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The Thermal Structure of the Continental Crust

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Abstract. In the United States, the surface heat flow can be separated into two main components. The first component is due to radioactive heat sources in the upper crust, and the second component is due to sources in the lower crust and upper mantle. The heat flow from the lower crust and upper mantle is constant over large regions, called heat flow provinces, and the transitions between provinces are very narrow (less than 100 km). High values of mantle heat flow ($>1.4 \text{ cal/cm}^2 \text{ sec}$) occur in the Basin and Range, Columbia Plateaus, Northern Rocky Mountains, Southern Rocky Mountains physiographic provinces, and in the Franciscan rocks east of the San Andreas fault zone. Normal or near-normal mantle heat flow (0.8) is found in the United States east of the Rocky Mountains, in the Colorado Plateaus, the Southern California batholith, and in the Puget Sound Region. Subnormal mantle heat flow (0.4, the lowest known anywhere) occurs in the Sierra Nevada Mountains. The variations in mantle heat flow are attributed to the thermal effects of sea-floor spreading during the Cenozoic. Measurements on other continents suggest heat flow provinces there with mantle heat flow values similar to those found in the United States. Temperatures are calculated for the three heat flow provinces under a variety of assumptions. The mantle heat flow is the main determinant of crustal temperatures, and thus vertical variations in electrical conductivity due directly or indirectly to temperature effects must vary in depth between the heat flow provinces. The region in the United States with the lowest crustal temperatures in crystalline terrain is the western foothills of the Sierra Nevada; hence this area should be the most favorable for feasibility studies of crustal transmission of electromagnetic waves.

The most important parameters influencing the variation of electrical resistivity with depth in the crust and upper mantle of the earth are fluid content and temperature; composition is relatively unimportant [Brace *et al.*, 1965; Brace and Orange, 1968]. Brace [1971] discusses in detail the effect of these parameters; he uses some of the temperature information discussed here. The emphasis in this paper will be on review of the distribution of continental heat flow, discussion of the parameters that influence this distribution, and presentation of several different crustal temperature-depth curves for different heat flow provinces. According to preliminary studies of the variation of electrical resistivity with depth in the crust, it appears that conditions are most favorable for the presence of an electromagnetic wave guide when the temperatures are lowest and crystalline rocks are exposed at the surface. Hence, areas of low heat flow in plutonic rocks will be of particular interest, and factors influencing the possible location of such areas will be discussed. Heat flow in the oceans is

rather clearly related to the age of the oceanic lithosphere, and temperatures can be calculated on the basis of the sea floor spreading models [McKenzie, 1967; Sclater and Francheteau, 1970], at least away from the trench-island arc areas, and will not be discussed here.

Throughout the paper, the units of heat flow used are $10^{-6} \text{ cal/cm}^2 \text{ sec}$ and the units of heat generation used are $10^{-13} \text{ cal/cm}^3 \text{ sec}$. The units will be referred to as hfu (heat flow units) and hgu (heat generation units), respectively.

DISTRIBUTION OF HEAT FLOW IN THE UNITED STATES

Effect of heat production in the upper crust. Two main factors influence the heat flow measured at the surface in the United States: the heat production from uranium, thorium, and potassium measured in the basement rocks in which (or above which, in the case of such areas as the midcontinent) the heat flow value is

measured; and the heat flow from the upper mantle [Birch et al., 1968; Roy et al., 1968a, 1971; Lachenbruch, 1968]. The key to the separation of these two components of heat flow for determinations made in plutonic rocks was the discovery that there is a linear relation between heat flow and heat production in such rocks [Birch et al., 1968]. The relationship is

$$Q = Q_0 + Ab \quad (1)$$

where Q is the surface heat flow, Q_0 (the intercept value) is the heat flow from below some layer whose thickness is related to b , A is the radioactive heat production of the plutonic rocks, and b (the slope of the line) is a constant. All data relating heat flow and heat production in the eastern United States are shown in Figure 1. The black circles are the original data that Birch et al. [1968] used to obtain (1). There are two extreme distributions of heat production versus depth that satisfy this empirical relationship: a constant heat generation from the surface to a constant depth given by b [Birch et al., 1968]; and a heat generation of the form in equation 2 where x is

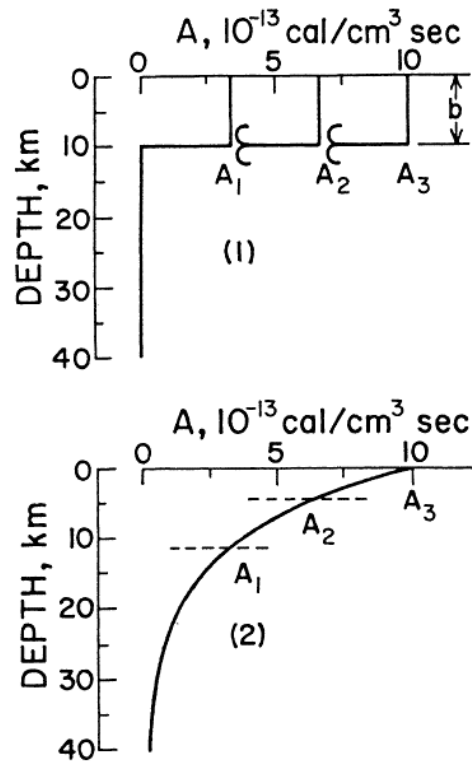


Fig. 2. Two models of heat production versus depth that satisfy the linear relationship of surface heat flow and surface heat production. Model 1 has constant heat generation to the depth b given by the slope of the line; thus different surface heat generation (A_1 , A_2 , and A_3 , for example) values imply lateral variations in the heat production of the layer. Model 2 has a heat generation decreasing exponentially with depth according to equation 2; different surface heat generation values imply differential erosion and-or geographic variations in the initial surface heat generation A_0 .

$$A(x) = A_0 \exp(-x/b) \quad (2)$$

depth and A_0 is the measured surface heat production [Lachenbruch, 1968; Roy et al., 1968a]. Values of the constant b range from 7.5 to 10 km. The model with constant heat production versus depth is illustrated in part one of Figure 2. In this model, different surface heat generation values require geographic variation in the heat production of the layer. The model with exponentially decreasing heat production versus depth is illustrated in part two of Figure 2. In the exponential model, different surface heat generation may reflect differential erosion or perhaps a different initial surface heat generation (A_0). If the exponential distribution is applicable, the depth of the layer would apparently have to be 2 or 3 times b [see Lachenbruch, 1970], and so Q_0 would be in effect the mantle heat flow. If the

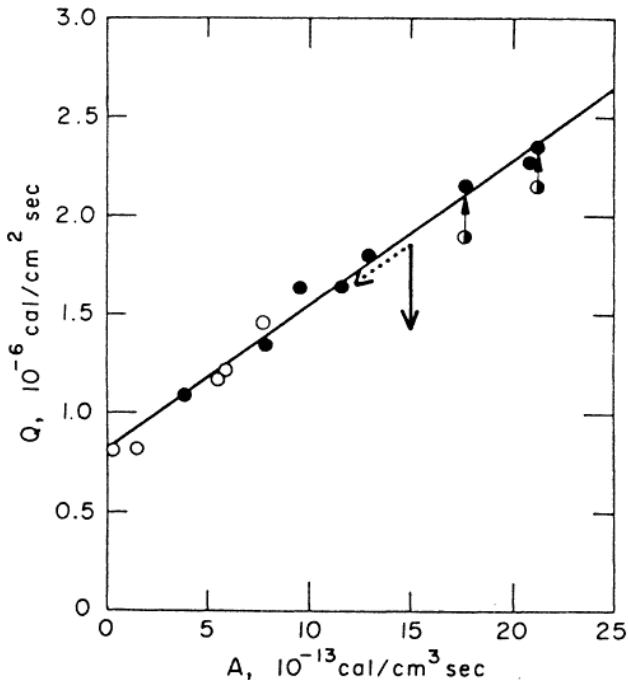


Fig. 1. Heat flow and heat production data for plutons in the New England area (black circles) and the central stable region (white circles) after Roy et al., [1968a]. The line is fitted to both sets of data. The significance of the heavy and dotted arrows is explained in the text.

constant heat production distribution is applicable, then the heat generation in the crust below the layer must be very low or very uniform for the linear relationship to be observed. Because the lower crust is probably more basic than the upper crust, it seems more reasonable that its heat production is small. *Lachenbruch* [1968] pointed out that the principal argument in favor of the exponential model is that the linear relationship between heat flow and heat production will not be affected by differential erosion.

The two arrows in Figure 1 show the effect of differential erosion at a locality originally having a surface heat production of 15 hgu and a surface heat flow of 1.92 hfu. If erosion affects only that locality, then the point will move relative to the other points, as shown by the dotted arrow if the heat production distribution follows (2) (remaining on the line) or as shown by the black arrow if the heat production is constant with depth. These two models clearly represent the extreme cases as stated by *Roy et al.* [1968a, p. 7], not including a systematic increase in heat production with depth (which seems very unlikely except perhaps in local situations) or a heat production decreasing faster than given by (2) with the proper value for **b**. In several areas, very rapid decrease in heat production with depth is observed or inferred [*Dolgushin and Amshinsky*, 1966; *Jaeger*, 1970; *Roy et al.*, 1971], but the significance of such cases to the linear heat flow-heat production relationship is not yet understood. This situation of very rapid decrease does appear to be rare, however. *Lachenbruch* [1970] added to the constant and exponential models a third heat production-depth relationship. For a given amount of differential erosion, this third model (with a linear decrease of heat production versus depth) diverges from the curve but less rapidly than the constant model. Obviously there are an infinite number of models between the constant and exponential models that diverge more or less rapidly from the curve depending on the rate of decrease of heat production with depth. Thus the introduction of additional models such as the linear one is unnecessary and indeed confusing until we have additional independent data on the behavior of heat production with depth.

Available data on the distribution of uranium, thorium, and potassium with depth in plutonic rocks is inconclusive as to the usual rate of variation with depth (if any). The values of **b** imply decreases in heat production of 7 to 10% per kilometer, and thus

vertical sections of several kilometers are necessary to overcome the inherent imprecision of U, Th, and K determinations (± 5 -10%) and the effects of natural fluctuations of radioelement content (10-20% from sample to sample [see *Rogers et al.*, 1965]). Surface exposures with vertical variations of 1 to 2 km are rare and occur only over lateral distances of several kilometers and there are few deep boreholes in homogeneous granitic rock. *Lachenbruch* [1968] suggested that the exponential model was valid for the Sierra Nevada, but in the areas where 20 to 30 km of erosion is required (the western foothills) the metamorphic grade is the lowest in the Sierra Nevada [*Clark*, 1960; *Best*, 1963], and in fact nowhere in the Sierra Nevada mountains is there evidence that the granitic rocks were emplaced at a depth of more than 5 to 10 km [*Kerrick*, 1970; *Bateman and Eaton*, 1967]. Finally, it appears that the rocks in the Sierra Nevada foothills are significantly different chemically and petrologically from the rocks along the crest [*Bateman and Dodge*, 1970; *Tilling et al.*, 1970]. Thus, the hypothesis that the rocks in the foothills represent deeply eroded roots of the rocks along the crest [*Lachenbruch*, 1968] appears invalid, and the inference that the exponential decrease in heat production with depth applies to the Sierra Nevada is unsubstantiated.

In a recent study of the distribution of heat production in another Mesozoic batholith of the western cordillera, the Idaho batholith, *Swanberg* [1971] develops strong evidence for a decrease in heat production with depth of emplacement that is consistent with the exponential decrement inferred independently from the heat flow-heat production studies. *Heitanen* [1967, 1968] mapped an extensive area in the northern part of the Idaho batholith and identified several generations of intrusive activity. The oldest rocks were intruded during regional metamorphism at conditions of temperature-pressure near the aluminum silicate triple point (a pressure of about 3.75 kb, according to *Holdaway* [1971]). The fact that the oldest quartz monzonites have primary muscovite indicates a minimum pressure of consolidation of about 4 kb [*Evans*, 1965]. *Swanberg* [1971] considers two groups of data, one using heat production values only from quartz monzonites with K content of between 2.8 and 3.4% and a second using heat production

values from an apparently genetically related suite of plutonic rocks ranging in composition from gabbro to granite. In both groups, heat production decreases with increasing depth of emplacement, and the decrease can be closely fitted with a curve of the form of (2) with \mathbf{b} equal to about 9 km. Thus, there is apparently a strong pressure control in the distribution of U and Th that may not operate for K. Uranium is particularly affected, since Th/U ratios vary from 3 to 5 for the shallow rocks to 6 to 8 for the muscovite quartz monzonite.

The actual distribution is likely to be much more complex and indeed will probably vary from constant to exponential with very low decrements (1 to 2 km). It is probably only in a gross average way that the exponential model holds, much as is shown in a figure of *Roy et al.* [1968a, Figure 4, model 2], particularly since gravity studies suggest that the thickness of individual plutons rarely exceeds 10 km [*Bott and Smithson, 1967*].

Variations in mantle heat flow. The observation that heat flow measurements over large areas are linearly related to the heat production of plutonic rocks implies that the heat flow from below the radioactive layer varies little in areas characterized by a single line e.g., Figure 1. In the exponential model of heat production, Q_0 is in effect the mantle heat flow. The constant model could result in having the linear relationship hold for large areas only if the heat production in the lower crust is very small, and again Q_0 would not be much above the mantle heat flow. Therefore, if we call Q_0 the 'mantle' heat flow, we cannot be far wrong. Thus, the fact that heat flow is linearly related to heat production in the large regions of the United States implies that the mantle heat flow is nearly constant in these areas. The transition zones between regions of different mantle heat flow values are generally very narrow compared with those between the regions of uniform heat flow [*Roy et al., 1971*].

From a study of the heat flow and heat production in plutonic rocks in the United States, *Roy et al.* [1968a] defined a heat flow province on the basis of its characteristic relationship between heat flow and heat production, computed the results, and identified three provinces: the eastern United States, where $Q_0 = 0.8$ hfu and $\mathbf{b} = 7.5$ km; the Basin and Range province, where $Q_0 = 1.4$ hfu and $\mathbf{b} = 9.4$ km; and the Sierra Nevada, where $Q_0 = 0.4$ hfu and $\mathbf{b} = 10$ km. the eastern Great Plains or for the Coastal Plain

From the geophysical point of view, the large variations of the intercept value Q_0 , which reflect variations in heat flow from the mantle, are of more interest than the slope \mathbf{b} , which varies much less from province to province and probably reflects variations in the geochemistry of the upper crust. With the relative importance of Q_0 and \mathbf{b} in mind, *Roy et al.* [1971] re-defined a heat flow province as a region with the same mantle heat flow (Q_0). Thus, within a single heat flow province there might be subareas with heat flow and heat production lines of different slopes but identical intercept values. They presented a map of Q_0 's and termed it a 'reduced' heat flow map. That map with additional data in the northwestern United States is shown as Figure 3. A 'reduced' heat flow value is Q_0 calculated from (1) transposed to $Q_0 = Q - \mathbf{b}A$. In regions with only a few data points such as the Peninsular Ranges of southern California, the Salinian block, and the Northern Cascades, et cetera, \mathbf{b} was assumed to be 10 km in calculating values of 'reduced' heat flow.

Figure 3 includes major physiographic provinces as well as heat flow provinces. The locations of reduced values are indicated, except in the Sierra Nevada and Peninsular Ranges, where the data are too closely spaced to be shown. The physiographic provinces make convenient units for discussion, since heat flow and physiographic boundaries often seem to be close to one another.

All available measurements of terrestrial heat flow in the western United States and adjacent portions of the Pacific Ocean are plotted in Figure 4. Although the heat flow contours shown in Figure 4 demonstrate that the western United States is characterized by large areas of differing regional heat flow, the map of reduced heat flow (Figure 3) is more useful and clearly indicates that the regional heat flow patterns are related to significant variations of heat flow from the upper mantle.

As indicated in Figure 3, the Appalachian Highlands, the central stable region, and the southern part of the Canadian Shield in the United States comprise the eastern United States heat flow province. No data are now available for provinces. The Basin and Range heat flow

province has been extended to include the Columbia Plateaus, Northern Rocky Mountains, Southern Rocky Mountains, the southeast part of the Colorado Plateaus, part of the Great Plains, and part of the Cascade Mountains [Decker, 1969; Blackwell, 1969; Roy et al, 1971]. In California, the Franciscan block east of the San Andreas fault has very high heat flow, whereas the Salinian block west of the San Andreas has a mantle heat flow intermediate between that of the eastern United States and the Basin and Range heat flow provinces. There are no heat flow measurements presently published for the Klamath Mountains, Oregon Coast Ranges, or Olympic Mountains. Apparently normal heat flow is characteristic of most of the Wyoming Basin and Colorado Plateaus, although determinations are sparse.

The most striking feature of the heat flow pattern is the band of normal to low heat flow in the Puget Sound depression, Sierra Nevada Mountains, and Peninsular Ranges, where mantle heat flow values

(Q_0) are 0.8, 0.4, and 0.7 hfu, respectively, flanked on the east by a broad region of high heat flow in the Basin and Range, Columbia Plateaus and Northern Rocky Mountains provinces and on the west by high heat flow in the Pacific Ocean.

The eastern United States heat flow province has been tectonically stable since early in the Mesozoic in the Appalachians and for somewhat longer in the other physiographic provinces. Thus, the province is considered characteristic of a 'normal' continent [Roy et al., 1968b]. The regions of high heat flow in the west ($Q_0 = 1.4$ hfu or greater) have all been the sites of extensive Cenozoic volcanism and tectonism. The physiographic provinces in the western United States with mantle heat flow significantly below 1.4 hfu have been less tectonically active in the Cenozoic and in general have had little or no Cenozoic intrusive or extrusive activity, although the Sierra Nevada Mountains and Peninsular Ranges were the sites of voluminous Mesozoic intrusive activity.

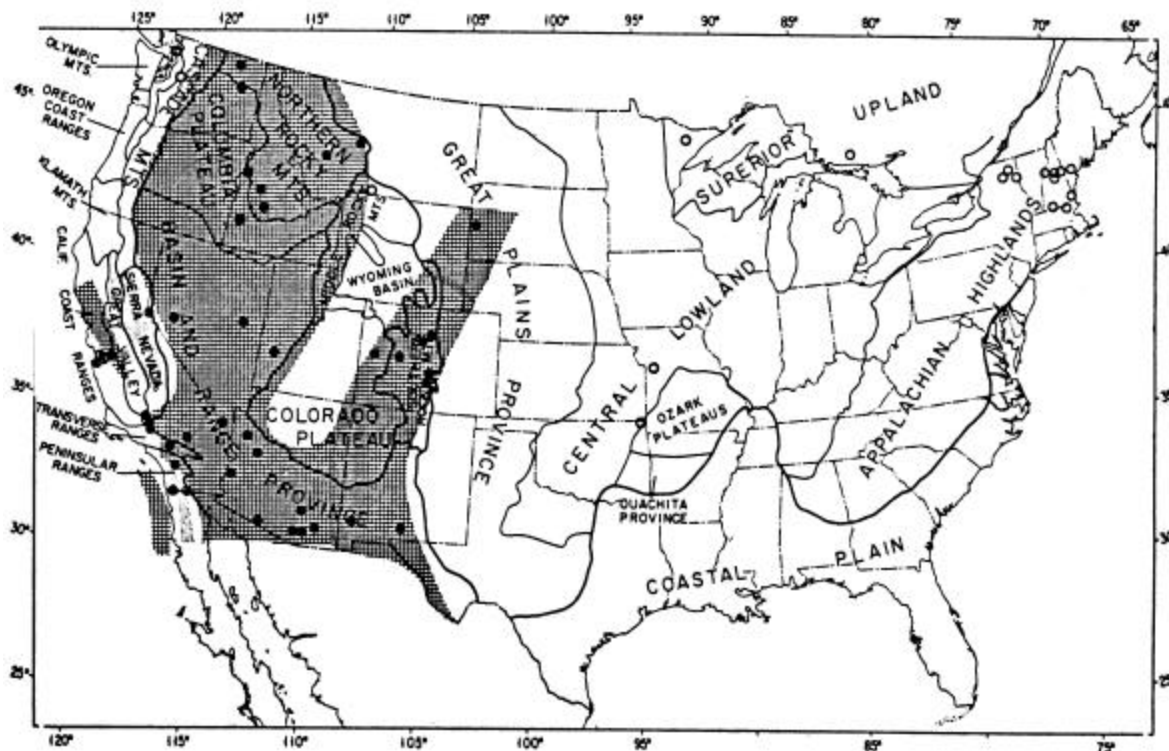


Fig. 3. Physiographic provinces, reduced heat flow values, and heat flow provinces in the United States. Sites indicated by white circles have reduced heat flow values of 0.8 ± 0.1 ; dotted circle sites have values of between 0.9 and 1.3; and black circle sites have values greater than 1.3 hfu. Regions of high reduced heat flow are designated by a square pattern; regions of low reduced heat flow are designated by a dot pattern. The low values in the Sierra Nevada and many determinations in the Pacific Coast provinces could not be plotted because of the small scale of the map (after Roy et al., [1971] with additional data in the northwestern United States).

**EXTENSION OF HEAT FLOW PATTERN TO
OTHER CONTINENTS**

Roy *et al.* [1968a, 1971] analyzed available data from other continents where combined heat flow and heat production measurements were available and concluded that at least two of the three heat flow-heat production curves discussed above might have a much broader significance than just relating heat flow and heat production in different parts of the United States. They found data from the shield regions of Canada and Australia that plotted close to the curve for the eastern

United States and a data point from the region of high heat flow in eastern Australia that plotted near the Basin and Range curve. They also pointed out that the similarity of the distribution of heat flow values [Lee and Uyeda, 1965] from the stable portions of all the continents (modes of 1.1-1.3 hfu, lowest values of 0.7-0.8 hfu) supports the inference about the applicability of the eastern United States curve to the stable portions of continents.

Jaeger [1970] discussed in detail the combined

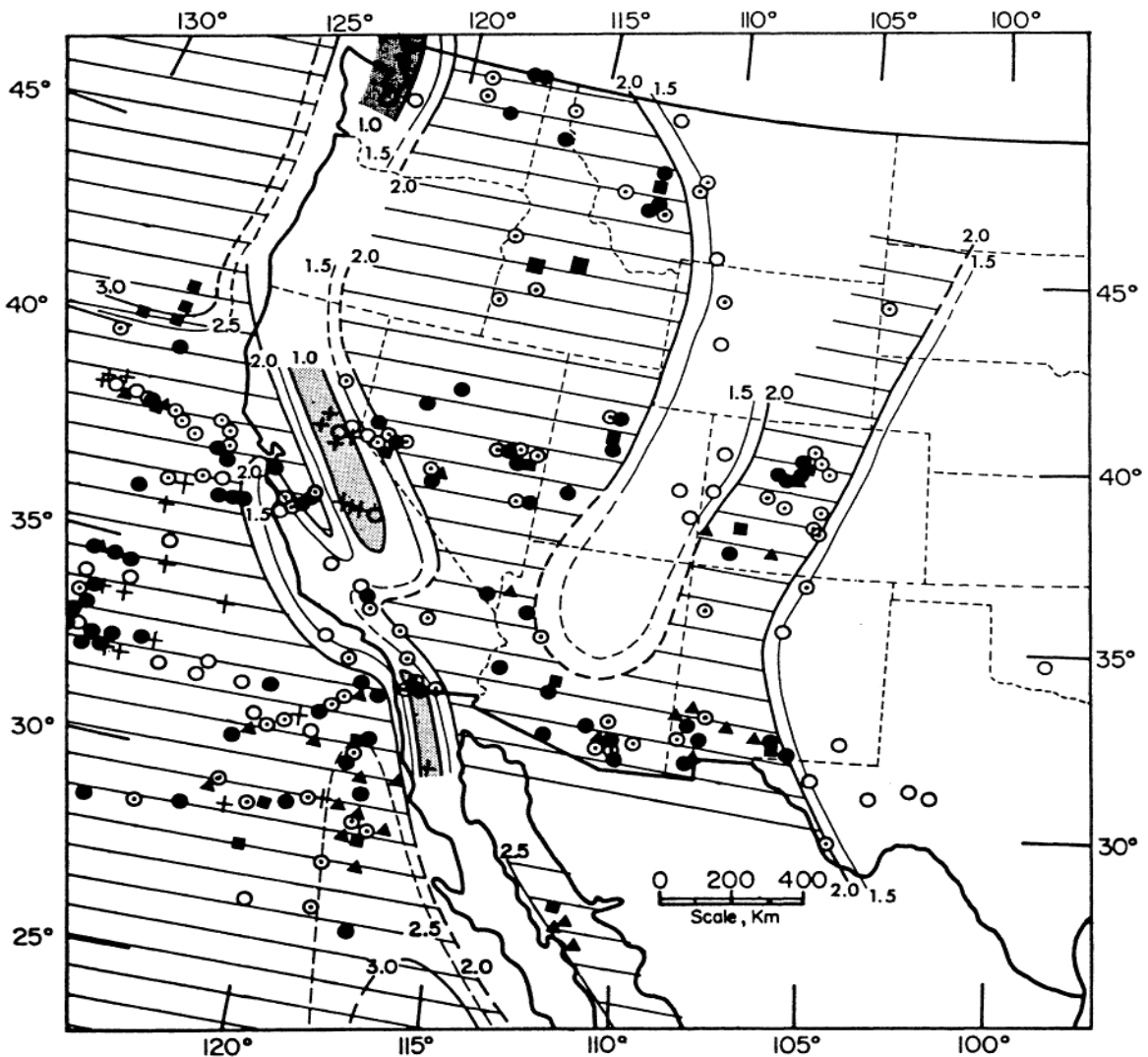


Fig. 4. Contour map of heat flow in the western United States (after Roy *et al.* [1971] with modifications in the northwestern United States). The contours delineate regions of high and low heat flow with average values of flux that would be measured in rocks with heat production within the range of granodiorite. Pluses represent observed heat flow values in the range 0-0.99; white circles, 1.0-1.49; dotted circles, 1.5-1.99; black circles, 2.0-2.49; black triangles, 2.5-2.99; and black rectangles, >3.0. Units are 10^6 cal/cm² sec.

heat flow and heat production data for Australia and found a linear relationship for the western portion of the Australian shield (using 3 points) with a Q_0 of 0.64 hfu and a b of 4.5 km. The rocks have isotopic ages in excess of 2.5 Gy. It will be interesting to see whether the 0.16-hfu difference between the curve for the eastern United States (based primarily on rocks of Grenville age (1.1 Gy) or younger) and for the Australian shield holds up as more data are collected. Most of data from the high heat flow region in eastern Australia fall near the curve for the Basin and Range heat flow province. However, several of the points are in metamorphic or sedimentary rocks and, as *Roy et al.* [1968a] emphasize, such data are not strictly pertinent, because the vertical distribution of heat sources may not be as uniform as in large bodies of plutonic rock.

Without concomitant consideration of the radioactive heat production on the rocks in which the heat flow values are measured, divisions of heat flow based on 'age' of the orogenic province [*Polyak and Smirnov*, 1968; *Hamza and Verma*, 1969; *Verma and Panda*, 1970; *Sclater and Francheteau*, 1970] have no clear significance. In the United States, for example, the late Mesozoic orogenic belt of the Sierra Nevada Mountains has the lowest heat flow. There may be a correlation for Mesozoic and Cenozoic orogenic belts, but the detailed nature of the correlation cannot be determined without much more heat production data. For the older orogenic belts, particularly of Precambrian age, the question of bias must be resolved. As *Jaeger* [1970] points out, a high proportion of mineral deposits in Precambrian rocks is in the greenstone belts, where heat production is low. Therefore, an average of measurements made in holes drilled for mineral exploration (as are most heat flow determinations) will be weighted toward rocks of low heat production.

The average heat production for the 'continental crust' is estimated to be 4.4 hgu by *Heier and Rogers* [1963]. An almost identical value was found by *Phair and Gottfried* [1964] for the area in the western United States underlain by Mesozoic batholiths (nearly 250,000 km²) and by *Shaw* [1967] for a large area of the Precambrian shield area in Canada (4.6 hgu). Thus, there is no geochemical evidence that a systematic decrease in surface heat production with age exists [*Roy et al.*,

1968a], and a model such as the one presented by *Sclater and Francheteau* [1970, figure 10] that assumes such a decrease is not supported by geochemical data. According to Figure 1, a range in surface heat flow of 1.1 to 1.3 hfu for the eastern United States corresponds to a range in surface heat production of 4.0 to 6.7 hgu. Because 1.1 to 1.3 hfu is the modal value for most continents, *Roy et al.* [1968a] suggested that such values might be the average continental heat flow if anomalous regions such as the Sierra Nevada and Basin and Range provinces were excluded. In turn, the surface heat generation implied to be the most common coincides remarkably with the values found by the geochemical investigations. This internal consistency is another argument for the broad applicability of the eastern United States heat flow-heat production curve. In the following section on temperature calculations, a value of 5.3 hgu is used for the surface heat generation of the models. The assumed heat production corresponds to a surface heat flow for the eastern United States of 1.2 hfu and is not much higher than the average surface heat production values inferred from the geochemical data.

CRUSTAL TEMPERATURES

The heat flow from below the upper crustal layer of heat production and the 'thickness' of this layer (the two quantities obtained from the linear relation between heat flow and heat production) and the limited range of models that can explain the relation provide a much more rational basis for calculation of crustal temperatures than information available in the past. Crustal temperatures are an important parameter bearing on the interpretation or calculation of electrical resistivity profiles, and several different heat production-depth models will be considered in this section for the three heat flow provinces defined by *Roy et al.* [1968a] in order to illustrate the differences in temperature that are compatible with different crustal models of heat production, thermal conductivity, and mantle heat flow. Temperatures were calculated with the assumption of steady state conditions. The validity of this assumption will be discussed below. The temperatures inside a layer of constant heat production and thermal conductivity are given by *Jaeger* [1965, equation 10]; they are

$$T(x) = T_0 + Qx/K - Ax^2/(2K) \quad (3)$$

where x is depth, T_0 is surface temperature, Q is surface heat flow, and K and A are, respectively, thermal conductivity and heat production of the layer. The temperatures in a layer with heat production decreasing with depth according to (2) are given by *Lachenbruch* [1968, equation 4]; they are

$$T(x) = T_0 + Q_0x/K + A_0b^2(1 - e^{-x/b})/K \quad (4)$$

The temperature due to the radioactive layer alone is:

$$Ab^2/K \quad (5a)$$

For the exponential case and

$$Ab^2/(2K) \quad (5b)$$

for the constant case. Thus the temperature difference due to the different heat production models at depths of 2 or 3 times b , if we assume constant thermal conductivity and no radioactive heat production in the lower crust, is merely $Ab^2/(2K)$; temperatures are higher for the corresponding exponential model. The temperature from (5) for a surface heat production of 5 hgu in the Sierra Nevada heat flow province is 42°C for the constant model and 84°C for the exponential model ($K = 6.5 \times 10^3$ cal/cm sec °C). The calculated Moho temperatures are about 350°, 500°, and 750°C for the three provinces (Figure 5), and a maximum difference of 42°C (12, 8, and 6% respectively) would be possible, owing to the radioactive surface layer alone (conductivity constant), with the assumed heat generation of 5.3 hgu. On the other hand, a variation of 10% in the mantle heat flow will result in about an 8% change in temperature (25°-30°C) at the Moho for the Sierra Nevada, an 8.5% change (40°-45°C) for the eastern United States, and a 9% change for the Basin and Range (65°-70°C). Similarly, a change in the conductivity values of 10% would result in 10% (35°, 50°, and 75°C) variations in Moho temperature. Therefore, we conclude that the uncertainty of temperature at the crust-mantle boundary is due as much (or more) to different possible values of mantle heat flow or crustal thermal conductivity as it is to different possible heat production-depth models that satisfy (1).

Small variations in crust-mantle temperatures may be caused by geographic variations in surface heat production. Such differences are only 70°C at 7.5 km for the constant heat production model or 140° at 35 km for the exponential model of heat production with a heat flow variation of 0.8 to 2.0 hfu in the eastern United States. These maximum temperature differences will probably not be reached, because the surface heat production varies laterally as well as vertically and the temperatures at the Moho will reflect some average surface radio activity rather than point-by-point surface variations.

To illustrate the range of crustal temperatures possible within the broad framework of the heat production-depth models, four different temperature-depth curves have been calculated for each heat flow province. The parameters assumed for each of the four models are listed in Table 1, and the resulting temperatures are listed in Table 2 and plotted in Figure 5. Of the four calculations for a particular province, models 1 and 2 were calculated assuming a layer of constant heat generation of thickness given by the constant b of (1) and a thermal conductivity of 6.5×10^3 cal/cm sec °C. The average thermal conductivity for approximately 100 sites in plutonic rocks in the United States reported by *Roy et al.* [1968b] is 7.0×10^3 cal/cm sec °C. The conductivity of 6.5×10^3 cal/cm sec °C allows a small decrease in that average value to take into account the temperature dependence of thermal conductivity. The conductivity of the lower crust was assumed to be 5.0×10^3 cal/cm sec °C, about the value for gabbro or granite of temperatures above 200°-300°C [*Birch and Clark*, 1940]. Surface temperatures different from zero can be included merely by adding the appropriate surface temperature to the temperature at each depth.

A value of 5.3 hgu was assumed for the surface heat generation in all models; this implies surface heat flow values of 0.95, 1.2, and 1.9 hfu for the Sierra Nevada, eastern United States, and Basin and Range provinces, respectively. The two values of heat generation assumed for the lower crust (0 and 1.5 hgu) span the range of likely values. Indeed a lower value (0.5 hgu) must be assumed for the Sierra Nevada model to avoid a mantle heat flow of zero. Model 4 for each province consists of only one layer that makes up the entire crust with a conductivity of 6.5×10^3 cal/cm sec °C, an A_0 of 5.3 hgu, and an exponential decrement given by b calculated from the linear plot for the appropriate province. Model 2 has the same constants as the

models discussed by *Roy et al.*, [1968a] and the models numbered 4 are in effect the models discussed by *Lachenbruch* [1970], with a conductivity of 6.5 instead of 6.0×10^{-3} cal/cm sec °C. The base of the crust was assumed to be at 40,

35, and 30 km for the Sierra Nevada, eastern United States, and Basin and Range provinces, respectively, although temperatures were extrapolated to 50 km, assuming the same

TABLE 1. Models for Temperature-Depth Calculations
(Units of thermal conductivity are 10^{-3} cal/cm sec °C.)

Model Number	Surf. Heat Flow, hfu	Mantle Heat Flow, hfu	Depth to Layer 2, km	Depth to Mantle, km	Surf. Heat Gen., hgu	Layer 2 Heat Gen., hgu	Thermal Conduct., Layer 1	Thermal Conduct., Layer 2
Sierra Nevada								
1	0.95	0.42	10	40	5.3	0	6.5	5.0
2	0.95	0.25	10	40	5.3	0.5	6.5	5.0
3	0.95	0.37	20	40	5.3	0.69	6.5	5.0
4*	0.95	0.43	...	40	5.3	...	6.5	...
Eastern United States								
1	1.20	0.78	8	35	5.3	0	6.5	5.0
2	1.20	0.37	8	35	5.3	1.5	6.5	5.0
3	1.20	0.73	15	35	5.3	0.69	6.5	5.0
4*	1.20	0.81	...	35	5.3	...	6.5	...
Basin and Range Province								
1	1.90	1.37	10	30	5.3	0	6.5	5.0
2	1.90	1.07	10	30	5.3	1.5	6.5	5.0
3	1.90	1.39	19	30	5.3	0.69	6.5	5.0
4*	1.90	1.42	...	30	5.3	...	6.5	...

*There is no second layer for this model.

TABLE 2. Temperature* versus Depth for the Models in Table 1

Depth, km	Sierra Nevada				Eastern		United States		Basin and		Range	
	1	2	3	4	1	2	3	4	1	2	3	4
0	0	0	0	0	0	0	0	0	0	0	0	0
5	63	63	64	64	82	82	84	84	136	136	138	138
10	105	105	116	116	153	152	157	157	252	252	263	263
15	147	146	160	160	230	223	225	225	389	385	381	381
20	189	184	200	200	308	286	309	290	526	511	501	494
25	231	220	247	236	385	342	389	353	663	629	645	605
30	273	253	291	271	463	390	467	415	800	740	786	715
35	315	384	333	305	541	431	542	478	937	847	925	857
40	357	312	371	339	618	468	615	558	1074	954	1065	999
45	399	339	408	381	696	505	689	639	1211	1061	1204	1140
50	441	366	445	424	773	543	762	719	1348	1168	1344	1282

* Temperature is given in degrees centigrade. Temperature at the base of the crust in each model is italicized

Temperature, °C

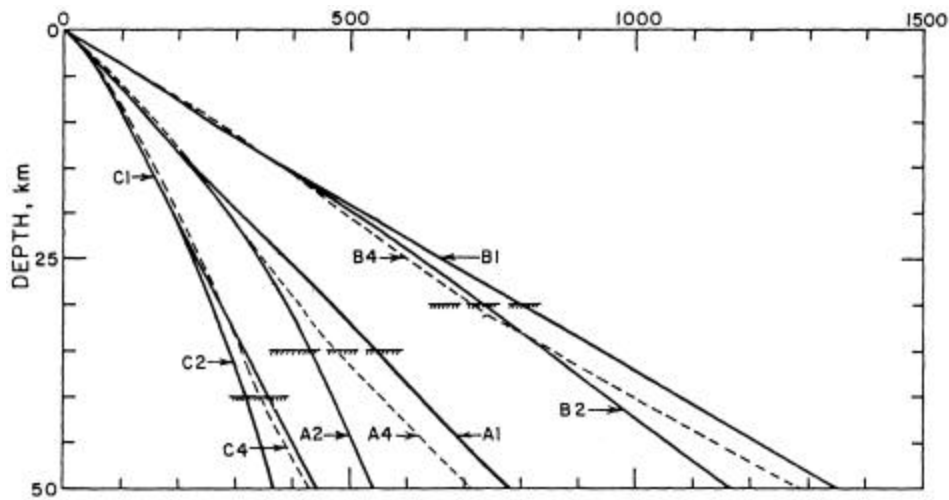


Fig. 5. Temperature-depth curves for the models with parameters listed in Table 1. The designations A, B, and C, refer to the eastern United States, Basin and Range and Sierra Nevada heat flow provinces, respectively. The base of the crust is indicated by hatching. The temperatures from models A3, B3, and C3 were not plotted because they nearly coincide with the temperatures from models A1, B1, and C1, respectively.

conductivity in the mantle as in the lower crust and no heat generation. The final model for each province is model 3. This crustal model was used in calculating crust and mantle temperatures by *Roy et al.* [1971] and *Herrin* [1971]. The upper crustal layer is assumed to extend to **2b**, where a second layer begins with an exponential decrement of 80 km and an ' A_0 ' of 0.69 hgu (calculated from $5.3e^{-2}$). The first layer has an exponential distribution of heat sources according to (2). In the models calculated here, the heat production layer was stopped at the base of the crust. This model suggests a continental crust composed of 15 to 20 km of granitic material and 10 to 20 km of more basic rock with lower heat production and thermal conductivity. This distribution of material is in reasonably close agreement with seismic evidence on the composition of the continental crust [e.g., *Pakiser and Robinson*, 1966]. Quite independently, *Shaw* [1970] suggested a similar model for the heat source distribution in the oceans as used in model 3 [Roy et al., 1971] for the lower crust and upper mantle. It must be emphasized that all temperatures below the base of the crust in each model are extrapolations assuming the same conductivity as in the lower crust and no heat sources. For the Basin and Range model particularly, these assumptions are unrealistic and can at best hold

only until the solidus curve for the mantle is reached.

Differences in Moho temperatures from those shown in Figure 5 due to departure from the assumed condition of steady state may be more important for the Sierra Nevada and Basin and Range provinces than variations in properties. The actual temperature distribution in the Basin and Range may be close to steady state because the source of the anomaly is near the base of the crust and has been operative for several tens of millions of years. In the Sierra Nevada, temperatures in the deep crust are undoubtedly underestimated, since the low mantle heat flow is interpreted to be a transient effect from a sink that ceased to operate 10 to 30 m.y. ago [Roy et al., 1971]; see the following section.

The first and most obvious result of the calculations is that the temperature differences between the three provinces are much larger than the uncertainties in calculated temperatures introduced by the several possible models used, and a second result is that the differences due to variations in lower crustal heat production or assumed thermal conductivity values. The temperatures at the crust-mantle boundary can be calculated to as close as $\pm 50^\circ\text{C}$ regardless of the model of radioactivity distribution assumed, if the heat production at the

surface is known. *Brace* [1970] used the temperatures from model 2 for each province in his discussion of electrical resistivity in the crust. His values will be an upper limit for depths in excess of 25 km for the eastern United States and Sierra Nevada provinces because model 2 predicts the lowest temperatures of the four models. Also the depth at which mineral conduction becomes important may be slightly shallower than his calculations show.

DISCUSSION

The local variability of heat flow in crystalline terrains (on the scale of a few kilometers) is due primarily to lateral variations in upper crustal heat production. On the other hand, regional variations are due to differences in mantle heat flow. In the United States, variations in mantle heat flow are found in the west in provinces of late Mesozoic and Cenozoic tectonic activity. Electrical resistivity values in the shallow part of the crust of 10^5 to 10^6 ohm-m, which seem to be required for long distance transmission of electromagnetic radiation [*Levin*, 1968] might be reached only in the areas with lowest temperature and fluid content.

Thus, regions with high surface radioactivity and normal mantle heat flow or of high mantle heat flow, such as the northern Appalachians, and the Basin and Range heat flow province (see Figures 3 and 4) are certainly least favorable for feasibility studies of electromagnetic wave transmission in the crust. Where the mantle heat flow is normal, the most favorable locations for a high resistivity crustal layer are in areas of low surface heat production and crystalline rock exposures, such as the anorthosite terrain in New York. An area like the mid-continent gravity high, where the crust is apparently composed predominantly of basalt or gabbroic material, might also be a possibility. The region in the United States with the lowest temperatures in the crust is the western foothills of the Sierra Nevada, where both mantle heat flow and surface heat production are low and crystalline rocks are exposed at the surface. Other areas of low to normal mantle heat flow and low surface radioactivity are in the Peninsular Ranges and in the Puget Sound region.

Important questions to be answered are the extent to which the distribution of heat flow found in the United States is typical of continental heat flow and the extent to which similar areas on other continents will have similar heat flow. To answer this question we must know the origin of the heat flow pattern in the United States. The most striking feature of the heat flow distribution is the couple of low heat flow in the Puget Sound-Sierra Nevada-Southern California areas and the high heat flow in the immediately adjacent Cordilleran Thermal Anomaly zone [*Blackwell*, 1969]. This couple is attributed to the thermal effects of sea floor spreading during the Cenozoic [*Roy et al.*, 1971]. During most of the Cenozoic (and probably much of the Mesozoic), the North American continent drifted toward the East Pacific rise, and a subduction zone existed along the coast [*Bullard et al.*, 1965; *Atwater*, 1970]. Thus the western margin of the continent was a continental island-arc system. The characteristic heat flow pattern associated with an island-arc system is shown on the left side of Figure 6. A band of low heat flow (100-300 km wide) is found oceanward of a much broader band of high heat flow [*McKenzie and Sclater*, 1968; *Yasui et al.*, 1970; *Hasebe et al.*, 1970].

The zone of low heat flow has usually been ignored in discussions of the thermal effects of subduction [*McKenzie*, 1969; *Oxburgh and Turcotte*, 1970] but does appear to be present. For example, the low heat flow in Puget Sound is above a subduction zone that operated at least as recently as a few thousand years ago [*Dickinson*, 1970]. Such a zone of low heat flow eliminates the possibility that the subduction zone acts as a heat source along its entire length. *Miner and Toksoz* [1970] calculate several models that illustrate the maximum extent of low heat flow that might be associated with a subduction zone. *Hasebe et al.* [1970] present calculations that fit the observed data best. They assume that no heat is generated along the fault above a vertical depth of about 100 km. Thus, the low heat flow band is a conduction anomaly. However, at some depth, the oceanic crust along the upper part of the sinking lithospheric block begins to melt (with or without help from heat generated at some point along the subduction zone) and penetratively convects into the upper mantle and

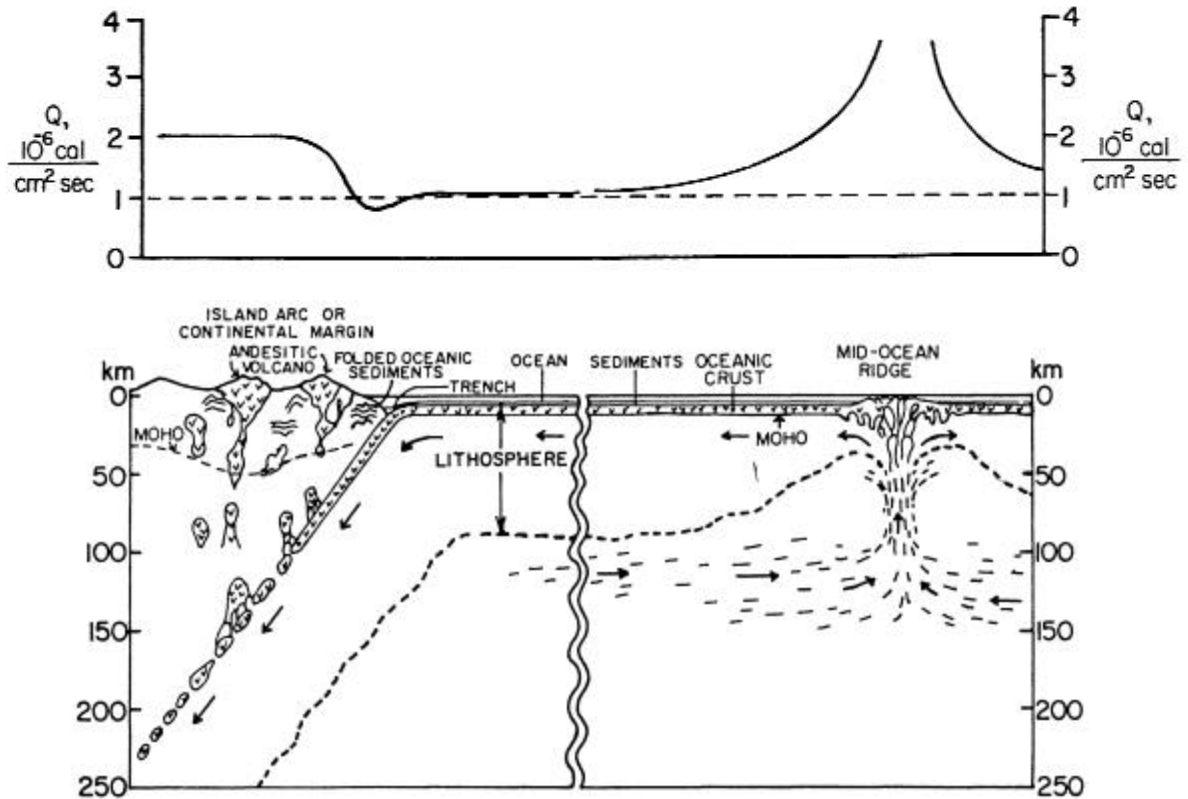


Fig. 6. Heat flow pattern and block movements associated with sea floor spreading. Not to scale.

crust to form calc-alkaline intrusives and andesitic volcanoes [see Dickinson, 1970]. The convection results in the sharp boundary between the low and high heat flow regions. Hasebe *et al.* [1970] generated the convective portion of the model by assuming a very high effective thermal conductivity.

Thus, during the late Mesozoic, a trench existed at the site of the Franciscan terrain in western California [Ernst, 1965, 1970; Hamilton, 1969]. Inland from the trench, melting along a subduction zone fed the batholiths forming in the Peninsular Ranges, Salinian block, Sierra Nevada, and Klamath Mountains, *et cetera*. Near the beginning of the Cenozoic, the direction, dip, or rate of underthrusting changed so that the region of high heat flow shifted inland and the crust beneath the Sierra Nevada and Peninsular Ranges began to be cooled by conduction of heat into the cold sinking block of lithosphere [Roy *et al.*, 1971]. The high heat flow in the Basin and Range was probably established with something near its present boundaries by early Oligocene.

Within the past 10 to 30 m.y., the continent has

interfered with the spreading from the rise and the pattern has become more complex; the San Andreas began to function as a transform fault, subduction ceased between the north end of the Acapulco trench and the Mendocino Fracture zone, and part of the continent was split by a new branch of the East Pacific rise (in the Gulf of California) This interaction has been summarized in detail by Atwater [1970] However, because of the thermal time constant of the crust, the pattern that was established during the early and middle Cenozoic can still be recognized in the Sierra Nevada and Peninsular Ranges.

A cross section illustrating variations in heat flow in the far western United States at about 38°-39°N is shown in Figure 7; it illustrates the occurrence of low mantle heat flow in the Sierra Nevada next to the broad zone of high heat flow in the Basin and Range province. The heat flow in the Pacific Ocean is variable but usually high. If we refer to Figure 6, it is clear that as a trench and rise approach each other the temperatures in the sinking block will be progressively higher when it first starts to sink.

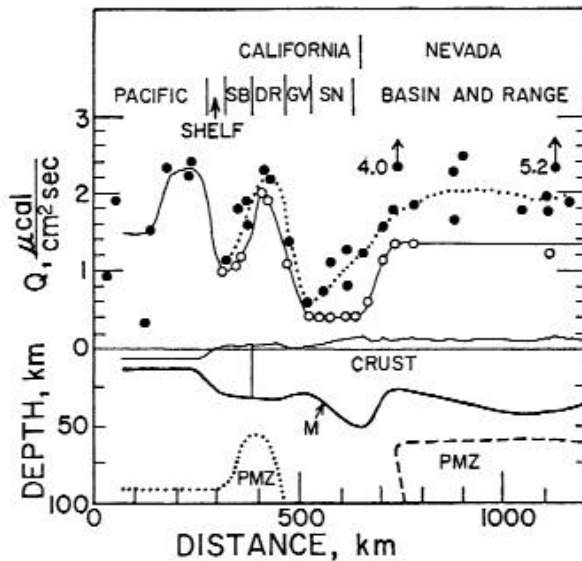


Fig. 7. Cross section of part of the western United States at 38°-39° N (adapted from Roy *et al.* [1971, Figure 18]). Black circles represent observed heat flow at the surface and white circles represent reduced heat flow. PMZ is the inferred partial melt zone. M represents the Mohorovicic discontinuity. The abbreviations for the Pacific Coast provinces are: SB is Salinian block; DB is Diabolo Range; GV is Great Valley; SN is Sierra Nevada.

Thus the high heat flow in the Pacific Ocean off the West Coast reflects the youth of the sea floor generated along the East Pacific Rise before spreading stopped. The heat flow is appropriate for the age of the oceanic crust [Sclater and Francheteau, 1970]. The high temperatures in the oceanic block (due to its youth) that are now being destroyed between the still active Juan de Fuca rise and the North American plate may explain the lack of deep earthquakes along the proposed zone of subduction there. The high and very high heat flow in the Salinian block and Diabolo range (Franciscan block) are probably due to recent changes in the thermal pattern associated with formation of the San Andreas fault and the northward translation of the Salinian block. The source in the Franciscan block must be within the crust because of the sharp boundaries of the anomaly. The mantle heat flow in the Basin and Range heat flow province is probably near the maximum for a broad region of a continent [Roy *et al.*, 1968a], since the partial melt zone in the mantle (based on the long range *P* wave profiles of Archambeau *et al.* [1969] rises very close to the crust. If it rose higher, melting of the crust would begin and buffer the additional heat input. At the

present time, 10% of the measured surface heat flow in the Basin and Range heat flow province is attributed to penetrative convection of material from the mantle to a shallow level in the crust [Blackwell, 1970].

Thus the three heat flow provinces defined for the United States may be general types. The curve found for the eastern United States may be typical of the stable portions of continents. The Basin and Range heat flow province may be typical of both high heat flow regions behind subduction zones and above continental extensions of rise systems, because it has the presumed uppermost limit of mantle heat flow possible for continental regions, and, finally, the Sierra Nevada heat flow province may be an example of a region of low mantle heat flow due to subduction of the oceanic lithosphere. Hence, tectonic and geochemical provinces similar to those in the United States, which are favorable to shallow zones of high electrical resistivity in the crust, should be favorable in other continents as well. Unknown at present, however, is whether such zones may be present in the oceans and how continental and oceanic zones might be connected across the continental shelves where there are no heat flow data.

Acknowledgments. This paper is based on ideas developed in cooperative work with R. F. Roy and E. R. Decker. E. Herrin, M. J. Holdaway, E. C. Robertson, and R. F. Roy read the manuscript and made useful suggestions.

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DISCUSSION

Madden: The complete absence of deep focus earthquakes in the Sierra Nevada makes a Benioff zone look incongruous. Not only is it not active, it seems to me it is not there.

Blackwell: The whole pattern was disrupted there is no spreading anymore. I do not know how long you want to follow the last bit of rock sinking under the Basin and Range province, but that is all gone now and the mantle under the Sierras has readjusted.

Evernden: When was this zone active?

Blackwell: Perhaps as recently as 5 to 10 million years ago.

Evernden: How do you explain the continuity of Sierra rocktype halfway out into the San Joaquin Valley?

Blackwell: The Basin and Range and the Sierra anomalies are part of one and the same problem and we are trying to explain both together. We do not particularly like our explanation, and you have difficulty, but we have not been able to come up with anything better.

Brace: I am interested in possible correlation of seismicity with the boundaries of heat flow provinces. It seems you can make a case for this

along the San Andreas, on each side of the Sierras, and along the Utah boundary. The earthquakes are shallow, of course, and the heat flow differences go much deeper.

Blackwell: The heat sources have to be relatively shallow because of the rapid transition between provinces of the order of 20 to 50 km, but of course the earthquakes are shallower than that. Perhaps the temperatures are so high that you get plastic deformation at depth.

Kennedy: In a single province you measure heat flow and radioactivity. Then you correct your heat flow on the assumption that the surface radioactivity extends uniformly down to 10 km and find a uniform heat flow from below. That is very surprising, as it proves that all the rocks at the surface extend to 10 km depth. It is incredible considering the variability in radioactivity.

Blackwell: On the exponential model you get the same thing with the heat production distributed through a thicker layer and decreasing with depth. We take our measurements in large granitic bodies, where we have some hope that we are looking at a valid sample of what is happening at depth. We avoid metamorphic rocks because there is likely to be a very complicated distribution of radioactivity.

Higgins: How does the thermal time constant influence the heat flow in the Sierras if you take some kind of erosion rate into account?

Blackwell: Any normal history of erosion tends to increase the heat flow. The important thing about the Sierra Nevada is that the mantle heat flow is low there now.

Higgins: Is that why you fix the time of cessation of the underthrusting as recently as you do? It would not take very long to establish an anomalously high heat flow with the kinds of erosion rates that people talk about.

Blackwell: That is right. The cooling effect of a block of lithosphere 75 km thick in the mantle beneath the Sierra would only persist for 20 to 30 million years.