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Thermal considerations and the Cajon Pass borehole†

by

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WHY DO WE WANT TO KNOW ABOUT HEAT FLOW ON THE SAN ANDREAS FAULT?

We want to know about the magnitude of fault friction and the stresses that cause earthquakes and resist plate motion. Figure 1 is a simple schematic representation of an earthquake as an unloading elastic spring. The work done during the earthquake is the area under the curve passing linearly from an initial stress (τ^*) to a final stress (τ') as the displacement increases. This work is the sum of the kinetic energy of elastic radiation (crosshatched area in Figure 1 which is work done by the apparent stress τ_a), and the energy that is dissipated and probably converted largely to heat (the shaded area in Figure 1 which is work done against the resisting stress $\bar{r}$). Seismologists report that τ_a is small (only a few tens of bars) and consequently whether the total elastic stress ($\tau_a+\bar{r}$) is large or small depends upon whether the frictional resistance ($\bar{r}$, Figure 1) is large or small. Many people who measure in situ stress and rock friction think the average fault friction should be large, say a few hundred bars to a kilobar. If that is true, a substantial local heat-flow anomaly, as illustrated in Figure 2, should develop over the fault in a million years or so. This suggests that heat-flow measurements in the vicinity of the fault should permit us to tell whether the tectonic stresses that cause earthquakes and resist plate motion are large or small.

WHAT HAVE WE LEARNED ABOUT HEAT FLOW ON THE SAN ANDREAS FAULT?

Over the last 20 years, about a hundred measurements of heat flow have been made in the vicinity of the San Andreas fault, and no evidence has been found for a local heat-flow anomaly there. This is illustrated by the data in Figure 3 taken from the Mojave segment of the fault zone (Figure 4). If there had been an average fault friction of only 500 bars, we should expect a heat-flow anomaly over the fault similar to that shown in the bottom of the figure. Note that with the possible exception of the uncorrected Cajon Pass data, there is no evidence for such a local anomaly. We shall return to a discussion of Cajon Pass later, but note here that the star represents the uncorrected heat flow at depth in the granitic rock there and the line represents a range of possible heat flows (corresponding to a range of possible porosities) in the overlying 2,000 feet of sediment. In Figure 5, histograms show that there is no significant difference between heat-flow near the fault and distant from the fault. Thus on the basis of observations made prior to those at Cajon Pass, we concluded that there was no observational evidence for a heat-flow anomaly over the fault inspite of experimental evidence for high friction; a paradox. (This problem was first discussed in a thesis by Tom Henyey in 1968, and subsequently in papers by Brune, Henyey and Roy, 1969; Henyey and Wasserburg, 1971 and Lachenbruch and Sass, 1973, 1980.)

These observations raise the following question: Is the friction high at depth but the frictional heat is carried off (e.g., by moving groundwater or some other sink), or is the friction low at all depths, for example, because of anomalously high fluid pressure or low friction coefficients? The alternatives are illustrated in Figure 6. For the high stress case, the gradient diminishes in the fractured upper layers because of a hypothetical circulation pattern that sweeps the heat away from the fault. Under such circumstances, the gradient and heat flow should increase with depth as we get into less fractured rock where the circulation is less intense. If the frictional heat were not removed, then according to the heat-flow observations, very little could be generated at depth, and frictional stresses greater than 100 bars would generally be inconsistent with the observations. To resolve this paradox, it is desirable to make heat flow and stress observations to depths of several kilometers in the fault zone. By far the deepest hole so far available from the San Andreas fault is the one at Cajon Pass, and it is instructive to see what we can learn from that before proceeding to drilling deeper ones.

WHAT HAVE WE LEARNED FROM THE DEEP HOLE AT CAJON PASS?

Figures 7A and C show equilibrium temperature measurements to a total depth of about 1.8 km at the Cajon Pass well. The profile has two noteworthy features: 1) the gradient is high, about 35°C/km, and 2) this gradient is the same in the low porosity granitic rock beneath 2,000 feet and the higher porosity sandstone lying above, in spite of the fact that the latter must have a lower thermal conductivity. Figure 7B shows the thermal conductivity as a function of depth determined from the drill cuttings. This represents the conductivity of the solid portion of the rock, i.e., with 0 porosity. The average value is almost identical for the sandstone and the granite (approximately 2.8 SI Units). These "chip" conductivity values provide an excellent approximation for the conductivity of intact granite, but they must be reduced substantially to accommodate the effects of porosity in the sandstone. Thus we can determine the "uncorrected" heat flow in granite with considerable confidence. It is about 100 mW/m^2 -- 40% higher than the background heat flow along this section of the San Andreas fault (see Figure 3). The vertical heat flow in the sandstone is less by an amount depending on the (unknown) porosity of the sandstone. If the porosity should be only 10% or less, the heat flow would be close to the value obtained in the granite. If the porosity were 20% or more, the heat flow in the upper 2,000 feet of sandstone would be about the same as the background heat flow measured along this region of the fault (see Figure 3). The Cajon Pass hole differs from the other observation holes in two respects: 1) it is much deeper, and 2) the uncorrected heat flow, at least in the deeper parts, is much higher. This can be seen in Figure 8 which compares the profiles in granitic rocks at the other sites with the profile from Cajon Pass.

Is the uncorrected heat flow higher at Cajon Pass because the hole is deeper or because the site is anomalous? Would we have found low heat flow and a paradox at Cajon Pass if the hole there were no deeper than the others studied from the area? The answer may depend upon the porosity of the sandstone. If the porosity is high, then the surface heat flow would be low suggesting resolution of the paradox in favor of high stress (high heat flow at depth; low heat flow near surface, Figure 6). If the porosity of the sandstone is low, the heat flow must be high at the surface as well, in which case there is no paradox at Cajon Pass. (In either case, it would seem that there is little to be gained from a deeper hole at this site to investigate the paradox.) Thus taken at face value, the existing Cajon Pass data might be viewed as supporting the high-stress model and probably as being quite anomalous relative to the existing observations. Before making such a conclusion, however, it is important to look at the complicated site conditions and their possible effects on these conclusions at Cajon Pass. In Figure 9, the upper diagram shows the simple horizontal stratified model usually assumed when sandstone overlies granite. The model requires that the heat flow be the same in both strata and the gradient must change if the conductivity does. This model, therefore, does not represent conditions at Cajon Pass (see Figure 7A). The second diagram shows some other extremes; if the hole were drilled in a narrow faulted pocket of sandstone with steep contacts, the vertical gradient would be approximately the same in both media (as observed in Figure 7A), and the appropriate conductivity to use would be the value for granite (leading to the high heat-flow estimate). On the other hand, if the granite should occupy a narrow vertically faulted region surrounded by sandstone, the gradient again would not change at the contact, but the conductivity of the sandstone would be the appropriate one to use leading to a low heat-flow estimate. Because these two conductivities (and heat-flow estimates) could differ by 40%, the uncertainty in this structural effect could, by itself, accommodate the discrepancy between the high uncorrected heat flow at Cajon Pass and the background measured elsewhere. [The lower diagram shows transitional effects of changing the contact angle. When the contact approaches the vertical, the gradient contrast again vanishes as observed. In this case the appropriate conductivity for calculating the crustal heat flow would be the average for the values of sandstone and granite.] We know that the structure is very complex at the Cajon Pass site and the purpose of this illustration is to demonstrate that extreme local complexities could affect our interpretation substantially; the matter probably would be resolved by deep drilling.

An additional thermal complication at Cajon Pass relates to its history of extremely active sedimentation and erosion. From his recent mapping, Ray Weldon (oral communication) estimates that about a kilometer of sandstone was probably deposited at the site during the last 1-3 m.y. and that somewhat more was subsequently eroded off during the last million years. Figures 10 and 11 give an indication of what sort of thermal effect these processes might leave behind. Figure 10 is a simple model for instantaneous deposition. It is seen from the shaded area (Figure 10B) that the effect would be to reduce the gradients observed today by perhaps 5-10%; this effect would not be substantially different at the bottom of a 5-km hole than at the near-surface. On the other hand, the erosion (Figure 11) can have a substantial effect on the gradient and probably is resulting in an increase in the heat flow at the site today. The model is for erosion of 1 1/3 km occurring uniformly over the last million years; it would bring the surface down and increase the gradient and heat flow accordingly (shaded regions, Figure 11). Judging from Figure 11B, erosion might have increased the heat flow we have observed by 25-30%. This is somewhat less than the observed anomaly, but it is enough to account for much of it. It is seen that for this particular model, we would expect the correction to be less in the bottom of the existing hole than at the surface, an effect not observed, and that in any case the erosion effect would be substantially reduced at the bottom of a 5-km hole.

These complications relating to structure, sedimentation, and erosion arise from complex tectonic conditions at the site. Although their thermal effects can probably be resolved by deep drilling, they add additional unknowns that could reduce the confidence of our ultimate interpretation of heat flow versus depth.

WHAT CAN BE LEARNED FROM MORE DRILLING AT CAJON PASS?

As we have seen, at face value, the Cajon Pass site looks anomalous relative to heat-flow measurements in the vicinity, but our uncorrected estimate may contain substantial disturbances from rapid erosion, structure, and perhaps hydrology that could change this view. With more complete information obtained in a hole to a depth of several kilometers, the basic questions that we should like to resolve are as follows:

1) Do heat flow, shear stress, and hydraulic head vary with depth? How?

2) Are they consistent with frictional models of faulting? What are the model parameters?

3) Is the frictional dissipation anomalous at Cajon Pass. If yes, is this related to fault geometry, arresting and initiation of rupture, or other local manifestations of fault behavior?

A complete answer to the third question in particular might have to await additional deep drilling in a portion of the fault with a more typical near-surface thermal regime.

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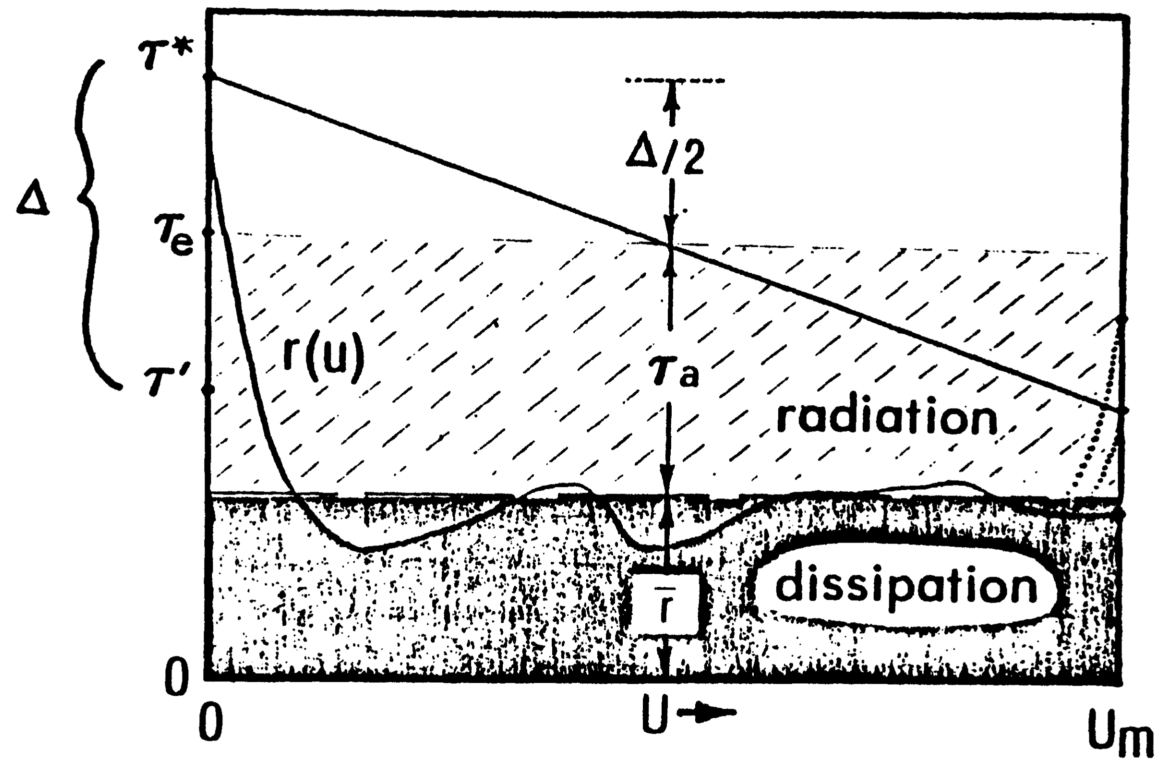

Figure 1. Schematic representation of relations among averaged values of initial stress τ^*, final stress τ', dissipative resistance $\bar{r}$, apparent stress τ_a, mean elastic stress τ_e, and stress drop Δ for an event with mean total displacement u_m.

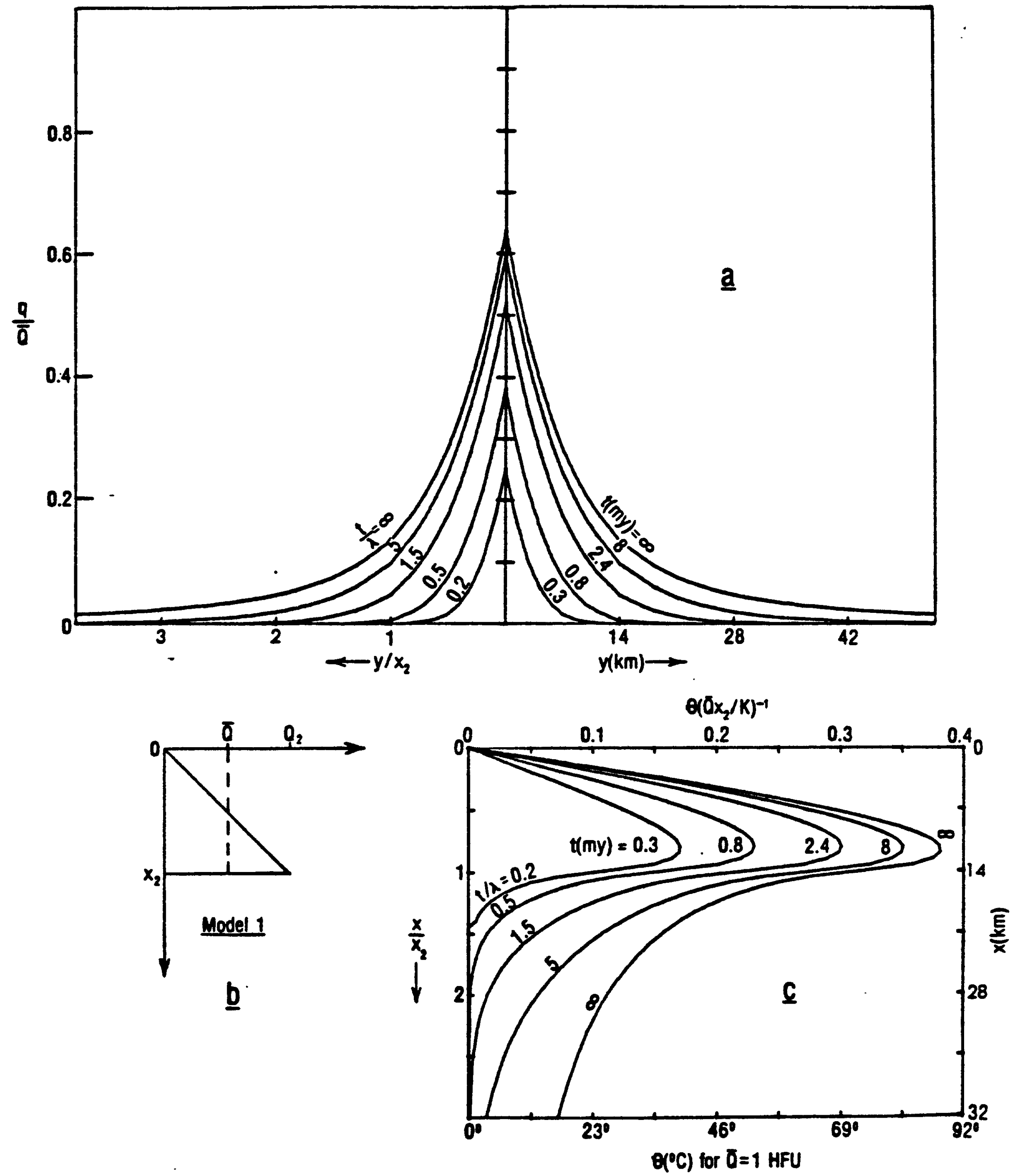

Figure 2. Surface heat flow q (part a) and fault plane temperature θ (part c) for a linear increase in source strength to depth x_2 (part b). t is time since initiation of faulting, and $\overline{Q}$ is average rate of frictional heat generation on fault. Dimensional results are for $x_2 = 14$ km, K = 6 mcal/cm s °C, and $\overline{Q} = 1$ HFU (equivalent to $2v \simeq 25$ mm/yr, $\overline{\tau} \simeq 500$ b).

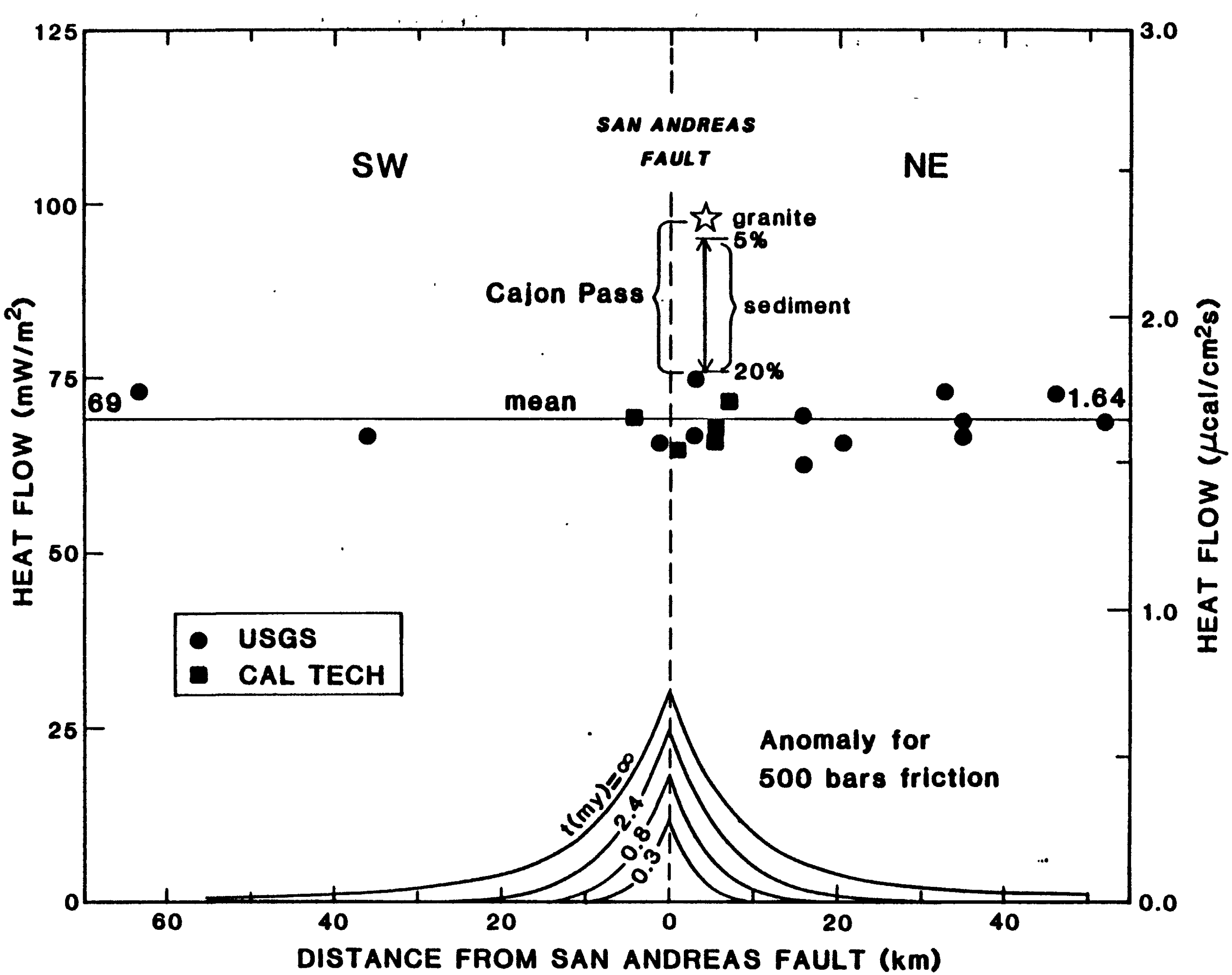

Figure 3. Heat flow versus distance from main trace of San Andreas fault in Mojave Segment (see Figure 4). Theoretical anomaly is for a slip velocity of 25 mm/yr and friction of 500 b computed from Figure 2. Uncorrected values from Cajon Pass are for granite (star) and sediments with porosity range from 5% to 20%.

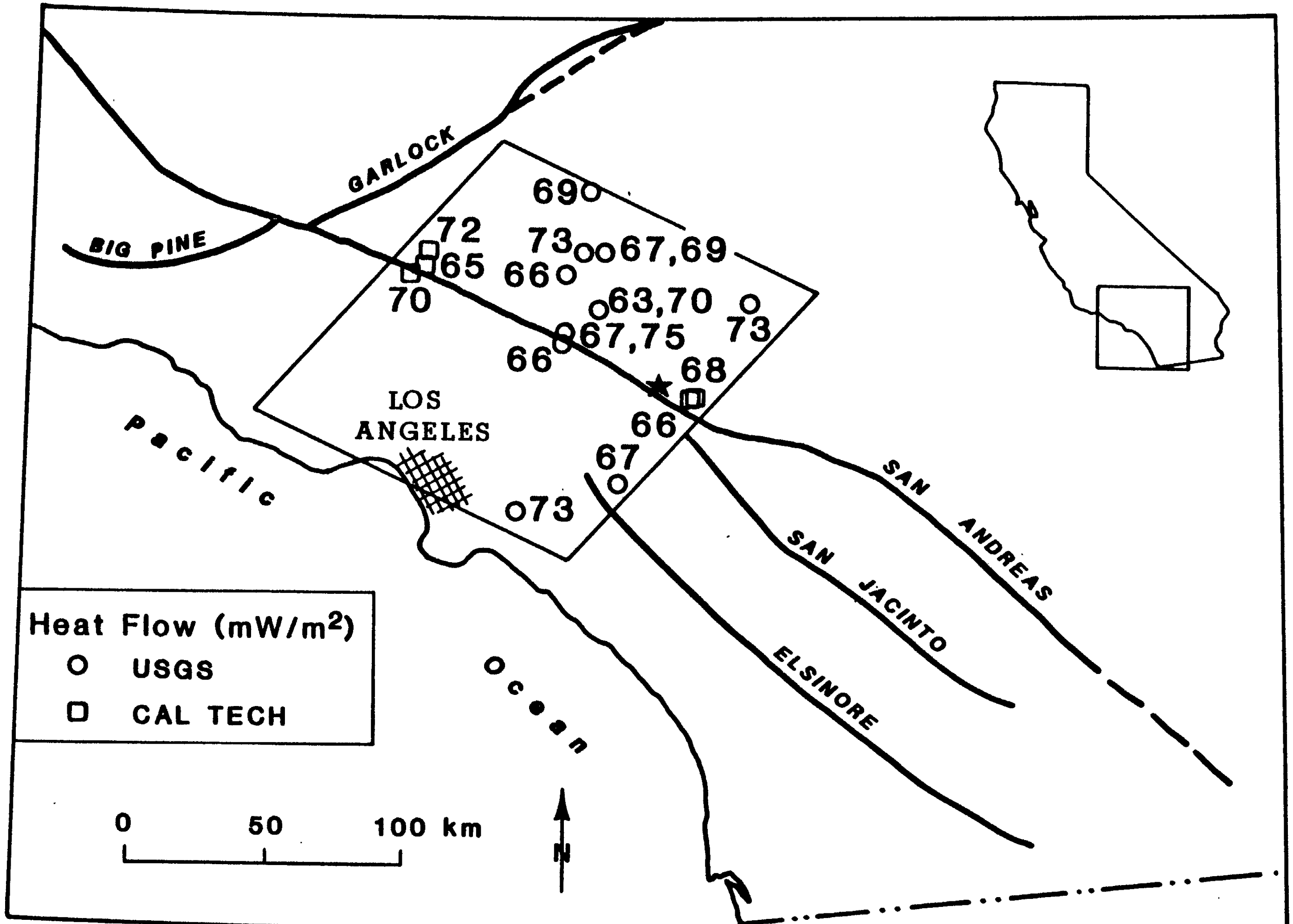

Figure 4. Heat-flow data from Mojave Segment of San Andreas fault (see Figure 3). Star shows location of Cajon Pass borehole.

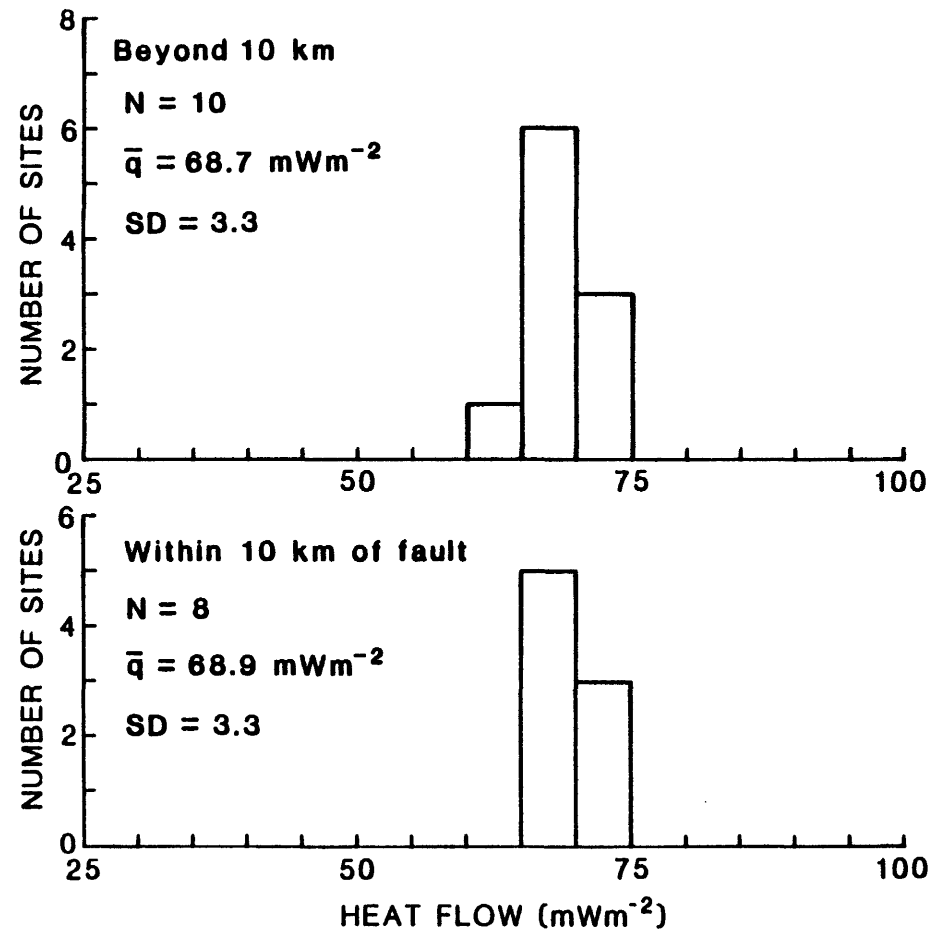

Figure 5. Statistics for heat flow in Mojave Segment of San Andreas fault zone.

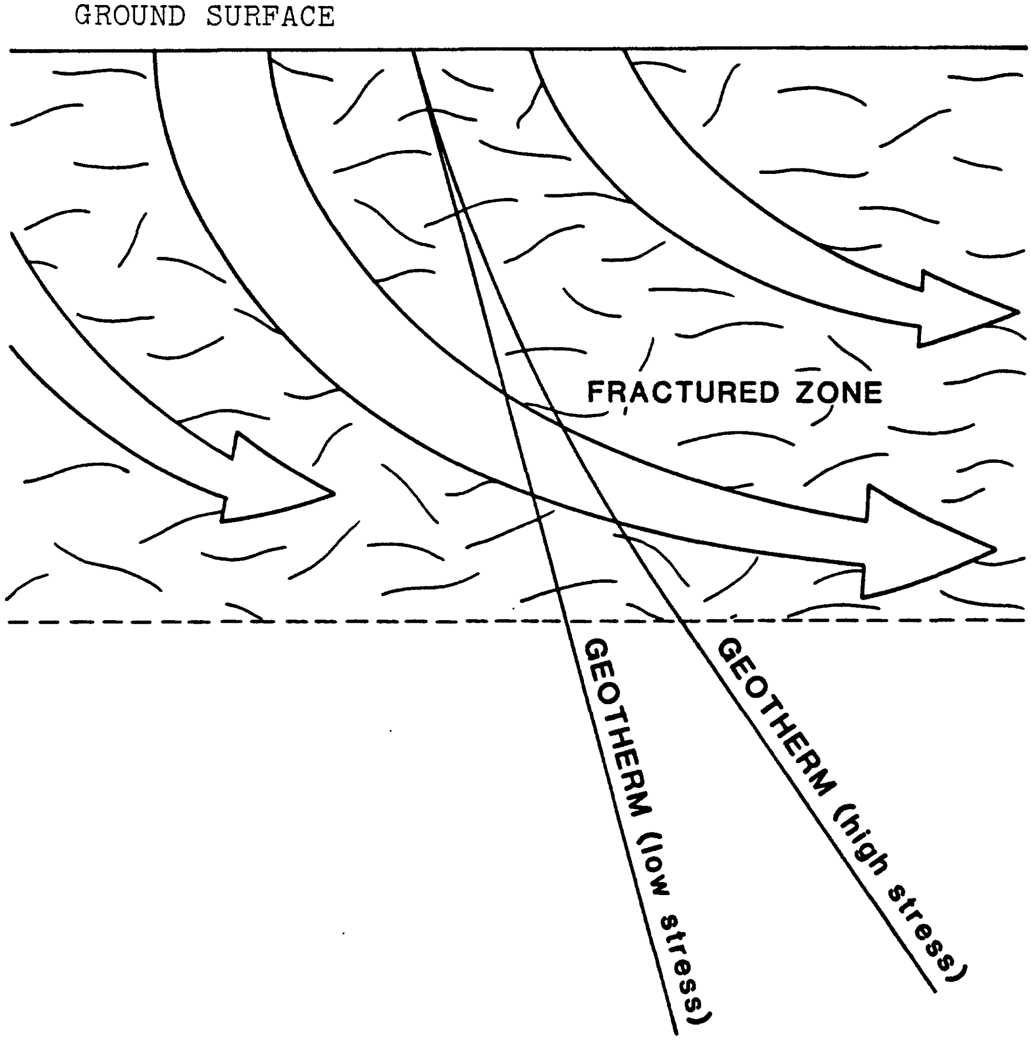

Figure 6. Schematic representation of water flow in a near-surface fracture zone removing heat to permit high stress and high heat flow at depth.

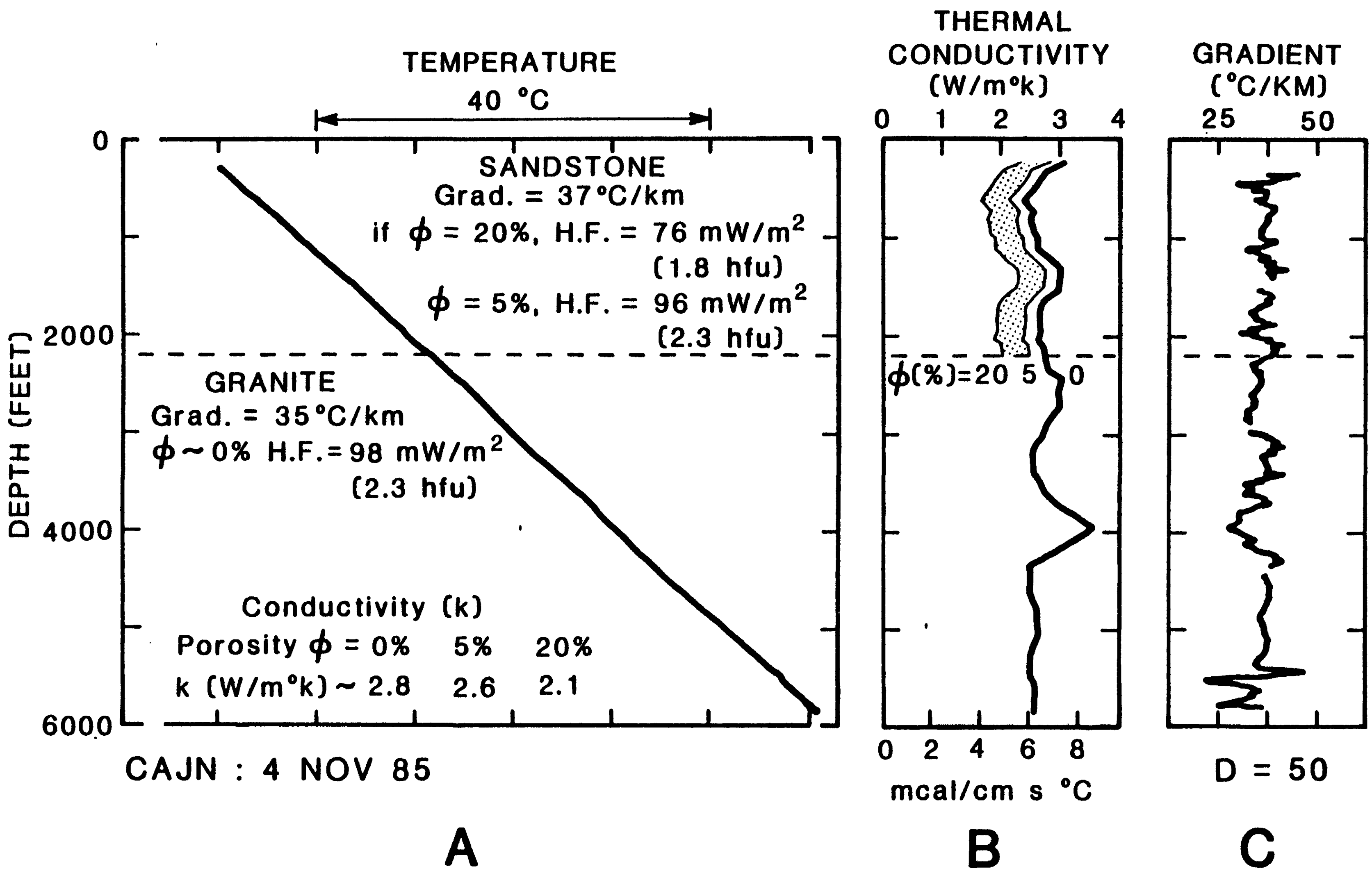

Figure 7. Data from Cajon Pass borehole. A, equilibrium temperature profile; B, heavy curve is conductivity of solids measured at 30-meter intervals on drill cuttings. Stippled region is range of sediment conductivity calculated for porosities from 5%-20%. C, thermal gradient for profile shown in a.

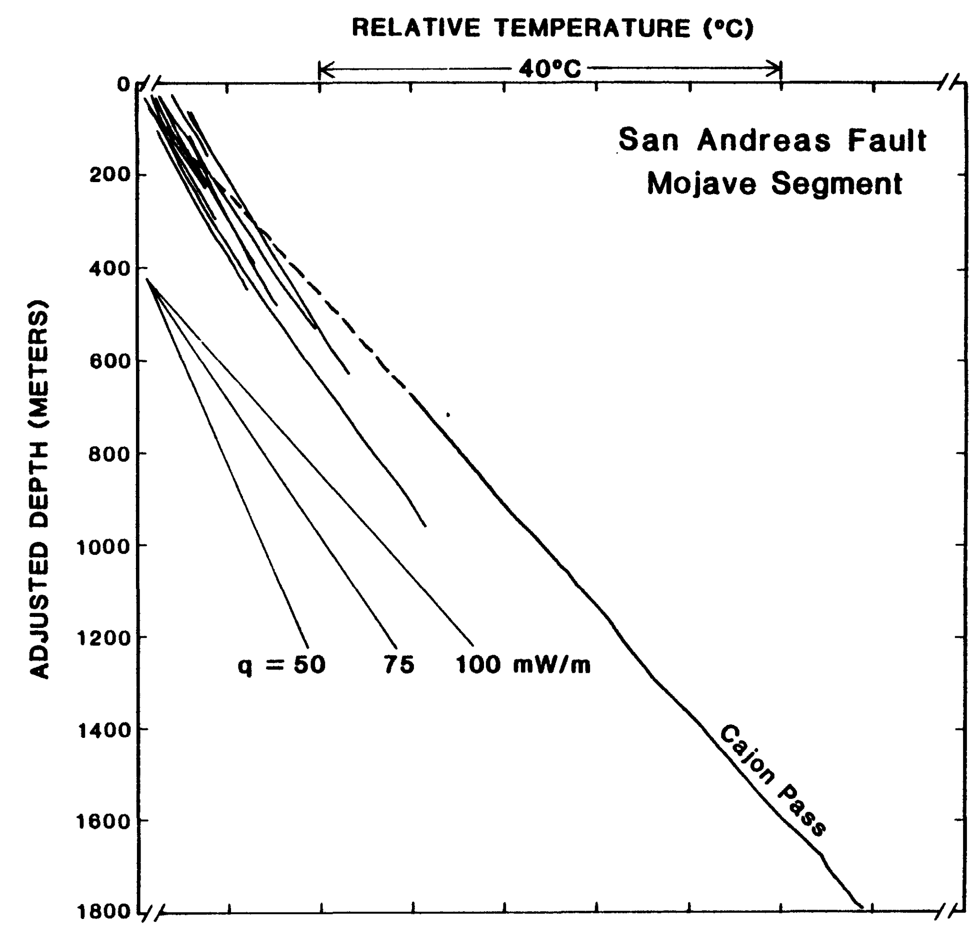

Figure 8. Comparison of temperature profile at Cajon Pass with other profiles in granitic rock near the fault in the Mojave Segment. Depth scale has been adjusted for variations in average thermal conductivity in each hole.

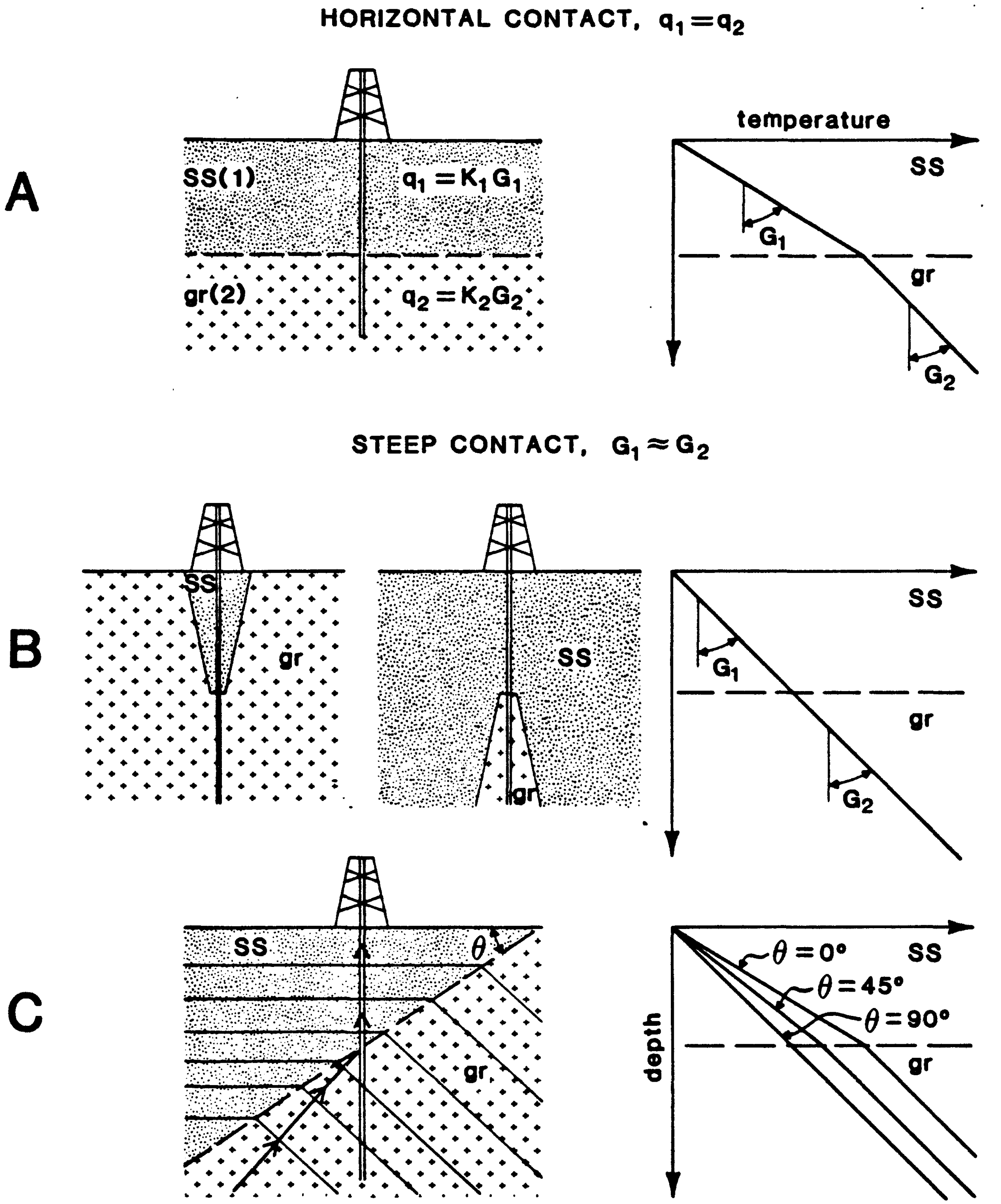

Figure 9. Effects of thermal refraction at a contact of rocks with contrasting conductivity. A, horizontal contact causes the expected gradient contrast. B, contrasting bodies with large depth-width ratios, or C, steeply dipping contacts are consistent with no gradient contrast and widely differing interpretations of crustal heat flow.

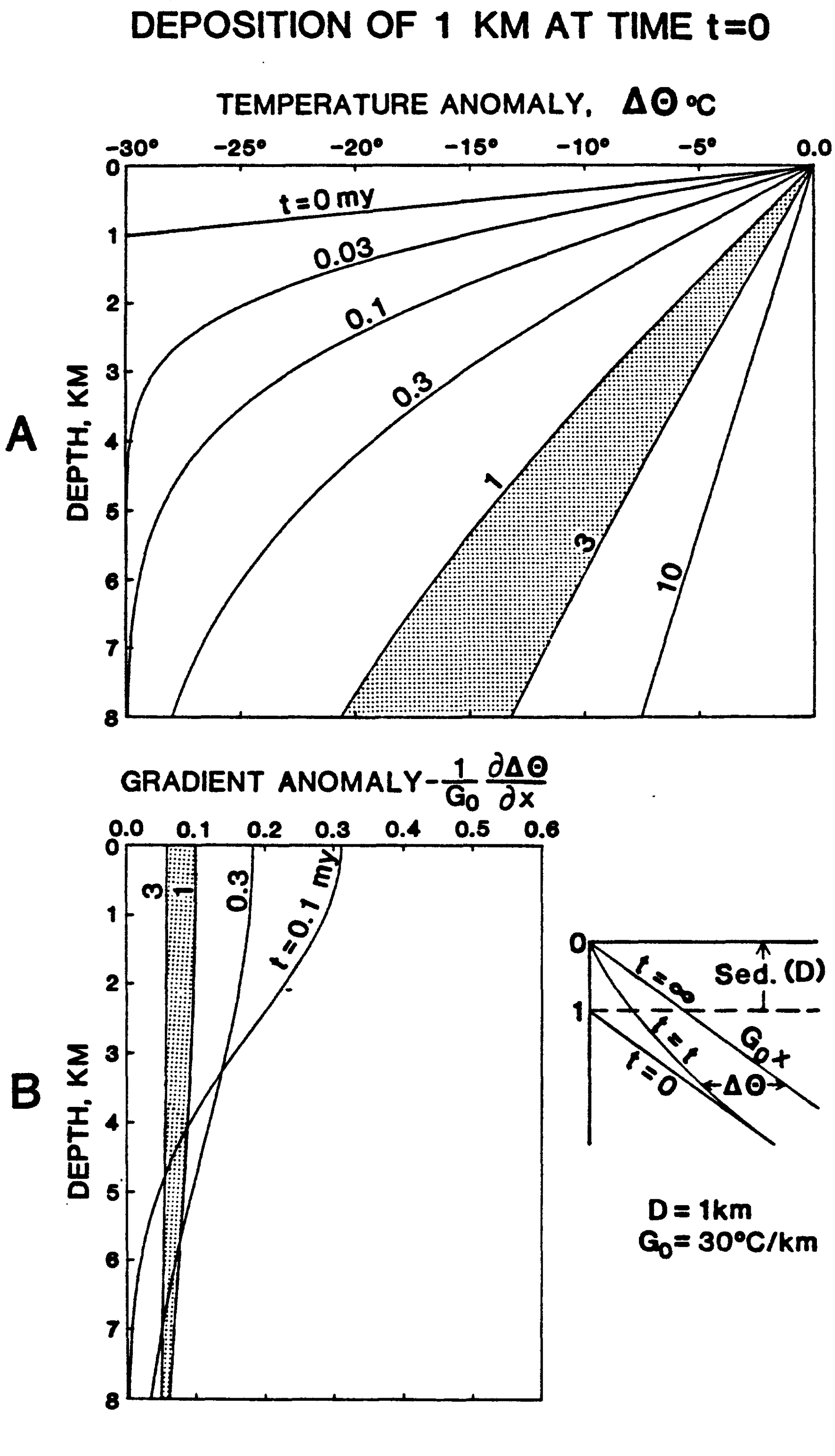

Figure 10. Reduction of temperature (A) and gradient (B) caused by instantaneous deposition of 1 km of sediments. Approximation for Cajon Pass lies between curves for t = 1 and 3 m.y.

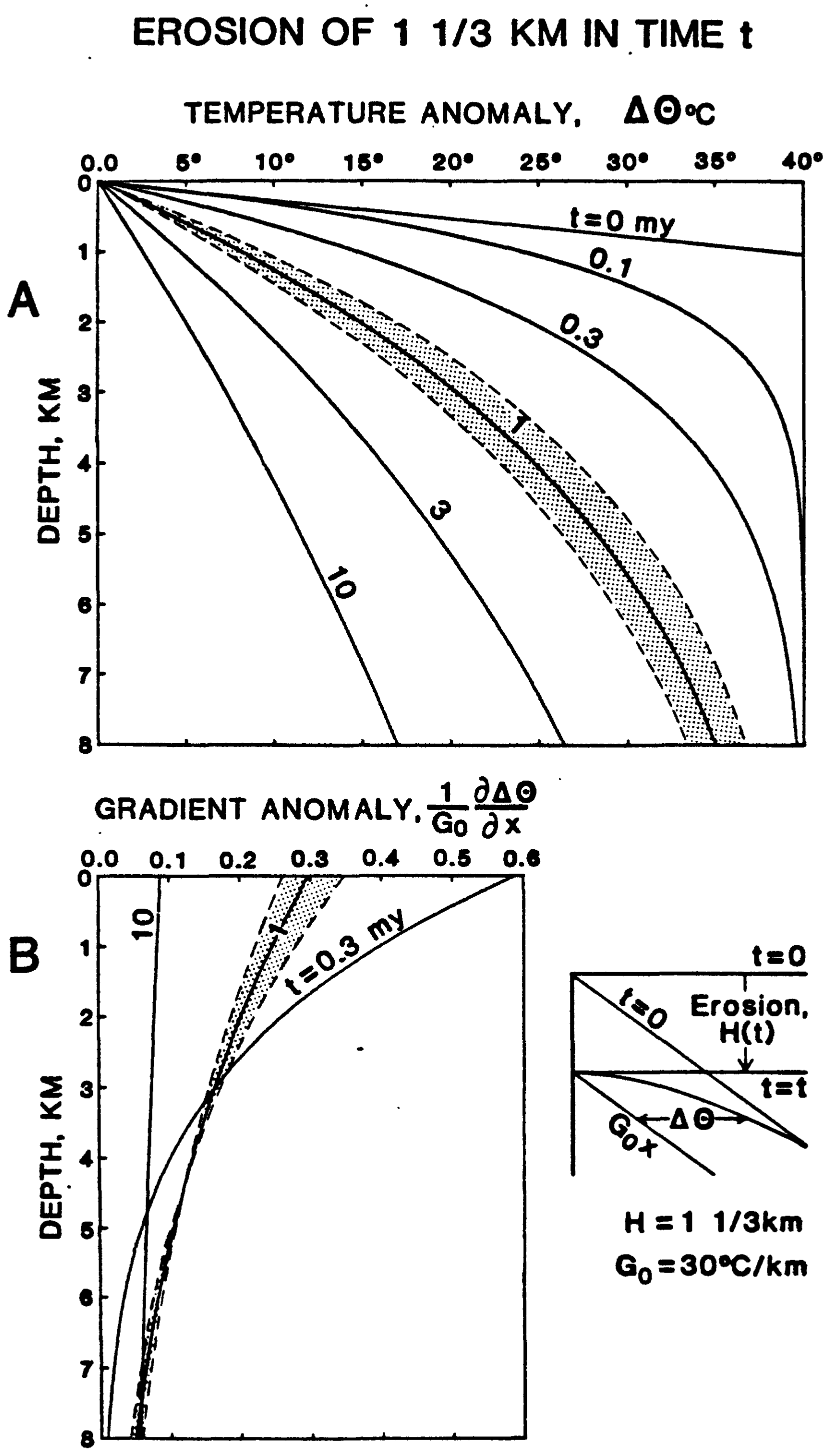

Figure 11. Increase in temperature (A) and gradient (B) caused by gradual erosion of 1 1/3 km over t yrs. Dashed lines enclose approximation for Cajon Pass (t = 1 m.y. ±25%).