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Abstract

The subsurface temperature regime influences the depth to the base of the continental seismogenic layer and probably the depth interval of the seismogenic layer as well. Heat-flow measurements are the best way to estimate the subsurface thermal regime; however, few heat-flow measurements are within several kilometers of main event epicenters with well-determined hypocenters. In this study the subsurface thermal regimes of two widely separated locations within very different geological environments are considered. The locations are along the San Andreas fault near Parkfield, California, and along the Coyote fault near Socorro, New Mexico. The San Andreas fault is a major strike-slip transform fault between the Pacific and North American plates. The Coyote fault is a normal fault along the eastern boundary of the Rio Grande rift where first motion studies of recent seismic swarms suggest primarily strike-slip events. The focal depth of the main event at Arroyo del Coyote, along the Coyote fault, is approximately the same as the focal depths of the two most recent magnitude 6 events near Parkfield. Heat-flow values near the magnitude 6 event at Middle Mountain and near Arroyo del Coyote suggest the main events are occurring at ~ 270 ± ~ 30°C*, a temperature in the higher part of the semi-brittle thermal regime for wet quartz. Is this coincidence, or does it suggest main strike-slip events at these two locations similarly depend on temperature at depths where crustal strength may be decreasing? High-quality heat-flow measurements at epicenters will be needed to better appreciate the relation between temperatures and earthquakes.

Introduction

Subsurface temperatures are important in determining the depth of the base of the upper crustal seismogenic layer where most continental earthquakes occur (e.g., Brace and Byerlee 1970; Sibson 1984). The mechanism of plastic flow in quartz beginning at ~ 300°C (Tullis and Yund 1977) relieves tectonic stresses that would generate earthquakes below the base of the seismogenic layer. Sibson (1984) suggests crustal composition, pore pressure, water content, stress and strain distribution, as well as geothermal gradient, influence the depth of the base of the continental seismogenic layer. These parameters should also affect the depth interval of the seismogenic layer.

The present study discusses subsurface temperatures at two main event strike-slip epicenters where both estimates of focal depth and heat flow exist. Main event hypocenters may relate more explicitly than subsequent events to the interaction between regional tectonic stresses and fault strength dependence on temperature because of stress changes subsequent to main events. Although heat-flow measurements are the best way to determine subsurface temperatures, there are few heat-flow sites in proximity to main event epicenters where focal depths are well determined. Two locales considered here are Middle Mountain along the San Andreas fault near Parkfield, California, where the 1966 magnitude 6 event occurred, and Arroyo del Coyote along the Coyote fault near Socorro, New Mexico, where a magnitude 3.8 event occurred in 1985. Heat-flow data, subsurface temperatures, and depth characteristics of the seismogenic layers at the two locations are discussed.

Coyote fault near Socorro

Heat flow

The Coyote fault is mapped as a down-to-the-west normal fault running north-south along the eastern boundary of the Rio Grande rift near Socorro, New Mexico (Fig. 1; Cather 1996; Machette et al. 1998). The rift near Socorro began to develop 32–27 m.y. ago (Chapin 1979). The north-trending basins and ranges in the area are extensional features superposed on Oligocene to late Miocene silicic volcanic centers. Calderas just west of Socorro are 32–24 m.y. old (Chapin 1989; Chamberlin 1983). A large modern magma body ~ 3,400 km^2 and ~ 100 m thick is at ~ 19 km depth beneath the rift at Socorro (Fig. 1; Sanford et al. 1973; Rinehart et al. 1979; Ake and Sanford 1988; Hartse 1991; Balch et al. 1997). The area has experienced several millimeters of uplift per year during the 20th century and perhaps during the last millennium, possibly due to replenishment of the magma body at depth (Larsen et al. 1986; Fialko and Simone 2001). Three of five studied earthquake swarms in the region are along the Coyote fault zone (Fig. 1; Balch et al. 1997). The Arroyo del Coyote swarm site is within ~ 2 km of the Chupadera Mesa heat-flow site (Fig. 1; Reiter et al. 1975).

The heat-flow value at Chupadera Mesa is 92 ± 2 mW m^{-2}, which is consistent with elevated heat flow measured elsewhere along the Rio Grande rift (Decker and Smithson 1975; Reiter et al. 1975, 1978, 1986). Reiter (2005) notes that the heat-flow value at Chupadera Mesa is probably a good approximation because similar values were measured over two depth intervals and the site is away from regions of expected ground water flow.

Seismogenic layer

Although the Coyote fault zone shows primarily normal faulting, first motion studies of the swarms along the fault indicate predominately strike-slip movement with some normal movement (Sanford et al. 1991; Balch 1997). In addition to the earthquake swarm at Arroyo del Coyote, two other swarm sites along the Coyote fault have been studied (Fig. 1; Hartse et al. 1992; Balch 1997; Balch et al. 1997). En echelon steps in the Coyote fault zone are spatially related to the three swarm locations. It is therefore uncertain if first motions are left lateral parallel to the north-south trend of the Coyote fault or right lateral approximately normal to the fault zone (R. Chamberlin pers. comm.).

Table 1 summarizes focal depth information for the three swarms along the Coyote fault. Main event hypocenters are between ~ 7 and ~ 9 km, increasing in depth from south to north. Average focal depths, including smaller magnitude events, also increase in depth from south to north as do the depths of the deepest and shallowest events in the swarms. This northward deepening trend of the seismogenic layer along the Coyote fault is consistent with a transition from higher heat flow in the southern Rio Grande rift to intermediate regional heat flow in the Albuquerque Basin (from ~ 95 mW m^{-2} to ~ 80 mW m^{-2}; Reiter et al. 1986).

*Metric conversions are on page 92.

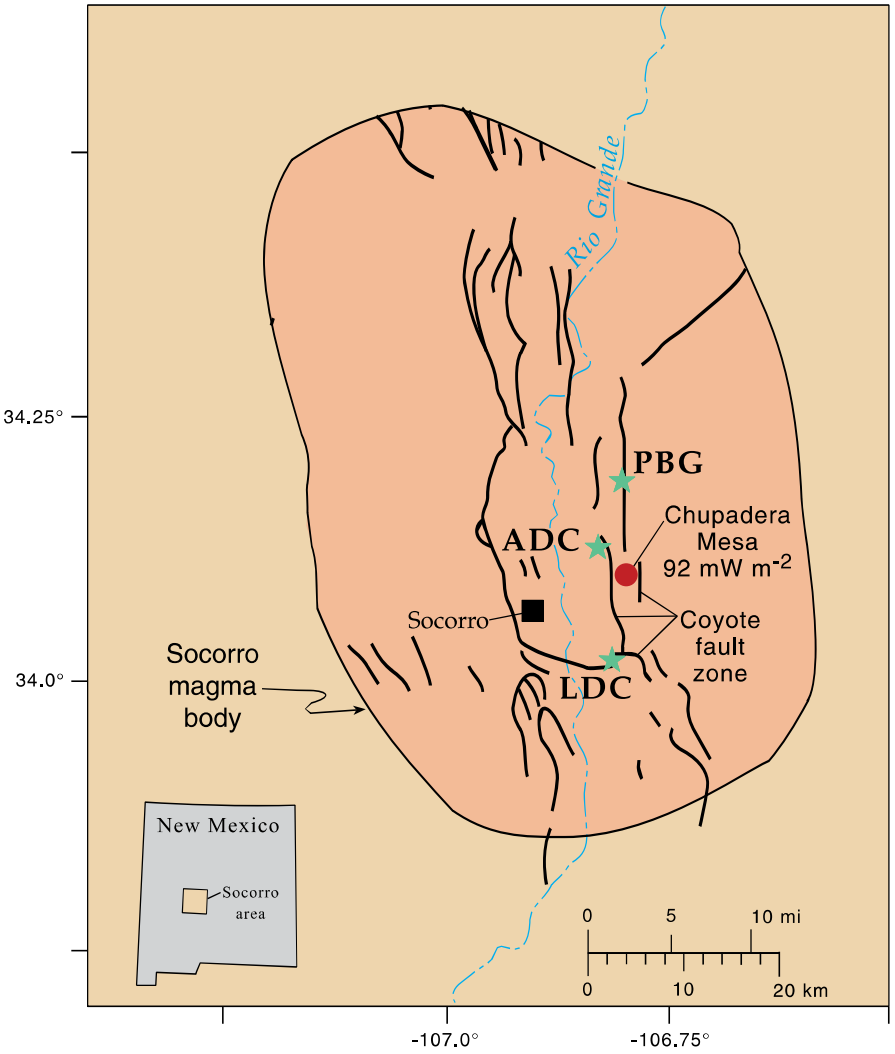

FIGURE 1—Study area near Socorro indicating the Socorro magma body and many of the Quaternary faults, notably the Coyote fault zone (Machette et al. 1998; Cather 1996). The Chupadera Mesa heat-flow site is shown (dot), as are the Puertecito de Bowling Green (PBG), Arroyo del Coyote (ADC), and Loma de las Cañas (LDC) swarm sites (stars); after Balch (1997) and Reiter (2005). Coordinates shown in decimal degrees.

At Chupadera Mesa, near the Arroyo del Coyote swarm site, the heat-flow measurement of 92 mW m^{-2} allows estimates of seismogenic layer temperatures. Fourteen events occur between 6.6 and 9.0 km depth. Including one standard deviation error bars the seismogenic layer is between 6 and 10 km depth (Hartse et al. 1992). Given a surface heat flow of 92 mW m^{-2}, temperatures at 6.6 km and 9.0 km are ~ 247°C and ~ 323°C (using conductive models by Lachenbruch and Sass 1978). Thermal conductivity and near surface radiogenic heat production at Chupadera Mesa are probably higher than values used in the subsurface temperature models (Reiter 2005), resulting in somewhat lower subsurface temperature estimates. A thermal conductivity of 2.9 W m^{-1} K^{-1} and surface radiogenic heat production of 2.9 μW m^{-3} yields temperatures at 6.6 km and 9.0 km of ~ 192°C and ~ 254°C. These temperature estimates for the seismogenic layer at Arroyo del Coyote overlap temperatures proposed for the semi-brittle zone of wet quartz, a zone where crustal strength is suggested to decrease (200–300°C; Kohlstedt et al. 1995; Reiter 2005).

San Andreas fault near Parkfield

Heat flow

The San Andreas fault is a major right-lateral strike-slip transform fault zone between the Pacific and North American plates. The area near Parkfield is quite dynamic, experiencing creep and recurring earthquakes over the past century. Heat-flow studies along the San Andreas fault provide valuable observations; for example, (1) the data do not show a thermal anomaly associated with frictional heat generated by strike-slip movement along a strong San Andreas fault with a coefficient of friction > 0.6, (2) the depth of the base of the seismogenic zone is related to the subsurface temperature regime, and (3) heat flow varies along and across the fault (Brune et al. 1969; Henyey and Wasserberg 1971; Lachenbruch and Sass 1980; Sass et al. 1997; Bonner et al. 2003; Williams et al. 2004). Sass et al. (1997) present 17 heat-flow measurements for the Parkfield region (Fig. 2); the mean value is 74 mW m^{-2}. These values are re-examined using three-dimensional terrain corrections and additional thermal conductivity considerations; the new mean is 77 mW m^{-2} and the variation is reduced from 38 to 27 mW m^{-2} (Williams et al. 2004). Fulton et al. (2004) consider terrain in the region and model topographically driven ground water flow effects on heat flow. They conclude ground water flow is not disguising a heat-flow anomaly. Extensive temperature data taken at the SAFOD (San Andreas Fault Observatory at Depth) site

TABLE 1—Summary of Coyote fault zone focal depths for LDC (Loma de las Cañas), ADC (Arroyo del Coyote), PBG (Puertecito de Bowling Green) best determined hypocenters. Data from Balch (1997); main event data at ADC from Hartse (1991).

Group	Main event			≥ 2		
Event magnitude	3.09[1]	3.77[1]	2.73			
Location	LDC	ADC	PBG	LDC	ADC	PBG
Average focal depth	6.96	8.17	8.73	5.7 ± 0.5[2] ± 0.4[3]	7.6 ± 0.4 ± 0.2	9.3 ± 0.5 ± 0.2
Number of events				2	4	5
Deepest event (km)				6.1	7.9	10.0
Shallowest event (km)				5.4	7.1	8.7

[1]Not included in the best determined hypocenters.
[2]Standard deviation of the data.
[3]Standard deviation of the mean (standard error).

to 2,200 m depth provide for a high-quality heat-flow measurement and show no thermal anomaly near the fault (91 ± 3 mW m^{-2}; Williams et al. 2004).

A heat-flow transition is suggested along the San Andreas fault near Middle Mountain with higher values to the northwest and lower values to the southeast (~ 89 mW m^{-2} and ~ 75 mW m^{-2} respectively; Williams et al. 2004). The closest revised heat-flow value to the 1966 magnitude 6 event at Middle Mountain is 78 mW m^{-2} (Fig. 2; Sass et al. 1997; Williams et al. 2004). The revised heat-flow value of 69 mW m^{-2} closest to the 2004 magnitude 6 event is perhaps less certain because: (1) the temperature log appears perturbed by ground water flow from ~ 190 to ~ 300 m, (2) thermal conductivity is estimated from formation averages of nearby sites, and (3) the six closest heat-flow values are variable (86, 91, 61, 77, 69, 69 mW m^{-2}; Sass et al. 1997; Williams et al. 2004).

Seismogenic layer

Bonner et al. (2003) and Williams et al. (2004) present studies relating heat flow to the depth of the bottom of the seismogenic layer near Parkfield. Bonner et al. (2003) indicate temperatures of ~ 350°C are reached at ~ 12 km depth along a profile crossing the San Andreas fault north of the SAFOD site. Earthquake activity is typically shallower than 12 km at this location, whereas isotherms and seismic activity deepen to the east. Williams et al. (2004) show the 350°C isotherm is at ~ 11.5 km depth just northwest of Middle Mountain, and most events are shallower than those to the southeast. Southeast of Middle Mountain the 350°C isotherm deepens to ~ 14 km, and little seismic activity occurs deeper.

The 1966 magnitude 6 event near Middle Mountain occurred at a depth of ~ 8.6 km or 9.0 ± 0.4 km (Southern California Earthquake Data Center; Nadeau and McEvilly 1999). The recent 2004 magnitude 6 event ~ 11 km south-southeast of Parkfield occurred at ~ 7.9 km depth (California Integrated Seismic Network). Within measurement error, these two hypocenter depths are approximately the same as the depth for the main event at Arroyo del Coyote (8.2 ± 0.9 km). Table 2 presents

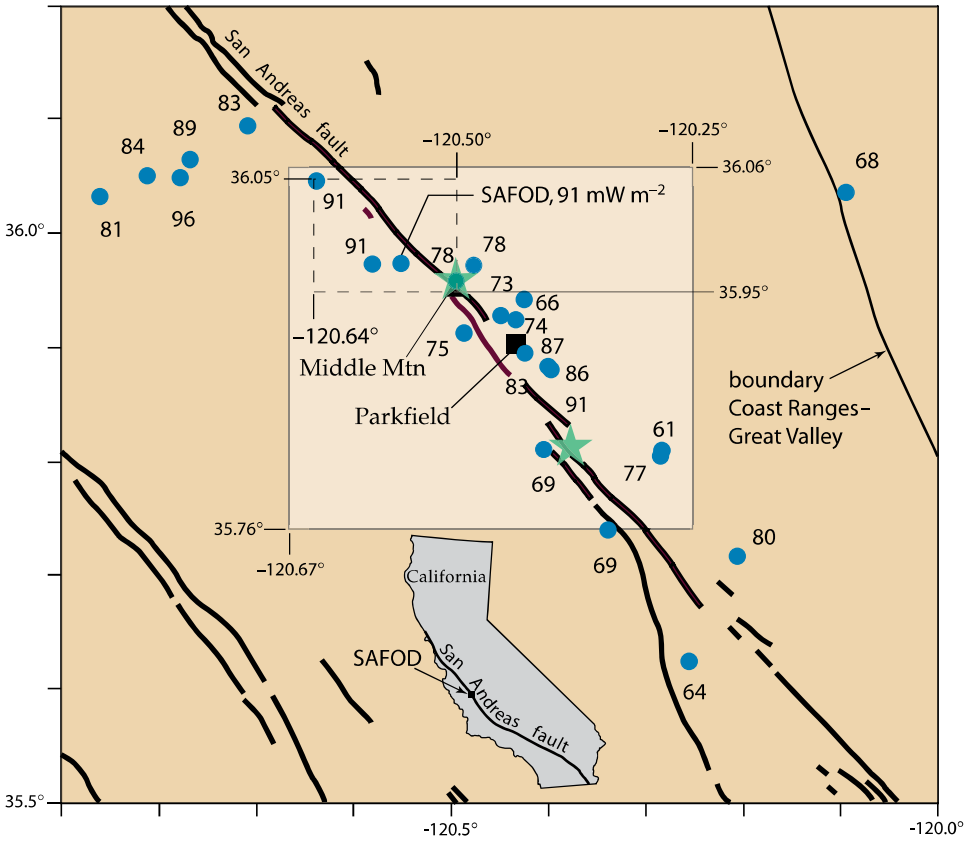

FIGURE 2—Heat-flow data and areas of consideration for seismic events near Parkfield. Base map after and modified from Williams et al. (2004). Dots indicate heat-flow sites, values in mW m^{-2}, data from Lachenbruch and Sass 1980; Sass et al. 1997; Williams et al. 2004. Heavy lines are active faults. Magnitude 6 events indicated by stars, event locations from Southern California Earthquake Data Center and California Integrated Seismic Network. SAFOD is the San Andreas Fault Observatory at Depth. Coordinates shown in decimal degrees.

event magnitude and focal depths, north and south of Middle Mountain in the Parkfield region (Fig. 2). Magnitude > 5 hypocenters north of Middle Mountain are deeper than those to the south; however, the number of events is small. Magnitude > 4 hypocenters north of Middle Mountain are again deeper than those to the south, although the statistical difference is not definitive (the means do not differ by twice the sum of the standard errors). Magnitude > 3 events north of Middle Mountain do have a mean depth less than the mean depth of events to the south, although again this is not statistically definitive. The trend of the mean focal depth for all events > 3 is implicitly consistent with a shallower cutoff depth for the seismogenic layer north of Middle Mountain. Interestingly Tables 2 and 3 show that the mean focal depth of events south of Middle Mountain does not change with increasing number of events (decreasing magnitudes); however, the mean depth of events north of Middle Mountain, and also in the smaller area around SAFOD, does decrease with increasing numbers.

The seismogenic layers in the Parkfield locations overlap the seismogenic layer along the Coyote fault, but are of much greater thickness and therefore cover a much greater temperature range. Nadeau

	≥ 1			≥ 0		
	LDC	ADC	PBG	LDC	ADC	PBG
	6.2 ± 0.4 ± 0.1	7.8 ± 0.7 ± 0.1	9.5 ± 0.4 ± 0.1	6.2 ± 0.4 ± 0.04	8.0 ± 0. 6 ± 0.05	9.5 ± 0.4 ± 0.05
	31	28	32	105	135	65
	6.9	9.2	10.5	7.1	10.1	10.5
	5.4	6.1	8.7	5.1	6.1	8.7

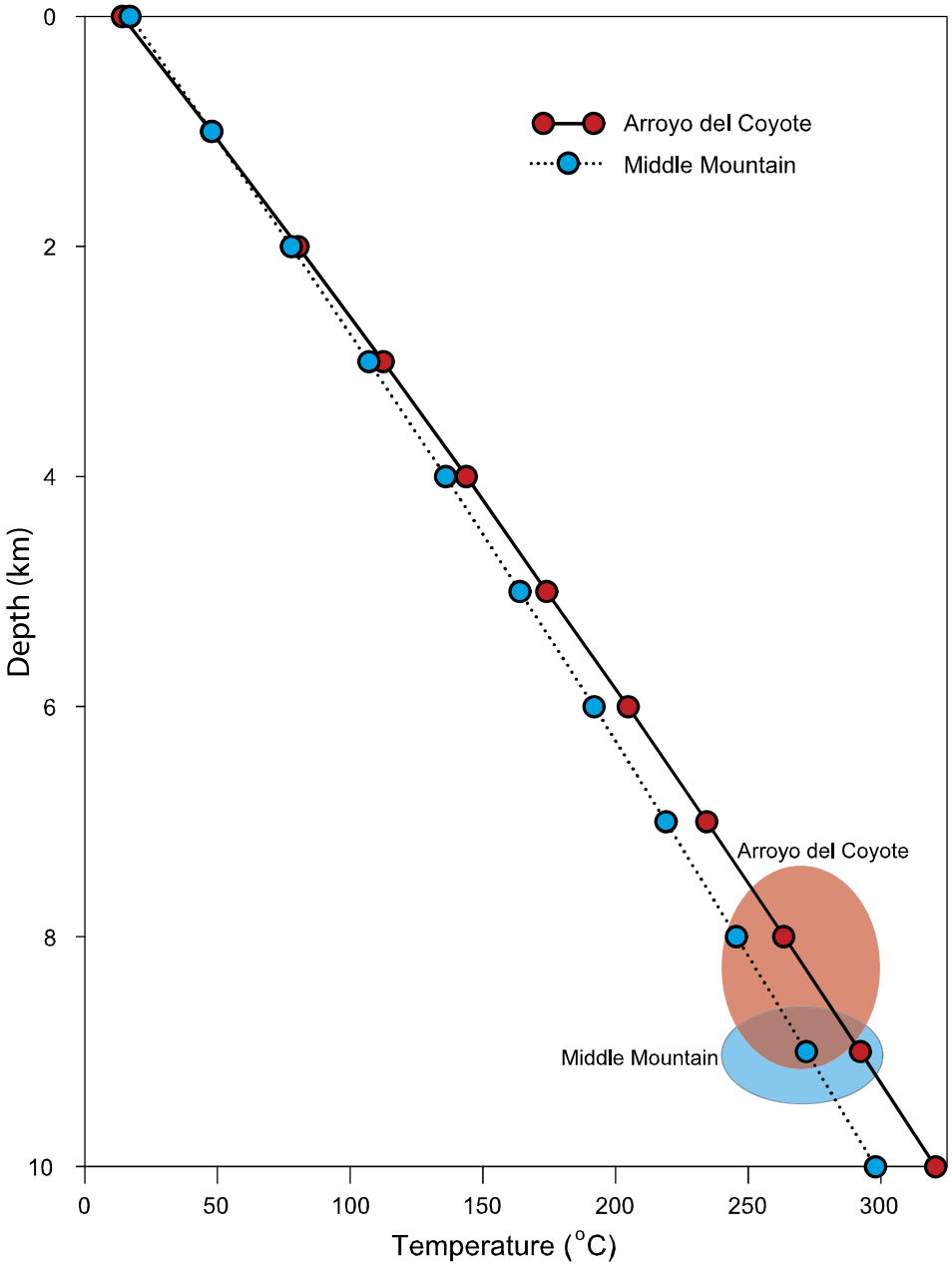

FIGURE 3—Temperature profiles for Arroyo del Coyote and Middle Mountain. Main event focal depth and associated temperature uncertainty ellipsoids shown. Temperatures calculated for steady state conduction model from Lachenbruch and Sass (1978).

and McEvilly (1999) show four main magnitude > 4 events, occurring in 1992–1994, at locations from ~ 2 km southeast to ~ 4 km northwest of Middle Mountain. These events occur between ~ 5.6 and ~ 9.4 km depth, at temperatures likely within the semi-brittle zone (~ 200–300°C).

Discussion

The mean focal depth near the SAFOD site for magnitude > 3 events (8.2 ± 2.6 km) is statistically the same as the mean focal depth at Arroyo del Coyote for events of magnitude > 0 (8.0 ± 0.6 km; Tables 1 and 3). The measured surface heat flows at these locations are the same, suggesting similar subsurface temperature regimes at mean focal depths. At both locations the seismogenic layer depth interval increases with increasing number, or decreasing magnitude, of events; suggesting conditions for smaller events exist over a larger depth interval than conditions for larger events. The seismogenic layer at SAFOD occurs over a much larger depth interval than the seismogenic layer at Arroyo del Coyote (8.5 vs. 4.0 km, Table 1, events ≥ 0; and Table 3, events ≥ 3). Greater strains and strain rates with larger and more frequent events near SAFOD likely affect in situ stress conditions over much larger volumes.

If the main events near SAFOD and Arroyo del Coyote result from processes largely dependent on regional tectonic stresses interacting with rock rheology and fault strength, estimating temperatures at the main hypocenters will provide insight into preferential thermal conditions for generating these strike-slip main events. In the SAFOD area the revised heat-flow value near the 1966 magnitude 6 event is 78 mW m^{-2} (Williams et al. 2004). Estimates of the hypocenter depth are 8.6 km and 9.0 ± 0.4 km (Southern California Earthquake Data Center; Nadeau and McEvilly 1999). From conduction models presented in Lachenbruch and Sass (1978) the temperature estimate at 9 km is ~ 272°C. The temperature uncertainty associated with hypocenter uncertainty is ~ ± 10°C, whereas, the uncertainty associated with a ± 10% heat-flow value (Sass et al. 1997) is ~ ± 30°C.

Heat flow at the Chupadera Mesa site is 92 mW m^{-2} (Reiter et al. 1975). The focal depth is 8.2 ± 0.9 km (Hartse 1991). Crustal thermal conductivity and radiogenic heat production are probably greater at the Chupadera Mesa site than the values used in the above conduction models for the Parkfield location (2.9 vs. 2.5 W $m^{-1}K^{-1}$ and 2.9 vs. 2.1 μW m^{-3} respectively; Reiter 2005). If values mid-way between these parameter estimates are used, the calculat-

TABLE 2—Summary of Parkfield area focal depths (07.01.66–10.17.04). Parkfield area defined: 35.76° to 36.06° latitude, -120.25° to -120.67° longitude. Coordinates given in decimal degrees. Data from Northern California Earthquake Data Center.

Event magnitude	**≥ 5**		**≥ 4**		**≥ 3**	
Location from Middle Mtn.	North	South	North	South	North	South
Mean focal depth (km)	11.2 ± 0.6[1] ± 0.3[2]	8.9 ± 0.2 ± 0.1	10.6 ± 1.4 ± 0.5	9.1 ± 1.3 ± 0.4	8.4 ± 3.2 ± 0.4	8.8 ± 2.2 ± 0.2
Number of events	4	2	7	13	57	102
Deepest event (km)	11.7	9.1	11.9	11.5	19.1 (13)[3]	12.4
Shallowest event (km)	8.5	8.8	8.5	6.7	0.2 (4.4)[4]	2.5

[1]Standard deviation of the data.
[2]Standard deviation of the mean (standard error).
[3]Second deepest.
[4]Second shallowest.

ed temperature at 8.2 km is ~ 269°C. High and low estimates for thermal conductivity and radiogenic heat production yield temperature uncertainties of ~ ± 24°C at the focal depth, whereas the uncertainty associated with focal depth is ~ ± 26°C and a heat-flow variation of ± 10% could change temperatures by ~ ± 28°C. I suggest that temperatures at the hypocenters of the Middle Mountain and Arroyo del Coyote main events are ~ 270 ± ~ 30°C. Temperature-depth profiles for Arroyo del Coyote and Middle Mountain are presented in Figure 3 along with uncertainty ellipsoids for focal depths and hypocenter temperatures. Uncertainties in the amount of under-plating, crustal intrusion and extension, and crustal characteristic radiogenic depth can also contribute several tens of degrees uncertainty to temperature estimates.

Conclusion

The best estimate of hypocenter temperatures at two main strike-slip event sites, one at Middle Mountain, California, and one at Arroyo del Coyote, New Mexico, is ~ 270 ± ~ 30°C. The hypocenter temperatures appear to be similar at these two sites with very different tectonic settings and very different magnitude main events. This observation suggests a potentially similar relationship between regional tectonic stresses and the dependence of crustal or fault strength on temperature at the two locations. A temperature of 270°C is in the higher part of the temperature range suggested for the semi-brittle zone of wet quartz (~ 200–300°C; Kohlstedt et al. 1995), a transition zone between brittle behavior and plastic flow across which crustal strength is suggested to decrease. If hypocenter temperatures can be better estimated with future measurements at the discussed locations (e.g. ± 5 to ± 10°C), a more definitive relation between temperature and focal depth may result.

The relatively small events along the Coyote fault appear to affect the local stress field over a small enough volume that the best determined focal depths for the swarm events are within a seismogenic layer that significantly overlaps semi-brittle zone temperatures. The swarm locations are also distinctly separated. Separation of swarm sites should allow future heat-flow measurements along the Coyote fault to explicitly relate subsurface temperatures to different seismogenic layer depths and main event focal depths

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TABLE 3—Summary of SAFOD area focal depths: 01.09.69–09.30.04. SAFOD area defined: 35.95° to 36.05° latitude, -120.50° to -120.64° longitude. Coordinates given in decimal degrees. Data from Northern California Earthquake Data Center.

Event magnitude	≥ 5	≥ 4	≥ 3	≥ 2
Mean focal depth (km)	11.0 ± 0.5[1] ± 0.3[2]	9.7 ± 1.9 ± 0.8	8.2 ± 2.6 ± 0.4	
Number of events	3	6	46	632
Deepest event (km)	11.5	11.9	12.9	17.3
Shallowest event (km)	10.4	8.5	4.4	0.02

[1]Standard deviation of the data.
[2]Standard error.

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Conversions of metric measurements used in this article

Metric	English	Metric	English
Length/depth/thickness		Area	
100 m	328 ft	3,400 km^2	1,313 mi^2
190 m	623 ft		
300 m	984 ft		
2,200 m	7,218 ft		
2.0 km	1.2 mi	Temperature	
4.0 km	2.5 mi	192 °C	378 °F
5.6 km	3.5 mi	200 °C	392 °F
6.0 km	3.7 mi	247 °C	477 °F
7.0 km	4.3 mi	254 °C	489 °F
7.9 km	4.9 mi	269 °C	516 °F
8.0 km	5.0 mi	270 °C	518 °F
8.2 km	5.1 mi	272 °C	521 °F
8.5 km	5.3 mi	300 °C	572 °F
8.6 km	5.3 mi	323 °C	613 °F
9.0 km	5.6 mi	350 °C	662 °F
9.4 km	5.8 mi		
10.0 km	6.2 mi		
11.0 km	6.8 mi		
11.5 km	7.0 mi		
12.0 km	7.5 mi		
14.0 km	8.7 mi		
19.0 km	11.8 mi		

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