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Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake

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[1] We have made observations of a heat signature that is associated with the frictional heat generated at the time of faulting for a large earthquake. Temperature measurements in a borehole that intersects the Chelungpu fault at a depth of about 1100 m, show a small increase near the fault even six years after the earthquake. The temperature signature has a symmetric shape with a width of about 40 m and is centered on the fault that slipped about 5 m during the 1999 Chi-Chi, Taiwan earthquake. The small amplitude of 0.06°C for the observed temperature anomaly indicates a very low level of friction that generated heat at the time of the earthquake.
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1. Introduction

[2] The frictional heat generated during earthquake faulting is thought to be the largest part (80 to 90%) of the total seismic energy budget, and geophysicist have been debating for over 50 years about the level of frictional heat generated active faults [e.g., *Terada*, 1930; *Brune et al.*, 1969; *Lachenbruch and Sass*, 1980]. The lack of significant heat flow values across the San Andreas fault has led to the 'Heat Flow Paradox' and the debate about the absolute level of stress that drives the fault [see *Scholz*, 2002]. Temperature measurements across the fault immediately after an earthquake could provide the clearest answer to this controversy, however, there has never been a clear near-fault temperature change observed for any previous large earthquakes that can be attributed to the frictional heating. Here we report on measurements of a heat signature, obtained from the Chelungpu fault, Taiwan and associated with the 1999 Chi-Chi earthquake (Mw7.7). An observation of a temperature increase, and thus an estimate of the heat generated, may provide information about the dynamic frictional strength, if the heat is assumed to have been generated by fault slip.

2. Temperature Measurements

[3] Following the September 21, 1999 Chi-Chi earthquake, the Taiwan Chelungpu-fault Drilling Project (TCDP) bored two holes which penetrated the fault at depths of about 1100 m (K.-F. Ma et al., Slip zone and energetics of a large earthquake: Results from the Taiwan Chelungpu-fault drilling project (TCDP), submitted to *Nature*, 2006, hereinafter referred to as Ma et al., submitted manuscript, 2006), near the town of Dakeng in the northern part of the rupture zone (Figure 1). During the earthquake, this area had large fault displacement of about 5 m. The boreholes provided the rare opportunity to make temperature measurements in a fault zone with large slip from a recent earthquake. The precise temperature observations were carried out in one of the boreholes during September 2005, six years following the earthquake. The borehole is cased with steel pipe so that there is little water flow between the borehole and surrounding rock, enabling very stable temperature measurements. For temperature measurements, uncased boreholes have more problems with possible water flow between the borehole and surrounding rock.

[4] There was a previous attempt to observe a temperature anomaly associated with the Chi-Chi earthquake, in another shallow borehole that penetrated the fault at 300 m depth [*Mori and Tanaka*, 2002], but the observed temperature anomaly is relatively broad implying that it might be affected by shallow ground water flow.

[5] In order to obtain a high resolution (0.003°C) temperature profile, we developed a borehole instrument containing two quartz oscillator thermometers separated by 3 m. During observations made on September 20 and 21, 2005, the instrument was slowly lowered (about 1.0 m/minute) and raised (about 0.4 m/minute) in the borehole between the depths of 900 and 1250 m, producing four independent temperature profiles across the fault zone. The continuous recording of temperature at 10 s intervals produced 5 to 15 readings per meter.

[6] The original data from the four profiles are shown in Figure 2. Note that all four profiles show a small increase of temperature (shaded areas in Figure 2) which is above the linear gradient, in the region of the fault zone, located at depths of 1105 to 1115 m (Ma et al., submitted manuscript, 2006). There are slight differences in the recorded depth and temperature of the anomaly among the four profiles due to the time constant of the temperature sensor and the speed with which the instrument was lowered and raised. A temperature signature of similar amplitude was also independently seen on a profile obtained with a coarser sampling of about 10 m intervals, using platinum resistance temperature gauges during observations from September 13 to 17.

[7] Figure 3 shows an average of the four profiles, with a linear temperature gradient (0.022°C/m) removed and the peaks of the anomalies aligned. The temperature increase as

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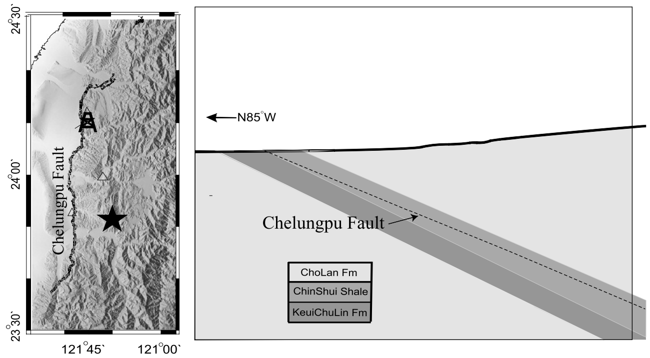

Figure 1. Map shows location of the drill site with respect to the surface faulting on the Chelungpu fault during the 1999 Chi-Chi earthquake. Star shows the location of the epicenter. Diagram on right shows the Taiwan Chelungpu Fault Drilling Project (TCDP) borehole that intersects the fault at 1111 m.

function of depth in the original data, is not perfectly linear, reflecting the spatial variations of the thermal conductivity [*Matsubayashi et al.*, 2005]. The different conductivity values caused by different rock types and water content can cause fluctuations in the observed temperature profile. For identifying a possible temperature anomaly caused by frictional heating of the fault in this study, we assume a linear temperature gradient in the region extending several tens of meters on either side of the fault zone. The x-axis is the distance to the fault, which is assumed to be at a depth of 1111 m and dips 30° to the east (Ma et al., submitted manuscript, 2006). The data clearly shows a nearly symmetric temperature signature with an amplitude of 0.06°C and a width of about 40 m centered on the fault zone. We interpret this anomaly to be the residual of the friction heat produced during faulting of the 1999 Chi-Chi earthquake.

3. Estimate of Frictional Heat

[8] To estimate the heat associated with the earthquake, we assume that the observed temperature anomaly is caused by the frictional heat generated at the time of the earthquake and any subsequent heat transfer is due entirely to conduction. The solution for one-dimensional conduction in the case of a sudden injection of a thin layer of hot material into an infinite medium [*Officer*, 1974], is given as a function of time (t) and distance (x)

$$T(x,t) = \frac{S}{2\sqrt{\pi\alpha t}} e^{-x^2/4\alpha t} \tag{1}$$

α is the heat diffusivity and the strength of the heat source S, which is heat divided by specific heat and the density of the medium with units measured in °C-m, is,

$$S = \frac{\tau \cdot u}{c \cdot \rho} \tag{2}$$

u is the fault displacement, c is the specific heat, ρ is the density, and τ is the shear stress. We fit equation (1) to the temperature data in Figure 3 to estimate the thermal diffusivity, α, and source strength, S. The value of α mainly controls the width of the curve and S the amplitude.

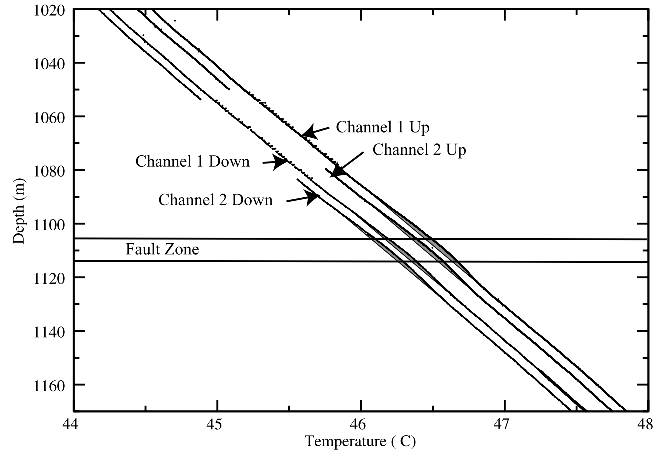

Figure 2. Original temperature profiles obtained near the fault zone. The shaded portions show the temperature anomaly that is a several hundredths of a degree above the geothermal gradient.

The heat source was assumed to be a thin layer located at the middle of the peak of the temperature anomaly, corresponding to the fault depth of 1111 m. We use values of u = 5 m for the fault displacement, c = 1700 J/(kg°C) for the specific heat, and ρ = 2200 kg/m^3 for the density. The time t is 1.89×10^8 s, about 6 years. A grid search for values of α and S gives the best fit for $\alpha = 3.4 \times 10^{-7}$ m^2/s and S = 1.5°C-m. To find the best fit values, we tested α from 1.0×10^{-7} m^2 to 9.0×10^{-7} m^2 at intervals of 0.2×10^{-7} m^2 and S from 1.0°C-m to 2.0°C-m at intervals of 0.01°C-m.

[9] From the value of S and equation 2, we estimate that the shear stress that generated the observed temperature anomaly is 1.1 MPa. Figure 3 shows the calculated temperature profile using the determined values for the diffusivity and shear stress, along with the observed data. For comparison, curves for other values of the shear stress are also shown.

[10] The obtained value for the diffusivity can be converted to thermal conductivity (κ) using the standard definition,

$$\alpha = \frac{\kappa}{c \cdot \rho} \tag{3}$$

which results in κ = 1.3 J/m/s/°C. The Chelungpu fault zone is located within the Chinsui shale and our estimated

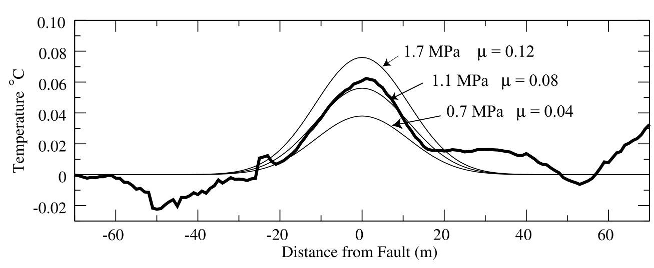

Figure 3. Fitting of the observed temperature anomaly (thick line) to model curves (thin lines) for a range of shear stress. The best fit values are for a shear stress of 1.1 MPa and a diffusivity of 3.4×10^{-7} m^2/sec.

conductivity is consistent with laboratory measurements for shales, which range from 0.9 to 2.5 J/m/s/°C [*Clark*, 1966]. This result suggests that the heat transported by water flow is not a dominant effect and the use of the simple conduction model is appropriate for these data.

[11] The calculated level of shear stress that produces the temperature anomaly is very small. The vertical stress (lithostatic stress minus hydrostatic stress) is estimated to be 13 MPa. Assuming the vertical stress is equal to the horizontal stress and resolving these values onto the dipping fault plane, we obtain a value for the apparent coefficient of friction of 0.08. For a thrust fault environment the maximum horizontal stress is larger than the vertical stress, possibly by a factor of two or more depending on the static stress conditions [*Sibson*, 1974]. If the horizontal stress is twice the vertical stress, the apparent coefficient of friction is 0.04. In any case, the shear stress of 1.1 MPa necessary to generate the observed temperature change is much smaller than the surrounding stress levels. Such a low value of shear stress implies that dynamic friction during the earthquake is extremely low for this portion of the fault. This level of (dynamic) friction is an order of magnitude smaller than typical laboratory values of the static coefficient of friction [*Byerlee*, 1978].

[12] It is difficult to evaluate if our estimate of very low friction is representative of the entire area of large slip for the Chi-Chi earthquake. Even if our results are applicable for only a localized patch, this portion of the fault shows low levels of dynamic friction. This indicates that there are mechanisms during faulting that reduce the frictional strength, such as lubrication, frictional heating or super-hydrostatic pore pressure. The small value of heat implies that fault melting probably did not occur. Another consideration is that we may not be at depths great enough to be in the true seismogenic zone of the fault and slip is occurring under low stress conditions.

4. Fluid Flow

[13] The possibility of fluid flow that can transport a significant portion of the heat is always an issue for thermal measurements [e.g., *Saffer et al.*, 2003]. However, if this were the case, we would expect to see a broader temperature anomaly with a higher value of diffusivity. Our estimate of diffusivity from the shape of the anomaly is similar to laboratory values for shale, suggesting that there is not a large fluid flow. Also measured values of permeability near the fault zone from the borehole core [*Sone et al.*, 2005] indicate that there should not be a high rate of water flow perpendicular to the fault.

[14] We calculated the effect of water flow on a temperature anomaly, as shown in Figure 4 using the equation [*Domenico and Schwartz*, 1997]

$$\alpha \frac{\partial^2 T}{\partial x^2} - \frac{n\rho_w c_w}{\rho c} v \frac{\partial T}{\partial x} = \frac{\partial T}{\partial t} \quad (4)$$

where v is flow rate, n is porosity, ρ_w is density of water, and c_w is specific heat of water.

[15] These curves show the effect on the predicted temperature anomaly for flow rates of 10^{-5} to 10^{-4} m/s, which are typical to high rates. The effect of the water flow is to move the anomaly downstream in position and broaden its shape. Since our observed temperature signature is located right at the location of the fault, as inferred from the core, this is another reason we think that there are minimal effects from fluid flow on our observed temperature signature.

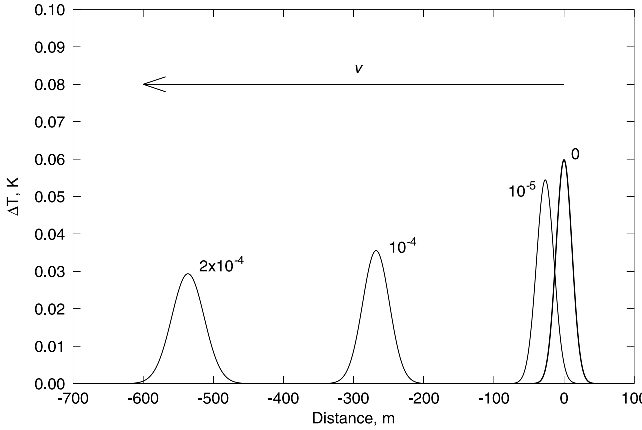

Figure 4. Predicted temperature anomaly including effects of water flow with flow rates of 0 (no water flow), 10^{-5}, 10^{-4}, and 2×10^{-4} m/s.

[16] Another possibility is that fluid flow along the fault may bring warm water from depth to produce a thermal signature along the fault. It is conceivable that the earthquake triggered such a flow to produce the signal that we see. If that is the case, the frictional heat produced by the earthquake is even smaller than the value we calculated.

5. Effects From Drilling

[17] Continuous monitoring of the temperature at a fixed depth in the borehole was also carried out from March to September 2005 to monitor the temperature changes that were caused by the drilling, which was completed in February. There was a continuously diminishing rise of the temperature in the region near the fault zone from March to July that stabilized to within about 0.01°C by August. The observed change likely represents the re-equilibration of temperature after the disturbances caused by the drilling. The temperature stabilization within a period of about 6 months is consistent with previous measurements in boreholes [*Williams et al.*, 2004]. This indicates that the temperature profile taken in September probably does not have significant effects from the drilling process.

6. Discussion and Conclusions

[18] Our results indicate that the level of dynamic friction was very low during rupture of this portion of the fault. It is possible, but not necessary, that this is an indication of low static friction. *Wang et al.* [2000] support a regional thin-skin model with a low-angle decollement at depths of 10 to 20 km, which includes the shallow and more steeply dipping Chelungpu fault. In this geometry the Chelungpu fault is a weak bedding plane fault that is inferred to have a low level of stress.

[19] Taking into consideration possible other explanations for the observed temperature signature, the calculated

heat in our results is an upper bound and implies a very low level of dynamic friction during faulting for this region of large slip (apparent coefficient of friction of 0.04 to 0.08). Laboratory determinations of the static coefficient of friction are generally quite high, 0.6 to 0.7 [*Byerlee*, 1978] or 0.35 to 0.5 for shales [*Morrow et al.*, 1992], and would produce much higher amounts of heat if these values are used for the dynamic coefficient of friction. The low level of friction we obtained needs to be confirmed for other events, and, if verified, indicates that low friction mechanisms are needed to explain the dynamic rupture process of large earthquakes.

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