Thermal Measurements in Boreholes drilled for Strain Meter Deployment

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INTRODUCTION

Heat flow determinations constitute the principle direct observation we have of the current thermal state of the continental lithosphere. Proxies for the thermal state of the lithosphere are ambiguous in their interpretation. Seismic velocity anomalies are a function of both temperature and petrology contrasts; electrical conductivity likewise is sensitive to temperature, composition, and the presence of fluids; elevation is sensitive to density through both temperature and mineralogy; and the depth extent of seismicity is sensitive to temperature, strain rate and lithology. The thermal state of the lithosphere greatly influences geologic processes and rock properties including: strength of the lithosphere, modes of deformation, the depth distribution of earthquakes, the concentration and orientation of stresses and viscoelastic relaxation. Thus an integral element to understanding rheology, continental deformation, evolution, and geodynamics involves careful consideration of surface heat flow and subsurface temperatures.

We contend that the benefits of thermal data coupled with the low cost of logging boreholes drilled for strain meter emplacement are strong arguments for thermal logging whenever possible. Because these boreholes will be accessible through time, with repeat logging, we can investigate the thermal stability of the entire borehole environment, possible thermal transients associated with deformation and/or fluid flow. In this sense we view these holes as 'legacy boreholes'. The combination of borehole strain meters, continuous GPS and interferometric synthetic radar which provide a broadband characterization of surface deformation present unique opportunities to collocate heat flow measurements with modern geodetic measurements. Integrating existing and new thermal information with geodetic data and with lithologic and structural information will help characterize crustal rheology in selected target areas. In particular we will seek an understanding of processes that are best addressed through a combination of thermal and geodetic data.

For example, there are a number of proposed target areas from south to north along the Eastern California Shear Zone. The southern most (proposed by Hager et al.) and northern most (proposed by Thatcher et al.) target areas indicate broad zones of strain. Although thermal data in these areas are relatively sparse, horizontal heat flow gradients [*Blackwell and Steele*, 1992] suggest a relatively wide transition from low values associated with the Pacific Coast and Sierra Nevadas to higher values associated with the Basin and Range Province. Between these northern and southern target areas (proposed by Furlong et al. and Hill et al.) the strain is more localized and the horizontal heat flow gradient appears higher. Is this association between high horizontal heat flow gradients and strain localization real or an artifact of the data? What is the role of lateral thermal regimes in localizing strain? How strongly is strain localization controlled by the lateral variation in heat flow? New thermal data coupled with existing data in this area would help to resolve horizontal heat flow gradients and will be used to investigate how the changing thermal regime localizes strain. Other questions directly pertinent to the objectives of PBO include: How do the upper and lower cutoffs in seismicity vary with the thermal field? How do variations in the thermal field correlate with estimates of viscosity as determined from geodetic data? How can the combination of thermal and geodetic data best resolve deformation models? Will this combination of data elucidate the state of friction on active faults? These questions are particularly important to proposed target areas along the San Andreas Fault system. The combination of readily available boreholes and thermal data collocated with modern geodetic data makes this proposal scientifically rich and economically attractive.

SCIENTIFIC OBJECTIVES

Simply stated, this proposal is aimed at a better understanding of variations in the crustal and deeper lithospheric thermal regime in selected PBO target areas and the interaction and influence of temperature on styles of deformation and rheology.

The thermal structure of the crust and upper mantle has a first order influence on styles of deformation and earthquake mechanics. For example, temperature is thought to be the predominant control on the seismic-aseismic transition [*Sibson*, 1982; *Tse and Rice*, 1986; *Scholz*, 1990; *Blanpied et al*., 1995]. Investigations of the brittle-ductile transition, often defined as the intersection between Byerlee's law of frictional failure and dislocation creep (as summarized with yield strength envelopes [*Brace and Kohlstedt*, 1980]), with the base of seismicity have highlighted a correlation between seismicity and heat flow. Areas of deep seismicity cutoff are often associated with areas of low heat flow and areas of shallow seismicity cutoff are often associated with high heat flow [e.g. *Wang and Chapman*, 1990; *Williams*, 1996]. One of the biggest obstacles to improving upon the general heat flow/depth of seismicity correlation is the fact that heat flow measurements are often widely scattered in space so that the correlation is dependent on crustal geotherms being extrapolated over large distances. We will couple the new heat flow data with new seismicity catalogues of well-located events to investigate the thermal influence on the depth extent of seismicity.

In contrast to the lower cutoff in seismicity, the upper cutoff in seismicity has received little attention. While the upper cutoff in seismicity is often understood in terms of low normal stress, the effects of pore fluids and dilatancy hardening, *Marone and Scholz* [1988], using only well-located hypocenters, found that only faults with significant net displacement and with thick gouge zones, indicate an upper cutoff in seismicity. Might this upper cutoff in seismicity also be thermally limited? At subduction zones with large accretionary prisms an up-dip limit of seismicity exists [*Byrne et al*., 1988], and may be due to the presence of stable sliding clays [e.g., *Wang* 1980; *Vrolijk*, 1990]. *Hyndman and Wang* [1993] argue that if mixed layer clays allow stable sliding, earthquakes will occur on subduction thrusts only where the temperature is great enough to dehydrate these clays, about 100-150° C. Their favored explanation is that this isotherm marks the dehydration of stable sliding smectite to illite. This explanation has also been proposed for the aseismic behavior of the San Andreas transform [*Vrolijk*, 1990]. The collocation of strain meters and detailed thermal studies will be used to test these ideas.

In addition to these elastic models, the importance of viscoelastic relaxation of the lower crust and upper mantle, is now recognized as an important influence on modes of crustal deformation as illuminated by modern geodetic data [*Reches et al.*, 1994; *Pollitz et al.*, 2000]. Almost all large earthquakes are followed by aftershock activity that lasts for months to years and whose energy decays exponentially with time. Along the San Andreas and Hayward faults, postseismic deformation [*Thatcher*, 1983], creep events [*Savage and Lisowski*, 1992; *Behr et al*., 1997] and slow earthquakes [*Linde et al.*, 1996] lasting hours to weeks, along the San Andreas fault as revealed by geodetic measurements, indicate the importance of viscous relaxation. In these viscoelastic models the exponential dependence of viscosity on temperature also points to the need for independent estimates of temperature in the lower crust and upper mantle sections of the lithosphere.

For example, *Pollitz et al*. [1998], used a combination of GPS and InSAR measurements to model postseismic viscoelatic relaxation of the lower crust and upper mantle following the 1992 Landers earthquake. These models indicated a best fitting viscosity of $8 \pm 4 \times 10^{18}$ Pa s for the uppermost mantle consistent with a temperature of 1120°C based on the Arrhenius relation representing effective viscosity. However to reconcile this temperature estimate with the crustal geotherms of Williams [1996] one requires a quasi-rigid thermal boundary layer at the base of the viscoelastic lower crust to accommodate a 500-600°C vertical temperature difference.

We will construct geotherms to estimate temperature at both the top and bottom of the seismogenic zone. We will specifically test 1) if variations in the depth to the top of the seismogenic zone are consistent with variations in heat flow and hence temperature; and 2) if the base of background seismicity is consistent with the depth to a particular geotherm. Most importantly, these geotherms will be compared against temperatures estimated from viscosity estimates derived from viscoelastic models of deformation [e.g., *Pollitz et al*., 2000].

TECHNICAL ASPECTS

Thermal physical rock properties (thermal conductivity, heat production, specific heat, density, etc) will be determined from a combination of rock chip samples collected during the drilling phase and disc samples taken from nearby outcrops using modern laboratory techniques. After the thermal effects of drilling have dissipated (typically 2-3 times the period it takes to drill the hole) thermal gradients will be determined. Temperatures are measured by lowering a thermistor at specific depths (typically 1 m). It takes approximately 2 hours to log 100 m, and does not interfere with the operation of the strain meter. Recent advances in technology and measuring techniques permit us to measure temperature with an unprecedented accuracy (uncertainty < 0.005 K). We estimate the cost of obtaining this thermal data at less than $1000 a borehole. Geotherms will be constructed from the combination of thermal gradient and thermal physical rock property determinations. Modern corrections will be applied to the thermal data where appropriate, with particular attention to discriminating between conductive heat flow determinations and those affected by ground water flow or other thermal transients (see appendix in *Chisholm and Chapman* [1992]). We are confident that heat flow determinations made in these boreholes will be of excellent quality because strain meter boreholes are sited in crystalline rocks with scientific objectives in mind, making them well suited for heat flow studies. Previous heat flow determinations made in boreholes drilled for strain meters have yielded high quality results [*Williams and Galanis*, 1994; *Sass et al.*, 1997].

A unique benefit of these boreholes is that they will be left open through time making them potential candidates for legacy boreholes. We propose to utilize this opportunity by relogging the boreholes to investigate and isolate thermal transients from the quasi steady state background heat flow. Relogging these boreholes may provide important tests between conductive heat flow regimes and those adversely affected by groundwater flow. Additionally these holes will be relogged immediately after seismic events to investigate potential thermal anomalies associated with seismicity.

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