Heat, Friction, and the Mechanics of Faults

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MOTIVATION
During an earthquake, two blocks of the Earth’s crust slide past one another generating massive amounts of frictional heat. In fact, Kanamori & Brodsky (2001) describe earthquakes as thermal events more than seismic events because most of the energy release during an earthquake goes into heat rather than seismic waves. While seismologists continue to collect valuable data, Earthscope’s SAFOD and PBO projects provide a unique opportunity for us to expand our knowledge of the earthquake process by understanding heat produced along large faults. Most notably, frictional heat could hold the key to unlocking the three-decade-old mystery about the frictional strength of plate boundary faults. This enhanced understanding of the rheology of plate boundaries will lead to improvements in mechanical models of faulting, stress-triggering, and earthquake rupture.

INTRODUCTION
Measuring Heat
Heat is generated during individual earthquakes or creep events and slowly accumulates in the Earth’s crust because of the relatively slow rate of conduction. Most studies have focused on quantifying the long-term accumulation of heat. Surface heat flow studies directly measure temperature in boreholes with high precision thermometers and have been a guiding force in understanding the mechanics of faulting. Lachenbruch & Sass, (1980) present a complete data set of surface heat flow in the vicinity of the San Andreas fault zone that reveals no observable increase in heat flow close to the fault. Using quantitative models, they constrain the effective coefficient of friction on that fault to be less than 0.1, or roughly an order of magnitude lower than the coefficient of friction measured by Byerlee (1978) on laboratory scale samples. This discrepancy launched a debate that remains largely unresolved and is frequently referred to as, “the stress-heat flow paradox.”

Monitoring Heat with Thermochronology
Other efforts have focused on reading the record of long-term heat accumulation using thermochronology (e.g., Scholz et al., 1979; Batt et al., 2000; Camacho et al., 2000; Xu and Kamp, 1999). These studies all look for increased paleo-temperatures near the fault caused by frictionally generated heat that results in reductions in the "apparent age" measured by thermochronology. In some cases the reduction is observed and in others it is not. However, both the surface heat flow and thermochronologic studies described above all focus on quantifying the heat accumulated by fault slip over millions of years over a very broad area. However, during each individual earthquake there should be a quick temperature spike with increases of several hundred degrees, as depicted in Figure 1. Such a pulse would be observable in a transect across the fault on the scale of a few meters like that from the SAFOD drill hole. While temperature probes from SAFOD could record such a signal, we would have to wait for a large earthquake to occur. Certain thermochronometers can record the localized effect of heat pulses from individual

![Figure 1. Time-temperature history at different distances away from a fault showing the quick pulse of heat expected from a "typical" earthquake. Note how brief and localized the effect is. Parameters used: Slip, 2 m; Depth 1.75 km; Dry Coefficient of Friction 0.7; Hydrostatic Pore Pressure](image-url)
earthquakes and preserve that signal in their cumulative thermal history and apparent age. This abstract discusses the type of information we could hope to collect from thermochronologic analysis of a profile through the San Andreas fault and highlights some of the specific issues that must be considered to interpret these data.

EXPECTED RESULTS

The ultimate goal of quantifying frictional heat is to enhance our understanding of crustal rheology, fault mechanics, and the earthquake process. Unfortunately, the path from heat to mechanical strength is inherently indirect. The amount of heat generated during fault slip is a fraction of the amount of work done by friction:

\[ Q = \overline{\tau}De \]

where \( \overline{\tau} \) is the average effective shear stress during slip, \( D \) is the amount of fault slip, and \( e \) is a coefficient representing the proportion of total work that is converted into heat rather than seismic energy or grain size reduction. Various studies have focused on the value of \( e \) (McGarr, 1999; Lockner & Okubo, 1983) and suggest that it is between 0.90 and 0.99. We can use thermochronology to constrain \( Q \), but both the average shear stress and the exact displacement history of the fault are unknown resulting in an inherently non-unique result. It turns out that the nature of several thermochronometers like fission track thermochronology makes the thermal history completely insensitive to small events (< M6) and dominated by the single largest earthquake ever to occur on the fault. By making some reasonable assumptions about the largest event to have occurred along the fault, we are therefore able to constrain the effective shear stress fairly well.

Unlike heat flow studies of accumulated heat revealed in surface measurements or thermochronology along transects several kilometers long, this method does not provide a crustal average estimate of shear stress but is instead a measure at a single point. Modeling of thermal histories from the thermochronometers can help constrain the paleo-depth of samples allowing us to link the shear stress to the normal stress and determine a coefficient of friction for that location. We cannot ignore that faults are heterogeneous and that we will be taking measurements at only one location. That is, alas, one of the drawbacks of having only one SAFOD hole!

A COMPLEX PROBLEM

We have performed a pilot study using apatite fission track thermochronology to constrain the amount of frictional heat on an exhumed fault (d’Alessio et al., in preparation). We developed a simple numerical model to explore some of the factors that affect our ability to observe frictionally generated heat at the scale that we would expect to observe in a project similar to the San Andreas Drilling Project. While our pilot project focuses on apatite fission track, the issues we present below are generalized to any method to observe heat pulses from individual earthquakes.

The Goldilocks Zone

To borrow the terminology of Carl Sagan, each thermochronometer has a "Goldilocks Zone" where the ambient temperature during fault slip is neither too hot nor too cold. If the ambient temperature is already above the closure temperature of the thermochronometer then there will be no thermal history to reset ("too hot"). If the ambient temperature (or corresponding shear stress) is too low, then the temperature increases expected from frictional heating will not be large enough to cause even partial reset ages ("too cold"). The specific temperatures bounding the Goldilocks Zone depend on the diffusion or annealing rates of the thermochronometer, the precision of the method (the ability to differentiate between ages that are unreset and those that are partially reset by very small amounts), and to some degree, the shear stress at the site (higher shear stresses will result in hotter temperature spikes for a given size earthquake). Using our simple numerical model, we find that the Goldilocks zone for apatite fission track typically requires ambient temperatures between 70 - 100°C. These temperatures represent a narrow range of depths only 1 - 2 km thick where apatite fission track will record the effects of frictional heat and is very sensitive to the geothermal gradient at the site. At the SAFOD project in Parkfield, the present day geothermal gradient from a well down to 1.5 km is about 37°C/km (Sass et. al, 1997). This suggests that the Goldilocks Zone for apatite fission track is between 1.9 - 2.7 km, however changes in the geothermal gradient during the last few million years can strongly affect the depth range of the zone. Analysis of the SAFOD pilot hole will allow us to determine the paleo-geothermal gradient at the site and the Goldilocks Zone for various thermochronometers. Besides apatite fission track, there is a suite of thermochronometers that each have their own Goldilocks Zones allowing us to examine a wide range of depths within the seismogenic zone, but we must be very careful to select the appropriate thermochronometer for the specific sample locality and depth.

Thin Slip Surfaces

While fault zones themselves may be as wide as meters to perhaps a kilometer, evidence from exhumed faults suggests that slip in an individual earthquake may be confined to more planar "principal slip surfaces" that are only a few millimeters thick (Chester & Chester, 1998). If the heat generation source is spread out over a wider zone, then the
temperature increase at any given point will not be hot enough to reset any thermochronometer. In our models, we therefore approximate a fault as a planar heat generation source.

**Transient and Localized Heating**

Figure 1 shows the temperature increase we could observe at different distances away from a planar fault after a "typical" earthquake. The extreme temperature increase is localized to within a few centimeters of the fault and persists for only a matter of hours. In order to record this signal, we need 1) a thermochronometer capable of being reset in a very brief heating event, and 2) to recover usable samples from within a few centimeters of the active slip surface. Apatite fission track is among several thermochronometers that meet the first criteria; laboratory experiments show that tracks can completely anneal with exposures to 400°C as brief as 20 minutes. The second criteria is a bit harder to meet. Samples taken from within a few centimeters of a major fault are usually comminuted and damaged, particularly if a wide gouge zone is present. We performed a pilot study at a locality along an exhumed fault where the "gouge zone" is only 1 - 8 centimeters thick so that we were always able to collect samples from intact rock that was within a few centimeters of the principal slip surface where heat generation occurred (d’Alessio et al., in preparation). However, exposures of plate boundary faults that are as narrow as a few centimeters are very rare. Chester and Chester (1998) show examples where the gouge zone can be as wide as 50 cm but the exposed principal slip surface is located very close to one of the edges of the zone. In such cases, intact rock could also be sampled on at least one side of the fault. In locations where the principal slip surface is surrounded by a wide zone of gouge on both sides, we would be forced to collect samples from within that zone. We have had limited success extracting a large enough quantity of usable apatite out of ultracataclasite, but more sophisticated sampling techniques could yield better results than we have experienced.

**Heat Transport and the Role of Fluids**

After heat is generated during an earthquake, it is transported away from the fault by conductive and advective heat transport. The thermal diffusivity of rocks can easily vary by about 20% resulting in sustained temperatures that vary by more than 60% in our models. Advective heat flow is much harder to quantify because it requires detailed constraints on the role of fluids in the earthquake process and the hydrologic regime of a site. There exist several conceptual models of the role of fluids in faulting (e.g., Sibson, 1986; Rice, 1992), but we have very few constraints from active faults to definitively support any specific theory. Earthscope’s SAFOD project will provide valuable data such as the present-day interseismic pore pressure and the permeability of the fault core. Quantitatively speaking, both Lachenbruch (1980) and Mase & Smith (1987) argue that the effects of advective heat transport are small because the amount of heat that can be transported by fluids is limited by the quantity of fluid present. Since typical porosities are well below 10% at seismogenic depths, the effects of advective heat transport are minimal. Even though fluids do not play a significant role in heat transport, they could play a crucial role in affecting heat generation because the effective coefficient of friction depends on pore pressure. SAFOD could provide valuable insight into this role by giving us information about the hydraulic structure of a major active fault.

**IMPLICATIONS FOR INTEGRATED EARTHSCOPE SCIENCE**

Thermochronology and more general studies of frictional heat fit well within the broader earth science goals of the Earthscope proposal. Most directly, thermochronology can be used in concert with the present-day monitoring of heat flow from the SAFOD observatory. Monitoring with borehole geophysical techniques can only give us information from a brief moment in geologic time and thermochronology will extend that view into the past. By combining the thermochronology and geophysical results from the deep SAFOD hole with individual shallow measurements of heat flow from the PBO borehole strainmeter array at Parkfield, we will be able to get a detailed picture of frictional heat at that site. Similar heat flow data from all PBO boreholes would significantly increase our database of heat flow throughout western North America. These data will illuminate localized heat flow anomalies as well as outline broad heat flow provinces that can expand our knowledge of continental dynamics, crustal rheology, and earthquake processes.

**REFERENCES**


