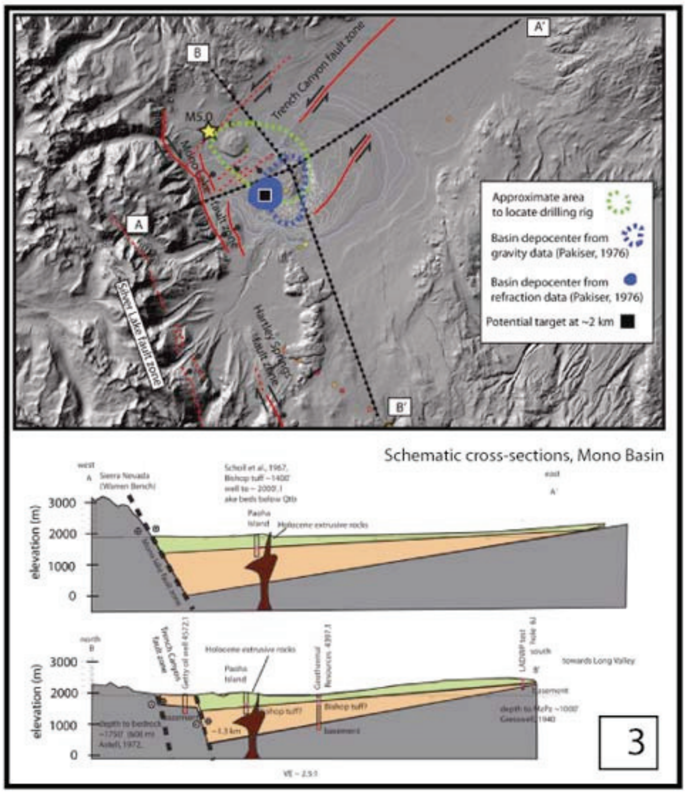


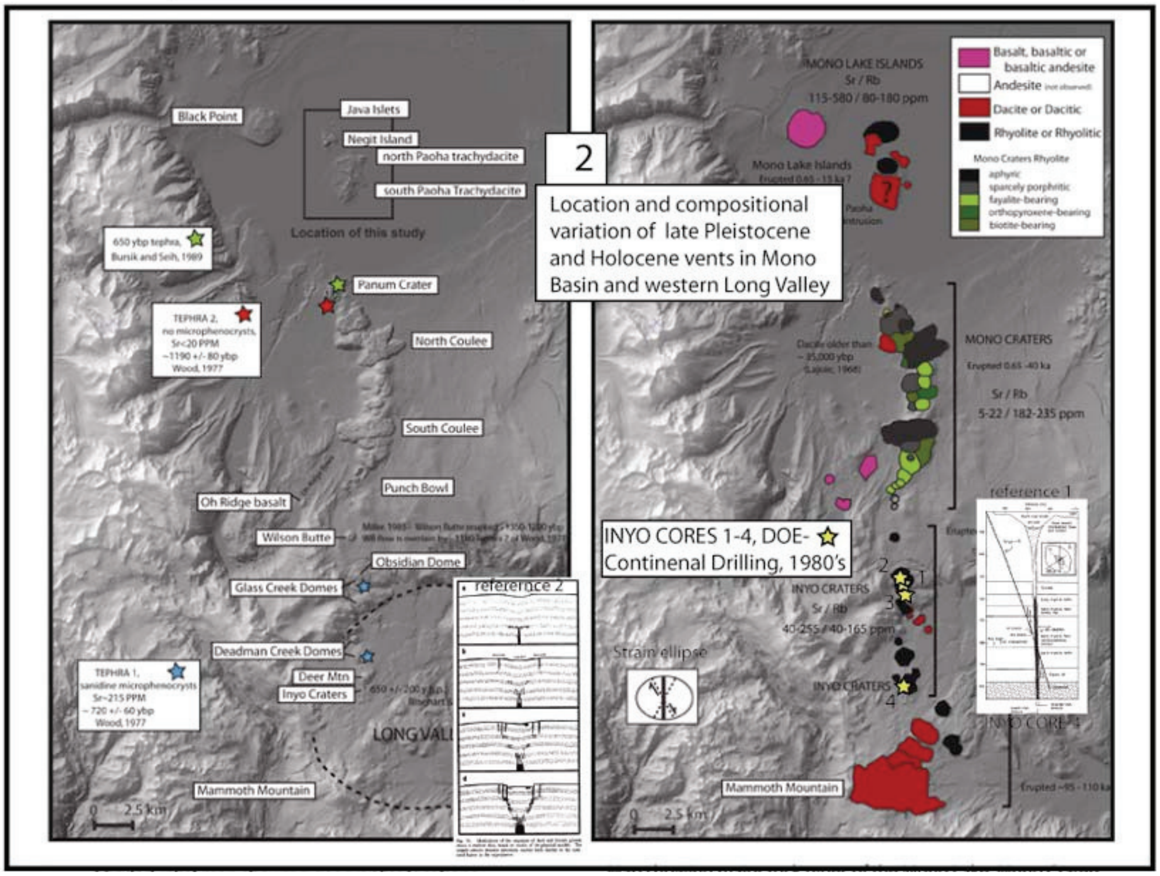
1

Location of Mono Lake, Walker Lane, western Great Basin



Schematic cross-sections, Mono Basin

3



2

Location and compositional variation of late Pleistocene and Holocene vents in Mono Basin and western Long Valley

INYO CORES 1-4, DOE- Continenal Drilling, 1980's

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 Reasearch 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 CO_2 storage: constraints from scientific drilling of natural CO_2 reservoirs, leaky faults and travertine deposits of the Colorado Plateau

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Introduction

Natural CO_2 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 CO_2 and CO_2 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 CO_2 in the subsurface. Studying such sites can address important questions about the security of CO_2 in geological reservoirs, the interactions of mantle and crustal fluids and the roll of magmatism, tectonics and climate in controlling the flux of mantle volatiles to the Earth's atmosphere.

CO_2 storage site analogues: objectives

Several of these CO_2 reservoirs are currently being studied in detail as important natural analogues to engineered anthropogenic CO_2 storage sites (e.g. Gilfillan et al., 2009; Kampman et al., 2009) and as 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 CO_2 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 CO_2 for more than 10,000 years.

In order to understand the long-term behaviour of supercritical CO_2 in engineered storage sites we need observations from natural CO_2 accumulations that can only be accessed by drilling. Critical questions for geological CO_2 storage that can be addressed by drilling such accumulations include;

1) The effects of supercritical CO_2 and CO_2-charged brines on reservoir caprocks;
2) The effects of supercritical CO_2 and CO_2-charged brines on fault rocks and fault zone permeability;
3) The long-term behaviour of CO_2 in reservoirs including its impacts on porosity/permeability,
4) The significance of fluid flow and diffusive CO_2 transport on CO_2 dissolution
5) The significant of CO_2 mineralization as a permanent trapping mechanism;
6) The use of travertines and fault zone carbonate mineral deposits to reconstruct fault hosted CO_2-leakage and its mechanisms and controls.

Many of these questions are best addressed by recovering core and fluid samples from natural CO_2 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 CO_2 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 CO_2 storage site, can only be understood by integrating field studies of this kind, using rock core recovered from faults that currently host CO_2-leaking or which have formed conduits for CO_2 and CO_2-charged fluids in the geological past.

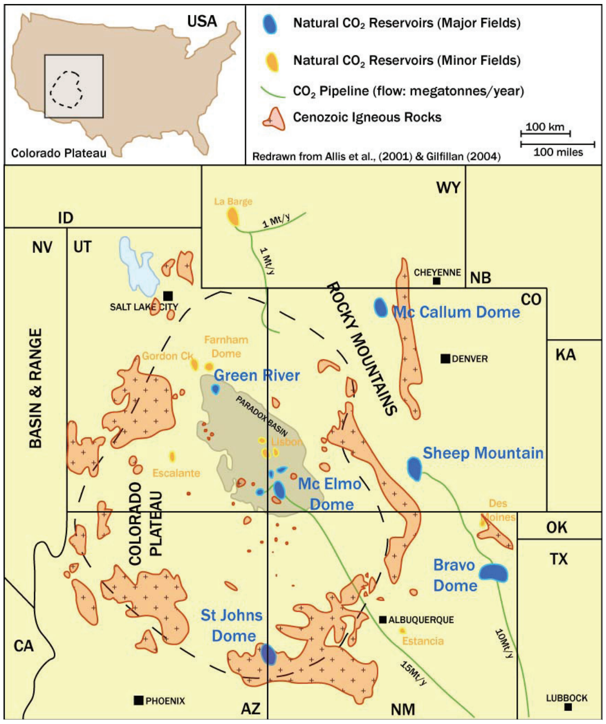
Redrawn from Allis et al., (2001) & Gilfillan (2004)

Figure 1 Natural CO_2 accumulations of the Colorado Plateau and southern Rocky Mountains. The region contains numerous large crustal reservoirs of CO_2, some of which are produced commercially. Much of the CO_2 is derived from Cenozoic magmatic activity and systems like Bravo Dome and CO_2-srpings and seeps in the Rocky Mountain region are thought to be undergoing contemporary recharge with mantle derived volatiles.

The origin of the CO_2 and processes controlling the stability of the reservoirs may be investigated where subsurface gases and fluids are accessible through commercial CO_2 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 CO_2 accumulation at Green River, Utah is currently providing critical information on the interaction of this CO_2 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 CO_2 reservoirs, the critical parts of these active reservoirs are buried and can only be accessed by drilling. Information on the impacts of supercritical CO_2 on caprocks, faults and reservoirs is critical to inform models of CO_2 behaviour in CO_2-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 CO_2-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 CO_2 and CO_2-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 CO_2 reservoirs has inherent technical challenges. Drilling into reservoirs containing supercritical CO_2 and high-pressure CO_2-charged brines, that will rapidly expand or degas CO_2 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 CO_2 reservoirs but also for drilling observation and injection wells in on-going CO_2 storage projects.

Reservoir Caprocks

Understanding the long-term geochemical and geomechanical behaviour of low permeability rocks, such as siltstones, mudstones and shales, that form CO_2-reservoir seals, especially where they are exposed to supercritical CO_2, is essential for predicting the long-term security of engineered storage sites. The advective-diffusive transport of CO_2 and CO_2-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 CO_2 and CO_2-charged brines can be used to reconstruct the impacts of the CO_2, and when combined with advective-diffusive modelling or isotopic dating, used to constrain the rates of the alteration.

Fault hosted fluid flow, CO_2 leakage and the geochemical, tectonic and climatic controls on the long-term hydraulic behaviour of CO_2-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;

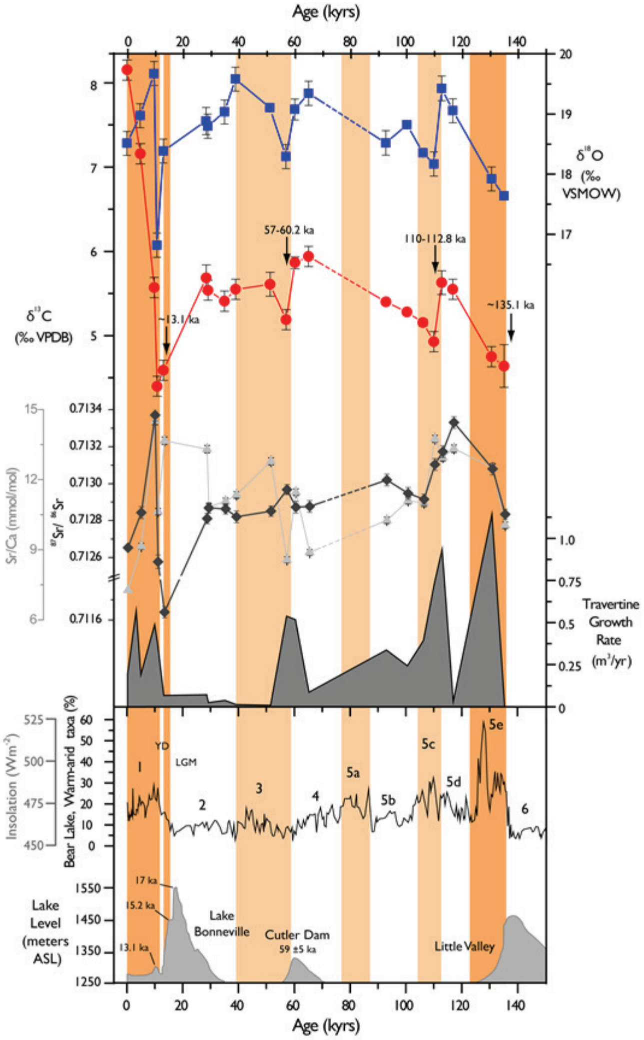

Figure 2 ~135 k.y. paleo-leakage history reconstructed for the CO_2-degassing fault at Green River, Utah. U-Th dated carbonate veins in the fault zone record changes in paleo-groundwater chemistry related to pulsed filling of the CO_2 reservoir following periods of climatic warm, with a periodicity controlled 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 CO_2 (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 CO_2-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 CO_2 field in eastern Arizona and western New Mexico, contain massive surface travertine deposits (>33 km^2) that record episodic CO_2-leakage from the reservoir through local normal faults, with volumetric CO_2-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 CO_2-leakage and its geochemical, tectonic and climatic controls assessed.

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Enhancing Data Management for Continental Scientific Drilling

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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 (CIF21[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

[2] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504730

[3] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504780

Mechanics of Normal Fault Systems

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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.

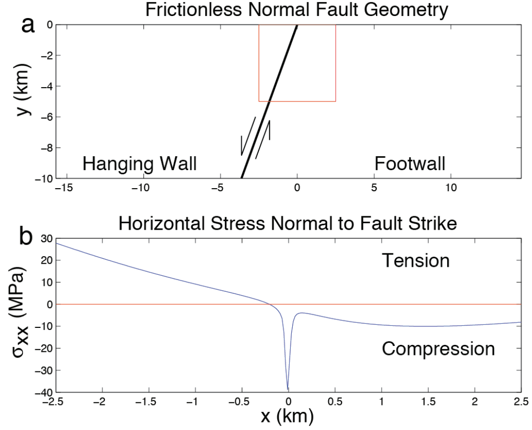

Figure 1. (a) Geometry of a frictionless planar model normal fault that dips 70° and extends to 10 km depth in an elastic half-space. The surface is at y = 0. The ambient stresses are taken as $\sigma_{yy} = \rho g y$ and $\sigma_{xx} = \sigma_{yy}/3$, where $\rho = 2700\, kg/m^3$. The red box shows the area of Fig. 2. (b) Theoretical plane strain horizontal stresses at the surface after faulting. Tensile stresses (positive) dominate the hangingwall, and compressive stresses (negative) dominate the footwall. Prior to faulting, the horizontal stresses at the surface equal zero.

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.

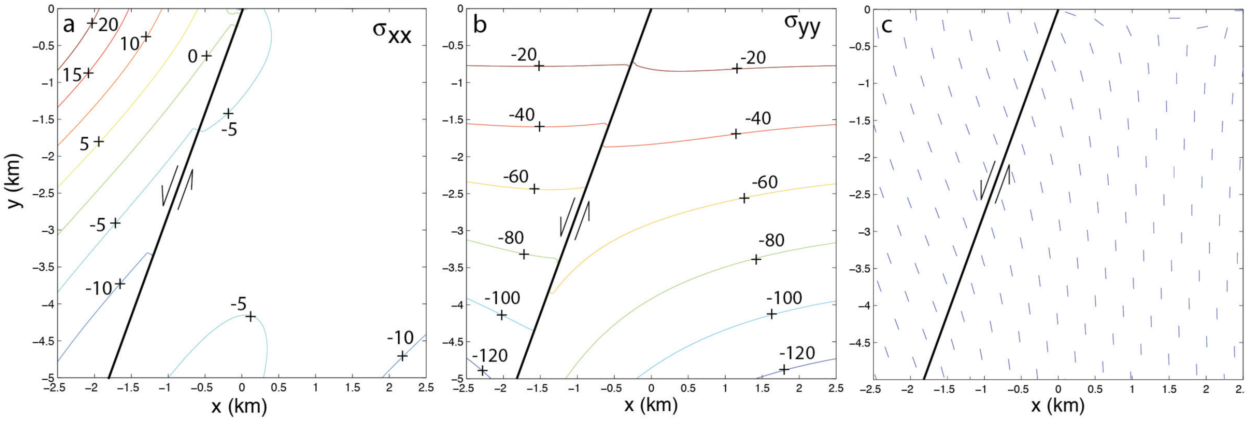

Figure 2. Theoretical two-dimensional total stress fields (plane strain) in the upper 5 km after slip on the model fault of Fig. 1. (a) Horizontal stress. (b) Vertical stress. (c) Trajectories normal to the most tensile stress (proxies for the orientation of opening mode fractures). Trajectories at the 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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Project Summary

SINOOK will drill the caldera of Okmok volcano, Alaska (Figure 1), and collect *core and fluid samples*, *temperature measurements*, and *borehole stress measurements* to a depth of 4 kilometers. Ideally, the sampling will penetrate the transition zone between the country rock and the magma chamber and culminate with direct sampling of quenched magma. This assemblage of in situ information will provide unprecedented constraints for interdisciplinary models of deformation, stress, geothermal systems, eruption history, and caldera formation for this active volcano. SINOOK will address an array of important scientific questions for the specific example of Okmok volcano and have far-reaching interdisciplinary implications.

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 multiphasic 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

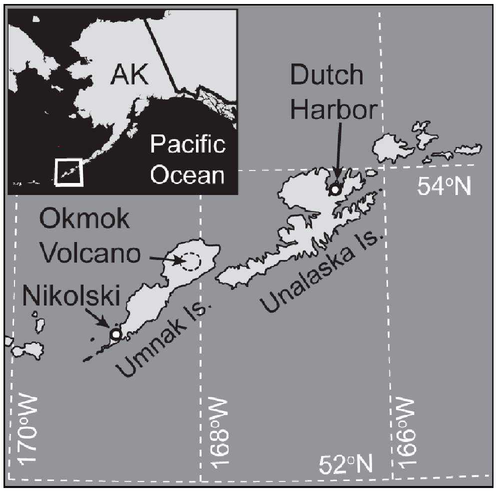

Figure 1. Target: Okmok Volcano, Alaska. Okmok occupies the northeast lobe of Umnak Island. White box in inset denotes the regional location of Okmok.

Okmok volcano is readily accessed from the deep sea port of Dutch Harbor (Figure 1) by boat, helicopter, and amphibious aircraft. The land is privately owned and operated as a cattle ranch, and the owners have been receptive to research activities. The ranch house has long provided lodging for scientists and helicopter pilots. Drilling would entail shipping equipment to the range dock, and then airlifting a short distance by helicopter to the center of the caldera. There is abundant water within the caldera to support drilling. Existing entities, such as DOSECC, have ample expertise and appropriate equipment for this kind of operation.

Okmok is representative of an array of caldera systems (e.g., Ksudach, Aniakchak, Aso, and Santorini) characteristic of island arcs. These volcanoes are characterized by the sudden appearance of voluminous silicic magma after a protracted period of mafic volcanism. The paroxysmal eruptions are usually strongly and discontinuously chemically zoned, followed by a return to small-volume mafic eruptions, and then may repeat this cycle after a few thousand years. The apparently rapid generation of highly explosive silicic magma in a predominantly mafic arc environment is both a petrologic puzzle and an important disaster risk that will be addressed by SINOOK's probing of Okmok's thermal regime.

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 [*Fournier 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,

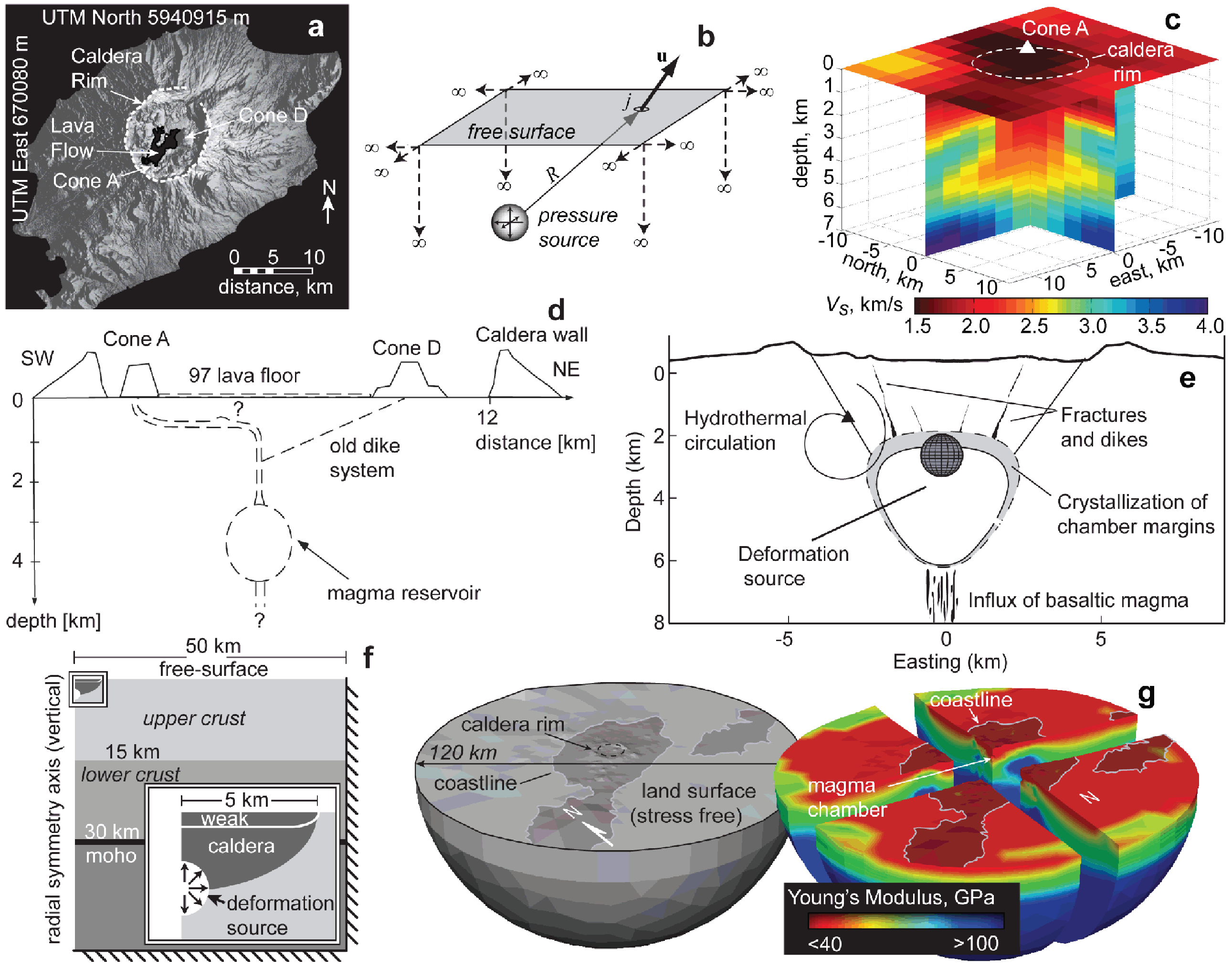

Figure 2. The interior of Okmok Volcano, Alaska. (**a**) Study site. Okmok occupies the northeast lobe of Umnak Island. See Figure 1 for regional location. (**b**) Standard elastic half-space (EHS) model (e.g., *Mogi* [1958]). (**c**) ANT images the internal structure of Okmok [*Masterlark et al.*, 2010]. (**d**) Interpretation based on InSAR and EHS models [*Mann et al.*, 2002]. (**e**) Interpretation based on GPS and EHS models [*Fournier et al.*, 2009]. (**f**) Conceptual deformation model accounting for caldera structure [*Masterlark*, 2007]. (**g**) Tomography results converted into a distribution of elastic material properties in a deformation model (FEM) domain [*Masterlark et al.*, 2012].

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 archeological impacts? Could SINOOK lead to geothermal energy resources for the region?

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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, it's 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-

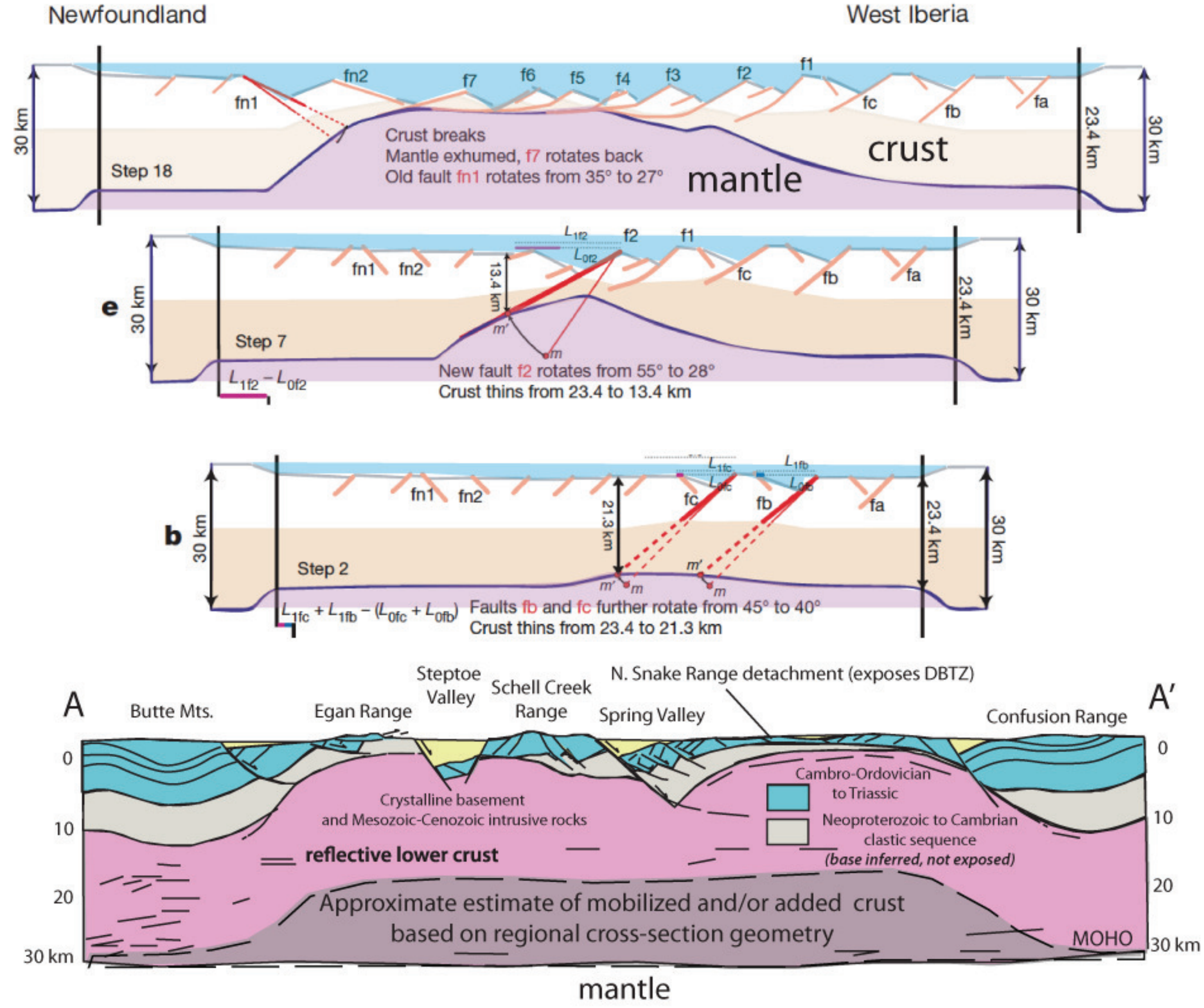

Figure 1. Contrast in fault-zone evolution during rifting of a continental margin (West Iberian margin as described by Ranero and Gussinyé, 2010) (top) with faulting and core complex development in continental crust in the Basin and Range (cross section A-A' modified after Gans and Miller (1983; 1985) and Gans (1987); see Fig. 2 for location) (bottom). Extensional faulting leading to continental break-up (top) does not expose the Elastico-Frictional to Viscous (EFV) transition and subsidence increases water depth. In contrast, regions of high extension in the Basin and Range do not thin the whole crust and are compensated at depth by flow of crust (or magma?) into more extended regions, causing uplift of the paleo EFV or seismogenic base of the upper crust. Cross-section A-A' also illustrates in a simple way how differential uplift related to deeper crustal flow can invert or uplift both fault systems and their associated basins, bringing once ductile levels of the crust to the surface or near surface during extensional faulting. It further illustrates how surface geology and the geometry of mapped extensional fault systems and balanced sections can be used to predict the location of the EFV and the extent and overall geometry of mobilized crust at depth.

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. Tirel 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.

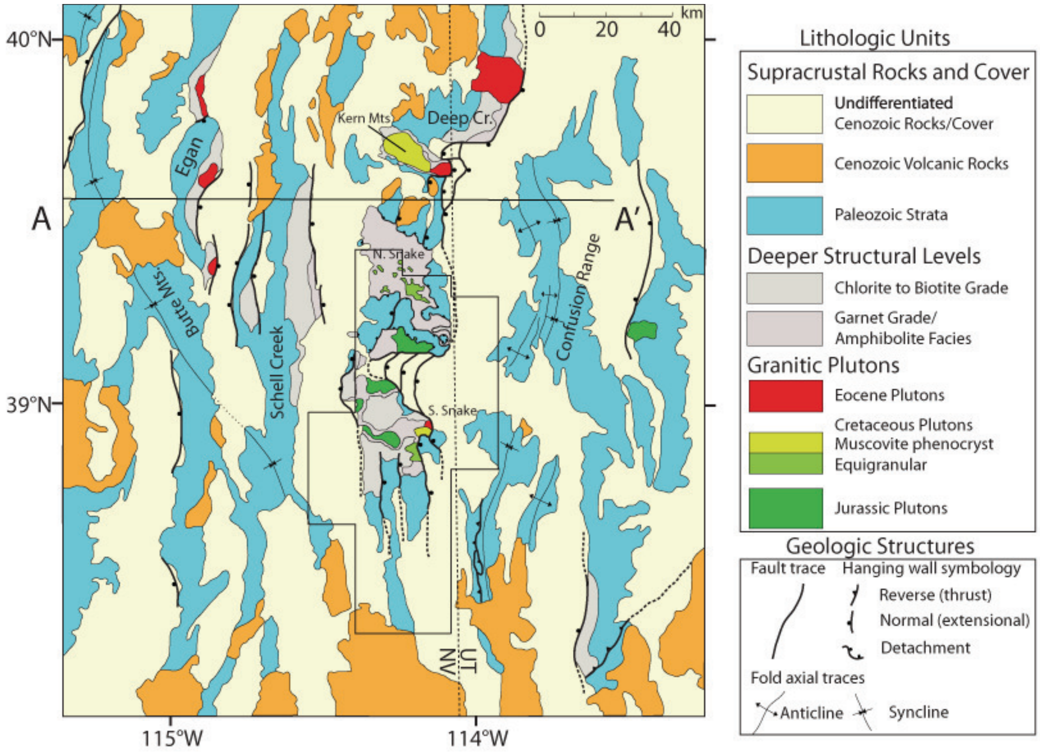

Figure 2. Simplified geologic map of east-central Nevada showing location of the northern Snake Range (modified after Miller and Gans, 1989). Box shows location of Figure 3. Cross-section A-A' is shown in Figure 1.

Proposed Drill Site—The Northern Snake Range: The Snake Range metamorphic core complex, in 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 decóllement (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

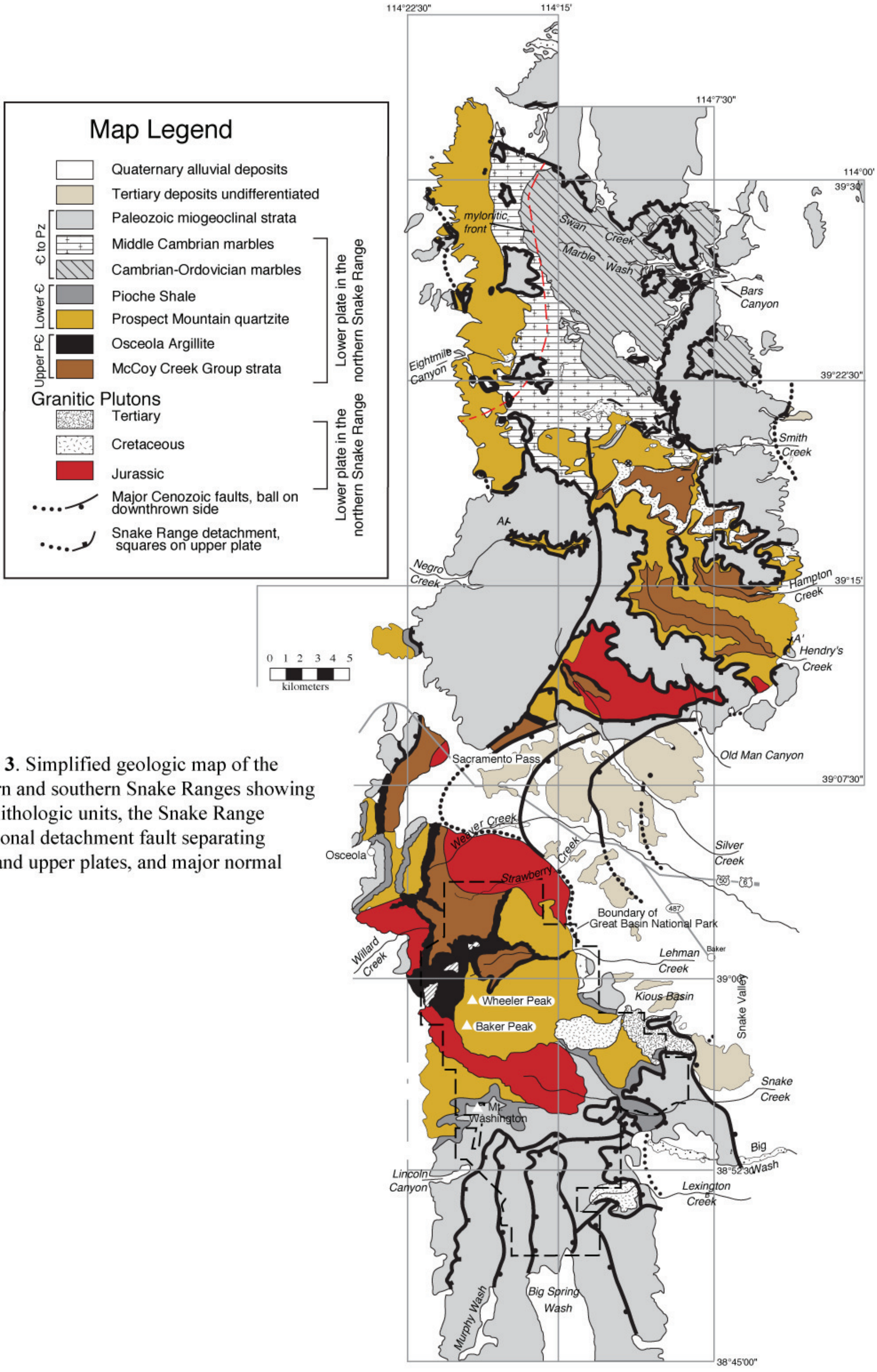

Figure 3. Simplified geologic map of the northern and southern Snake Ranges showing major lithologic units, the Snake Range extensional detachment fault separating lower and upper plates, and major normal faults.

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).

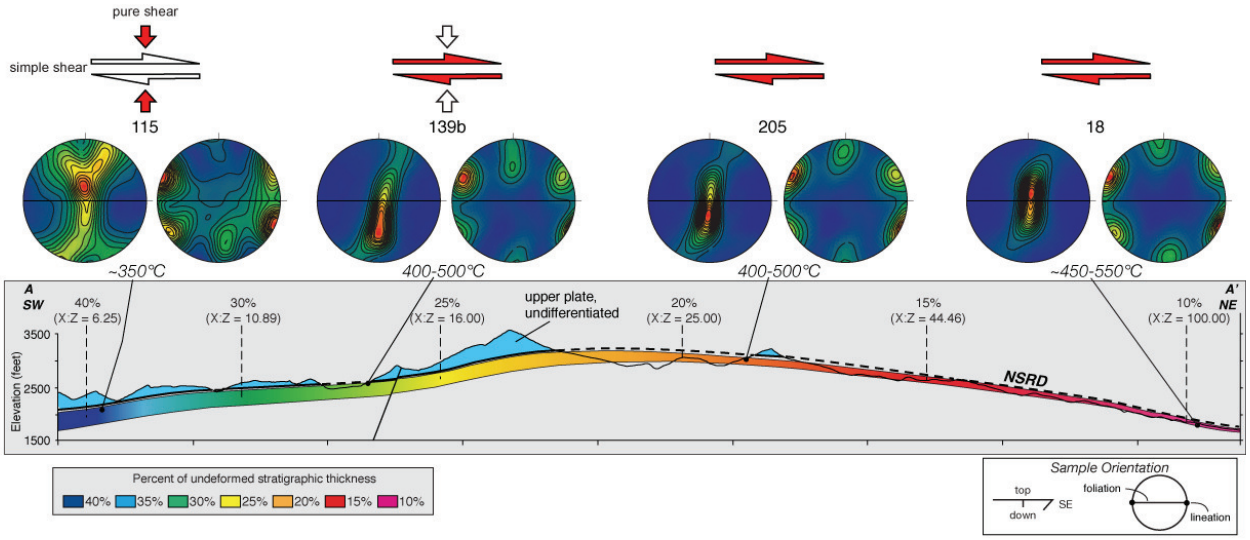

Figure 4. Simplified cross-section illustrating domal geometry of the NSRD, change in thickness of the Prospect Mountain quartzite as a percentage of its original stratigraphic thickness, and representative EBSD-generated c- (left) and a-axis (right) lattice preferred orientations (LPOs) used to determine kinematics of ductile deformation and, along with quartz microstructures, to estimate deformation temperatures. Finite strain was calculated using stretched pebbles from the western flank of the range and unit thickness in cross-section on the eastern flank; X:Z finite strain ratios assume plane strain (Lee et al., 1987). Kinematics of deformation are characterized by dominantely pure shear on the far west flank of the range, transitioning eastward to general shear with top-NE simple shear dominant, to nearly 100% top-NE simple shear on the east flank of the range. Cross-section is subparallel to the lower plate stretching lineation extending from Negro Creek on the west flank of the range to Hendry's Creek on the east flank; see Figure 3 for location of cross-section.

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. Mesoscopic 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).

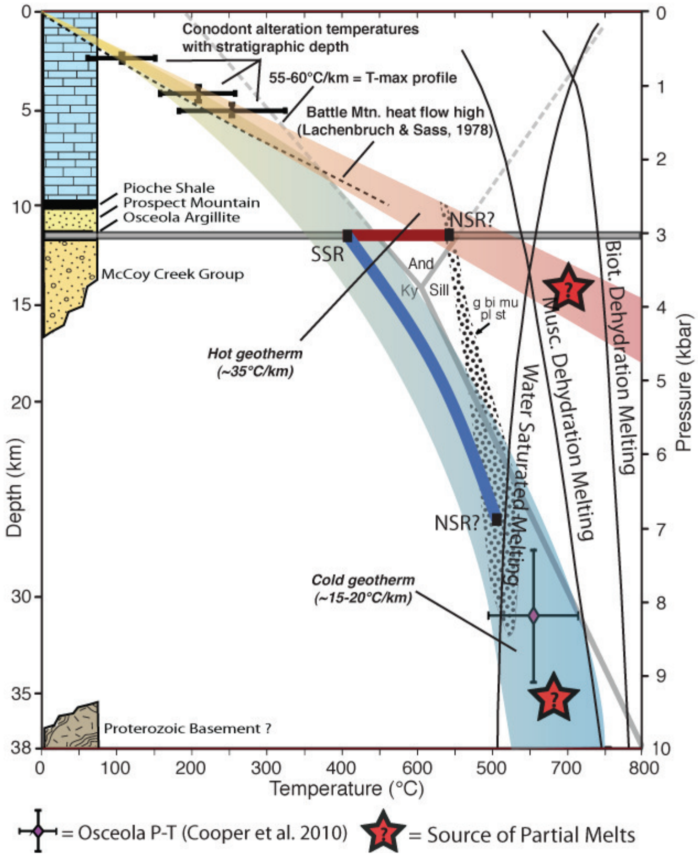

Figure 5. Two models (red swath & blue swath) for Cretaceous metamorphism of the Osceola argillite along strike from the S. Snake Range (SSR) to the N. Snake Range (NSR). Both models satisfy mineral assemblage constraints, but make different predictions as to depth of partial melting (red stars) depending on the geotherm. Hot geotherm (red swath) is based on field observations (Miller et al., 1988); cold geotherm (blue swath) is based on quantitative P-T data (Lewis et al., 1999; Cooper et al., 2010). Stippled region represents the pseudosection stability field for the NSR Ocesola argillite mineral assemblage (Cooper et al., 2010). Al-silicate stability fields (Holdaway, 1971); T-max determination from conodonts (Gans et al., 1987); model pelitic wet solidus (Thompson, 1982); muscovite dehydration (Thompson & Tracy, 1979) shown for reference.

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 paleo-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,

2011). 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.

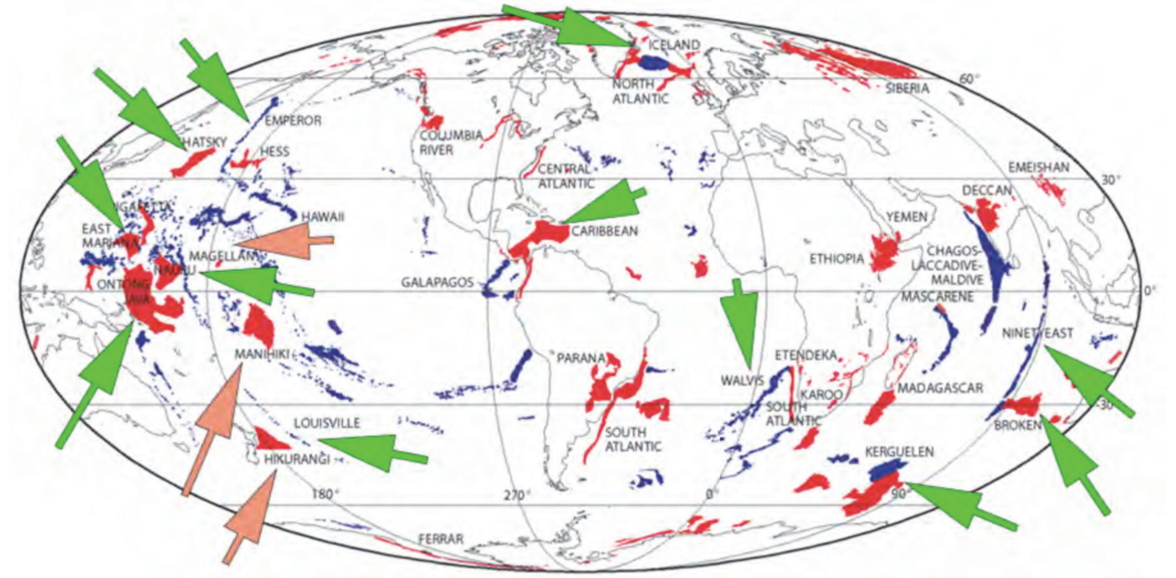

Fig. 1: World "LIP" map. Red = flood basalts, blue = long-lived volcanic chains. From [3]. Green arrows = LIPs drilled by DSDP/ODP/IODP. Light red arrows = potential IODP expeditions.

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 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.

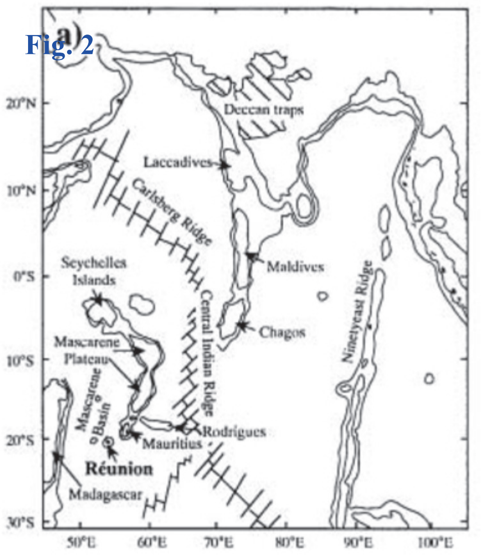

Fig. 2: Deccan Traps-Reunion hotspot.

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.

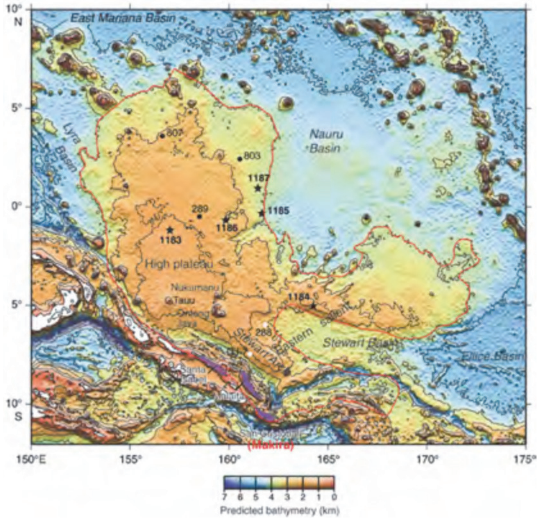

Fig. 3: Ontong Java Plateau drill site and location map.

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 hotpots; 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.

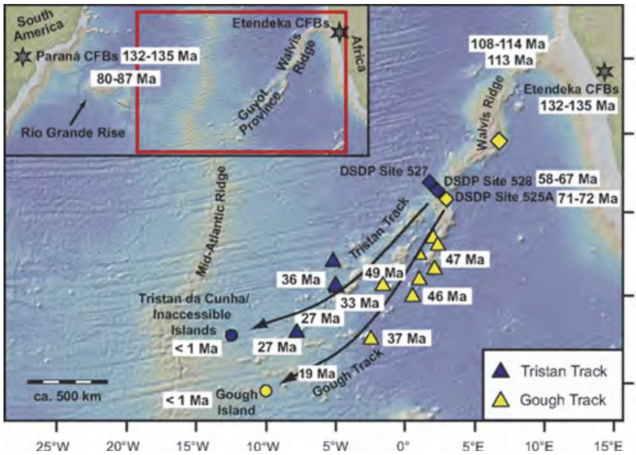

Fig. 4: Walvis Ridge-Etendeka location map with guyot ages [12].

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.

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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

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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.

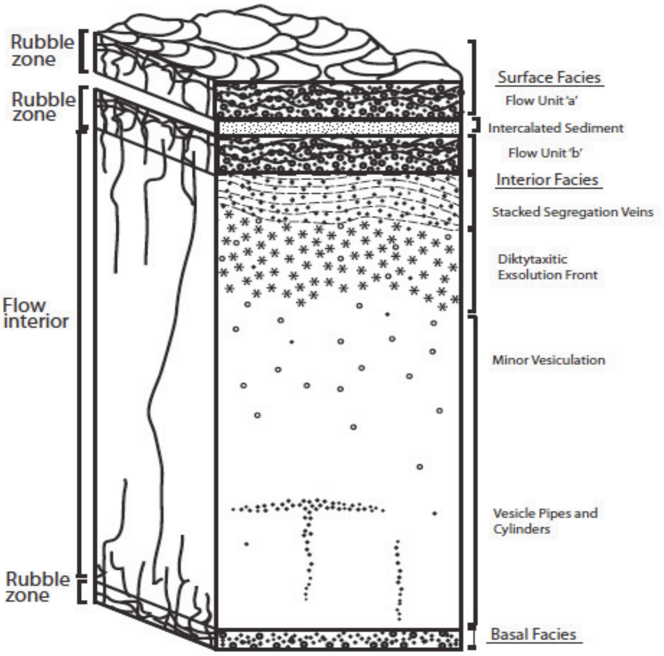

Figure 1: Facies model of typical inflated basalt flow units in the SRP subsurface after (Self et al., 1998). The depth from the surface to basal facies is 6.2 m.

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_2O concentration and correspond to changes in geochemistry such as those occurring between flow groups (Keys, 1990).

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 K_2O and high Fe_2O_3 (2.0 wt. % and 19.0-21.0 wt. %, respectively) relative to the olivine tholeiite composition (0.25-1.00 K_2O wt. %; 13.0-17.0 wt. % Fe_2O_3) observed in the majority of the core. Elevated K_2O and Fe_2O_3 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.

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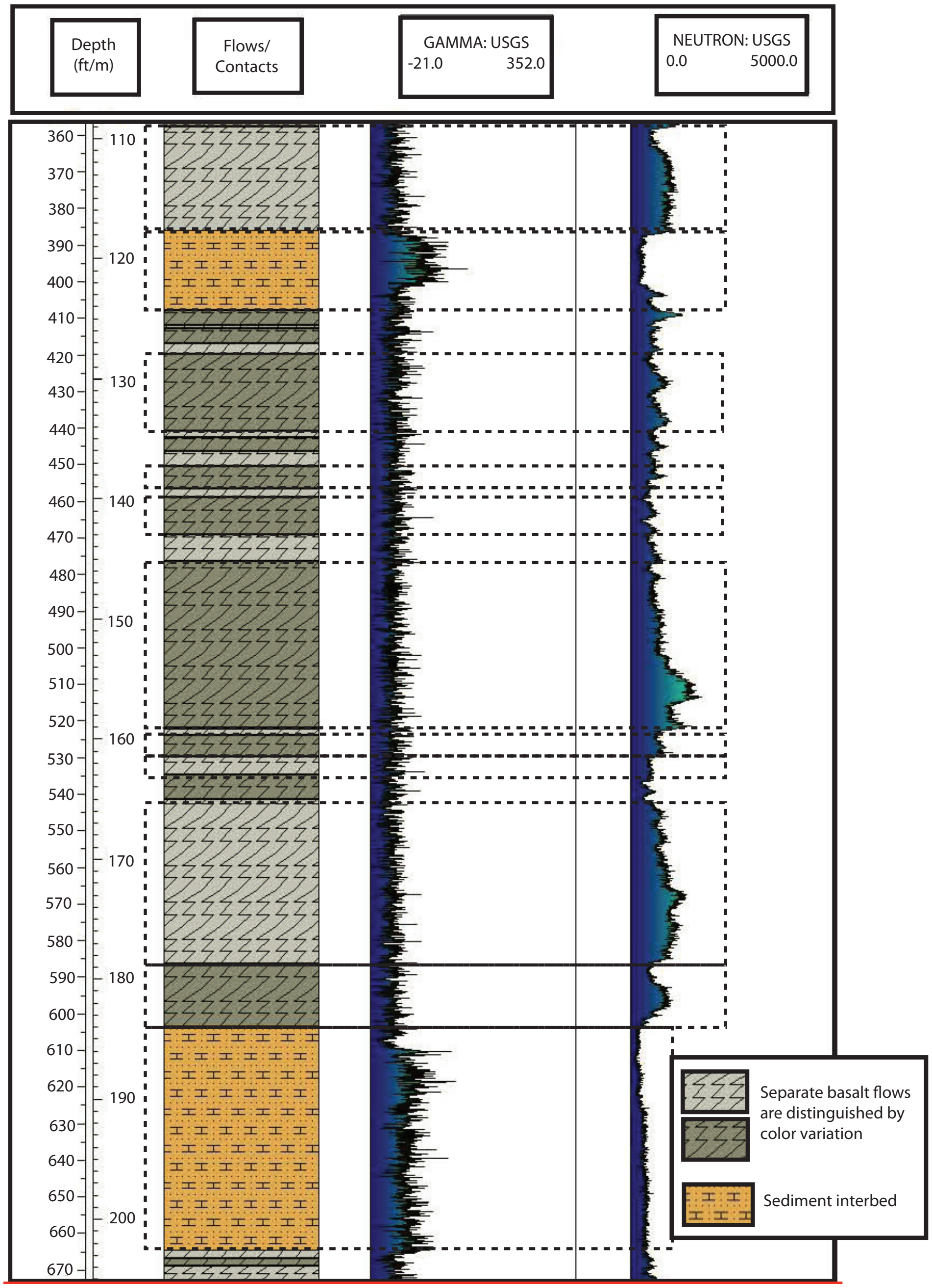

Figure 2: Composite lithologic, natural gamma, and neutron logs a cored section of basalt from a cored section of basalt and sediment. The correlation of facies observations and wireline log signals are evident as signal variations at intervals of intercalated sediment and rubbly flow and flow unit surfaces.

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 serpentine 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 serpentine-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 lithsophere 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.

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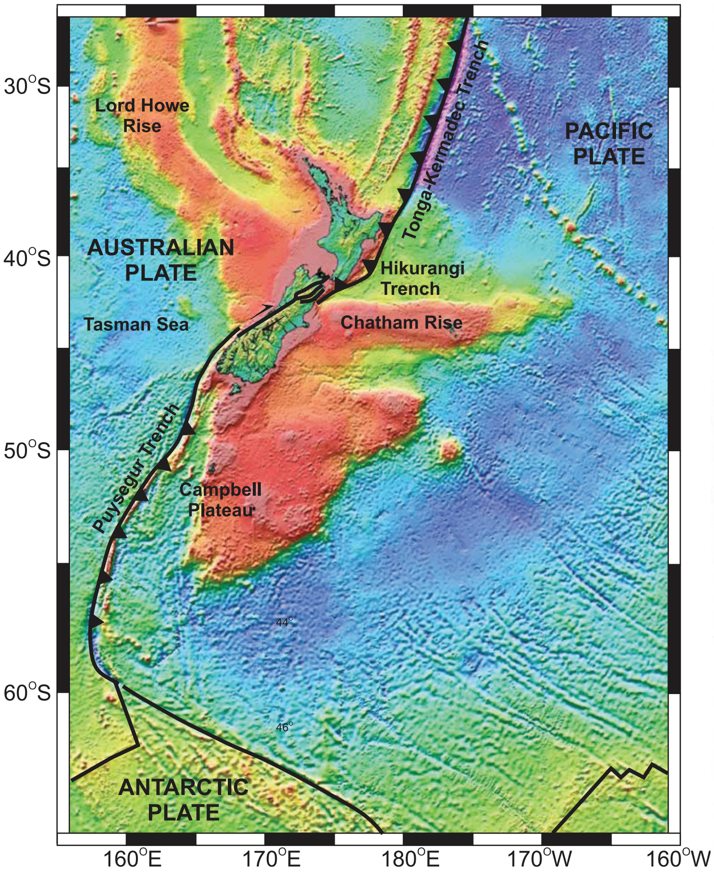

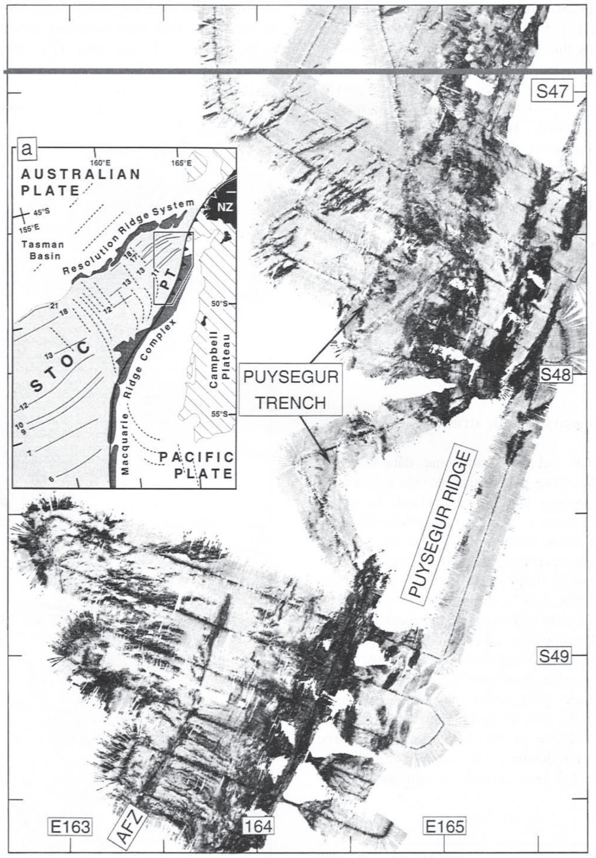

Fig. 1 (left): Topographic map of New Zealand and the surrounding oceans, illustrating the Pacific-Australian plate boundary. Puysegur Trench is at lower left.

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 Humuula 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 [*Abouchami et al., 2005; Weis et al.*, 2011]. This asymmetry in plume source components is attributed to heterogeneities in the lowermost mantle [*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 (e.g. HSDP; Haleakala, *Ren et al.* 2009; Kilauea, *Marske et al.* 2008). By contrast, the Loa side has not been as well studied.

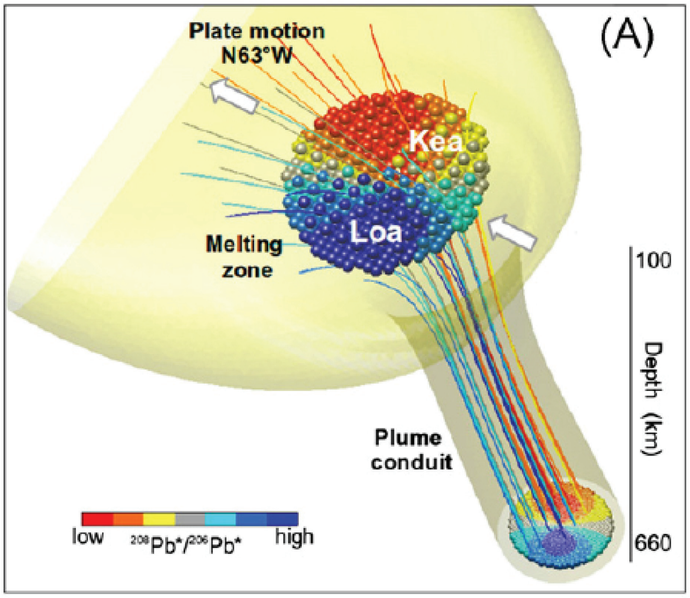

Fig. 1 Numerical simulation of Hawaiian plume asymmetry [*Farnetani et al.,* 2012].

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 [*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 [*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 [*Jicha et al.*, 2012] show that the lavas are over 2 ka older than predicted by Hawaiian volcano growth models [*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 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.

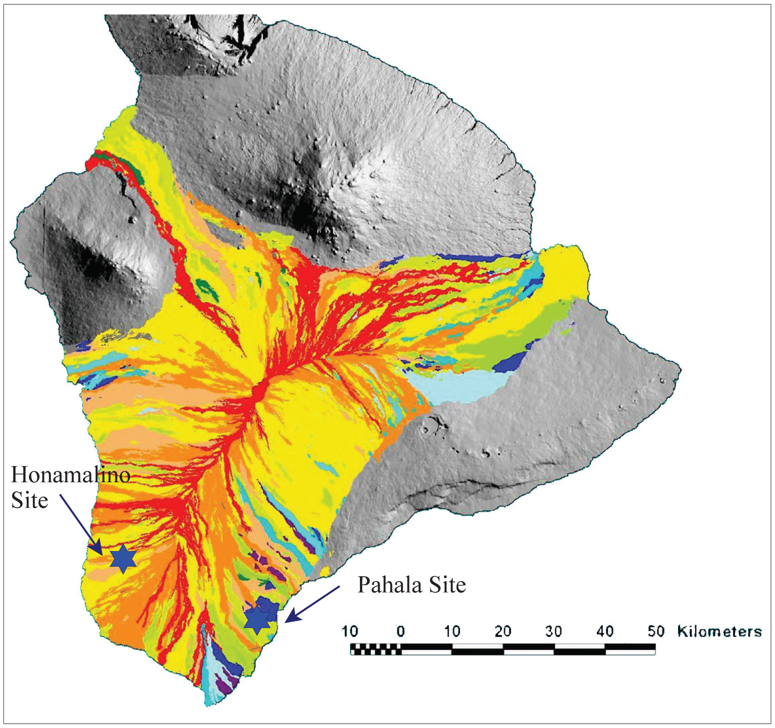

Figure 2 Potential Mauna Loa drill sites (shown as blue stars).

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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 down-hole 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.

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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.

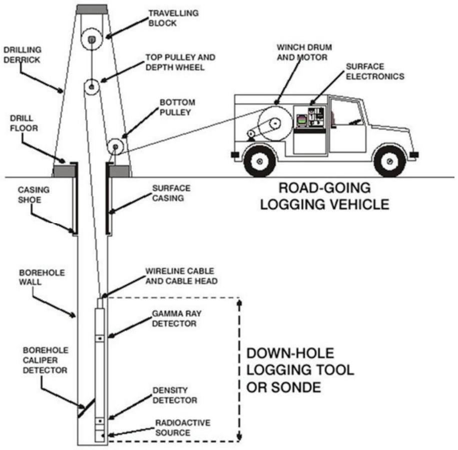

Figure 1. General configuration of borehole geophysics set up.

II. Borehole logging tools

There are a variety of logging tools the user may implement to address their scientific project goals:

Logging Tool	Property
Temperature	Temperature
Pressure Transducer	Pressure
Caliper	Borehole Geometry
Dipmeter	Borehole Geometry, lithology orientation
Natural & Spectral γ	U, Th, K
Neutron	Measure of H content, Proxy for porosity
γ-γ Density	Rock Density, Estimate porosity
Magnetometer	Magnetic Susceptibility & Field
Electrical Logs	Resistivity; Conductivity; Self Potential, Fluid resistivity
Borehole Televiewer	Oriented unwrapped images (ultrasonic or optical) of borehole wall
Sonic	P & S Wave Velocity
Borehole Seismic	Two Way Time, Reflectivity, Seismic Velocity
Wireline Packers	Stress measurement, Pressure testing
Fluid Samplers	Fluid chemistry, gases
Flow Meters	Motion of fluids within wellbore

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 deplete 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 televiewer 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.

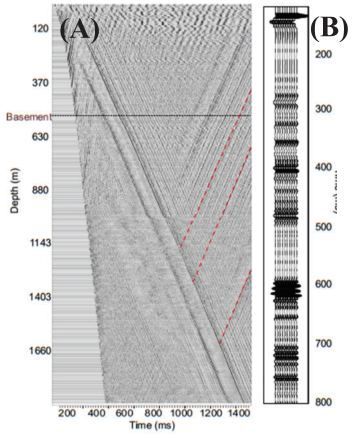

Figure 2. Processed vertical seismic profile from Huntwell borehole, Alberta (A). Red lines indicate tube waves. To identify reflectors and multiples the data is represented as a corridor stack (B).

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 Plane, Idaho.

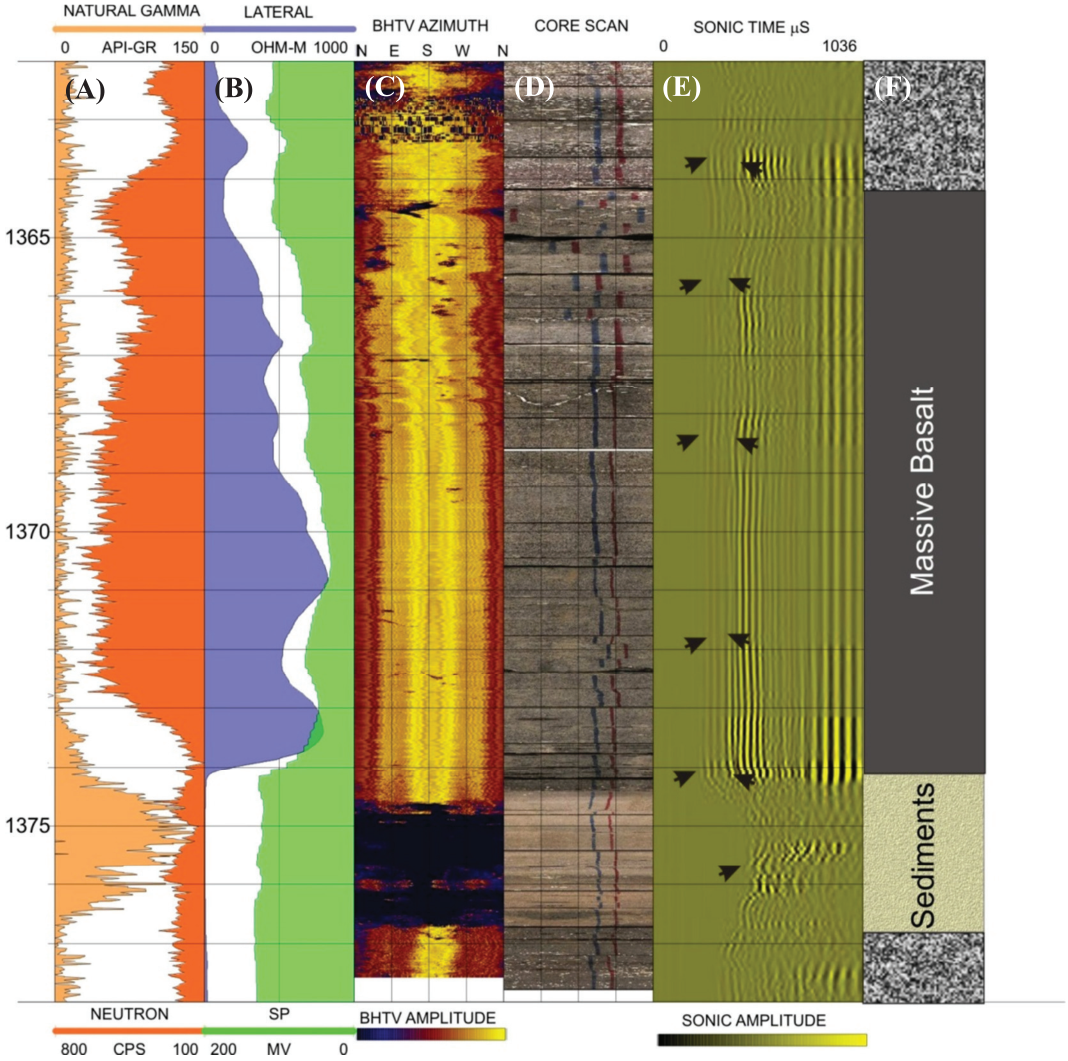

Figure 3. Comparison of geophysical and core scan logs through a massive basalt flow, 1362–1378 m in the Kimama 1B borehole. The logs shown are the observed natural gamma radioactivity (in counts per second, CPS), the returning scattered neutron response (in reversed counts per second), the lateral electrical 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 televiewers 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 televiewers 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.

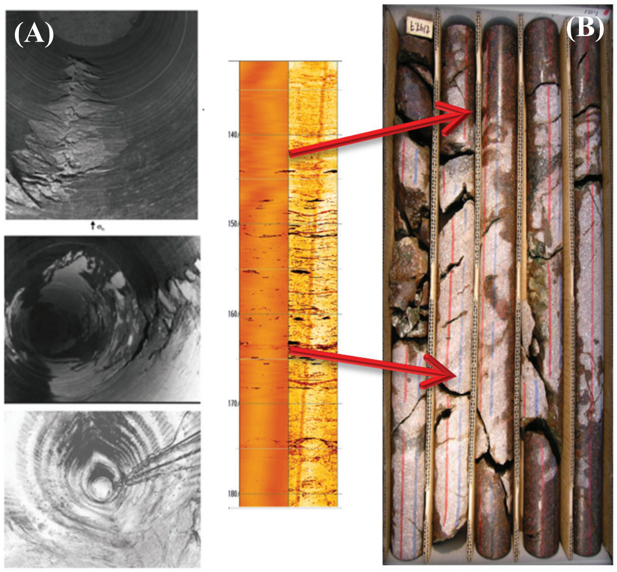

Figure 4. (A) Breakouts and (B) tensile fractures are examples of macro- and microscopic fractures that occur during the drilling process.

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.

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White Paper: Drilling the Josephine Ophiolite – Direct Observation of a Subduction Zone Mantle Wedge

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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#s, 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+ km^2 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.

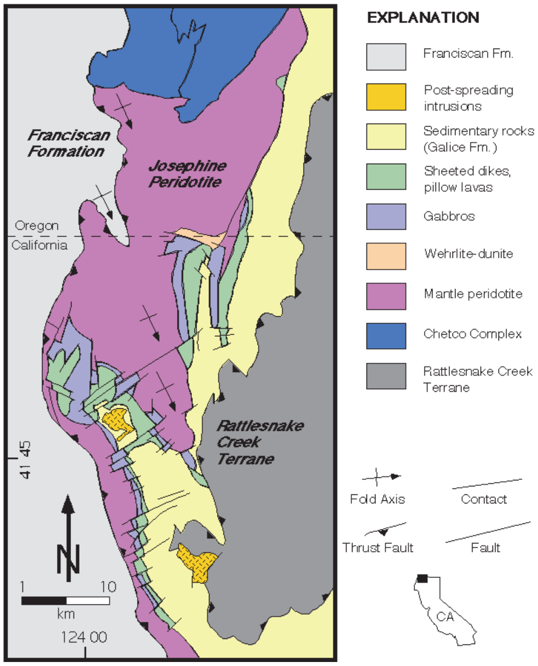

Figure 1. Geologic map of Josephine ophiolite, based on mapping of Harper (1980, 1984, 1988, 1990-94) and Yoshinobu (1996-1999). www.depts.ttu.edu/gesc/Fac_pages/Yoshinobu/Josephine/JOSLocation.html

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 elments 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.

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Tracking the Yellowstone Hotspot Through Space and Time

John Shervais, Barry Hanan, Eric Christiansen, Douglas Schmitt
and the Hotspot Science Team

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.

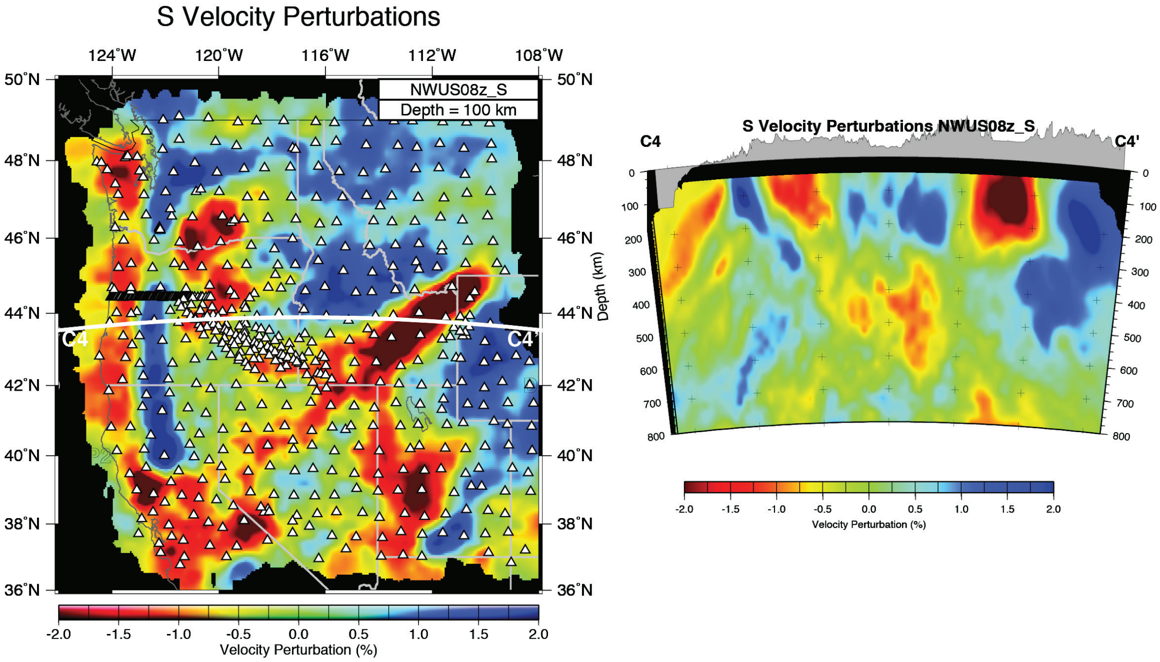

Figure 1. (A) S-wave velocity perturbations at 100 km under NW USA; slower velocities in hot colors (red, yellow), faster velocities in cool colors (blue). Big white triangles = Earthscope Transportable Array stations, small white triangles = High Lava Plains array, white line = plane of section in 2B. (B) Cross section along line C4, showing remnant of Farallon slab (dark blue), warm area below HLP, and extremely hot channel below Snake River Plain, which dominates the section . Note that section not parallel to axis of SRP. From James et al 2009.

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 km^3) low aspect ratio lavas, vast (≈1000 km^3) 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.

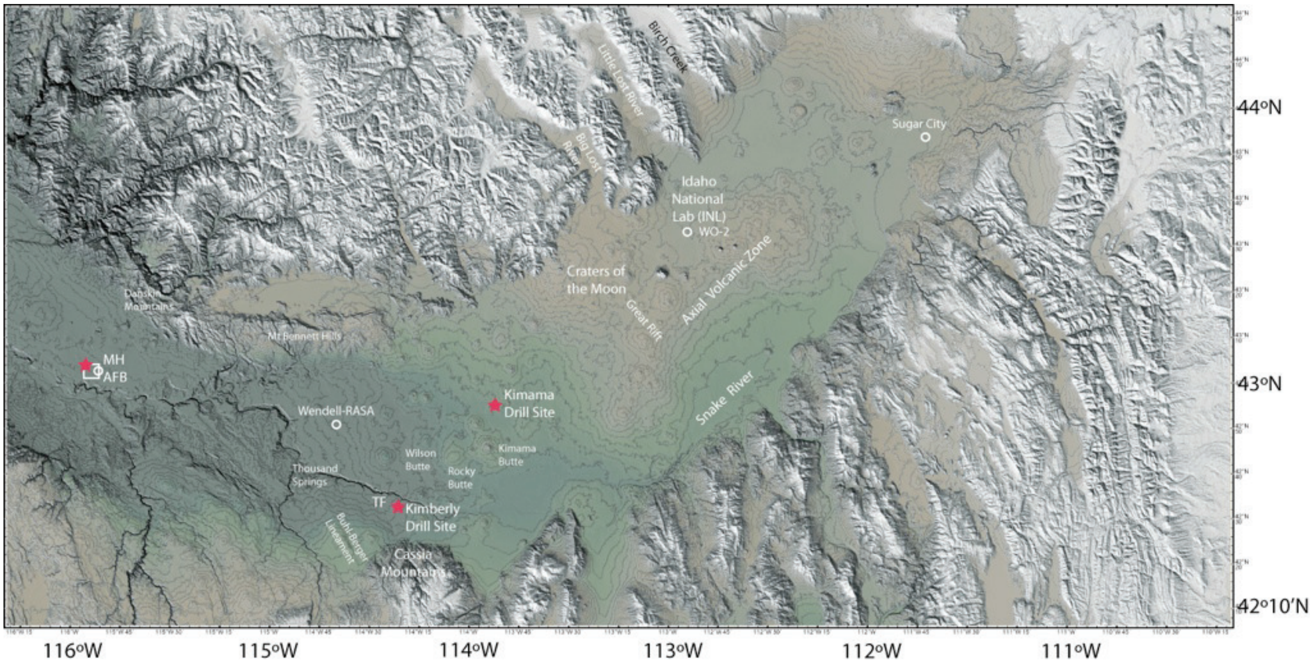

Figure 2. Topographic-relief map of southern Idaho showing location of the three drill sites (red stars), previous drill sites (white circles) and some of the features referred to in the text.

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.

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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).

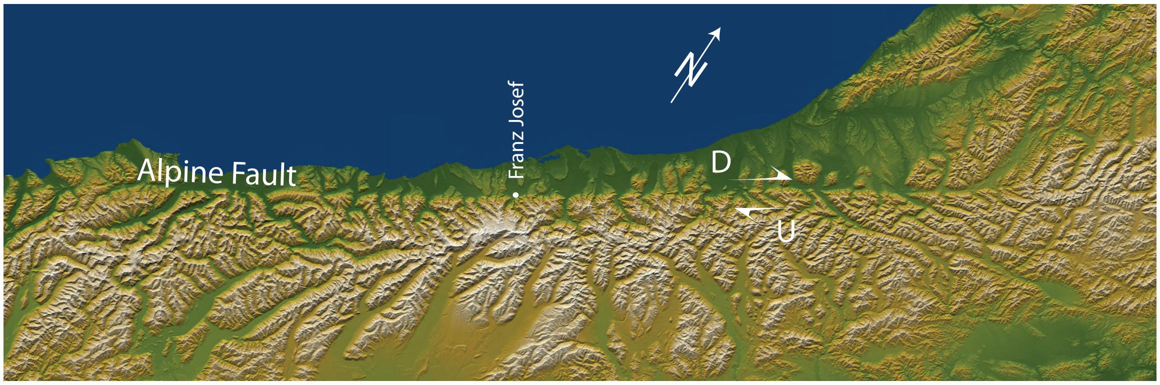
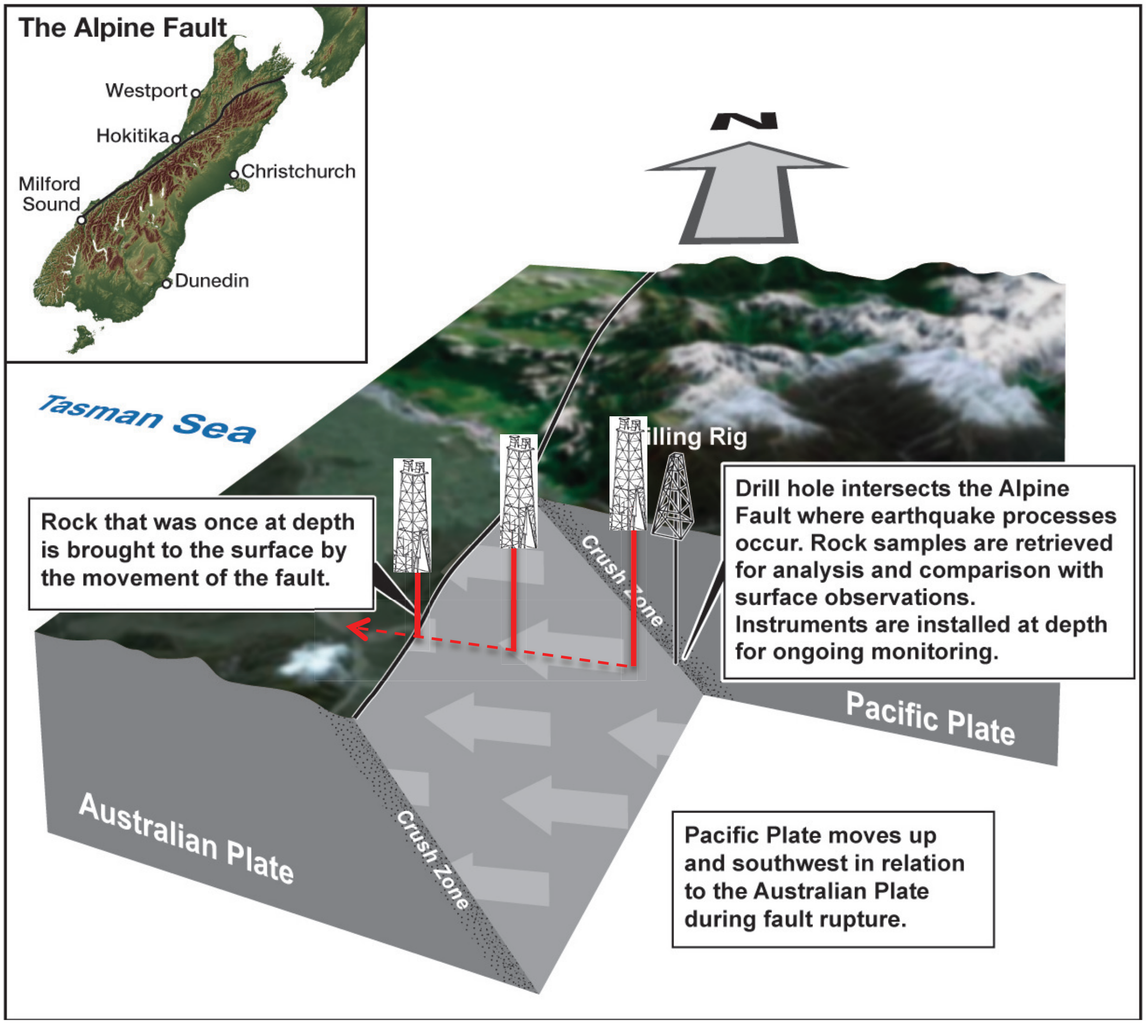


Fig. 1: The dramatic linear surface expression of the Alpine Fault is highlighted by snow that is localised on high peaks in the hangingwall in this satellite image, obtained from http://earthobservatory.nasa.gov/Images/

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.



Rock that was once at depth is brought to the surface by the movement of the fault.

Drill hole intersects the Alpine Fault where earthquake processes occur. Rock samples are retrieved for analysis and comparison with surface observations. Instruments are installed at depth for ongoing monitoring.

Pacific Plate moves up and southwest in relation to the Australian Plate during fault rupture.

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 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.
3. Ben van der Pluijm (University of Michigan): NSF-EAR-1118704: Fluids in continental fault zones; Evidence from neomineralized clays, 2011-2014.

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.

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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

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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 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.

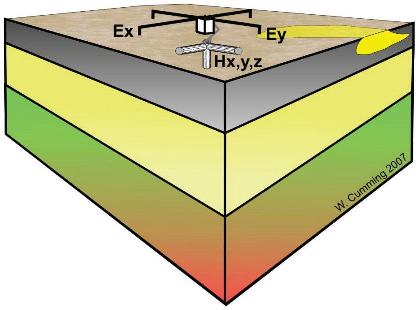
Magmatic Underplating and High-Enthalpy Geothermal Resources

P. Wannamaker (UU/EGI), J. Faulds (UNR), B. M. Kennedy (LBNL), B. Delwiche (Ormat Inc.)

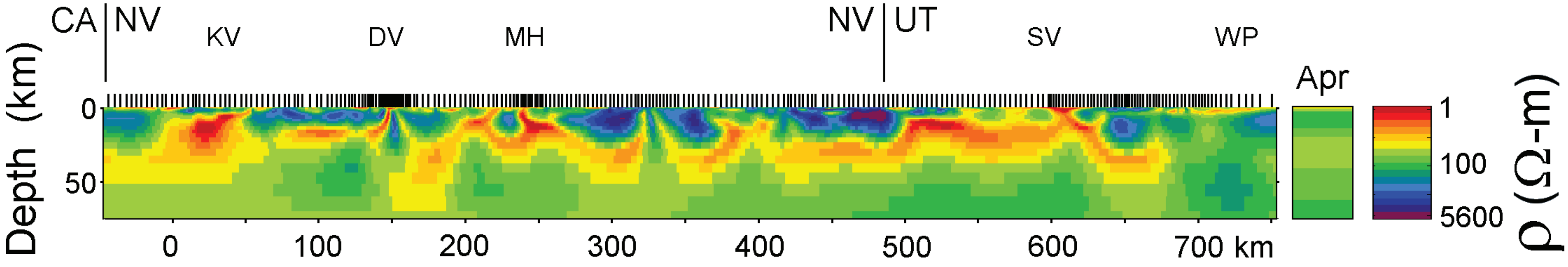
- Recon MT surveying revealed likely deep magmatism, connections to systems.
- Deep magmatic input supported at Dixie Valley by $^3He/^4He$ (Ra) ratios, CO_2 flux.
- Systems form in zones of active structural dilatency.
- Can we verify these concepts with another system; test at new McGinness Hills?

Dixie Valley (DV)

(MH) McGinness Hills



2D and 3D MT Surveys
Structural Geology
Soil/Fluid Geochemistry

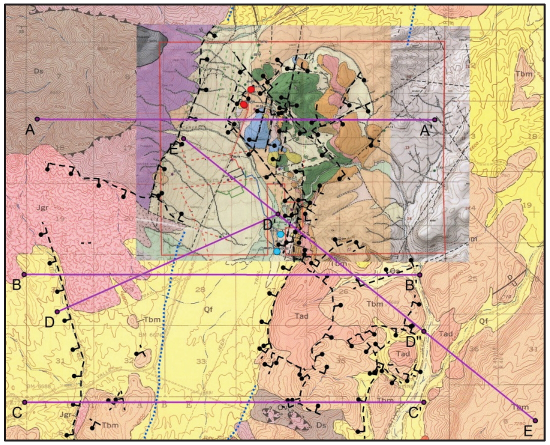


Great Basin MT Resistivity Transect Inversion

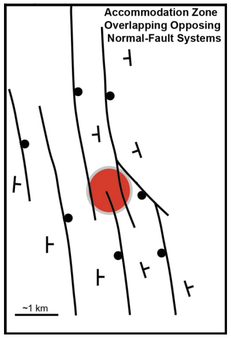
U.S. DOE contract DE-EE0005514

McGinness Hills Geothermal System – Natural Lab for Deep Sources

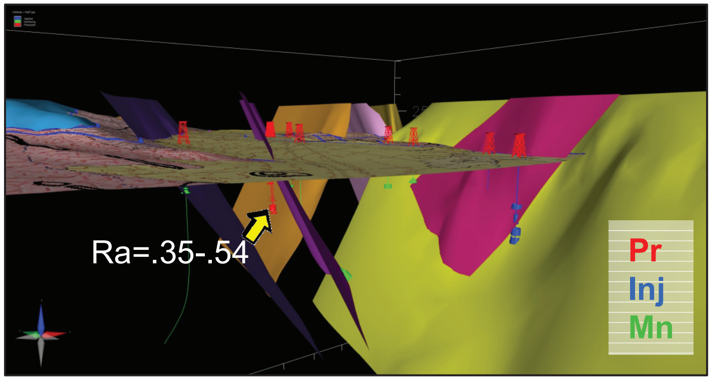
- Structural setting as accommodation zone
- Deep magmatic connection from elevated Ra
- CO_2 flux anom. along Nly NW fault zone (first data)



⇦



after J. Faulds

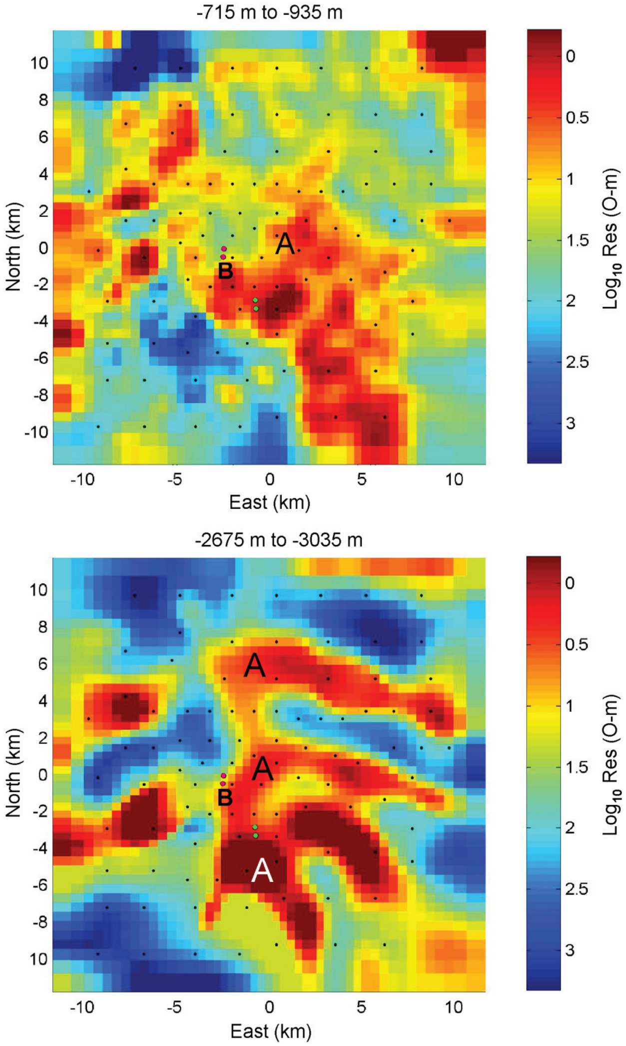


⇧ 3D structural perspective view from mapping and wells; high He Ra in production wells

⇦ Purging sample port on well 36-10 for He sampling (L. Owens, Ormat)

U.S. DOE contract DE-EE0005514

- 3D MT confirms 2D recon
- Connection of prod. to depth
- NW-SE trends at multi-scale



3D MT Resistivity Plan Views

B is production, A is deep regional