Appendix B: Abstracts

EarthScope Education and Outreach: Opportunities and Partnerships

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EarthScope, both through its Facility Operations and through its Science and Education Program, presents spectacular opportunities for advancing Earth Science literacy and raising the general profile of the field. First, EarthScope has a continent-scale geographic footprint that offers access to a unique broad cross-section of the U.S. population and the U.S. educational system. Second, EarthScope epitomizes high-tech and real-time aspects of modern seismology, geodesy, and other fields and thus presents new opportunities to attract the attention of a new generation of Earth Science students. Third, EarthScope promises a scientific legacy that can spur a new level of broad interest in the science of the dynamic Earth and emphasize the core societal importance of Earth Science. Realizing these opportunities while optimizing human and other resources will require sustaining extensive partnerships between the Facility and existing institutions, organizations, funding sources, and societies. First, major programs (e.g., IRIS, AGU, AGI, FEMA) exist now with substantial capabilities and interests in exactly these areas. A further key partnership opportunity is with regional institutions of higher education. Local collaboration between the Facility and regional seismic and geodetic networks, for example, offers numerous possibilities for win-win associations in public outreach to advance institutional, and government awareness of local activities, and to develop high-impact public education vehicles such as mass media, museum displays or public lectures. A final key partnership will be with the peer-reviewed Program efforts of the EarthScope research community itself (including specific E&O oriented efforts). To live up to its full potential, the EarthScope Program and Facility must advance such partnerships to achieve an Education and Outreach impact commensurate with its scientific ambitions. In doing this, EarthScope can also serve as a broader vehicle to translate a decade or more of recent associated scientific progress in Earth Science into a new level of public awareness and educational influence.

Pressure-temperature-time-deformation histories in the context of EarthScope

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Petrologic and thermochronologic data can be used to track the pressure-temperature-time-deformation (P-T-t-D) histories of rocks as they move from depth within the Earth's crust towards the surface. Isotopic variations preserved within minerals are kinetic thermometers and record thermal histories which can be revealed using thermochronology. The composition of minerals, and the fabrics they preserve, record the P-T-D paths of rocks. P-T-t-D studies can potentially contribute to all components of the EarthScope initiative by documenting 1) ages of crystallization and cooling of igneous rocks, 2) ages of deformation and metamorphism, 3) protolith ages of sedimentary rocks and 4) thermal and exhumation histories of the Earth's crust. For example, • USArray will reveal the present-day continental structures and active deformation of the North American continent. P-T-t-D data can provide insight into the particle paths of rocks as they move from depth within the Earth's crust to the surface. These data provide constraints (e.g., boundary and initial conditions) for 4-D thermal and mechanical models of the lithosphere and thermal processes influencing continental dynamics. • Analyses performed on fault zone rocks recovered from SAFOD can reveal their P-T-t-D history. • The PBO will study the 3-D strain field resulting from deformation across the PAC-NoAm plate boundary. Considerable along strike variability in heat flow and hence rheologies potentially exists within plate boundaries. P-T-t-D data can constrain initial and boundary conditions for 4-D models of the thermal state of the lithosphere and reveal how the plate boundary has evolved over geologic time.

2004 Heat Flow Map of North America and Heat Flow Studies in the 21st Century

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A revised Heat Flow Map of North America will be published by AAPG in April, 2004. This map forms a framework for heat flow studies in North America in the 21st century. The US portion of this map is based on about 14,500 sites where BHT has been converted to heat flow (using calibrated AAPG BHT data from the 1970,s Geothermal Survey of North America, GSNA), about 4,000 sites from geothermal areas where heat flow has been measured or estimated (compiled from data from geothermal gradient exploration from the 1970's and 1980's), and about 3,700 conventional heat flow sites (over 90% of which are from before 1990. This map has much more detail than the 1992 GSA DNAG map and so the contour interval has been decreased to 5 mWm^{-2}. There is reasonable coverage for most of the US and about 1/2 of Canada. There are some data in Mexico, but little data in Central America and the Caribbean. While the regional patterns are basically the same as on the 1992 GSA-DNAG map, there are many subregional to small scale patterns that are shown for the first time. The regional pattern in western North America is dominated by the thermal effects of the subduction that has occurred over the last 100+ Ma. The subregional and smaller scale patterns that can now be seen in many cases need to be investigated in detail to understand their significance and origin. There are as well important features of the pattern, such as the horizontal scale of thermal transitions, that have not been defined in accurate enough detail to constrain interpretations of the cause of the variations. The EarthScope project forms an obvious vehicle for such investigations.

While few field heat flow studies have been carried out over last 15 years or so there has been an explosion in the technology for temperature measurement in boreholes. Temperature equipment is now commercially available that can measure temperature in any well drilled (at any depth, at any pressure, and at any temperature) with a precision that was considered research quality 10 years ago. Equipment is also available that can make repeat logs of a km deep well at intervals of 5 to 10 minutes and perform a monitor function over long times. As a result of these developments, details of thermal effects in wells can be investigated in ways never before possible. Probably the rate of drilling today is as great as at any time in the past so there are plenty of opportunities for relatively expensive studies. But the necessity for research drilling has only been increased by the lack of such activity over the last 20 years.

The EarthScope program offers an opportunity to regain momentum in thermal understanding of the continental crust and lithosphere. We will describe examples of studies that illustrate the contemporary problems and ways that can be used to solve them with examples of results from a wide variety of crustal regimes. Examples are described from the San Andreas fault, the Snake River Plains, The Geysers area in California, the Dixie Valley area in Nevada, and several sedimentary basins. Contemporary thermal studies are needed to resolve the horizontal scale of the contrasting thermal regions, to help investigate the mechanics of earthquakes, to measure the vertical and horizontal scales and magnitudes of crustal permeability, to study long term climatic effects, and to understand the implications of the crust as a thermal resource base.

Generating Databases of Radiogenic Heat Production vs. Depth for the North American Crust: Method and Preliminary Results from the Sierra Nevada California

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Current understanding of radiogenic heat production as a function of depth in the North American crust is largely dependent on modeling of surface heat production/heat flow data (*Saltus and Lachenbruch, 1991; and refs therein*) and a limited number of geologically constrained heat production vs. depth models, which have poorly constrained depth axes and generally extend only to mid-crustal depths (*e.g. Swanberg, 1972; Swanberg and Blackwell, 1973; Fountain and others, 1987; Ketcham, 1996*). By applying inductively coupled plasma mass spectrometry and modern geobarometric methods, we can realistically determine both depth of emplacement and heat producing element abundance for many hundreds of samples per year and thereby develop significantly larger, better-constrained databases. Preliminary results from the Sierra Nevada, California suggest that heat production vs. depth in the Sierran crust is roughly approximated by, but shows important deviations from, the widely accepted exponential model of Lachenbruch (*1968*). Our initial compilation of 81 data points, which come from a depth range of ~2-40 km, is overall better fit by a curve that shows lower heat production in the upper 3-5 km, and significantly higher heat production through the rest of the crust. Notably, heat production in rocks from 25-40 km depth is often greater than 1μW/m^3.

Influence of water on the viscosity of the western US upper mantle

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Differences in the viscosity of the earth's upper mantle beneath the western US (~10^{17}-10^{19} Pa-s) and global average values based on glacial isostatic adjustment and other data (~10^{20}-10^{21} Pa-s) are generally ascribed to differences in temperature. We compile geochemical data on the water contents of western US lavas and mantle xenoliths, compare these data to water solubility in olivine, and calculate the corresponding effective viscosity of olivine, the major constituent of the upper mantle, using a power law creep rheological model. These data and calculations suggest that the low viscosities of the western US upper mantle reflect the combined effect of high water concentration (near the saturation value for olivine) and moderately elevated temperature. The high water content of the western US upper mantle likely reflects the long history of Farallon plate subduction, including flat slab subduction, which effectively advected water into the upper mantle as far inland as the Colorado Plateau.

Low-temperature thermochronology in the context of EarthScope

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The goal of EarthScope is to increase the knowledge and advance the understanding of the three dimensional structure of the North American continent throughout time. Low temperature thermochronology can complement other techniques to achieve this goal. Thermochronologic techniques such as apatite fission track thermochronology and apatite (U-Th)/He dating provide powerful constraints on near-surface temperature-time (T-t) histories of rocks. These methods are commonly used to constrain the timing, amounts and rate of cooling/denudation associated with mountain building, crustal deformation, extensional tectonics and landscape evolution. This in turn permits constraints on the timing and magnitude of tectonic events, the relative roles of tectonics versus climate during exhumation, understanding geologic processes as well as testing lithospheric/crustal geodynamic models. In this overview presentation we examine what low-temperature thermochronology is, what are the most common methods, how to use them, the information they provide and how they can be used to complement other techniques to address the goals of EarthScope. The importance of hypothesis testing is stressed in order to design an appropriate sampling strategy depending on the tectonic environment and the controlling cooling/exhumation mechanisms. The importance of particle paths during exhumation, sampling strategies, integration of different thermochronologic techniques, and the dynamic thermal environment in both the 1D and 2D situations will be discussed in the context of data interpretation. Examples from the Basin and Range (extensional), Antarctica (rift flank), the Pyrenees (continent-continent convergence), the central Alaska Range (strike-slip) and other locations will be used to illustrate these concepts.

Can hydrothermal activity record short-lived deformation pulses?

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A major goal of EarthScope is to understand the contemporay deformation of the western US plate boundary region. Initial results of geodetic networks across portions of the plate boundary have shown that interpretation of geodetic data s may not be trivial where they do not agree with geologically derived fault slip rates (e.g.,Wernicke et al. 2000, GSA Today; Friedrich et al. 2003, JGR and in press, Tectonics). Such mismatches between geologic and geodetically derived fault slip rates are often attributed to incomplete geologic data, but may also be due short-term variations in strain release or transient accumulation relatd to the seismic cycle. In order to determine which of these cases may apply, time-series much longer than the duration of the strain rate variations would be required (timescale of 100-1000 ka?). Unfortunately, paleoseismic data are limited to the last few earthquake cycles (<< 100 ka), whereas geomorphic and geologic data provide limited or no event resolution on the desired timescale (<100-1000 ka). A much longer geologic timeseries derived from a single data source may be provided by thermal processes associated with active faulting. I propose to determine the timescale over which such hydrothermal activity may be a sensitive recorder of changes in deformation rate, i.e., whether it will be possible to link variations in hydrothermal activity to short-lived deformation pulses. Therefore, a goal may be to determine the age of hydrothermal activity and the duration of, paleo'-hydrothermal activity associated with active and inactive fault zones in the PBO region.

Is There An Anomaly In The Scatter? Re-Evaluation of Heat Flow Data to Further Resolve Fault Strength

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By systematically accounting for processes that produce scatter in heat flow data or have the potential to mask a local-scale heat flow anomaly, we have shown that we can more adequately distinguish between competing models of frictional strength along a plate boundary fault where there has previously been uncertainty. Our analyses show that the standard deviation of a heat flow dataset near the SAFOD site is greatly reduced by re-correcting the data to account for effects of 3-D topographic refraction (terrain effects) and variable solar insolation. In addition, we have been able to constrain the extent of possible heat advection by groundwater flow by comparing simulated heat flow (also corrected for terrain effects) from numerical models of coupled fluid flow and heat transport for various hydrologic scenarios to the corrected data. The corrected heat flow data show no indication of a near-fault thermal anomaly from frictional heating along a San Andreas Fault that supports shear stresses > 100 MPa averaged over the seismogenic zone. Our modeling results demonstrate that it is unlikely for this missing heat to be redistributed by topographically-driven groundwater flow in a manner that is consistent with the corrected data. In agreement with recent stress analyses, the corrected heat flow data is most consistent with a SAF far weaker than predicted - supporting shear stresses < 20 MPa averaged over the seismogenic zone.

Modeling Geologic Scale Rock Mechanics using a visco-poroelastic, strain-history dependent rheology

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There is increasing interest in the formulation of geomechanics problems while considering damage (*Turcotte, 2004; Lykhovsky, 2003; Bercovici, 2003*). Known attempts have dealt with elastic solids for which methods of the non-equilibrium thermodynamics are used to derive new damage rheologies. The results have shown that viscous and viscoelastic materials bear potential for strain localization through strain weakening and healing. In this work we introduce damage within the framework of poro-viscoelasticity theory. We use the so called semi-Terzaghi approximation of the poroelastic theory in the transient viscoelastic regime. We propose a model for a poro-viscoelastic material with dynamic power law rheology (as strain damaged-healing with time). A semi-analytical consideration of the simplest micro-mechanical model is used to track mechanical properties of the porous solid at isotropic deformations. Examples of the localized viscous deformations are considered including:

- partial melt experiments
- flow in the vicinity of an active faults
- extension of the thermally stratified crust in the presence of the magma chamber and fault.

Linking EarthScope observations to thermal processes using geodynamic models

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The multidisciplinary approach that is inherent to the EarthScope initiative requires that information from seismology, geodesy and geology is integrated. Geodynamic modeling combines this information in an attempt to understand the plate and local interactions that led to North America's current structure and predict its behavior in response to the forces that act on North America. Temperatures play a critical role in geodynamic models in that they dominate (body) forces that drive geodynamic processes, and they control the resistance to flow in terms of the viscosity of rocks. The multidisciplinary potential of EarthScope therefore hinges on improving our knowledge of North America's current temperature structure, and of the thermal processes that caused it. I discuss two geodynamic models and how they are affected by thermal processes to illustrate these points. The first model focusses on post-seismic relaxation of a moderate earthquake sequence in the central Apennines in Italy. Here, available data consists of GPS measurements, regional tomography, refraction seismics, focal mechanisms, and surface heat flow measurements. These data are integrated to show an acceptable level of consistency, but only if we modify laboratory-derived viscosities to allow substantially more rapid rebound at lower temperatures. In our second modeling study we show how tomographic information is used to infer temperature anomalies that act to drive flow in so-called STEP regions. Here, tearing of oceanic lithosphere is shown to be a stable process that has a strong impact on the geology, geodesy, and geodynamics of a region.

Tectonic implications of the thermal regime, San Francisco Bay Area, California

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An integral element to understanding rheology, continental deformation, evolution and geodynamics is knowledge of the subsurface thermal regime. Five boreholes, recently drilled for strain meter emplacement along the San Andreas Fault System (SAFS) in the San Francisco Bay Area, California provided an opportunity to collect new heat flow values within in this dynamic area. These new values fill gaps in existing heat flow coverage in the central and northern Bay Area, and help constrain the role of temperature in determining the spatial and temporal pattern of deformation within this plate boundary zone. The five boreholes vary in depth from 140 to 220 meters and penetrate Cretaceous and Jurassic age sedimentary, metamorphic and igneous rocks of the Franciscan and Salinian blocks. Temperature profiles were recorded in each borehole, and more than 200 thermal conductivities were measured on drill cuttings and core samples. Reliable heat flow values were acquired at four of the five sites and range from approximately 78 to 92 mW m^{-2}. The average heat flow from these four sites together with 12 previously published values from the San Francisco Bay Area west of the Calaveras fault is 87 mW m^{-2} with a standard deviation of 8 mW m^{-2}. The new data within the SAFS are consistent with elevated heat flow that characterizes the California Coast Ranges and confirm the continuation of this thermal regime along both the northern segment of the Hayward fault and the section of the San Andreas fault offshore San Francisco. Previous studies suggest that variations in the maximum depth of seismic moment release on the San Andreas and other active faults are influenced by crustal thermal conditions. These new heat flow measurements suggest that discrepancies between observed surface slip along the SAFS after the 1906 San Francisco earthquake and geodetic models for coseismic slip may be explained in part by changing thermal conditions through its influence on the maximum depth of seismic moment release along the SAFS.

The roles of tectonic inheritance and dynamically evolving thermal conditions on deformation and magmatism in the continental lithosphere

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The strength of the continental lithosphere is controlled primarily by its thermal state and composition. These parameters are defined largely by the tectonic and magmatic history of the continent. Geodynamic models show that lateral and vertical heat fluxes that develop during continental deformation result in a feedback that dynamically modifies the strength of the lithosphere, thus changing the deformation style. This partly controls whether extension is diffusely distributed over a broad region (e.g., Basin and Range) or focused in a narrow region (e.g., Rio Grande rift). In some circumstances, "runaway" thermal weakening of the lithosphere may occur, in which case extension progresses rapidly toward continental breakup. In other circumstances, cooling of the lithosphere may occur, resulting in a shift of extensional deformation to other regions. All of this is strongly dependant upon extension rates, initial conditions, and the preexisting rheological and thermal structure of the lithosphere. Particular issues that EarthScope needs to address are the conditions under which preexisting tectonic setting (structural fabrics, crustal heat production, and lithosphere and asthenosphere thicknesses) dominate over dynamically evolving heat fluxes, and how these two processes interact to control the structural and magmatic evolution of the continent during major tectonic events. Emphasis should be placed on predictable consequences of these issues and how they can be used to test models of continental structure and evolution.

Compositional and Thermal Contributions to North American Elevation

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Continental elevations result from a combination of buoyancy (i.e. compositional and thermal) and geodynamic forces. Lithospheric variations in bulk density and crustal thickness can potentially produce relief greater than nine kilometers, variations in the thermal regime can produce nearly three kilometers of relief between cold shield platforms and hot rift zones, and geodynamic contributions to elevation are at most a few kilometers. Data collected as a result of EarthScope activities will greatly enhance our ability to resolve between compositional and thermal buoyancy and geodynamic forces. In the meantime we have compiled geologic and geophysical data coverage over North America to estimate the contributions each of these processes make to continental elevation. Median elevations are estimated using the digital elevation model GTOPO30 for 29 tectonic provinces. Province elevations are adjusted for the effects of compositional buoyancy by equating the density-thickness product of an observed region to a standard crustal section (40 km thick crust with average density of 2830 kg/m^3). Crustal thickness and P-waves seismic velocity (Vp) structure is determined from seismic refraction models, [*Chulick and Mooney, BSSA, 2002*]. Densities are computed using a four empirical Vp-r (velocity-density) relationships derived from laboratory data including two P-T-Vp-r (pressure-tempreature-velocity-density) relations [*Christensen and Mooney, JGR, 1995*], one pressure dependent relation [*Ravat et al., Tectonophys., 1999*], and the Nafe-Drake relation [*Barton, Geophys. J. Int., 1986*]. Thermal buoyancy is estimated by computing the difference between the integrated thermal structure of the province and a standard continental lithospheric geotherm (characteristic of surface heat flow 40 mW/m^2) to 250 km depth. Heat flow is drawn from a global data set [*Pollack et al., Rev. Geophys., 1993*] and supplemented with more recent heat flow data. Anomalous heat flow at individual sites are examined for possible disturbances resulting from thermal conductivity and heat production variations. This study yields a continental heat flow — elevation relation, and is used to identify province outliers where the thermal state is anomalous (transient, disturbed, etc.), the elevation is anomalous (dynamically supported, anomalous mantle, etc.) or both. Discriminating between these sources of elevation provide insights into the geodynamics of North America.

The Development of Shear Zones in the Crust of the Northern California Coast Ranges as Determined by Regional Strain Models

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The Coast Ranges of California have formed with the passage of the Mendocino triple junction through Northern California over the past 20 million years. Understanding the crustal structure in terms of thickness and seismic velocity structure is key in determining the way in which processes driven by the passage of this triple junction have influenced crustal evolution of this area. We have combined crustal structure models from seismological receiver functions generated at a suite of broadband stations in the region with 3D tomography to develop a model of the crustal architecture over the entire Coast Ranges. The resulting crustal model is used to construct shear strain models of the North American crust. Analyzing these results in combination with predictions from the Mendocino Crustal Conveyor model has allowed us to develop a 3D model of present-day crustal strain in the Coast Ranges. Results identify a crust with three main interfaces: a shallow layer of approximately 12km thickness that does not vary significantly across the model, and mid- and deep-crustal layers that accommodate the thickening and thinning associated with the passage of the triple junction. The models can also be used to produce differential strain rates and velocity maps that delineate where shear zones develop within the crust. Initial results identify vertical shear zones in the same locations as the Rodgers Creek and Ma'acama Faults, as well as several horizontal shear zones interpreted as mid-crustal detachments. In the west, these detachments may link the San Andreas Fault system to the Hayward Fault system, while in the east this decoupling separates the shallow crust from the deeper crust, explaining the lack of thickness variation in the upper-crustal layer.

Continental mobile belts and subduction zone backarcs

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As a regional background to the thermal regime and geodynamics of the western US, we present a general model of all continental backarc mobile belts. The US Cordillera is an example of such a mobile belt, a region that exhibits a long history of distributed deformation, including convergence, strike-slip and extension. A critical problem of continental tectonics is the existence of long-lived active mobile belts compared with the long-term stability of cratons and platforms. Mobile belts are mobile because they are sufficiently weak to be deformed by plate boundary forces, whereas cratons and stable platforms are too strong. We conclude that they are weak because they are hot, and they are hot because they are in present or recent subduction zone backarcs. Most continental backarcs (e.g., western North America and South America) are hot, not just those with extensional or rift zones. The thermal effects of extension and other deformation are superimposed on the high temperatures associated with regional backarc shallow asthenosphere convection. Surface heat flow is commonly ~75 mW/m^2 over backarc widths of as much as 1000 km, with Moho temperatures of 800-900°C, and a lithosphere thicknesses of 50-60 km. In contrast, cratons exhibit surface heat flow of 40-50 mWm^2, Moho temperatures of 400-500°C and a 200-300 km thick lithosphere. The difference in thermal regime results in backarc lithosphere being more than a factor of 10 weaker than cratons. Backarcs may be hot because shallow asthenosphere convection results from viscosity reduction by water from the subducting plate.

Heat flow and crustal heat production in the Canadian Shield

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In order to determine the thermal regime of the deep lithosphere in stable continents, it is necessary to determine the heat flow and to estimate the crustal heat production. Crustal heat production has been derived by systematic sampling of rocks from different composition and origin. Surface heat flow measurements also provide a means to estimate the crustal heat generation. Two end models have been proposed that relate surface heat flow to crustal heat production. One model assumes that mantle heat flow variations are proportional to variations in surface heat flow, the other model assumes that most of the variability in surface heat flow is due to crustal heat production and that the mantle is almost constant.

The heat flow and heat generation data sets in North America (Canadian Shield and Appalachians) are extensive enough to test these models. We have found that, in the Shield, the mean heat flow is the same in all provinces (*Table 1*). Variations are found at the smaller scale of individual subprovinces with different lithologies. Within the Archean Superior Province, the mean heat flow is lower in greenstone terranes (37 mW m^{-2} for the Abitibi) than in the rest of this Province (45 mW m^{-2}). The same trend was found in the PaleoProterozoic Trans Hudson Orogen where juvenile crust is less radiogenic and the heat flow is lower (37 mW m^{-2}) than in the Thompson Belt (53mW m^{-2}) which is made up of reworked Archean crust. Different methods have been used to estimate the crustal and mantle contribution in different regions of the Shield. The range of mantle heat flow values is very narrow 11 - 15mW m^{-2} and within the error limits ± 2 mW m^{-2} of the estimate, implying that most of the variations are in the crustal heat production.

There is a sharp discontinuity with higher heat flow in the Appalachians than in the Shield. This difference can be accounted for by the crustal heat production higher in the Appalachians than in the Shield.

Within individual provinces or subprovinces, there are no well defined heat flow-heat production relationships. However, the mean heat flow, $\overline{Q}$, and the mean production $\overline{A}$ in all the subprovinces of the Shield and Appalachians fit a "*linear relationship*":

$$Q = Q_o + \overline{A} \times D$$

with D = 9 km and Q_o = 33mW m^{-2}. This relationship implies that the deep heat flow is the same in all provinces.

Using all the available data from the Canadian Shield, we have estimated the average crustal heat production to be 0.7 - 0.8 mW m^{-2} for the Precambrian Provinces and 1.05mW m^{-2} for the Appalachians. These results are consistent with worldwide averages (*Table 2*).

In North America, the heat flow remains poorly documented in the northern areas, including Hudson Bay. The Slave Province (with only two heat flow values) is an important target for further heat flow studies because the heat production measured on surface amples in much higher (>1 μW m) than in other Archean Provinces, while geothermobarometry on xenoliths indicate lower mantle temperature in the Slave than in other Provinces. There are also indications from seismic data that the lithosphere is colder in the northwestern part of the Canadian Shield.

Table 1. Mean Heat Flow and Heat Production in Different Belts and Provinces of North America

	Q	σ_Q^b	N_Q^c	A	σ_Q^b	N_Q^d
	$mW\ m^{-2}$			$\mu W\ m^{-3}$		
Superior (> 2.5 Ga)	42 ± 2	12	57	0.95 ± 0.15	1	44
Superior (excl. Abitibi)	45 ± 2.4	12	26	1.4 ± 0.26	1.2	21
Abitibi	37 ± 1	7	26	0.41 ± 0.07	0.33	21
Trans Hudson (1.8 Ga)	42 ± 2	11	49	0.73 ± 0.07	0.50	47
THO (juvenile crust only)	37 ± 1.4	7	38	0.6 ± 0.08	0.48	36
THO (Thompson Belt)	53 ± 1.6	5	10	1.12 ± 0.10	0.32	11
Grenville (1.1 Ga)	41 ± 2	30	30	0.80[e]		
Appalachians (<0.5 Ga)	57 ± 1.5	79	79	2.6 ± 0.27	1.9	50

[a] mean ± one standard error

[b] standard deviation on the distribution

[c] number of sites

[d] number of heat production values. Each value is based on many samples

[e] area-weighted average

Table 2. Estimates of bulk continental crust heat production from heat flow data

Age Group	A^a	$Q^b{}_c$	% Area[c]
	$mW\ m^{-3}$	$mW\ m^{-2}$	
Archean	0.56 – 0.73	23 – 30	9
Proterozoic	0.73 – 0.90	30 – 37	56
Phanerozoic	0.95 – 1.21	37 – 47	35
Total Continents	0.79 – 0.99	32 - 40	

[a] range of heat production

[b] range of the crustal heat flow component

[c] fraction of total continental surface

Heat on top and bottom of the Sierra Nevada, California

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Understanding the creation and diffusion of heat in the continental lithosphere is of profound importance in interpreting two datasets from the Sierra Nevada: low-temperature geochronology and surface heat flow. In the first case, U-Th/He geochronology of two transects in the Sierra has been interpreted to show the presence about 50 Ma of local relief greater than that present today (*House et al., 1998, 2001*). This interpretation would revise our understanding of this mountain chain, suggesting that it has in fact been much higher earlier in the Cenozoic than today and thus not a young mountain chain. This interpretation is predicated on the assumption that heat production varies insignificantly along each transect. Limited heat production information available in the literature suggests that this might not be true: areas with older dates were obtained from rocks with lower heat productions. It is possible that there was no significant topography when these samples cooled and the variations in ages are entirely the result of variations in the local heat production. Further problems in interpreting these data might exist as the thermal structure at the sample sites would depend on the amount of heat being produced by material above the samples. Since different areas sampled plutonic rocks originally emplaced at different depths, it is quite possible that vertical gradient in heat production above the samples was quite different in different places. The second case is a more traditional heat flow problem. Recent work has strongly suggested that asthenosphere was emplaced against the crust at about 3.5 Ma under the southern Sierra. If accomplished through the development of a Rayleigh-Taylor instability, this probably occurred faster than heat could conduct across the body being removed, so the basal boundary condition for crustal heat flow might have changed extremely rapidly. This suggests that the heat flow at the surface of the Sierra records the transient response from cold to hot temperatures at the Moho and thus might provide important constraints on the mechanism of removal of the lower lithosphere. Grossly speaking, heat flow values intermediate between cold western Sierra values and high Basin and Range values are found over the area where material is inferred to have been removed. The question to the community is, do we know enough about heat transport through the crust to be able to use this information to constrain the tectonic interpretation? If not, what else must we learn to be able to use this information both here and elsewhere in the tectonically active areas EarthScope will study?

Terrestrial High-Temperature Hydrothermal Processes and EarthScope

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High-temperature terrestrial hydrothermal systems transport less than 1% of Earth's total heat flux; however, they provide energy resources, localize sites of ore deposition, and host unique biological ecosystems of considerable importance. Moreover, hydrothermal systems in magmatic areas are linked to hazards such as phreatic eruptions and hydrothermal explosions. High temperature hydrothermal systems are fundamentally controlled by the strength and distribution of magmatic heat sources and by the magnitude and distribution of crustal permeability; consequently, hydrothermal systems respond rapidly to both tectonic and magmatic processes. Temporal changes in hydrothermal activity result in changes in the subsurface temperature field, which in turn may result in observable crustal deformations that occur over a range of temporal and spatial scales. Hydrothermal activity and the subsurface temperature distribution may also be affected by climate changes. All of these links among magmatic, tectonic, climatic, and hydrothermal processes as reflected in temporal changes crustal deformation are essentially unexplored and are ripe for study under EarthScope. The data provided by EarthScope can constrain hydrothermal models in ways that have not been possible previously.

The role of temperature in lithospheric-scale deformation

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Better understanding spatial distributions and temporal scales of continental deformation is a major goal of EarthScope. We expect ductile flow rheology to determine, e.g., timescales of postseismic rebound and the localization of lithospheric extension. However, models of rebound and steady-state velocities ignore the exponential decay of effective viscosity with increasing temperature that is intrinsic to power-law creep. Models of steady-state velocity describe lithospheric rheology via an integrated “effective viscosity”, and postseismic rebound models assume an elastic layer overlying a constant viscosity halfspace. Using geothermal constraints (from surface heat flow) plus compositional constraints (from seismic velocities) yields a more realistic depth dependence of viscosity and greater insight into physical controls on rheological behavior without increasing the number of unknowns. Geothermal constraints have been used to estimate rheology from the relationship of surface heat flow to effective elastic thickness (Te) of the lithosphere (a strength measurement derived from gravity and topography data). Uncertainties in estimates of effective viscosity reflect uncertainties in heat flow measurements and Te estimates, uncertainties in parameters of the geotherm (radiogenic heat production, thermal conductivity), uncertainties in parameters of the bending stress (plate bending curvature, strain rate, brittle-field friction) and unmodeled processes (advective heat transfer, dynamic flow stress). Monte-Carlo modeling of these uncertainties suggests that, at high confidence, there is compositional as well as thermal control on lithospheric strength of the western U.S. Mapping these lithospheric rheology estimates to integrated effective viscosity yields estimates similar to independent studies of kinematic velocity, indicating thermal constraints may also improve geodetic models.

Patterns and dynamics of plate boundary deformation: Integration of geodetic, seismic, and thermal data

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GPS measurements have revolutionized our understanding of how strain is accommodated along major faults and across wide plate boundary zones. With ~ 800 new GPS stations, PBO will provide a very detailed picture of deformation of the western US. In order to understand the kinematic picture, we need to integrate these measurements with a broader understanding of what controls the strain and stress distribution. The thermal regime of the lithosphere and its surface heat flow expression are critical elements of this puzzle. We present an example of such an integrated study in the Northern Canadian Cordillera. GPS and seismicity data show that, in response to the collision of the Yakutat Block, crustal strains concentrate in the collision front and in the foreland thrust belt, both regions being separated by a 500-600 km quasi-rigid block. The key to the dynamics of this system is the very high heat flow (70-80 mW/m^2) across the whole Cordillera. The associated high temperatures (800-900°C at the Moho) produce a decoupling of the upper crust and mantle, which allows for the quasi-rigid translation of the Northern Cordillera. As an extension to our example, we examine how various temperature indicators (surface heat flow, heat production, upper mantle velocity) correlate with lithospheric strength. The location of potential weak zones in the crust and mantle vary with the assumed composition but, to a first order, the thermal profile controls the strength of the lithosphere and thus the kinematic and deformation patterns observed by GPS.

New and Old Instrumentation to Address Thermal Processes within the EarthScope Initiative: Examples and Recommendations

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The acquisition of repeated, quality thermal data will be critical to the EarthScope initiative if the stated goals of investigating "the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions" are to be attained. Recent advances in wireline (electric-line and slick-line) and distributed temperature systems (DTS) can provide immediate high resolution (spatially and thermally) information on the subsurface in both high and low temperature settings.

Of particular relevance to the EarthScope initiative is the ability to acquire high-quality temperature data during continental drilling or roving campaigns of interest with a minimal of setup and data reduction. Recent advances in DTS systems allow the simultaneous measurement of temperatures (and pressures) in spatially diverse regions remotely. Hence, quantifying the thermal filed in time and space is greatly simplified.

In addition to answering fundamental unresolved heat flow questions such as the change (if any) in the half-width of heat flow anomalies through time in response to magma migration and quantifying anomalous regions of high/low mantle heat flow, the acquisition of repeated high quality thermal data via either wireline or DTS systems can be used to monitor local changes in subsurface fluid movement in response to stress transients. The instrumentation at the San Andreas Fault Observatory at Depth (SAFOD) and the numerous Plate Boundary Observatory (PBO) sites slated for installation presents a unique opportunity for thermal data to complement the geodetic and seismic data that will be collected and completely characterize the thermal/fluid response to deformation.

Regional Variations of Seismic Q in the Crust and Upper Mantle beneath Continents and its Relations to Temperature Variations

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Tomographic maps of the regional variation of seismic Q (a measure of the efficiency of propagation of waves) for Lg coda , as well as models of shear-wave Q at crustal depths, in many continental regions, exhibit a significant inverse correlation with with maps of inferred temperature variation in the upper mantle. Lowest Q values typically occur above subducting lithosphere and are likely to be associated with fluids from hydration processes that are occurring, or that occurred in the past, in the subducting material. This correlation has been most extensively documented in southern Eurasia where Lg coda Q and shear-wave Q patterns at crustal depths correlate directly with upper mantle shear-wave velocities and inversely with upper mantle temperatures. Q values in southern Eurasia, however, remain relatively low well to the north of regions underlain by active subduction. Maps of upper mantle temperature variation, in some portions of southern Eurasia, extend as far northward of subduction processes as the low Q values but in other regions they do not. This suggests either that we need to improve our understanding of the processes that contribute to regional varations of Q and temperature at crustal and mantle depths or that improved estimates of crust and upper mantle temperature are needed in Eurasia.

The need to integrate thermal, seismic, geodetic and petrologic studies of volcanoes: toward a complete understanding of volcano physics

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To date, most volcanic deformation studies use a surprisingly small portion of the available geophysical data to constrain rheologic properties that directly affect the ground deformation created from an inflating magmatic source. Regardless of source geometry most all studies of volcanic deformation assume the source is surrounded by an isotropic homogeneous Poisson's half-space. Though this may be useful for a preliminary understanding of the approximate location of a magmatic source, it is certainly a gross approximation that will hide potentially useful information about the true source geometry, volume and pressures at depth, which are all important information for developing a more realistic understanding of volcano source physics which is fundamentally necessary for accurate eruption forecasts. Along with petrologic, seismic and gas chemistry studies, heat flow measurements, both near surface and at available deep well sites, are necessary for developing an accurate understanding of the rheologic structure that controls such deformation. Accurately characterizing the temperature profile while using seismic and petrologic information to determine boundaries and material types, we can best describe the rigidity and possibly viscosity of the material surrounding a magmatic pressure source. It is this information along with the bulk modulus, that controls the surface expression of such activity at depth by way of ground deformation. For example, since rigidity scales directly with pressure for a given source geometry and volume, a range of approximations for rigidity around a magmatic source (varying between 1 and 30 GPa) correspond to a 30 fold difference in estimated pressures at depth, a necessary parameter for accurately forecasting eruption capabilities of such activity. Hence, in order to best understand the physics of volcanic activity, particularly deformation, we should strive to incorporate thermal analysis with geodetic, seismic and petrologic studies on all volcanic bodies that are planned focus areas for EarthScope (Long Valley, Yellowstone, Cascades, Aleutians).

Land–Atmosphere Coupling Related To Earthquake Activity

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Satellite thermal imaging data indicate long-lived thermal anomaly fields associated with large linear structures and fault systems in the Earth s crust but also with short-lived anomalies prior to major earthquakes. Positive anomalous land surface temperature excursions of the order of 3-4°C have been observed from NOAA/AVHRR, GOES/METEOSAT and EOS Terra/Aqua satellites prior to some major earthquake around the world. The rapid time-dependent evolution of the thermal anomaly suggests that is changing mid-IR emissivity from the earth. These short-lived thermal anomalies , however, are very transient therefore there origin has yet to be determined. Their areal extent and temporal evolution may be dependent on geology, tectonic, focal mechanism, meteorological conditions and other factors.This work addresses the relationship between tectonic stress, electro-chemical and thermodynamic processes in the atmosphere and increasing mid-IR flux as part of a larger family of electromagnetic (EM) phenomena related to seismic activity.

Geothermal Studies and Processes that Depend on the Thermal Regime of the Crust

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Accurate heat flow measurements provide important information about the temperature field in the crust and upper mantle. In the conterminous United States temperature data from depths of a few hundred meters to depths greater than one km provide useful data regarding ground water flow patterns and climate change during the past several centuries. Because these phenomena affect the temperature regime, it can often be difficult to obtain temperature measurements that represent the remainder of the crust. It has even been suggested by some that advection by ground water may mask the frictional heat generated along the San Andres fault. Hopefully deeper temperature data are generally more representative of deep conductive crustal temperatures than shallower data because deeper data are more removed from the shallow temperature influencing phenomena. Understanding the reological properties of crustal rocks will be important in studies of processes such as crustal extension and earthquake mechanisms, because the reology of crustal rocks is most dependent upon temperature. To acquire deep representative temperature logs in regions of continental dynamics studies would be very valuable.

Thermodynamic constraints on seismic inversions

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We discuss two types of thermal contraints on seismic inversions that can be usefully applied in the context of EarthScope. The first constraint involves assimilating heat-flow measurements in seismic inversions which can improve seismic models beneath continents, particularly beneath cratons and continental platforms. The second constraint derives from a reformulation of the seismic surface wave inverse problem in terms of a thermal model of the upper mantle. We apply the method to estimate lithospheric structure across much of the Canadian Shield and show that the constraint helps in the estimation of lithospheric temperature and thickness and of the mantle component heat flux.

Shear heating, rheology and thermo-mechanics of faulting

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The physical processes active during the evolution of the earthquake cycle in the Earth are related to the rheological structure of fault zones and the deformation that occurs in response to tectonic stress. The deformation in a fault zone may be accommodated by seismic and aseismic fault slip as well as distributed deformation. These in turn depend on variables which include the rheology of crustal rocks, the thermal structure, far-field stresses, and frictional fault strength. Our understanding of how deformation in the lithosphere is partitioned between slip and plastic movement is dependent on the thermal state of a shear zone. Moreover, both types of deformation can generate shear heating. We must be able to specify their respective contributions when evaluating the implied thermal perturbations. Using numerical models we can find relationships between thermal structure and the deformation characteristics of a fault zone. These can provide a framework for integrating geodetic, seismic and heat flow data. To address the problem of thermo-mechanics of fault zones, important new observations that would be provided by the EarthScope program are: the composition and constitutive properties along fault zones and at depth (USArray and SAFOD data); high resolution data of variations in microseismicity in space and time and precise measurements of surface displacements and strain (PBO). The addition of thermal and heat flow data are essential to providing constraints for the interpretation of these EarthScope data.

3-D terrain corrections, groundwater flow, and the SAF heat-flow paradox revisited

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Abstract: Interpretation of the strength of the San Andreas Fault near Parkfield, CA based on thermal data is limited by a large degree of scatter in existing heat flow data, and by large uncertainties in the effects of heat advection by topographically-driven groundwater flow, topographic refraction, and thermal conductivity. Here, we re-evaluate the heat flow data in this area by correcting for full 3-D terrain effects. We then investigate the potential role of groundwater flow in redistributing fault-generated heat, using numerical models of coupled heat and fluid flow for a wide range of hydrologic scenarios. We find that a large degree of the scatter in the data can be accounted for by 3-D terrain effects, and that for plausible groundwater flow scenarios frictional heat generated along a strong fault is unlikely to be redistributed by topographically-driven groundwater flow in a manner consistent with the 3-D corrected data.

Using Thermal Data to Constrain Lateral Heterogeneities along a Fault and Their Effect on Strain Accumulation

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Changes in lithology, elastic properties or rheology on either side of a fault can influence the pattern of surface strain accumulation and release. Thermal studies show it is possible to constrain some of these properties, in particular, the seismogenic depth (which may be used to approximate the elastic thickness) and viscosity. Large offset strike-slip faults are likely to juxtapose terrain with different mechanical properties and may affect the pattern of strain accumulation. The Carrizo segment of the San Andreas Fault (SAF) exemplifies this behavior by juxtaposing different lithologies on opposite sides of the fault. Different rheologies across the fault may explain the asymmetric strain accumulation pattern in the Carrizo segment (*Lisowski et al., 1991*). This area is appropriate for detailed study because deformation is dominated by a single strike-slip fault, and geophysical and geologic studies provide constraints on the parameters controlling strain accumulation. In this paper, we evaluate the effect of lateral heterogeneity in the elastic layer on the observed velocity field. Using a finite element code, we simulate a layered lithosphere (elastic over viscoelastic) to analyze the effect of laterally varying mechanical properties (in particular elastic thickness) on the interseismic strain accumulation and the earthquake cycle. We use thermal data to constrain the seismogenic thickness, and we compare the resulting surface velocity field to SCEC3.0. In order to adequately constrain the model and to fully prove an asymmetric strain accumulation, more heat flow measurements in the region are needed along with better geodetic data on the eastern side of the SAF.

The effects of temperature, petrological trends, and pressure on uppermost mantle thermal expansivity and velocity

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The wealth of data that will be collected by the USArray component of EarthScope will allow improved estimates of crustal and mantle velocity structure. This will significantly improve measurements of lithospheric mantle density (estimated, for instance, from crustal uplift), and seismic velocity. Both density and velocity can then be used to estimate lithospheric mantle temperature. The parameters relating density to temperature (thermal expansivity) and velocity to temperature (anelastic and anharmonic velocity-temperature derivatives) are primarily affected by temperature, pressure, and composition. In many studies, mantle thermal expansivity and anelastic velocity-temperature derivatives are determined from olivine at standard temperature and pressure. Actual parameter values in lherzolite at lithospheric pressures and temperature can be significantly different. Using experimental measurements of the effect of melt removal on the composition of spinel and garnet lherzolite, as well as xenolith mode measurements, we will present th ermal expansivity and seismic velocity-temperature derivatives for spinel and garnet lherzolite at mantle conditions, and discuss the effects of melt depletion and silica enrichment on parameter values. Among our findings are that the density effects of melt depletion relative to temperature are often overestimated, implying the isopycnic assumption, often applied to tectosphere, is more restrictive than generally thought. Also, we will provide directions for future mineral physics work that will provide more accurate thermal expansivity and velocity-temperature relations for peridotite.

Intraplate earthquakes and thermo-mechanical

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EarthScope's targets include strain accumulation and intraplate earthquakes in eastern North America. Despite the scientific and societal significance of these earthquakes, understanding of them is comparable to that of plate boundary earthquakes prior to 1960's, as we have observations but only vague ideas about underlying processes. We can think of two end-member models. In one, intraplate earthquakes occur almost randomly in that the continental interior contains many long-lived fossil weak zones. Minor variations in intraplate stress due to platewide driving forces and local stresses such as from glacial-isostatic adjustment and other density variations cause transient seismicity as the locus of strain release migrates. If so, present regions of intraplate seismicity do not significally differ from the many similar fossil weak zones which are less active. In the other view, seismicity concentrates on long-lived weak zones, which are likely to be associated with high heat flow and lower seismic velocities. For example, if such a zone under the New Madrid area relaxed recently, transient release of accumulated stress would allow larger earthquakes to occur more frequently than implied by geodetic or earthquake frequency-magnitude data. Such models can explain the lack of surface strain accumulation shown by GPS data, but there is little evidence for such weak zones or their recent initiation. EarthScope, in particular USArray, gives an unprecedented opportunity for improved understanding of the tectonic processes causing these earthquakes, controlling their distribution in space and time, and assessing the resulting hazards provided we combine seismological results with geodetic, thermal (including new heat flow measurements), and mechanical studies.

Thermal processes and electrical conductivity: providing insights to temperature regime, lithospheric hydration, rheology, and magmatism

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Material properties determine how continents respond to applied forces. Such properties in turn depend on temperature, but also on composition, which can include both major and minor components. Electrical conductivity to a large degree is a thermally activated physical property and thus can be a proxy for rheology and the presence of fluids or melts. For example, fluidized zones in the lower crust deform most likely through diffusion creep and thus are extremely weak. The depth to top of interconnected fluid in ductile rocks commonly is associated with a jump in conductivity, thus providing a first order temperature constraint. Hydrous defects in olivine-dominated mantle mineralogy increase conductivity and reduce rock strength, and can provide a strong indicator of fabric anisotropy. On the other hand, the diversity of means of enhancing conductivity in thermal regimes introduces non-uniqueness to the interpretation of physical state. Thus, application of the property to understanding earth processes can benefit from external constraints. An example to be discussed is the broad-scale electrical conductivity structure of the Great Basin region, where electrical conductivity and thermal profiles from heat flow and seismic tomography show that mantle hydration at least for the central province is rather low, that the lower crust throughout the region contains a small fraction of hypersaline brines, and that lower crustal fabric inherited from the Proterozoic continental margin may still be preserved to the present day.

Continental Dynamics Driven by Rayleigh–Taylor-type Instability: An Example from the Southern Sierra Nevada, California

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EarthScope is “a bold undertaking to apply modern observational, analytical and telecommunications technologies to investigate the structure and evolution of the North American continent.” As stated in the scientific rationale for EarthScope: “These new observations will permit scientists to relate surface geology and detailed crustal structure to driving forces and thermal processes within the mantle.” One example of crust-mantle interactions is provided by an ongoing removal of the dense batholithic root beneath the southern Sierra Nevada. The removal was initiated between 10 and 3 Ma with a Rayleigh–Taylor-type instability, but with a pronounced asymmetric flow into a mantle downwelling (drip) beneath the adjacent Great Valley. The low heat flow in the Sierra Nevada and occurrence of earthquakes to depths of >30 km in the Sierran foothills suggest present day Moho temperatures beneath the foothills are less than ~500°C. Approximately 100 km east, Quaternary volcanism, xenolith geothermometry, and magnetotelluric measurements suggest much higher Moho temperatures (>1000°C) beneath Owens Valley. This large lateral temperature gradient, developed during the past 5-10 Myrs as part of the mantle instability, and may have driven dehydration or melting reactions that promoted formation of a blind detachment shear zone, as well as volcanism (e.g. Long Valley) in the wake of the SW-directed mantle flow. We will examine this example as a case study of how future EarthScope projects might investigate linkages between crustal and mantle processes and their surface manifestations.