No frictional heat along the San Gabriel fault, California: Evidence from fission-track thermochronology

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ABSTRACT

Large earthquakes generate frictional heat, and the magnitude of heating is related to the slip magnitude, the applied effective normal stress, and the frictional strength of the fault. We looked for evidence of this heating in apatite fission-track age and track-length distributions of samples from adjacent to and within the San Gabriel fault zone in southern California. The fault is thought to be an abandoned major trace of the San Andreas fault system active from 13 to 4 Ma and has since been exhumed from depths of 2–5 km. At our sample locality, as much as 40 km of total slip is thought to have accumulated along a localized ultracataclasite layer just 1–8 cm thick. We see no evidence of a localized thermal anomaly in either fission-track ages or track lengths—even in samples within just 2 cm of the ultracataclasite. Because of the absence of any measurable impact on fission tracks, we have been able to use forward modeling of heat generation, heat transport, and fission-track annealing to constrain the frictional properties of the fault. We find that either there has never been an earthquake with $>$4 m of slip at this locality, or the average apparent coefficient of friction must have been $<$0.4.

Keywords: faults, frictional heat, fission-track thermochronology, San Gabriel fault.

INTRODUCTION

Faults live and die by their frictional properties. Friction determines how and when a fault slips, how faults interact with each other, and influences fault geometry. Frictional strength affects heat production and stresses in the rocks around faults. Despite the fundamental role of friction in controlling fault behavior, different techniques for determining fault strength in nature have produced radically different estimates of the coefficient of friction, and many of these estimates conflict with values determined in the laboratory. The first constraints on the frictional strength of large faults in nature came from measurements of surface heat flow (Brune et al., 1969; Lachenbruch and Sass, 1980). During fault slip, a significant amount of frictional heat should be generated, resulting in measurably high heat flow adjacent to the fault after a few million years of fault activity. The fact that no heat-flow anomaly has been observed in surface measurements suggests that the coefficient of friction for major natural faults is 0.1–0.2, a factor of 3 to 7 times lower than measurements from laboratory experiments (Byerlee, 1978). Studies of heat flow assume that conduction is the sole mechanism of heat transport, but strong evidence for fluid circulation at seismogenic depths (e.g., O'Neil and Hanks, 1980) indicates that advective heat transport could dramatically change estimates of fault strength. Even though Lachenbruch and Sass (1980) presented strong arguments against the role of fluids, they conceded that heat-flow data alone cannot rule out contamination of the signal by advective heat transport. We therefore seek independent constraints on the frictional heating of faults.

In this study, we use fission-track thermochronology and first-order models of frictional heating to constrain the amount of heat generated by individual fault-slip events and over geologic time periods. We collected samples from transects perpendicular to an exhumed fault and use evidence of complete or partial annealing of fission tracks to infer the magnitude of transient temperature pulses from repeated large earthquakes.

Frictional Heating

Heat is generated virtually instantaneously during an earthquake, causing a transient and localized temperature increase. The amount of heat generated per unit area (Q) is related to the amount of work done by friction:

$$Q = e\tau D, \tag{1}$$

where D is the amount of slip, τ is the average shear stress during 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. McGarr (1999) presented calculations of seismic efficiency that are in agreement with laboratory experiments (Lockner and Okubo, 1983), which indicate that e is probably between 0.90 and 0.99. We have adopted a value of 0.90 for our calculations. We used the relationship $\tau = \mu_{app}\sigma_n$, where μ_{app} is the average apparent coefficient of friction and σ_n is the normal stress. In our forward model, we assumed values for μ_{app} and determined the normal stress from the weight of the overburden ($\sigma_n = \sigma_v$). The apparent coefficient of friction includes the effects of pore pressure and the relative compressibility of the fault-zone materials (Harris, 1998). Higher pore pressures will result in lower values of μ_{app}, thus making the fault appear weaker. We calculated the temperature versus time histories shown in Figure 1 by approximating heating events as instantaneous plane sources of heat (Lachenbruch, 1986) and using simple analytical solutions for one-dimensional conductive heat flow (Carslaw and Jaeger, 1959). For a single earthquake, the most significant temperature increases are confined to within ~10 cm of the fault surface, and temperatures return to within a few

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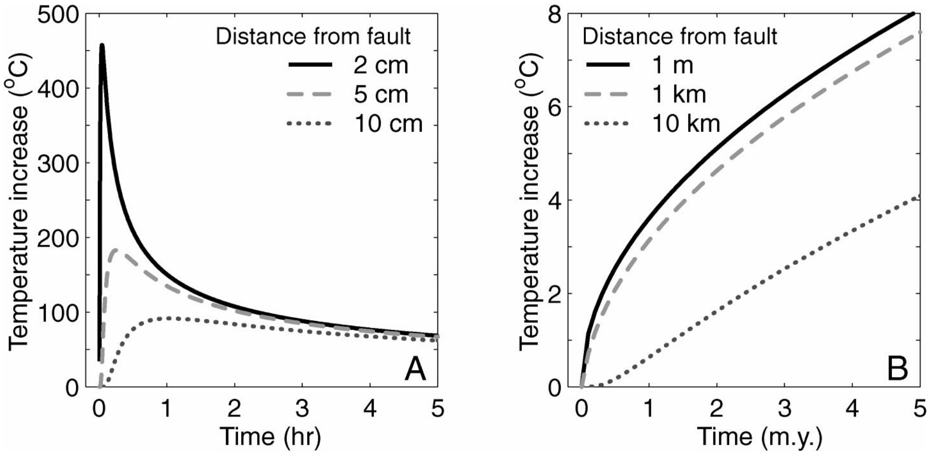

Figure 1. Typical temperature vs. time histories calculated for different distances away from fault for (A) transient frictional heating from single earthquake with 4 m slip and (B) cumulative heating from geologic slip rate of 4.4 mm·yr^{-1}. Note extremely different scales of x and y axes. Parameters used: depth = 2.3 km, apparent coefficient of friction = 0.35.

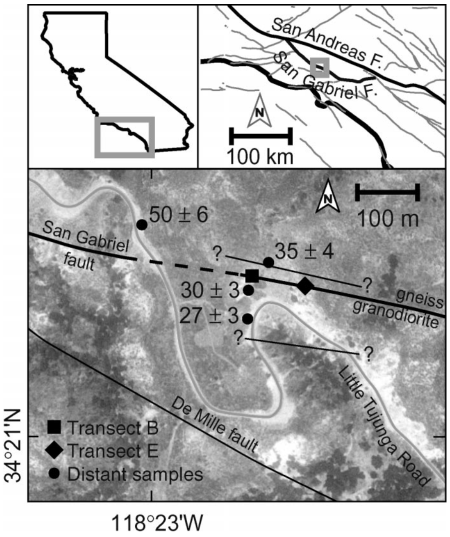

Figure 2. Locations of samples along San Gabriel fault in southern California, ancient and abandoned trace of San Andreas fault system. Samples far from fault show apatite fission-track ages (Ma) and 1σ uncertainty. Ages along transects B and E are shown in Figure 3.

degrees of their preearthquake levels within a few days (Fig. 1A).

As earthquakes recur, more heat is generated before residual heat from previous events can escape to the surface, eventually leading to temperature increases of several degrees within a few tens of kilometers of the fault (Fig. 1B). Note that the heating signature of the long-term buildup covers a much broader area and persists for millions of years longer than the localized and transient spike shown in Figure 1A. Existing studies of frictional heat from surface heat flow are only able to investigate the broad anomaly from the cumulative buildup of heat (e.g., Lachenbruch and Sass, 1980).

Thermochronology and Frictional Heat

There have been several attempts to use thermochronology to demonstrate thermal anomalies around natural faults (e.g., Scholz et al., 1979; Xu and Kamp, 2000; Batt et al., 2000; Camacho et al., 2001). Like studies of surface heat flow, these efforts focus on observing the broad anomalies that are produced by the accumulation of heat over millions of years. In addition to concerns over advective heat transport on these time scales, observing frictional heat with thermochronology requires that profiles tens of kilometers long have minimal differential uplift. Further, Figure 1B shows that slip rates of <5 mm·yr^{-1} may not cause temperature increases large enough (~20 °C) to be resolved by thermochronology.

Fission-track thermochronology can record thermal events lasting from minutes to millions of years and could therefore resolve the quick heat pulses from single earthquakes in addition to the long-term accumulation of heat. Exposure to high temperatures causes fission tracks to heal and shorten, i.e., to ‘‘anneal.’’ Large thermal events can cause the tracks to disappear entirely, resetting the apparent age of the sample. Thus, frictional heating should cause fission-track lengths to be shorter or ages to appear younger adjacent to a fault. Green et al. (1986) performed laboratory experiments showing that fission-track ages in apatite can be completely reset by heating events as short as 20 min if the temperature exceeds ~400 °C, and exposures to more moderate temperatures (>80–100 °C) over geologic time can also cause resetting.

To resolve transient heat pulses from individual earthquakes, we can compare samples within a few centimeters to samples tens of meters from the fault. These samples have undergone nearly identical long-term thermal histories (including any cumulative buildup of frictional heat), but samples close to the fault also might have been subject to transient frictional heating. As illustrated in Figure 1A, temperatures hot enough to reset fission tracks will only be reached within ~0.1 m of the fault and will persist for <1 h.

Fission tracks can only image frictional heating in a reasonably narrow depth range, a ‘‘Goldilocks zone.’’ Fission tracks are not present at depths where the ambient temperature is hot enough to continuously anneal damage to the crystal lattice (~120 °C in apatite), corresponding to depths ~3.5 km near the present-day San Andreas fault. If the depth is too shallow, shear stresses may be too low, so that even large earthquakes will not generate enough frictional heat to raise temperatures enough to anneal tracks. The depth range of the Goldilocks zone depends on geothermal gradient, normal stress, and the apparent coefficient of friction of the fault. Considering these factors, the approximate depth range in which apatite fission-track thermochronology can record frictional heat from individual earthquakes corresponds to depths of ~2.0–3.5 km, under the conditions of a 30 °C·km^{-1} geothermal gradient.

SAN GABRIEL FAULT ZONE

The San Gabriel fault is thought to be an ancient and abandoned trace of the San Andreas fault system that accommodated ~40 km of plate-boundary motion from 13 Ma to 4 Ma (Powell, 1993). Since that time, uplift and erosion have exposed features that were originally 2–5 km deep while the fault was slipping (Chester et al., 1993; Blythe et al., 2000).

Site Description

The specific site we examined in this study (Fig. 2) is located along Little Tujunga Road near Pacoima Canyon (Oakeshott, 1958; Anderson et al., 1983; Evans and Chester, 1995). At this site, the San Gabriel fault consists of a 1–8-cm-wide ultracataclasite zone that juxtaposes the Mendenhall gneiss to the north with the Josephine granodiorite to the south. Because of this extremely narrow fault zone, our heat-transport models can approximate the fault as a planar source of heat. Evans and Chester (1995) showed that fluids were not present in appreciable amounts at this locality while the fault was active.

Samples

We collected samples along two transects perpendicular to the fault (B and E, Fig. 2) that are ~75 m apart along the strike of the fault. The samples closest to the slip surface are as narrow as 2 cm in the direction perpendicular to the fault. As the temperature versus

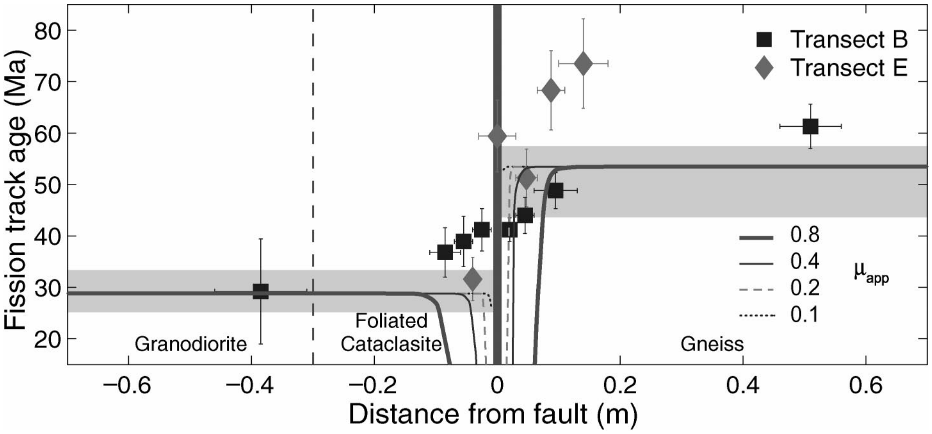

Figure 3. Apatite fission-track age as function of distance from San Gabriel fault. Symbols show data from two transects with x axis error bars indicating width of samples and *y* axis error bars showing 1σ uncertainty in age. Shaded gray area shows 1σ uncertainty range for samples 10–70 m from fault (Fig. 2B). Curves are theoretical calculations for expected age of samples exposed to frictional heat from single 4 m slip event at 2.3 km depth and range of apparent coefficients of friction (μ_{app}). Foliated cataclasite zone is present along transect B only.

time curves in Figure 1A illustrate, we require such spatial resolution to observe the extremely localized effects of transient frictional heating. The most distant samples are from ~70 m away from the fault. Because this distance is comparable to the distance between the transects, we use the same samples far from the fault as the end points of both transects.

FISSION-TRACK RESULTS AND ANALYSIS

We plot the fission-track age of samples along our transects in Figure 3 (see also Fig. DR1 and Table DR1[1] for additional information about fission-track procedures and results). Far from the fault, the apparent age on the granodiorite side (30 ± 3 Ma) differs from the gneiss side (50 ± 6 Ma), indicating that the two sides underwent slightly different thermal histories (likely owing to vertical offset along the fault) or that the chemistry of the apatite crystals is sufficiently different that they anneal at slightly different rates (Donelick et al., 1999). Although there is some variability in ages adjacent to the fault, none of the samples is reset to the 13–4 Ma time of fault slip.

For both transects on the gneiss side of the fault, fission-track ages are youngest in samples closest to the fault, a feature qualitatively consistent with a frictional-heating signature. Quantitatively, however, none of these ages coincides with the timing of San Gabriel fault activity, implying that either the ages were partially reset by frictional heating or this thermal signature predates the fault. We evaluate these two possibilities by examining the lengths of the fission tracks. Our forward modeling shows that heat pulses that partially reset fission-track ages always cause existing tracks to shorten, resulting in a lower mean track length. Our data have the opposite feature: the mean track length close to the fault (12.5 mm for both transects) is slightly longer than the mean for samples far from the fault (12.2 mm), not significantly different at the 95% confidence level (Table DR2 and Fig. DR2; see footnote 1). Therefore, frictional heating did not raise the temperature enough to cause a measurable decrease in track lengths and thus cannot explain the apparent reduction in ages near the fault.

We utilize the observation that there is no localized reduction in age or track length to constrain the magnitude of frictional heat that affected this locality. By using the fission-track annealing equations of Laslett et al. (1987), we compute the maximum temperature increase the samples close to the fault could have undergone without causing a measurable change in fission-track age or track-length distribution. We find that the temperature in these samples could never have exceeded ~380 °C for >20 min while the fault was active. The amount of annealing for a given heating event depends nearly linearly on the duration of the event and exponentially on its temperature. For example, it takes 20 min to completely anneal tracks in apatite at 400 °C, but it will take nearly 40 yr to accomplish the same annealing at 200 °C.

If there are multiple earthquakes on the same fault, the largest earthquake will cause the most annealing because it will have the largest temperature increase but similar duration of heating. Multiple earthquakes of identical size have the effect of increasing only the duration, and thousands of earthquakes are needed before there is a measurable difference between a single earthquake and multiple earthquakes of equal slip. A plate-boundary fault with as much as 40 km of total slip may have had tens of thousands of large earthquakes of similar magnitude. Because we have no information about the total number of earthquakes on this strand of the San Gabriel fault, or their relative size, we have focused our analysis on the effect of the single largest earthquake.

Our estimates of the approximate depth of the samples during fault activity (13–4 Ma) rely on traditional modeling of fission-track length distributions to determine exhumation history (e.g., Ketcham et al., 2000). We have found that the ambient temperature at this locality was 70–80 °C while the fault was active (Fig. DR3; see footnote 1); the gneiss side was consistently ~5 °C cooler than the granodiorite side. If a geothermal gradient of 30 $°C \cdot km^{-1}$ and a 10 °C surface temperature are assumed (Williams et al., 2001), then these ambient temperatures correspond to ~2.0–2.3 km depth (with <350 m of vertical offset across the fault during its entire history).

CONSTRAINING FAULT STRENGTH

We constructed a forward model integrating heat generation by fault-slip events, heat flow, and fission-track annealing. By using our model, we can provide constraints on the frictional strength of the fault at this locality. The solid lines in Figure 3 show our calculations of fission-track age along the transect for a model slip event with 4 m of slip at 2.3 km depth. Apparent coefficients of friction >0.4 would result in reset ages in the samples closest to the fault, but we do not observe any such reset.

Equation 1 shows that it is not possible to use estimates of heat generation to uniquely constrain the coefficient of friction (μ_{app}) without assuming a slip distance (D), or vice versa. We must therefore assume a reasonable slip magnitude appropriate for a major plate-boundary fault, remembering that the largest event will dominate the thermal history. Additional uncertainty stems from our estimates of the paleodepth of the transect because the overburden affects the amount of normal stress on the fault. Paleodepth estimates rely on both our estimate of paleotemperature and geothermal gradient at the time the fault was active—both of which have associated uncertainties. Figure 4 shows how different slip magnitudes and paleodepths affect our constraints on the apparent coefficient of friction. We plot a range of depths appropriate for pa-

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[1] GSA Data Repository item 2003077, Figures DR1–DR3 and Tables DR1–DR2, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

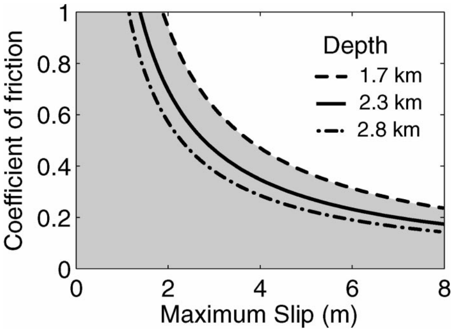

Figure 4. Constraints on maximum value of apparent coefficient of friction (μ_{app}) at our sample locality for different assumptions about largest-magnitude slip event and paleodepth of samples. Uncertainty in estimates of ambient temperature and geothermal gradient while fault was active contribute to uncertainty in estimates of paleodepth. Range of depths shown here corresponds to estimates of ambient temperatures between 70 and 80 °C and geothermal gradients of 25–35 °C·km^{-1}. Region below curves is shaded to emphasize that curves represent upper bounds on coefficient of friction.

leotemperatures between 70 and 80 °C and geothermal gradients ranging from 25 to 35 °C·km^{-1}, the most likely paleodepth being between 1.7 and 2.8 km.

CONCLUSIONS

At one locality along the exhumed San Gabriel fault, we see no evidence in fission-track thermochronology for a localized thermal anomaly from transient frictional heating caused by individual earthquakes. The absence of measurable changes in fission tracks allows us to conclude that the temperature near the fault never exceeded 380 °C for $>$20 min while the fault was active. Given the best estimated depth of the section during fault activity from 13 to 4 Ma, this thermal constraint suggests that either no single earthquake ever exceeded 4 m of slip on a frictionally strong fault ($\mu_{app} \geq 0.6$), or that the apparent coefficient of friction on the fault is $<$0.4.

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