Heat flow in the SAFOD pilot hole and implications for the strength of the San Andreas Fault

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[1] Detailed thermal measurements have been acquired in the 2.2-km-deep SAFOD pilot hole, located 1.8 km west of the SAF near Parkfield, California. Heat flow from the basement section of the borehole (770 to 2160 m) is 91 mW m⁻², higher than the published 74 mW m⁻² average for the Parkfield area. Within the resolution of the measurements, heat flow is constant across faults that intersect the borehole, suggesting that fluid flow does not alter the conductive thermal regime. Reanalysis of regional heat flow reveals an increase in heat flow along the SAF northwest of Parkfield. This transition corresponds to a shallowing base of seismicity and a change in fault behavior near the northern terminus of the M6 1966 Parkfield earthquake rupture. The persistence of elevated heat flow in the Coast Ranges to the west appears to rule out frictional heating on the SAF as the source of the SAFOD value. INDEX TERMS: 0915 Exploration Geophysics: Downhole methods; 5134 Physical Properties of Rocks: Thermal properties; 7230 Seismology: Seismicity and seismotectonics; 8130 Tectonophysics: Heat generation and transport; 8164 Tectonophysics: Stresses—crust and lithosphere. Citation: Williams, C. F., F. V. Grubb, and S. P. Galanis Jr. (2004), Heat flow in the SAFOD pilot hole and implications for the strength of the San Andreas Fault, Geophys. Res. Lett., 31, L15S14, doi:10.1029/2003GL019352.

1. Introduction

[2] The state of stress at seismogenic depths in the vicinity of the San Andreas Fault (SAF) has been the subject of intense investigation and controversy [see Townend and Zoback, 2004]. One approach to quantifying the average resisting stress on active faults has been to examine evidence for heat generation from frictional sliding. For Coulomb failure with dynamic and static friction coefficients consistent with laboratory measurements [e.g., Byerlee, 1978], the average frictional strength of the SAF should be on the order of 100 MPa. Sustained fault slip over geologic time against this frictional resistance should produce a detectable heat flow anomaly centered on the fault [Brune et al., 1969; Lachenbruch and Sass, 1980]. In a comprehensive survey of heat flow in the vicinity of the SAF, Lachenbruch and Sass [1980] followed on the work of Brune et al. [1969] and Henyey and Wasserburg [1971] in establishing the absence of the predicted frictional heat flow anomaly. On the basis of these results Lachenbruch and Sass concluded that the average static strength of the SAF does not exceed 20 MPa. Subsequent heat flow measurements in the 3.5-km-deep Cajon Pass scientific drillhole confirmed the results of the shallow (typically <200 m) measurements near the Mojave segment of the SAF [Sass et al., 1991], although questions remain regarding potential advective and convective disturbances to the conductive thermal regime [Williams and Narasimhan, 1989; Saffer et al., 2003].

[3] Sass et al. [1997] published the results of 17 heat flow measurements along a 50-km long segment of the SAF near Parkfield, filling a large gap in the near-fault heat flow dataset. In contrast with the majority of heat flow measurements in California, the accuracy of those acquired at Parkfield was limited by sparse thermal conductivity measurements, a relatively shallow depth of investigation compared to the likely effects of surrounding topography, and possible thermal refraction due to juxtaposition of low conductivity sediments with higher conductivity Salinian and Franciscan basement rocks in the shallow subsurface [Sass et al., 1997]. Although scattered, the results were consistent with a low-strength fault, with the average Parkfield heat flow of 74 mW m⁻² representing a transitional value between high heat flow (~85 mW m⁻²) in the Coast Ranges to the west and lower heat flow (<65 mW m⁻²) in the Great Valley to the east.

[4] The SAFOD experiment, in addition to yielding in situ information on the chemical, thermal and physical properties of the fault at depth, provides an important opportunity to compare the shallow Parkfield data with a deep profile of heat flow. The greater depth of the measurements reduces the influence of surface topography and refraction. A detailed examination of vertical variations in heat flow, particularly across faults and lithologic contacts, also provides quantitative constraints on the possible magnitude of advective heat transport.

2. Heat Flow in the Parkfield Area

[5] The SAFOD site is located northwest of Parkfield, approximately 1.8 km west of the SAF (Figure 1). This places it northwest of all but one of the Parkfield heat flow measurements reported by Sass et al. [1997] and approximately 20 km southeast of a set of five heat flow measurements in and near Pancho Rico Canyon published by Lachenbruch and Sass [1980]. Because the Parkfield and Pancho Rico data include heat flow values that were determined from both measured and estimated thermal conductivities and were not corrected for the thermal effects of varying topography by the same method, the combined dataset was reexamined using a single, consistent approach. Temperature gradients were corrected for local topography using the three-dimensional terrain correction method of Birch [1950], and heat flow values for those holes with measured thermal conductivities were distinguished from
those with conductivities estimated from formation averages. The revised values are summarized in Table 1 and shown in Figure 1.

For the data published by Sass et al. [1997], the average of the revised values is similar (77 vs. 74 mW m⁻²), but the range of variation has been reduced by 28 percent, from 38 to 27 mW m⁻². Two new points, PRSN (Pearson 1-B exploratory oil well) and SFD1 (SAFOD pilot hole) have been added. The SAFOD results are discussed in full below. The value for PRSN was determined by combining the PRSN thermal conductivity measurements from the SAFOD pilot hole over intervals that could be correlated between the two wells. Porosities for the sedimentary section in PRSN were determined from electric log density measurements and applied in the geometric mean model of Woodside and Messmer [1961] to determine whole rock thermal conductivities.

### Table 1. Heat Flow in the Parkfield Region

<table>
<thead>
<tr>
<th>Well</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Q_{PUD}(mW m⁻²)</th>
<th>Q_{REV}(mW m⁻²)</th>
</tr>
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<td>120°15.31'</td>
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<td>64</td>
</tr>
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<td>120°16.92'</td>
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<td>61</td>
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</table>

Q_{PUD} are measurements published in Lachenbruch and Sass [1980] and Sass et al. [1997]. Q_{REV} are new and revised measurements.

\[ \lambda(T) = \frac{\lambda_0}{a + bT} \]  

Figure 1. Map of Parkfield region showing heat flow measurements (circles and squares), active faults (gray) and the Coast Ranges-Great Valley (CR-GV) physiographic boundary (black). Solid symbols represent heat flow determined in holes with thermal conductivity data. Open symbols represent heat flow determined from average formation conductivities. Squares are measurements northwest of a line normal to the SAF through the SAFOD site. Circles are measurements southeast of that line.

Figure 2. Temperature, temperature gradient, thermal conductivity (squares), and heat flow in the SAFOD pilot hole. Open circles in heat flow are estimates assuming a sediment porosity of 0.2. These estimates were not used in calculating the average SAFOD heat flow.
where $\lambda(T)$ is the thermal conductivity at temperature $T$, $\lambda_0$ is the conductivity at 0°C, $a = 1.0$, and $b = 0.0024 - 0.0052/\lambda_0$, as determined by Williams and Sass [1996] from measurements on representative Coast Ranges rocks at elevated temperature and pressure.

[9] Heat flow was calculated over 100 m intervals from 700 to 2200 m except at 1380 m where both the measured gradient and conductivity show significant offsets (Figure 2). Each measurement represents the product of the harmonic mean thermal conductivity and the least-squares temperature gradient over the specified depth interval. The heat flow values range from 85 to 93 mW m$^{-2}$, with a mean of 91 ± 3 mW m$^{-2}$ (95% confidence limits). Plotted with the heat flow measurements in Figure 2 is a predicted curve for a surface heat flow of 93 mW m$^{-2}$ and a decrease in heat flow with depth of 1.4 mW m$^{-2}$ per km due to the contribution of radiogenic heat production as estimated from SAFOD electric log natural gamma data using the relation of Rybach [1986]. This predicted decrease with depth yields the average value measured in the basement section.

[10] Within the resolution of the measurements, heat flow in the SAFOD pilot hole does not vary beyond the modest decline due to the decreasing contribution of radiogenic heat production with depth, and even that predicted decline cannot be differentiated from constant heat flow with depth. Heat flow is constant across the fault zones and fractured intervals that intersect the borehole at 1150–1220, 1345–1420 and 1820–1880 m [Boness and Zoback, 2004]. This result is consistent with the view that heat transport in the upper crust along this segment of the SAF is by conduction and is not influenced by ground-water flow. One-dimensional models for the combined thermal effects at the SAFOD site of uplift and erosion over the past 10 Ma along with earlier Tertiary sedimentation indicate that the resulting disturbance to measured heat flow is less than 5% [Blythe et al., 2004; Lachenbruch et al., 1995].

4. Analysis

[11] The predominant feature of the new and revised heat flow measurements is the contrast in heat flow along the SAF northwest and southeast of Middle Mt. (Figure 1). Mean heat flow for the five sites northwest of Middle Mt. with values determined from temperatures and thermal conductivities measured in the same borehole is 88.5 ± 5.6 mW m$^{-2}$, compared to a mean of 74.5 ± 4.7 mW m$^{-2}$ for the equivalent eight sites southeast of Middle Mt. Only one of these eight measurements southeast of Middle Mt. (EDE2 – 83 mW m$^{-2}$) exceeds the lowest value among the five to the northwest (PR1 – 81 mW m$^{-2}$).

[12] This increase in heat flow along-strike correlates with other characteristics of the SAF near Parkfield. The hypocenter of the 1966 M6 Parkfield earthquake was located under Middle Mt., with coseismic slip focused exclusively to the southeast. As first defined through geodetic modeling by Harris and Segall [1987] and confirmed through refined analysis of GPS data by Murray et al. [2001], the section of the fault ruptured by the 1966 earthquake currently forms a locked patch, with fault slip at rates greater than 5 mm/yr occurring only in the upper 2 to 3 km of the fault and below the seismogenic zone at approximately 14 km. The locked patch as defined by Murray et al. [2001] is eroded to the northwest along strike with increasing slip rate from both above and below through a transition to the creeping segment of the SAF. Along the creeping section fault slip exceeds 25 mm/yr through the entire seismogenic zone. According to Eberhart-Phillips and Michael [1993], the onset of fault creep corresponds with a region of low crustal seismic velocities in the Franciscan terrain northeast of Middle Mt. which may reflect elevated pore fluid pressure in the rocks bounding the SAF along the creeping segment.

[13] The lower boundary of the seismogenic zone also shallows along this segment of the fault. The depth above which 95% of the earthquakes occur averages approximately 13 km southeast of the SAFOD site and approximately 10 km northwest of the SAFOD site (Figure 3). This relative depth variation is confirmed in seismicity near Middle Mt. relocated by the double-difference technique (W. Ellsworth, personal communication). To examine the relationship between the shallowing base of seismicity and deep thermal conditions, isotherms were calculated for each of the measurements in Table 1. According to Williams [1996], for conductive heat flow in a crustal layer of constant heat production A, surface heat flow $q_s$, and thermal conductivity given by equation (1), temperature varies with depth $z$ according to

$$T(z) = \frac{1}{B} \left[ \exp(c_1z - c_2z^2 + c_3) - a \right]$$

(2)

where $c_1 = bq_0/\lambda_0$, $c_2 = bA/2\lambda_0$, and $c_3 = \ln(a + bT)$. The calculated depth to the 350°C isotherm for each heat flow measurement is plotted in Figure 3. Both the 350°C isotherms and the base of seismicity shallow from southeast to northwest by approximately 3 km. The average depth of the 350°C isotherm northwest of Middle Mt. is 11.0 km and southeast of Middle Mt. is 14.2 km.

[14] Although spatially correlated, the relationship between active fault slip and elevated heat flow is not straightforward. Fault slip along the creeping section is a
Although there remains significant scatter among the measurements in the SAFOD pilot hole average 91 ± 3 mW m⁻², there are no resolvable thermal perturbations due to advective transport of heat along the faults and fracture zones that intersect the borehole. The SAFOD heat flow value is consistent with a transition in heat flow along the SAF from an average of 77 mW m⁻² in the region southeast of Middle Mt. to an average of 88 mW m⁻² to the northwest. This thermal transition correlates with a shallowing of the base of recorded seismicity and with the southeastern boundary of the creeping section of the SAF. Thermal weakening of the SAF at depth and the corresponding thinning of the portion of the fault characterized by brittle failure may facilitate the extension of fault creep from the surface down through the entire seismogenic zone. Analysis of the new heat flow measurements with revised published values confirms the absence of a fault-centered frictional heat flow anomaly.

Figure 4. Southwest-northeast section normal to the SAF showing the SAF and San Gregorio-Hosgri fault (SGF), heat flow, the predicted frictional heat-flow anomaly (solid red), the modeled CR-GV heat flow transition (solid black), and the superposition of the anomaly on the model (dashed red).

5. Summary

Heat flow measurements from 770 to 2200 m depth in the SAFOD pilot hole average 91 ± 3 mW m⁻², and there are no resolvable thermal perturbations due to advective transport of heat along the faults and fracture zones that intersect the borehole. The SAFOD heat flow value is consistent with a transition in heat flow along the SAF from an average of 77 mW m⁻² in the region southeast of Middle Mt. to an average of 88 mW m⁻² to the northwest. This thermal transition correlates with a shallowing of the base of recorded seismicity and with the southeastern boundary of the creeping section of the SAF. Thermal weakening of the SAF at depth and the corresponding thinning of the portion of the fault characterized by brittle failure may facilitate the extension of fault creep from the surface down through the entire seismogenic zone. Analysis of the new heat flow measurements with revised published values confirms the absence of a fault-centered frictional heat flow anomaly.

References


