Continental Heat Flow

Roy, R.F., D.D. Blackwell and E.R. Decker, Continental heat flow, chapter 19, in The Nature of the Solid Earth, ed. E.C. Robertson, p. 506-544, McGraw Hill, New York, 1972.

By Robert F. Roy, David D. Blackwell, and Edward R. Decker

*To my mind no single outstanding problem is more important for understanding of geological processes than the problem of the distribution of temperature throughout the upper 100km or so, as dependent upon such factors as time, sedimentary cover, and deformation; and probably no geological or geophysical problem has resisted solution more stubbornly. The principal difficulty is our ignorance of the distribution of the radioactive heat producing elements. We have no difficulty in finding possible distributions, consistent with our meagre observational data. But none of the possible distributions really imposes itself as conclusive. The differences between the possible distributions with regard to temperatures are very great, and probably entirely different geological processes would have to be invoked for some of the more extreme types. Thus, every conceivable method of introducing further restrictions on the possible distributions requires careful study.**

The correlation of heat flow with the radioactivity of surface rocks, as first proposed by Francis Birch, has done much to clarify the patterns of continental heat flow and, as an additional dividend, has raised interesting questions about the vertical distribution of radioactive elements. It now seems possible to establish the regional heat flow pattern for a whole continent with a few dozen measurements properly located with respect to knowledge of basement radioactivity.

Results of measurements in the United States are presented in the form of a map of reduced heat flow. In most of North America east of the Rocky Mountains and north of the Gulf Coast geosyncline, large variations in heat flow at the surface are attributed entirely to variations in the radioactivity of the upper crust with a uniform flux from the lower crust and upper mantle. This portion of North America has been stable since the Triassic or longer. It is suggested that the same relationship between heat flow and radioactivity will be found on stable portions of other continents. The most prominent feature on the map is the large region of high flux generally following the North American Cordillera. Smaller regions of abnormally low heat flow are found in the Sierra Nevada and Peninsular Ranges. High values are found in the Franciscan block east of the San Andreas fault and normal values in the Salinian block west of the San Andreas fault. Transition zones between provinces have been studied in six places. All are narrow (less than 100 km wide), implying a shallow depth to partially molten upper mantle in the high heat flow provinces, with cold roots under the regions of abnormally low heat flow.

Considering these facts in terms of the concepts of plate tectonics, we feel it is possible to explain zones of abnormally

> low heat flow on the ocean side of regions of high heat flow, if the low heat flow is attributed to transient cooling by recently overridden portions of a cold oceanic plate. Subsequent warming of the subsiding block to mantle temperatures combined with heat sources in the oceanic plate would lead to partial melting in a few tens of millions of years. Upward convection of partially molten material would soon result in the high temperatures near the base of the crust that are necessary to explain the heat flow distribution observed at the surface.

*Birch (1947a), p. 793.

INTRODUCTION

Birch’s discussion in 1947 properly emphasized the importance of the distribution of radioactive heat-producing elements to understanding the temperature field in the outer part of the earth and the major tectonic processes that are driven by thermal energy. Heat flow at the surface is the observational boundary condition that all acceptable thermal models must satisfy. Throughout his career, Birch has placed a high priority on obtaining additional measurements of heat flow and investigating the various factors that must be considered in reducing raw heat flow data to a common base suitable for regional comparisons. These investigations have included analyses of the corrections required for subsurface temperature effects of topography (Birch, 1950), flowing water in drill holes (Birch, 1947b), climatic variations (Birch, 1948, 1954a), geologic evolution (Birch, 1950; Birch, Roy, and Decker, 1968), the thermal properties of major rock types (Birch and Clark, 1940), and the significance of combined studies of heat flow and radioactivity (Birch, 1947a, 1950, 1954b; Birch, Roy, and Decker, 1968; Roy, Blackwell, and Birch, 1968).

As a result of the work of the last decade, we now believe that there is sufficient information to provide preliminary answers to some of the important questions raised by Birch. The effects of climate, culture, topography, and hydrology can usually be regarded as secondary corrections to individual measurements of heat flow, whereas variations of geologic history and basement radioactivity are more fundamental. Examples of a few secondary corrections are given in the following section, but our aim in the bulk of the study is to summarize the broad scale implications of results obtained from recent studies of heat flow and radioactivity on the continents.

MEASUREMENTS IN SHALLOW HOLES

Prior to the early 1960’s, most heat flow measurements were made in tunnels, oil wells, and holes drilled for mineral exploration. These measurements were few in number; each was treated with considerable care; and out of these studies came the standard corrections for topographic irregularities, uplift, erosion, climatic changes, drilling disturbances, and the like. Experience in working with data from holes drilled for mineral and oil exploration suggested that the majority were badly disturbed in the upper few hundred meters with irregular, even negative, gradients, which rendered that portion of the hole unusable for heat flow measurements. Thus attention focused on cored exploration holes deeper than 200 meters, where long segments of “undisturbed” (at least consistent) temperatures could be obtained and the upper portions could be ignored. With the advent of drilling for heat flow studies this disturbed zone received closer scrutiny, and it can now be demonstrated that most of the problems arise from three basic causes: (1) movement of ground water up or down a hole between previously unconnected fracture systems or aquifers; (2) changes in the mean annual surface temperature resulting from activities of man that cause transient disturbances to underground temperatures; (3) temperature anomalies at the surface resulting from contrasts in vegetation that lead to steady-state disturbances to underground temperatures.

An example of disturbed temperatures resulting from water movement in a hole is shown in Fig. 1. In this case, there was artesian flow at a rate of approximately 30 gal/mm. This problem can usually be overcome by installing casing and filling the annulus between pipe and hole with a chemical grout or cement.

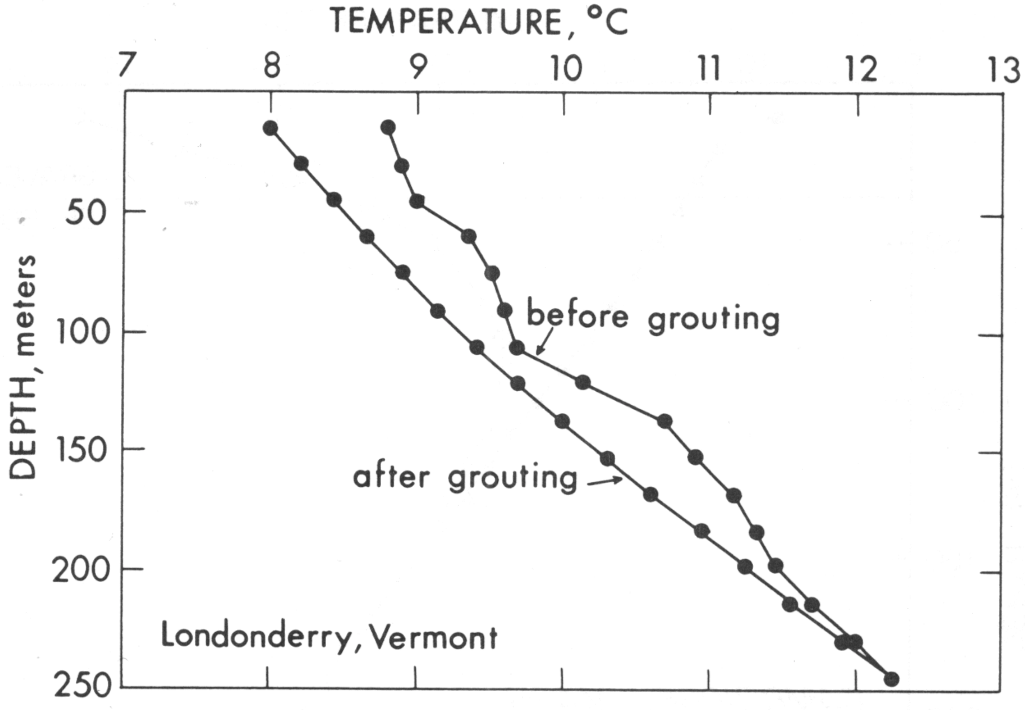

Fig. 1. Temperatures measured in a drill hole at Londonderry, Vermont. Before grouting, the hole had an artesian flow of approximately 30 gal/min.

Figure 2 shows the subsurface temperatures in a part of Cambridge, Massachusetts, where most of the buildings were constructed between 1910 and 1920. If we assume that the heated basements led to an increase in the mean annual surface temperature of 5°C, the undisturbed temperatures can be estimated using a solution from Carslaw and Jaeger (1959, p. 321, 322). The average of the mean annual air temperatures for six weather stations surrounding Cambridge (Bedford, Blue Hill, Boston Airport, Chestnut Hill, Reading, and Weston) corrected to the elevation of the Cambridge site assuming an adiabatic\ lapse rate of 4.5°C/km (Birch, 1950) is 9.7°C. The mean annual soil temperature, estimated by substituting 0°C for the months with snow cover, is about lO.3°C, which agrees fairly well with the corrected temperatures extrapolated to the surface. We have observed similar temperature depth curves in the cities of Concord, New Hampshire, and Glens Falls, New York. Other human activities such as clearing forests and planting crops (or natural phenomena such as forest fires) cause similar disturbances, which may be significant to depths of 100 meters or more depending on time and the diffusivity of the rock. In most cases it is not possible to make accurate corrections for these transient effects; the only solutions are to avoid such areas or drill deeper holes.

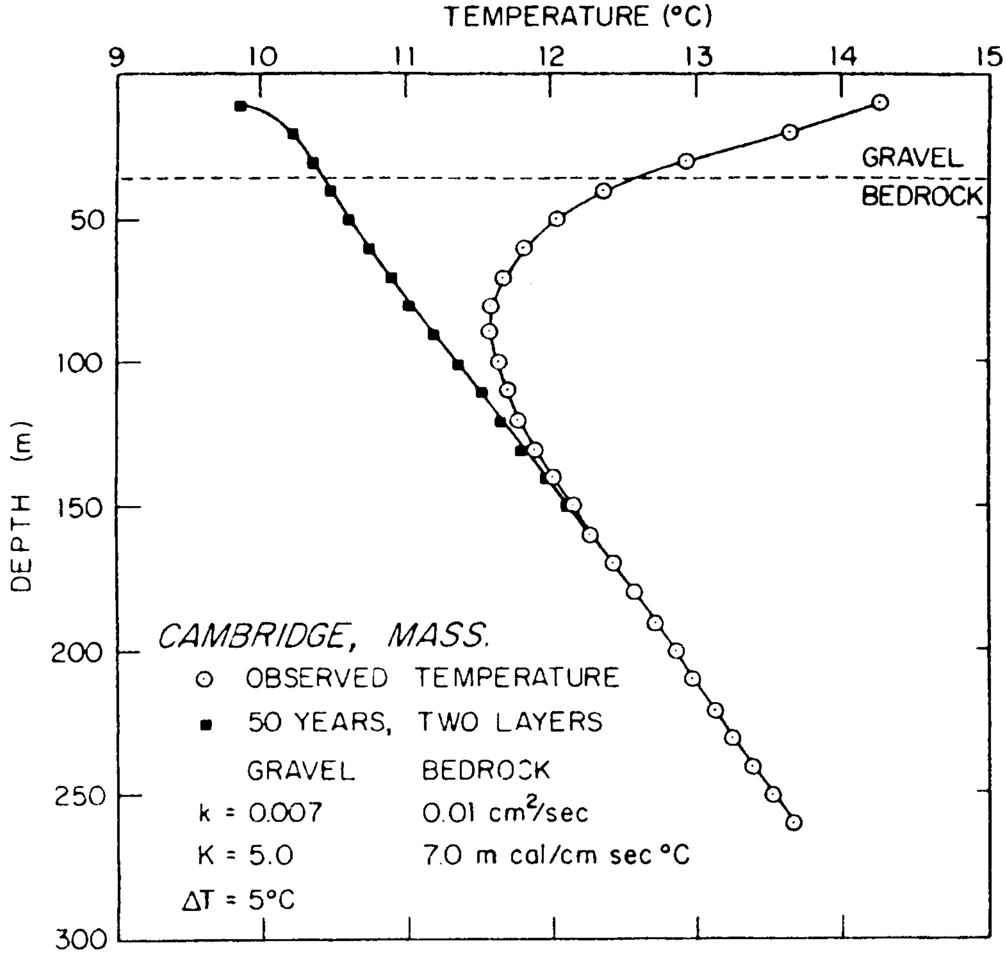

Fig 2. Observed temperatures and estimated undisturbed temperatures in a drill hole at Cambridge, Massachusetts. Correction assumes that a sudden increase in mean annual surface temperature of 5°C took place 50 years ago as a result of building construction.

Figures 3 and 4 show the effects of steady-state contrasts in surface temperatures resulting from variations in ground cover. The hole at Blodgett Forest was drilled at the edge of a small clearing in an extensive forest of virgin pine. The vegetation in the clearing consists mainly of small broadleafs reflecting the different soil that has devloped over an erosional remnant of an andesite flow. If the mean annual surface temperature of the clearing is approximately 0.5°C higher than in the surrounding forest, the temperature in the upper part of the temperature-depth curve is easily explained using methods described by Lachenbruch (1957). A similar disturbance, although opposite in sign, is found at Loomis, California, (Figs. 5 and 6) where the hole was drilled near a small stream with a fringe of trees traversing open grasslands. As with the transient case, the uncertainties in corrections are uncomfortably large, and it is best to avoid such problems when locating drill sites.

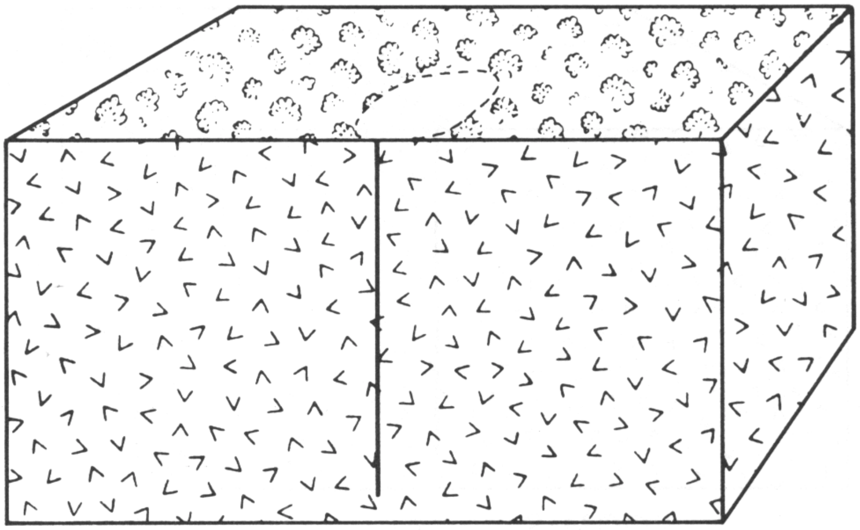

Fig. 3. Block diagram showing contrast in natural vegetation near the drill site at Blodgett Forest, California.

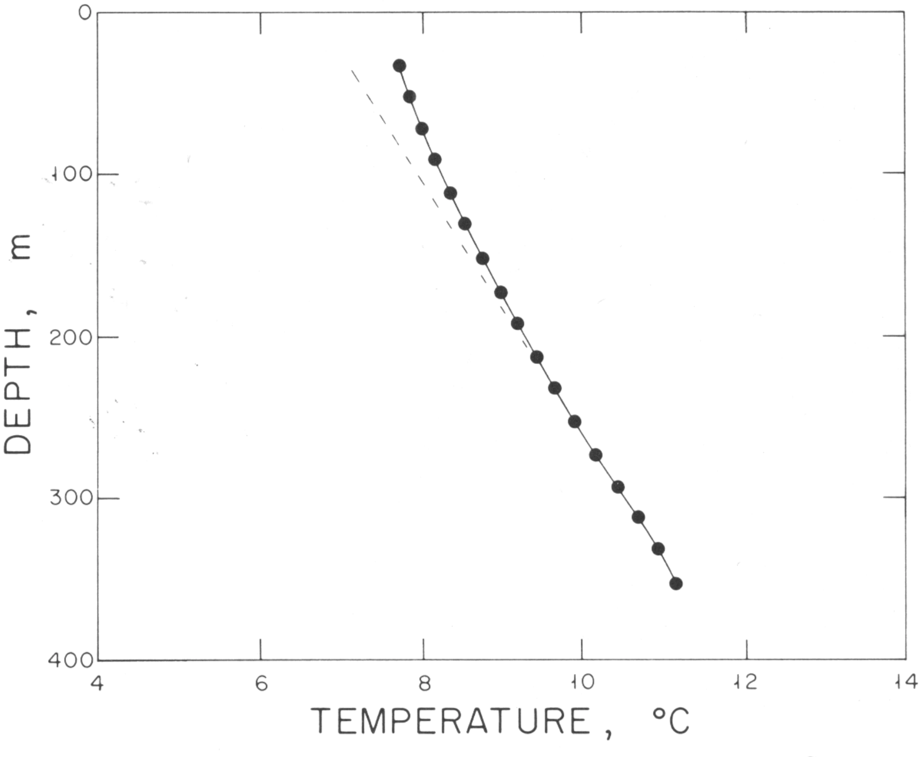

Fig. 4. Temperatures measured in the drill hole at Blodgett Forest, California. Dashed line represents temperatures corrected for a steady-state temperature anomaly of +0.5°C in the clearing.

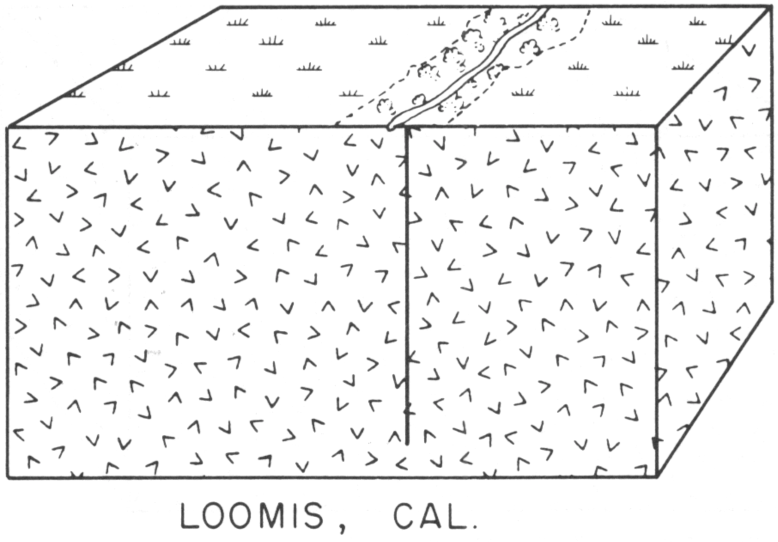

Fig. 5. Block diagram showing contrast in natural vegetation near the drill site at Loomis, California.

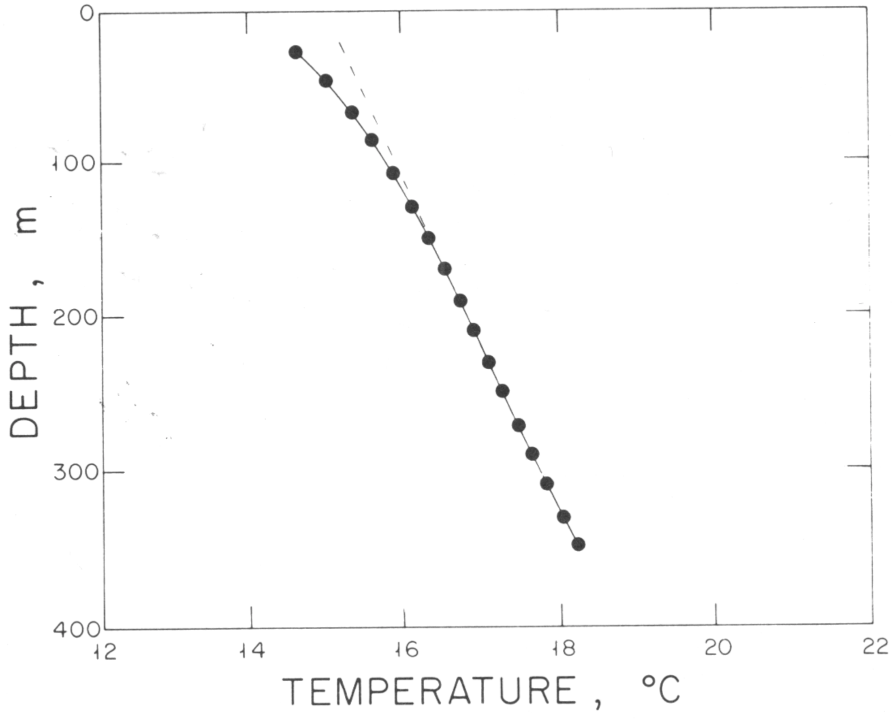

Fig. 6. Temperatures measured in the drill hole at Loomis, California. Dashed line represents temperatures corrected for a steady-state temperature anomaly of −1°C near stream and trees.

Hualapai Mountains, Arizona (Fig. 7), is one of many localities where there is no evidence of human activity or contrasts in vegetation, and topographic relief is small. There is no significant change in gradient between 50 and 250 meters.

Details of these and other effects of climate, culture, hydrology, and topography will be presented elsewhere; the point we wish to emphasize here is our conclusion that with careful site selection, reliable heat flow values can be measured in holes 100 to 150 meters deep by conventional methods.

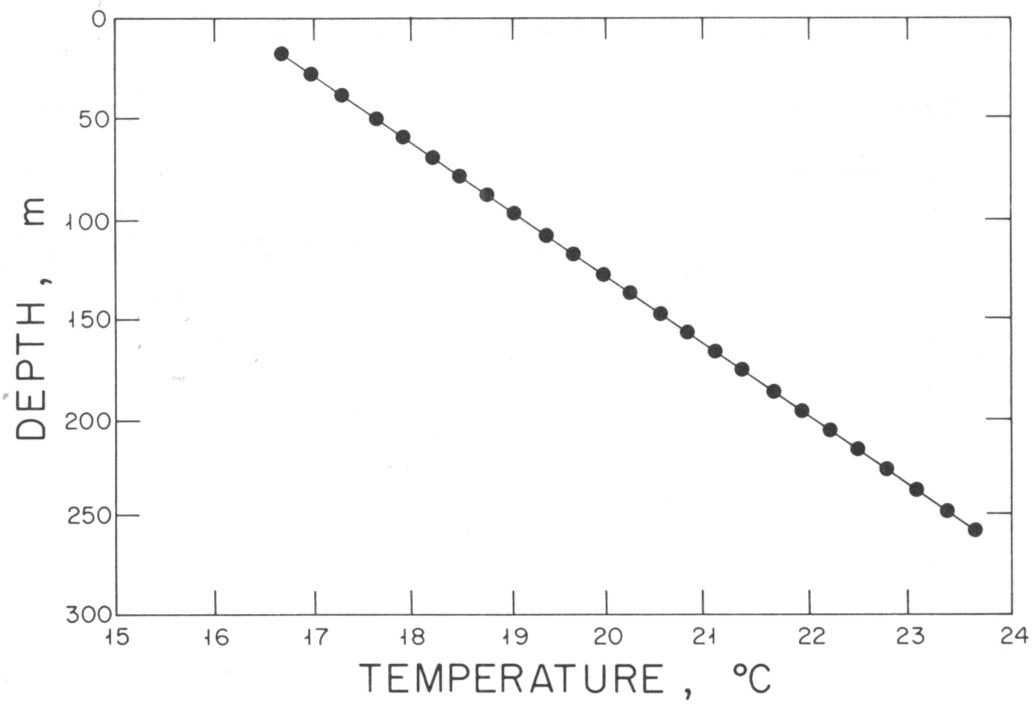

Fig. 7. Temperatures measured in a drill hole in the Hualapai Mountains, Arizona. There are no contrasts in natural cover or evidences of human activity (except for drilling) at this site. We have observed many similar temperature depth curves in the western United States where the natural vegetation appears to be in equilibrium with the environment.

Oceanographic Techniques on Land

Sass, Munroe, and Lachenbruch (1968) have demonstrated that heat flow can be measured at shallow depths (under 200 meters) in unconsolidated sediments by utilizing closely spaced temperature and conductivity measurements within short cored intervals, similar to methods used by oceanographers. Strictly oceanographic techniques have been applied by Hart and Steinhart (1965), Von Herzen and Vacquier (1967), Steinhart, Hart, and Smith (1969), and Sclater, Vacquier, and Rohrhirsch (1970) to large deep lakes with isothermal bottom water. The advantages of working in large, deep lakes with oceanic techniques are limited by the small number of such lakes, their locations, and the need for large vessels with heavy hoisting equipment. Measurements in small, meromictic lakes (Diment, 1967; Johnson and

Likens, 1967; Reitzel, 1966) have large, uncertain corrections for temperature differences at the edges that render them unreliable for studies of regional heat flow, useful as they are for limnological purposes (Likens and Johnson, 1969).

Lakes of moderate size (2 km or more in diameter) are abundant if not ubiquitous, have much smaller corrections for the “warm rim effect,” and show promise for quick inexpensive measurements, particularly in northern latitudes where it is possible to work from a stable ice surface during the winter (Williams and Roy, 1970). Although these lakes do not enjoy the advantage of constant temperatures in the bottom water, the annual temperature cycle is rapidly attenuated by the low diffusivity of the mud (about 0.002 cm^2/sec) and becomes negligible below about 15 meters for a temperature range of 10°C at the mud-water interface (Ingersoll, Zobel, and Ingersoll, 1954, p. 47). Utilizing piston coring techniques developed by limnologists (Wright, 1967; Wright, Livingstone, and Cushing, 1965), we have been able to penetrate more than 20 meters of lake mud with nearly complete core recovery. The holes are cased with plastic pipe and temperatures measured after transient disturbances have subsided. Conductivities are measured on the core with needle probes (Von Herzen and Maxwell, 1959). Details of this technique will be presented elsewhere (Williams et al., 1971). Figures 8 and 9 show the data from measurements at Elk Lake, Minnesota, and Figure 10 the results of measurements in lakes and drill holes near the Mid-Continent Gravity High. With the lake technique still unproved by comparison with nearby conventional measurements, it is premature to speculate about the heat flow on the Mid-Continent Gravity High beyond noting that it does not appear to be extraordinarily low as in the Sierra Nevada.

VERTICAL DISTRIBUTION OF RADIOACTIVITY

The first observation of the linear relation between heat flow and radioactive heat generation of plutonic rocks was made by Francis Birch and reported by Birch, Roy, and Decker (1968). This relation is expressed by

$$Q = a + bA \quad (1)$$

where Q is the heat flow at the surface in units of 10^{-6} cal/cm^2 sec; A is the heat production of the surface rocks in units of 10^{-13} cal/cm^3 sec; a is the intercept value of heat flow measured in rocks of zero heat production; and b is the slope of the line relating Q and A and has the dimension of depth. Throughout the remainder of the paper the units of Q and A will be those cited above and will be omitted from the text.

The relation expressed by Eq. (1) has led to major advances in our understanding of the vertical distribution of heat sources, our ability to calculate more reliable temperature depth profiles, and our ability to accurately map lateral variations of heat sources in the upper mantle. The following sections will discuss these aspects of modern geothermal studies and their implications as to the distributions of subsurface temperatures, heat sources, and the other geological and geophysical parameters of the crust and upper mantle beneath continents.

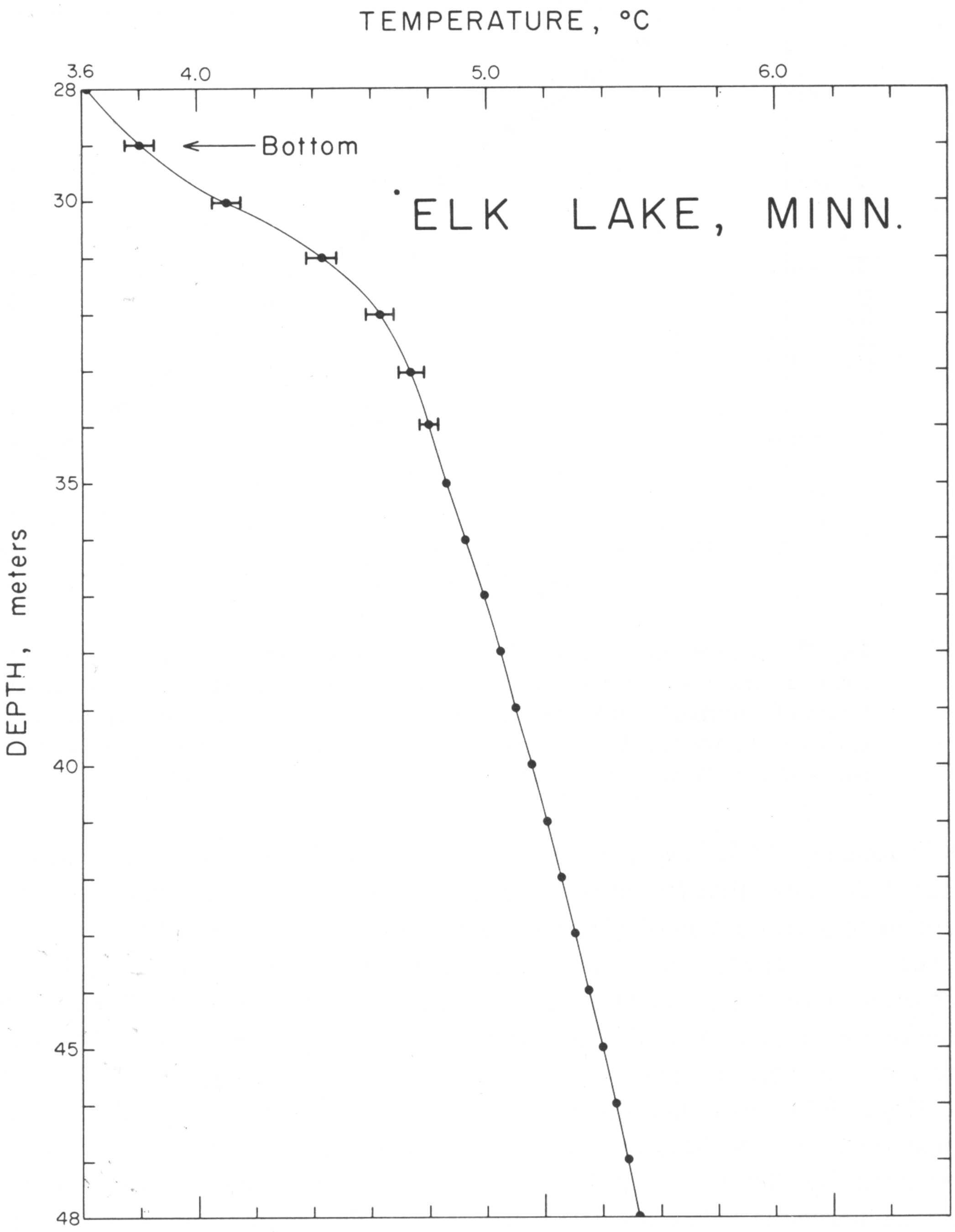

Fig. 8. Temperatures measured at Elk Lake, Minnesota. The error bars indicate points where temperatures were unstable (±0.1°C); at the points without error bars temperatures did not change more than 0.001°C in 5 min. (transducer time constant about 3 sec.).

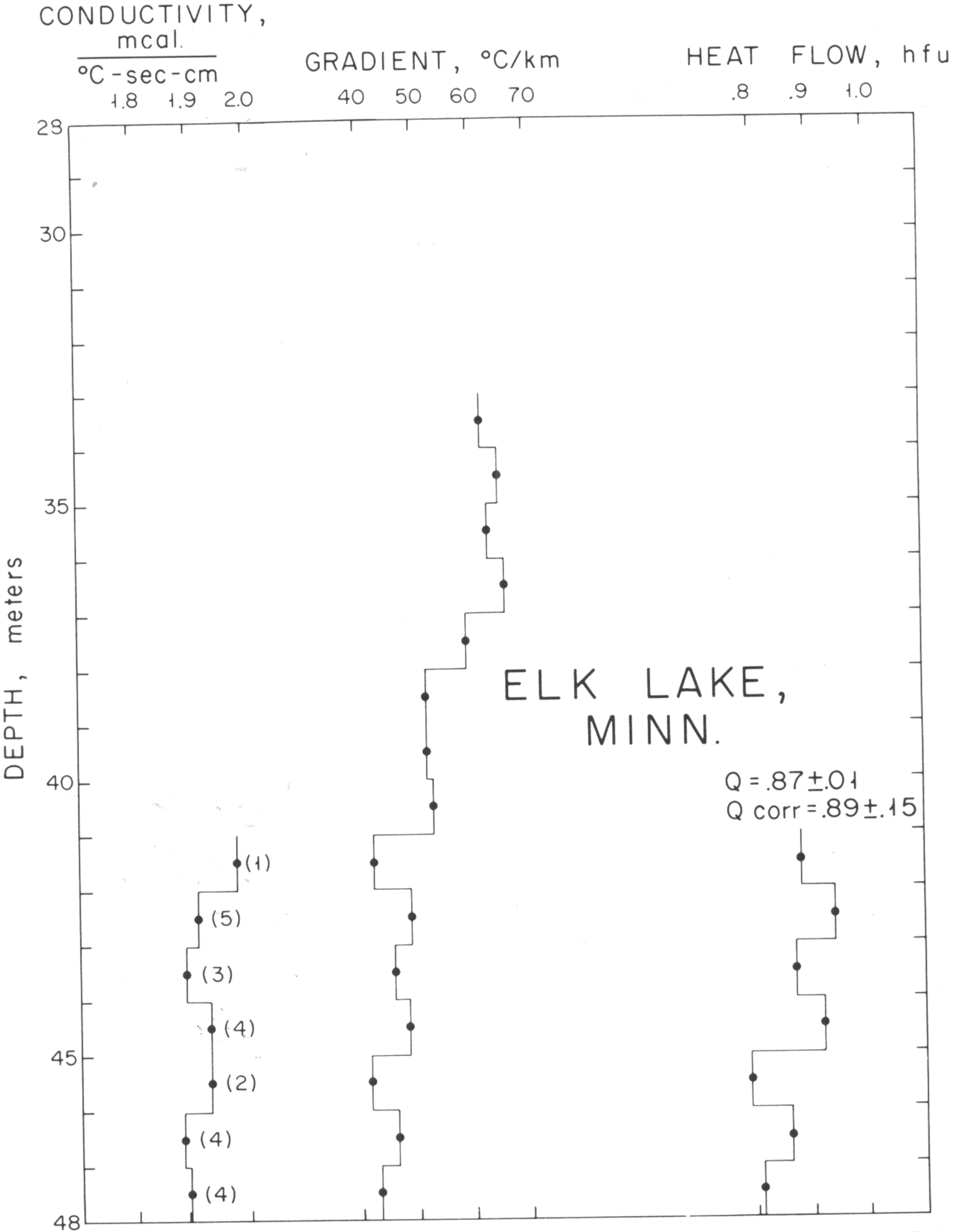

Fig. 9. Thermal conductivity, gradient and heat flow over 1-meter intervals at Elk Lake, Minnesota. The numbers in parentheses near the conductivity curve are the number of needle-probe measurements made in that interval. *Q* is the uncorrected heat flow computed by the resistance integral method (Bullard, 1939). *Q* corr includes corrections for warm rim effect, recent sedimentation, and refraction.

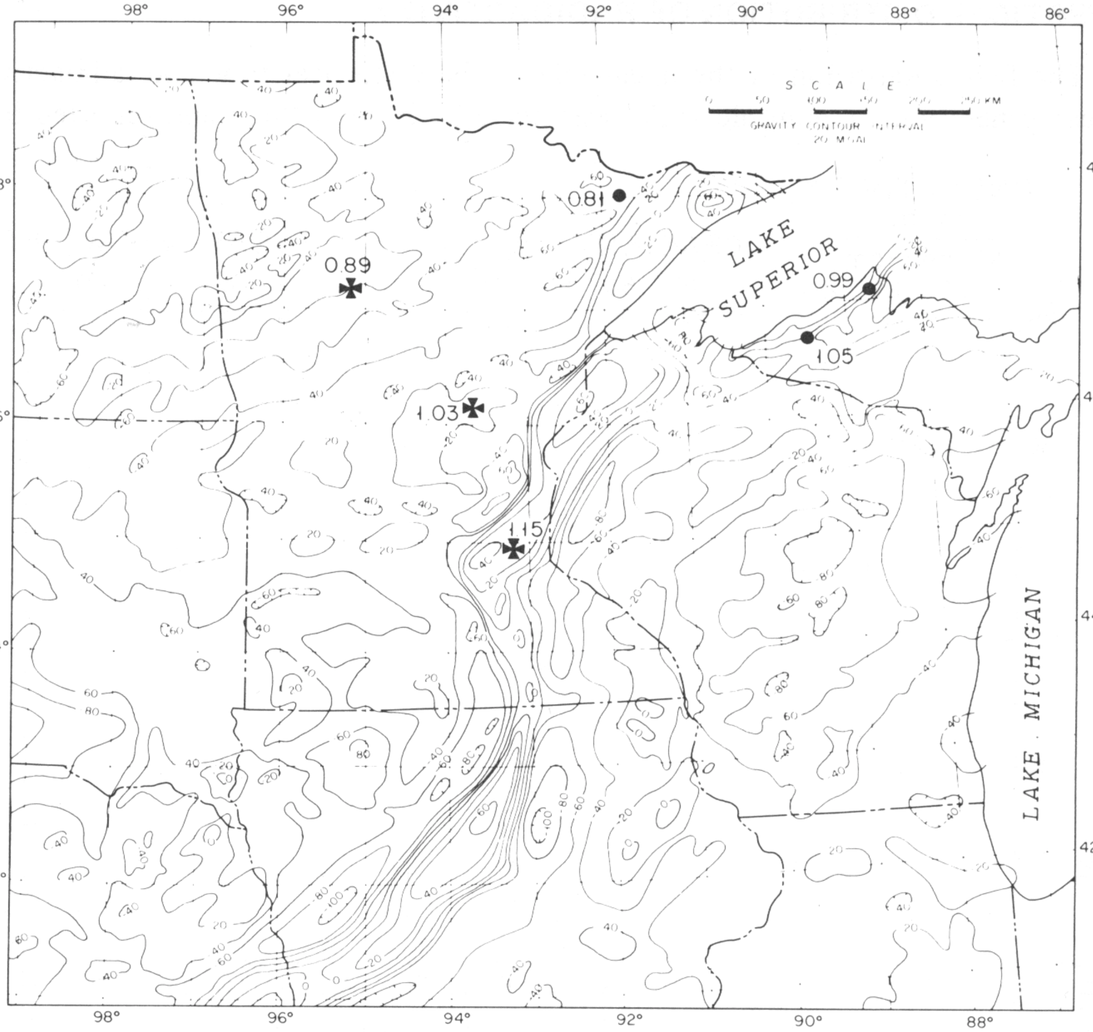

Fig. 10. Heat flow measurements near the Mid-Continent Gravity High. The gravity contours are after Woollard and Joesting (1964). The Maltese cross indicates measurements in lakes by Williams et al. (1971). The solid dots represent the locations of conventional measurements in drill holes reported by Roy, Decker, Blackwell, and Birch (1968). A large number of measurements in Lake Superior (nearly 180) by Steinhart, Hart, and Smith (1969) could not be plotted on this scale. They show a few measurements as low as 0.6 in western Lake Superior with the remainder of the lake between 0.8 and 1.3.

Two vertical distributions of radioactivity have been proposed that are consistent with the observed linear relation between heat flow and heat generation (Birch, Roy, and Decker, 1968; Lachenbruch, 1968; Roy, Blackwell, and Birch, 1968): Model (1), A constant to the depth given by the slope of the straight line; Model (2), A exponentially decreasing with depth according to the relation $A=A_0e^{-x/b}$ where A_0 is a constant, b is the slope of the straight line, and x is depth. The intercept a in the model with constant heat generation is the heat flow from below the radioactive layer (approximately 7 to 10 km thick). For the model with exponentially varying heat generation, the constant a is the heat flow from the mantle. The relationship between heat production and heat flow, whatever the model used to explain it, implies that beneath large intrusive bodies the whole crust has been affected and the original distribution of U and Th modified in some regular way.

The conclusion that the vertical distribution of uranium and thorium can be inferred from a study of the surface heat flow and heat production is an extra bonus from recent heat flow studies and has important geophysical and geochemical ramifications. In geophysics a definite model for the vertical distribution of heat sources allows a much more accurate calculation of subsurface temperatures with resulting implications to the physical properties of rocks in the crust and upper mantle and possible phases involved. An interesting geochemical implication is that similar models might apply to other trace, or even major, elements. For example, Zartman and Wasserburg (1969) extended the regular variation of heat producing elements, inferred from the heat flow data, to the trace elements Sr, Rb, and Pb and were able to explain some of the apparent inconsistencies in the distribution of isotopes in the Rb-Sr, U-Pb, and Th-Pb systems studied in surface rocks. Thus, it is clear that the implications of a heat production versus depth model are so broad that more detailed studies of vertical U and Th distribution at suitable locations are of great importance.

Roy, Blackwell, and Birch (1968) have cited the evidence for uniform radioactive heat production over vertical ranges of about 1 or 2 km. Lachenbruch (1968) and Roy, Blackwell, and Birch (1968) both note, however, that the linear relationship between heat flow and heat production also are consistent with an exponential decrease of radioactivity with depth. Vertically decreasing radioactivity has been observed in a few deep (3 km) drill holes (Lachenbruch and Bunker, 1969), one survey of surface samples (Dolgushin and Amshinsky, 1966), and there is some evidence (Decker, unpublished) that an exponential relationship may exist between observed surface radioactivity and estimated mean erosion over four batholiths of Silver Plume granite in the Colorado Front Range (Fig. 11). The decreases of radioactivity in the drill holes are not clearly exponential (Lachenbruch and Bunker, 1969) and the b values (1 to 2 km) calculated from the Front Range and other surface data are all significantly lower than those (7 to 10 km) determined for the observed heat flow-heat production lines. Moreover, all other observational data are ambiguous because the accuracy (± 10%) of present heat generation measurements is roughly equivalent to the magnitude of the analytically predicted decreases with depth (10%/km; Lachenbruch and Bunker, 1969).

The recent combined studies of radioactivity and heat flow have provided us with the first reliable means for accurately mapping variations of temperature and heat flux in the upper mantle, but we believe that present radioactivity information is inconclusive and that the actual vertical distribution of heat production implied by Eq. (1) remains a very significant geochemical problem.

HEAT FLOW DISTRIBUTION

Regardless of the distribution of radioactivity preferred to explain Eq. (1), the intercept value a is obviously the parameter of importance in an investigation of regional variations in heat flow from the mantle. From a study of the heat flow and heat production in plutonic rocks in the United States, Roy, Blackwell, and Birch (1968) defined a heat flow province on the basis of its characteristic relationship between heat flow and heat production and identified three provinces: the eastern United States, where $a = 0.8$ and $b = 7.5$ km; the Basin and Range province, where $a=1.4$ and $b = 9.4$ km; the Sierra Nevada, where $a=0.4$ and $b=10$km.

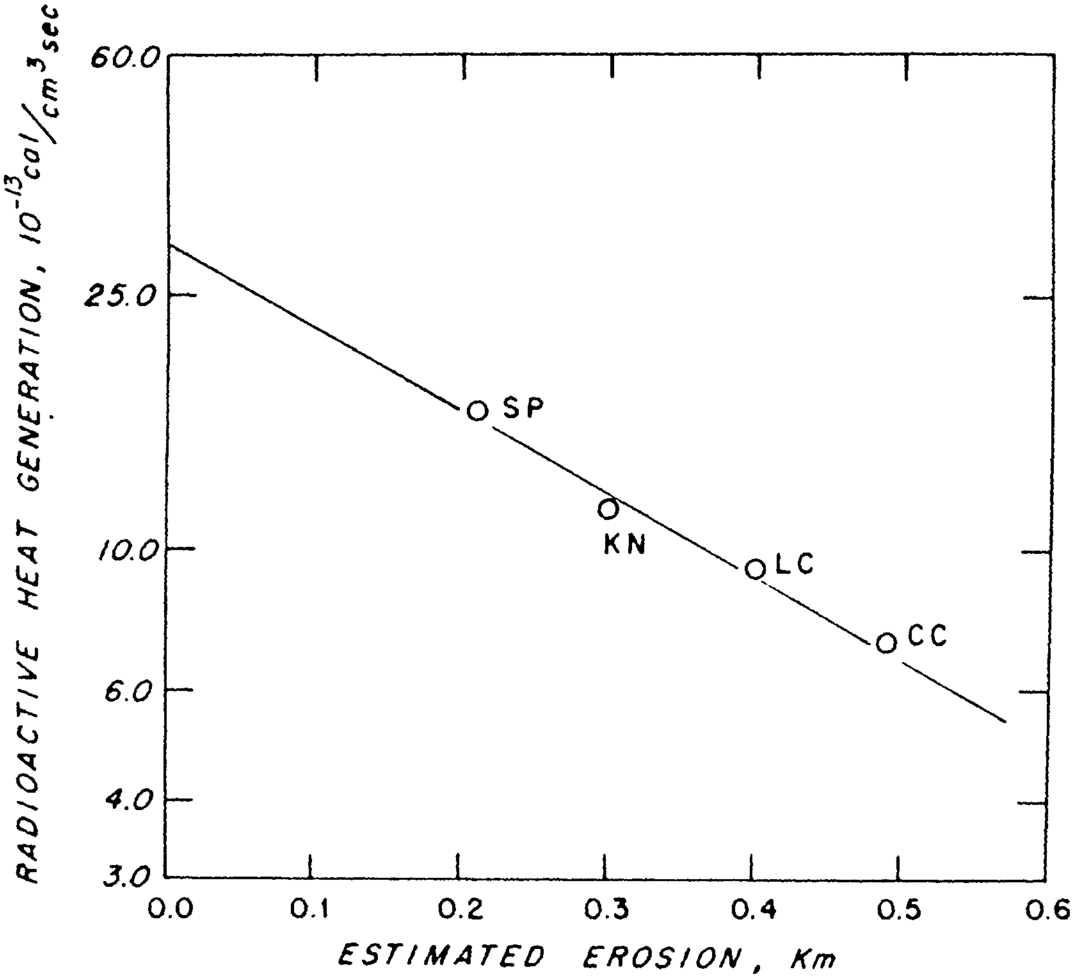

Fig. 11. Radioactive heat generation as a function of mean erosion over four batholiths of Silver Plume type granite in the Colorado Front Range. SP, KN, LC, and CC represent the Silver Plume, Kenosha, Log Cabin, and Cripple Creek batholiths, respectively. Radioactive heat generations are after Phair and Gottfried (1964). Estimated mean erosions by Decker (unpublished).

From the broad scale geophysical point of view, the large variations of the intercept value a, which reflect variations in heat flow from the mantle, are of more interest than the slope 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 a and b in mind, we have prepared a "reduced" heat flow map of the United States (Fig. 12). A reduced heat flow value is a calculated from Eq. (1) transposed to a = Q — bA. Points in the eastern United States, Basin and Range province, and Sierra Nevada reduce, of course, to 0.8, 1.4, and 0.4, because they were used to determine a and b for these regions initially. New data points in these and other regions have to be examined with care because there may be subprovinces with different slopes (b) but the same intercept (a) within the major provinces. In new regions with only a few data points such as the Peninsular Ranges of southern California, the Salinian block, the northern Cascades, etc., we have taken b=10 km in calculating values of reduced heat flow.

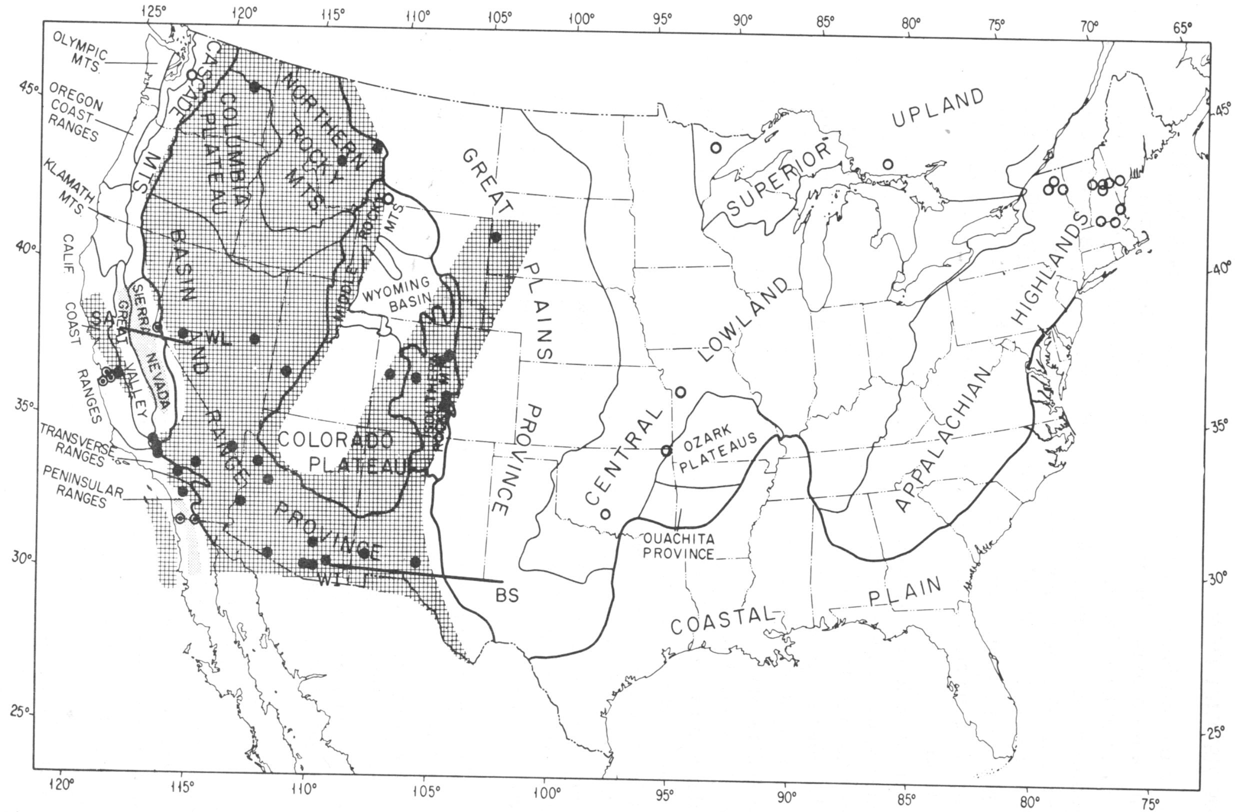

Fig. 12. Physiographic provinces, reduced heat flow values and heat flow provinces in the United States. Sites indicated by circles have reduced heat flow values of 0.8 ± 0.1; dotted circles, values between 0.9 and 1.3; solid dots values greater than 1.3. The extent of the regions of high reduced heat flow are designated with a square pattern, those with 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. The lines SA-WL and WI-BS are the locations of Figs. 16 and 17.

Figure 12 is a map of the major physiographic and heat flow provinces in the United States. The locations for which we have reduced values (Roy, Blackwell, and Birch, 1968; Roy, Blackwell, and Decker, unpublished) 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 as 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 Fig. 13. A similar map of the present distribution of heat flow in the eastern United States has been presented by Diment (this volume). Although the heat flow contours drawn in Fig. 13 show that the western United States is characterized by large areas of high and low regional heat flow, the map of reduced flux (Fig. 12) is more useful and clearly indicates that the regional heat flow patterns are related to significant variations of flux from the upper mantle.

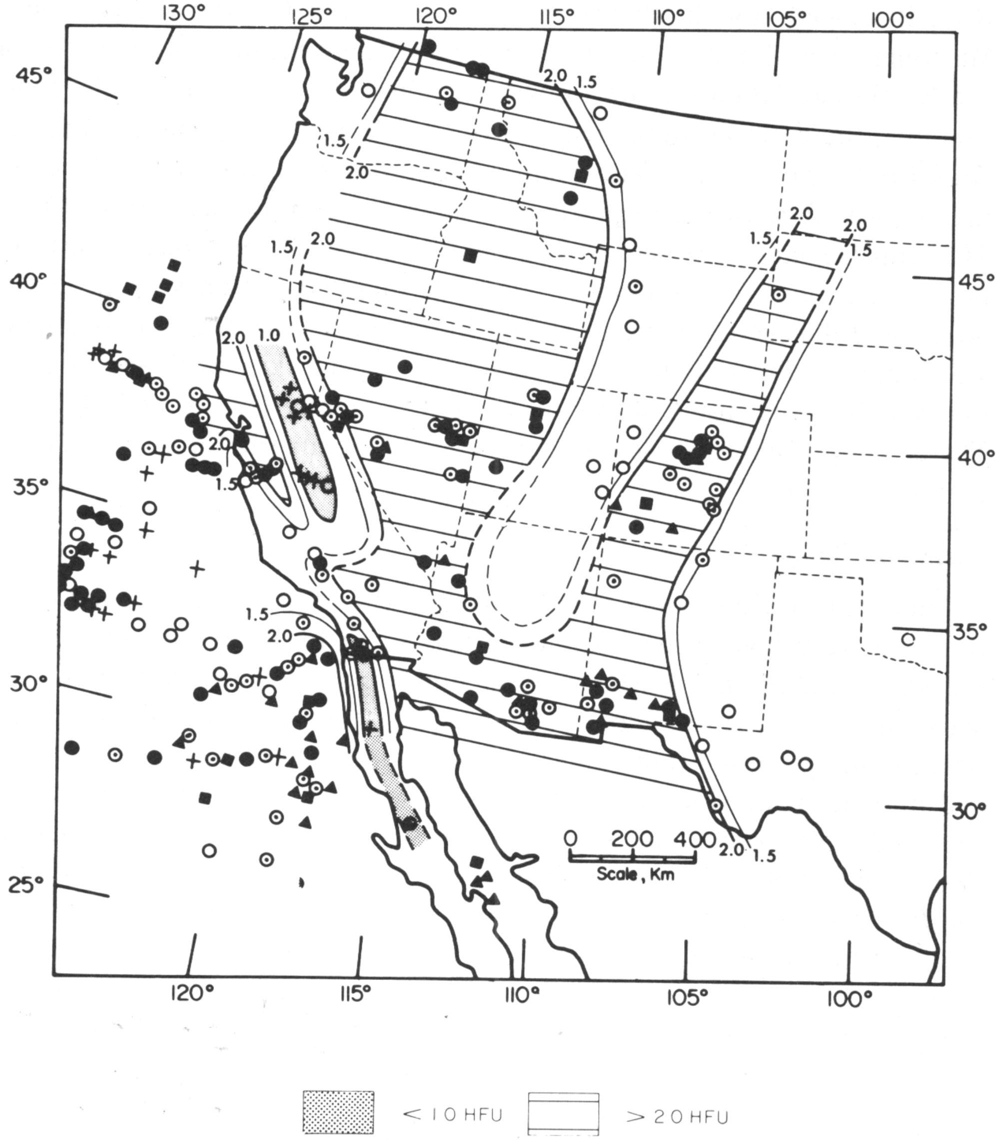

Fig. 13. Measurements of heat flow in the western United States and adjacent portions of the eastern Pacific Ocean. The contours delineate regions of high and low heat flow with average values of flux that would be measured in rocks with surface radioactivity within the range of granodiorite. Published heat flow data are from Benfield (1947), Herrin and Clark (1956), Clark, (1957), Foster (1962), Von Herzen (1964), Spicer (1964), Lee and Uyeda (1965), Lachenbruch, Wollenberg, Greene, and Smith (1966), Burns and Grim (1967), Vacquier, Sclater, and Correy (1967), Costain and Wright (1968). Roy, Decker, Blackwell and Birch (1968), Sass, Lachenbruch, Greene, Moses, and Monroe (1968), Henyey (1968), Warren, Sclater, Vacquier, and Roy (1969), Blackwell (1969), Decker (1969). Unpublished data by Roy, Blackwell, and Decker are also included. Pluses represent heat flow values in the range 0 to 0.99; open circles, 1.0 to 1.49; dotted circles, 1.5 to 1.99; solid circles, 2.0 to 2.49; solid triangles, 2.5 to 2.99; solid rectangles, > 3.0. A few measurements in the Pacific Coast Provinces have not been plotted because of lack of space on this scale.

Eastern United States

The reduced heat flow values in the United States east of the Rocky Mountains are all 0.8 ± 0.1. New data points in this region since the summary by Roy, Blackwell, and Birch (1968) are in southern Ontario (Sass, Killeen, and Mustonen, 1968) and southern Oklahoma (Blackwell, unpublished). Outside of the Northeast, data are sparse: however, other provinces may still be found; for example, there are no measurements of heat flow, reduced or unreduced, in the Gulf Coast geosyncline. There are no indications, however, of differences in mantle heat flow of the magnitude of those found in the western United States. The Appalachians have been stable geologically since early in the Mesozoic and the other regions for even longer. The crust ranges in thickness from about 30 to 50 km and the average *P* wave velocity in the lower crust is generally high (7.0 to 7.5 km/sec). *Pn* velocities are high (8.1 - 8.3 km/sec), and there is no low-velocity zone for *P* waves in the upper mantle (Green and Hales, 1968). There is only a moderate low-velocity zone in the mantle for *S* waves (Brune and Dorman, 1963).

Basin and Range

Reduced heat flow values in the Basin and Range province are 1.4 ± 0.2 except for some very high values that we attribute to local thermal anomalies (Roy, Blackwell, and Birch, 1968). The Basin and Range province has been tectonically active throughout the Cenozoic. The deformation is characterized by generally northtrending normal faults, many with vertical displacements of 3 km or more, and province-wide volcanic activity. Hot springs abound in the province and the east and west borders are presently the sites of bands of earthquake activity (Woollard, 1958). The crust is thinner than normal for the average elevation and the *Pn* velocities are only 7.8 to 7.9 km/sec (Diment, Stewart, and Roller, 1961; Eaton, 1963, 1966; Healy, 1963; Hill and Pakiser, 1966; Pakiser, 1963). There is an upper mantle low-velocity zone for *P* waves between about 60 and 170 km (Archambeau, Flinn, and Lambert, 1969), and *S* waves are hardly transmitted at all (Wickens and Pec, 1968).

Northern Rocky Mountains—-Columbia Plateau

The Northern Rocky Mountains are composed of Precambrian, Paleozoic, and Mesozoic miogeosynclinal sediments in the east and Paleozoic and Mesozoic eugeosynclinal sediments in the west. The sedimentary rocks are intruded by many large bodies of Mesozoic plutonic rocks such as the Colville, Loon Lake, Kaniksu, Idaho and Boulder batholiths. The Cenozoic history is marked by several episodes of normal faulting and graben formation and by moderate amounts of volcanism. Hot springs are abundant in the southern part of the province and the eastern boundary is a zone of active earthquakes. Data obtained by Blackwell (1969, unpublished) show the same average surface and reduced heat flow as in the Basin and Range. The crust in the Northern Rocky Mountains is thin and the *Pn* velocities are 7.8 to 7.9 km/sec (Asada and Aldrich, 1966: Steinhart and Meyer, 1961; White and Savage, 1965; White, Bone, and Milne. 1968). Thus the Northern Rocky Mountains Province is an extension of the Basin and Range heat flow province with a similar crustal structure and Cenozoic geologic history.

The Columbia Plateau physiographic province has a diverse geology. In much of the province, Cenozoic volcanic rocks cover in varying thicknesses a Mesozoic bedrock similar to that in the Basin and Range and Northern Rocky Mountains. In at least part of the Columbia Plateau proper and in part of the Snake River Plains, Miocene, and Pliocene and Pleistocene basalts, respectively, make up much if not all of the crust (Hill, 1963; Hill and Pakiser, 1966). Sparse data suggest a high heat flow similar to that in the Northern Rockies and Basin and Range province. Thus Blackwell (1969) has combined the Basin and Range, Northern Rockies, and Columbia Plateau into a single geophysical province called the Cordilleran Thermal Anomaly Zone.

Southern Rocky Mountains

Previously unpublished heat generation and heat flow data for seven sites in the Southern Rocky Mountains are plotted in Fig. 14. Neither the slope (10km) nor the intercept (1.3) of the line calculated from these data is statistically different from the line calculated for the Basin and Range province. So at the present time, until more data in both areas either confirm or deny this equivalence, we consider the Southern Rocky Mountains to be a prong of the Basin and Range heat flow province. The Southern Rocky Mountains are composed of Precambrian granite and metamorphic rocks extensively faulted and uplifted in the Cenozoic and intruded and covered in places by late Cretaceous to Recent igneous rocks (Curtis, 1960). The long-period magnetic variation studies in the area by Porath, Oldenberg, and Gough (1970) indicate an upwarping of the low electrical resistivity layer similar to that beneath the Basin and Range province, but much smaller in lateral extent.

Although the geophysics and the Cenozoic geology of the Southern Rocky Mountains resemble those of the Basin and Range in many ways, there is a major difference in the crustal thickness. The crust is about 50 to 55 km thick and is thus much thicker than in the Basin and Range (Jackson and Pakiser, 1965; Ryall and Stuart, 1963), but the crust does appear to be 5 to 10 km thicker in the adjacent Great Plains even though elevations are lower (Jackson, Stewart, and Pakiser, 1963). The difference in crustal thickness between the two high heat flow areas demonstrates that high heat flow is not confined to regions with a thin crust.

The boundaries of the zone of high heat flow extending through the Southern Rockies are shown in Fig. 12 and 13 as are the data on which the boundaries are based. Blackwell (1969) inferred an extension of the zone of high heat flow at least to the Black Hills in South Dakota.

Sierra Nevada

All reduced heat flow values in the Sierra Nevada Mountains are within 10% of 0.4, only one-half that found in the eastern United States. As presently known, the province is only about 150 km wide by 600 km long, but is still of crucial importance as it is, at the present stage of heat flow investigations, unique on the earth. The bedrock of the range is composed of Paleozoic and Mesozoic geosynclinal sediments and volcanics that were introduced by middle and late Mesozoic granitic rock on a grand scale. The range has been relatively quiescent during the Cenozoic although the east flank was uplifted in the late Cenozoic. The crust is 50 km thick under the crest and thins uniformly westward to about 20 km beneath the foothills (Eaton, 1963, 1966). Independent evidence for low temperatures in the upper mantle is not available, but investigations such as determinations of the electrical resistivity structure in the mantle and seismic wave velocities are obviously of crucial importance to our understanding of the heat flow anomaly.

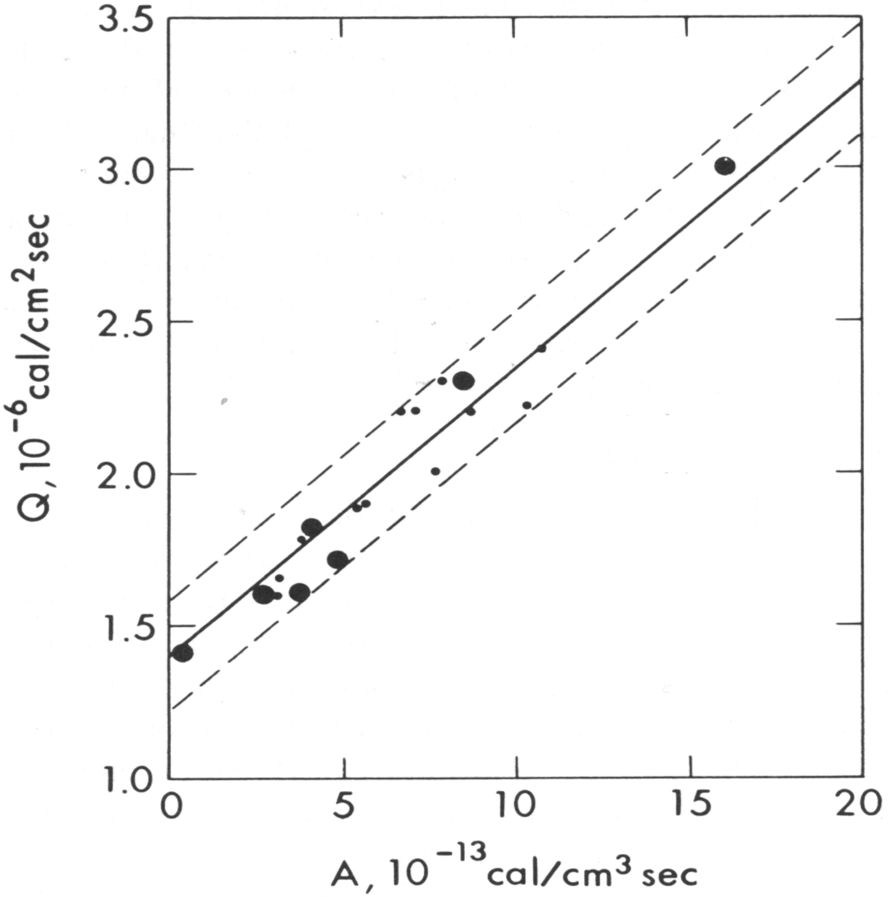

Fig. 14. Heat flow and radioactive heat production data for the Southern Rocky Mountain region. Large dots are Southern Rocky Mountain points; small dots are points in the Basin and Range province (Roy, Blackwell, and Birch, 1968). The solid line is the relationship between heat flow and heat production determined by Roy, Blackwell, and Birch (1968) for the Basin and Range province. Heat flows in the Southern Rocky Mountains are from Birch (1950), Roy, Decker, Blackwell and Birch (1968), Decker (1969), and Decker, unpublished. Heat generations after Phair and Gottfried (1964), Phair (personal communication, 1966), and Rogers (personal communication, 1969).

Colorado Plateau—Wyoming Basin—Middle Rocky Mountains

This group of physiographic provinces has been investigated by a total of only seven heat flow determinations of which only two have reduced values. A reduced value in the Beartooth Plateau is about 0.9, while one at the eastern edge of the Colorado Plateau is about 1.3. unreduced values of 1.3 (Sass, Lachenbruch, Greene, Moses, and Monroe, 1968) in the Wind River Range and 1.2 in the central Colorado Plateau may indicate a region of normal intercept values. A high unreduced value was measured in the Absaroka volcanic region. Our inferences on the heat flow are shown in Figs. 12 and 13.

Most of the area in these provinces is inferred to be normal based on: (1) the few heat flow data;(2) the conclusions of Porath, Oldenberg, and Gough (1970) that the low-resistivity layer is found at about the same depth beneath the Great Plains and the Colorado Plateau; (3) suggestions that the crustal structure changes abruptly crossing from the southern Colorado Plateau into the Basin and Range (Warren, 1969) and from the Basin and Range into the Middle Rocky Mountains (Willden, 1965); (4) evidence presented by Julian (1970) that the Colorado Plateau is structurally similar to eastern North America. The crust is about 40 km thick in the Colorado Plateau, and although the *Pn* velocity is only 7.8 km/sec (Roller, 1965), travel times from the Gasbuggy shot indicate higher average upper mantle velocity beneath the Colorado Plateau than beneath the provinces to the west.

The heat flow pattern is particularly hypothetical in northern Wyoming and indeed the two zones of high heat flow might connect instead of remaining separate as we have indicated on Figs. 12 and 13.

Pacific Coast Provinces

The heat flow along the Pacific coast is variable on a much smaller scale than in the provinces to the east of the Sierra Nevada. Determinations in granitic rocks in the Peninsular Ranges of southern California and Baja California (Roy and Brune, unpublished data) have reduced values of 0.6 to 0.7 near the center of the range rising sharply to 1.2 near the edge of the Imperial Valley. Although the reduced values in the center of the Peninsular Ranges are not as low as in the Sierra Nevada, we believe they are extremely important to the tectonic interpretation and have indicated a narrow zone of abnormally low heat flow for this region on Fig. 12 and 13.

In the granitic rocks of the Salinian block west of the San Andreas fault, reduced heat flow values are slightly above normal, 1.0 to 1.1 (Roy, Brune, and Henyey, in preparation). In contrast, the Franciscan block east of the San Andreas fault has high heat flow at the surface, 2.2 to 2.4 (Sass, Monroe, and Lachenbruch, 1968; Roy, Brune, and Henyey, unpublished data). If we take $A = 2.8$ for the Franciscan (Wollenberg, Smith, and Bailey, 1967) and $b=10$ km, the reduced heat flow would be 1.9 to 2.1, approximately 0.6 higher than the Basin and Range. The extent of this region of extraordinarily high heat flow is not well known; on Figs. 12 and 13 we have extended it to the north to include the region near Clear Lake where the geothermal steam fields are an obvious indication of high heat flow.

There are no measurements of heat flow, reduced or unreduced, in the Pacific Coast provinces between Menlo Park, California, where Sass, Monroe, and Lachenbruch (1968) have reported a value of 2.2 and the northern Cascades where Blackwell (unpublished) has a reduced value of 1.0. More measurements are urgently needed in this region of complex interaction between continental and oceanic plates (Atwater and Menard, 1970; McKenzie and Morgan, 1969; Silver, 1969).

Heat Flow Provinces Outside the United States

Roy, Blackwell, and Birch (1968) suggested that the linear relationship between heat flow and heat production found in the eastern United States is the characteristic curve for normal continental heat flow in regions that have been tectonically stable for at least 100 to 200 m.y. The data they cited for Australia and the recently published data from three sites in

Paleozoic plutons in New South Wales, Australia (Hyndman, Jaeger, and Sass, 1969), and two sites in sediments above Precambrian granitic rocks in the Canadian Shield (Lewis, 1969; Sass, Killeen. and Mustonen, 1968) lend strong support to that conclusion (see Fig. 15). The extension of this hypothesis to other continents gains support from the low values of flux measured in diorite and serpentinite (which almost certainly have low values of heat production) at Virtasalmi and Nivala, Finland (Puranen. Jariimaki, Hamalainen, and Lehtinen, 1968), which are in the range (0.65 to 0.81) of the reduced heat flows in the eastern United States.

In his classic paper on heat flow in South Africa, Bullard (1939) measured a heat flow of 1.52 in the Dubbeldevlei borehole, which penetrated "Old Granite" of the Transvaal. Based on radium determinations on granites from the Cape Province by Immelman (1934), he estimated a heat production of 7.4×10^{-13} cal/cm^3 sec. This point plots slightly above the line for stable continental regions. It is perhaps more appropriate to combine the heat productivity of the Cape Granites with the heat flow determinations (1.21 to 1.45) by Gough (1963) in the southern Karoo. These points straddle the line characteristic of stable regions.

Thus far the only locality outside the United States that plots close to the Basin and Range line is the Snowy Mountains in Australia (Sass, Clark, and Jaeger, 1967). This region is tectonically similar to the Basin and Range province with normal faulting, Tertiary volcanism and late *P* wave arrivals (Cleary, 1967; Hyndman, Jaeger, and Sass, 1969).

One of the important objectives of future studies of heat flow is to test the hypothesis that the same relationship exists between heat flow and heat production on other continents. If this relationship can be well established, it will strengthen the conclusion that all continental crust has developed by upward differentiation of sialic material from the underlying mantle.

HEAT FLOW TRANSITIONS

Zones of transition between the heat flow provinces previously discussed have been investigated in a few places. In all cases, the transition regions are narrow compared to the widths of the provinces. As examples, two profiles will be discussed: one across the Basin and Range-eastern United States transition (Fig. 16) and one across the Sierra Nevada-Basin and Range transition (Fig. 17).

Basin and Range-Great Plains Transition

Heat flow data along a profile from Wilcox, Arizona, to Big Spring, Texas, are shown in Fig. 16; the location of the profile (WI-BS) is indicated on Fig. 12. Data are from Warren, Sclater, Vacquier, and Roy (1969), Roy, Decker, Blackwell, and Birch (1968), Decker and Birch (in preparation). Although reduced heat flow values are available at only two sites, it appears that the high heat flux in the Basin and Range province extends at least as far as Cornudas, New Mexico, where Schmucker (1964) put the eastern edge of the "Texas Anomaly" in his study of the long-period magnetic variations. The heat flux is 0.9 about 100 km to the south and 50 km to the east near Van Horn, Texas. A heat flow of 1.1 was found by Herrin and Clark (1956) at Carlsbad, New Mexico, about 120 km due east of Cornudas. That value also was found at several other sites in the southern Great Plains (Herrin and Clark, 1956). Although no reduced values are available in the Great Plains, it is clear that the transition occurs within a horizontal distance of 50 to 100 km

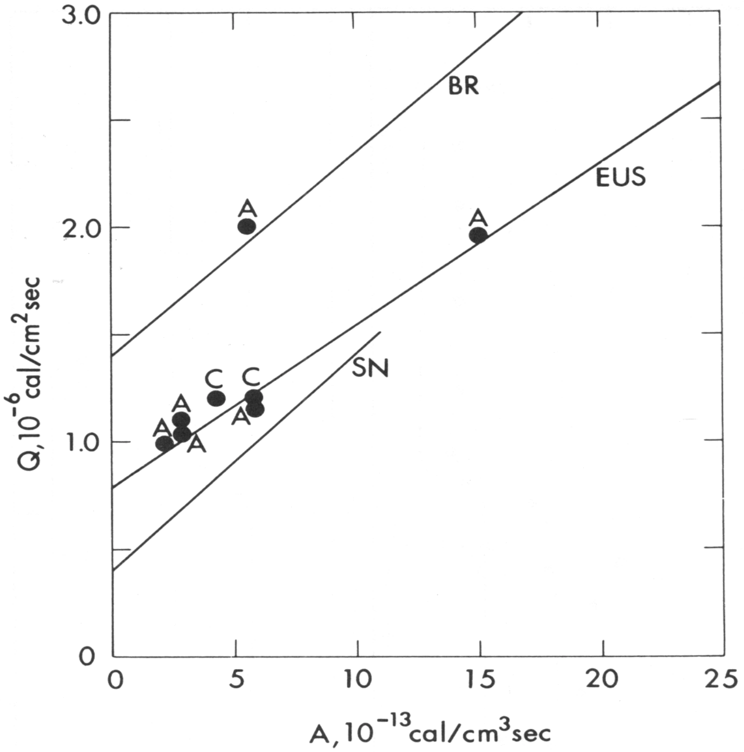

Fig. 15. Heat flow and heat production relations for the Basin and Range (BR), eastern United States (EUS), and Sierra Nevada (SN). Data points labeled A are from Australia, C from Canada.

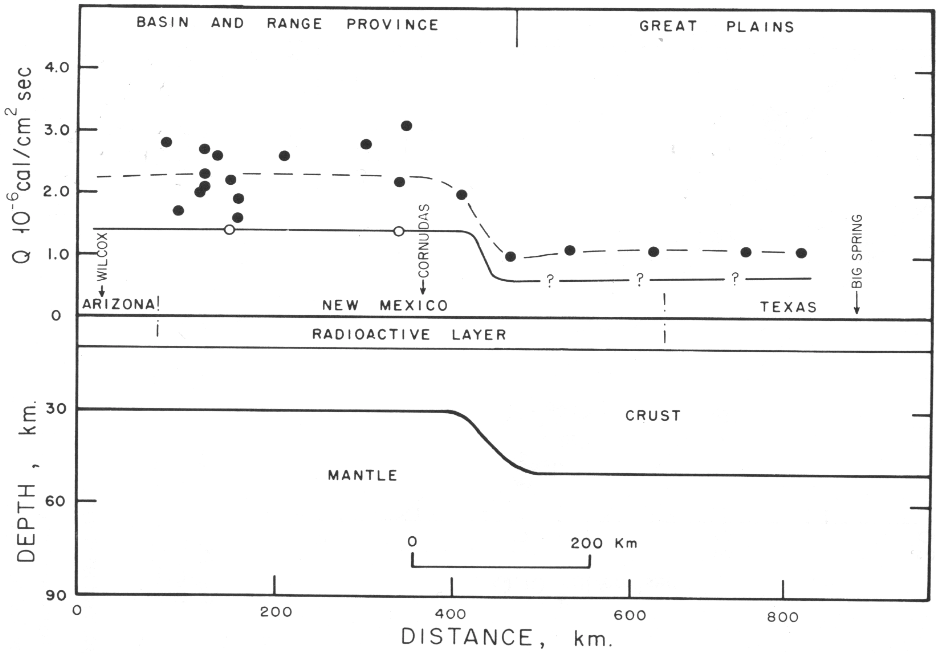

Fig. 16. Summary of the heat flow and other geophysical data for a profile from Wilcox, Arizona, to Big Spring, Texas (see line WI-BS, Fig. 12). The solid circles are heat flow values measured at the surface and the open circles are "reduced" heat flow values. The solid line represents the reduced heat flow from the lower crust and upper mantle.

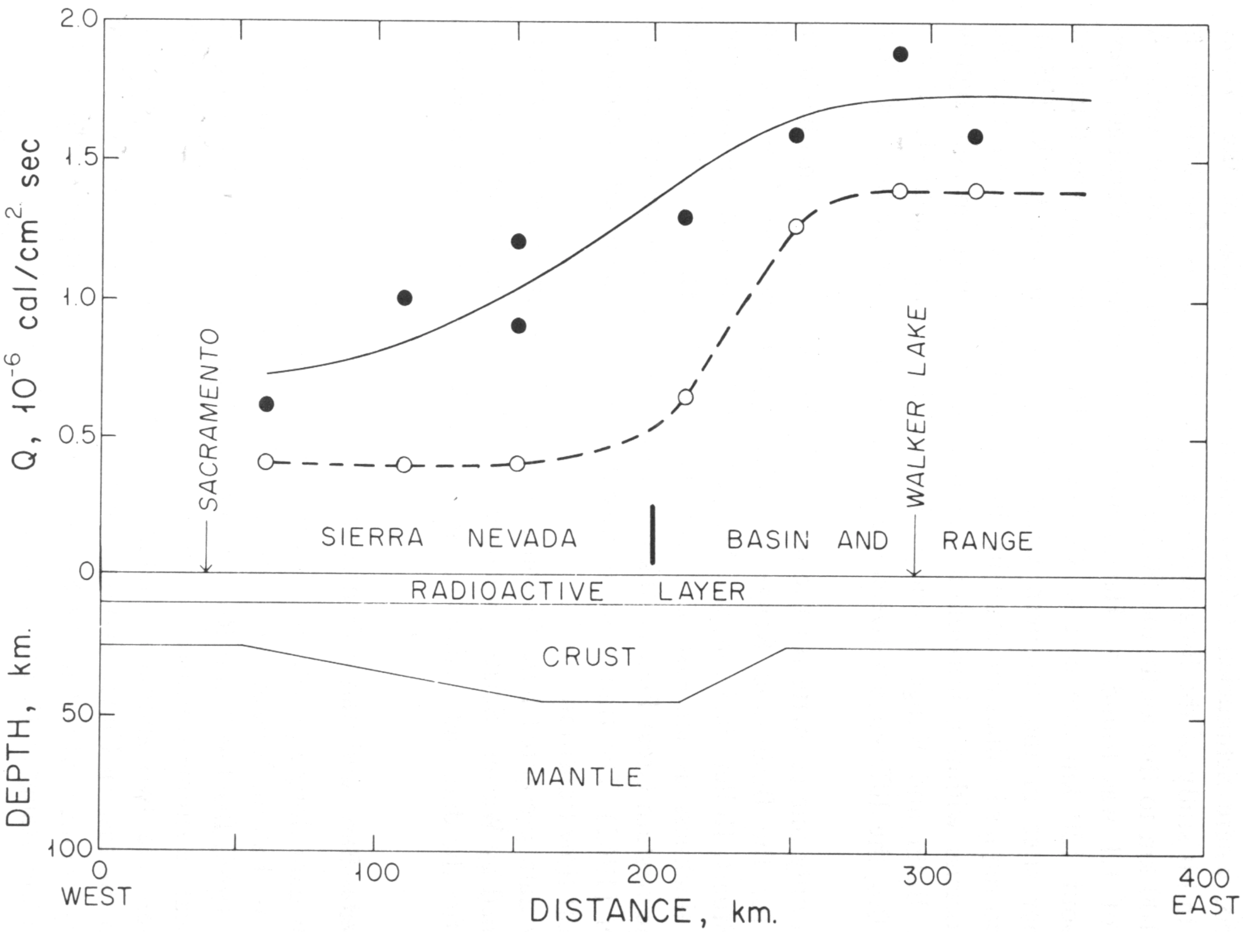

Fig. 17. Summary of heat flow and other geophysical data for a profile from Sacramento, California, to Walker Lake, Nevada (see line SA-WL, Fig. 12). Solid circles are heat flow values measured at the surface and open circles are "reduced" heat flow values. The dashed line represents the reduced heat flow from the lower crust and upper mantle.

and slightly within the Basin and Range physiographic province. The amplitude of the anomaly is 0.6, the difference between the intercept values for the two heat flow provinces.

Although only one estimate for the crustal thickness (30 to 35 km) has been published for the Basin and Range province in southwestern New Mexico (Stewart, Stuart, Roller, Jackson, and Mangan, 1964), the crust is inferred to be of similar thickness as far east as Cornudas (Fig. 16). The crustal thickness beneath the western Great Plains (50 km) is from a profile published by Stewart and Pakiser (1962). The transition in crustal structure is assumed to coincide with the heat flow transition.

The new data presented here demonstrate that the transition is more abrupt than assumed by Warren, Sclater, Vacquier, and Roy (1969), hence their model no longer fits the data and a shallower source or sharper rise in the isotherms is necessary.

Sierra Nevada—Basin and Range Transition

Heat flow data along a profile (line SA-WL, Fig. 12) at 39^0N from Sacramento, California, to Fallon, Nevada, are plotted in Fig. 17 (Roy, Decker, Blackwell, and Birch, 1968; Blackwell and Roy, in preparation). Both surface and reduced values indicate a simple transition; however, we believe that, unlike the previous profile, there are two anomalies and that the transition must be compound. Relative to the eastern United States as the standard for normal heat flow, there is a negative anomaly of 0.4 in the Sierra Nevada and a positive anomaly of 0.6 in the Basin and Range so that the total anomaly is about 1.0.

The center of the transition in heat flow occurs about 50 km inside the physiographic boundary of the Basin and Range province and coincides with the rapid thinning of the crust from 50 km under the Sierra Nevada to 25 km beneath the Basin and Range (Eaton, 1963; 1966). A north trending zone of earthquake activity extends about 100 km into the Basin and Range province from the physiographic boundary (Ryall, Slemmons, and Gedney, 1966).

The maximum distance for the transition in heat flow of about 1.0 is 100 km. The observed anomaly curve shown in Fig. 17 can be fitted only to transient models because the shape of the curve is not similar to that produced by a steady source buried 20 to 50 km. Our preferred explanation is that there is an instantaneous sink in the crust and upper mantle beneath the Sierra Nevada and an instantaneous or continuous source in the upper mantle (less than 50 km deep) beneath the Basin and Range. The ages necessary to explain the present day data are 5 to 20 m.y.

Other Transitions

Data on transitions in regional heat flow between the Peninsular Ranges and the Basin and Range, the Salinian and Franciscan blocks, and the Southern Rockies and Colorado Plateau (Roy and Brune, unpublished; Decker, unpublished) also suggest characteristic widths of as little as 20 km to a maximum of 100 km. Hence, it is clear that the sources and/or sinks affecting the regional heat flow values are at a depth of less than 50 to 100 km beneath the surface (in the uppermost mantle or in some cases within the crust).

Variations in electrical conductivity structure of the upper mantle are in excellent general agreement with the results of surface heat flow measurements (Porath, Oldenberg, and Gough, 1970; Schmucker, 1964). If the boundary they map is an isotherm, however, it must be well below the source of the anomalous heat flux, which must be within a few tens of kilometers of the surface.

UPPER MANTLE SECTIONS

Our estimates on the distribution of temperatures and physical characteristics of the heat flow provinces in the western United States are summarized in Figs. 18, 19, and 20. These figures depict three east-west cross sections from the Pacific Ocean to the Great Plains: one typical of an east-west band of western North America from about 30 to 340N latitude; one typical of a band from 36 to 40^0N latitude; and a third typical of a band from 44 to 50^0N latitude. The sections were drawn approximately along the 32, 38, and 47^0 parallels, and heat flow measurements within about 100 km of each side of the parallels were projected to the sections. The sections were chosen to be representative and to go through areas with the most data. The sections end at the Great Plains because published data suggest little variation in heat flow from the upper mantle in the eastern United States (Roy, Blackwell, and Birch, 1968). The pertinent assumptions made in preparing the cross sections will be summarized in three parts: heat flow, crustal and upper mantle seismic structure, and temperature calculations.

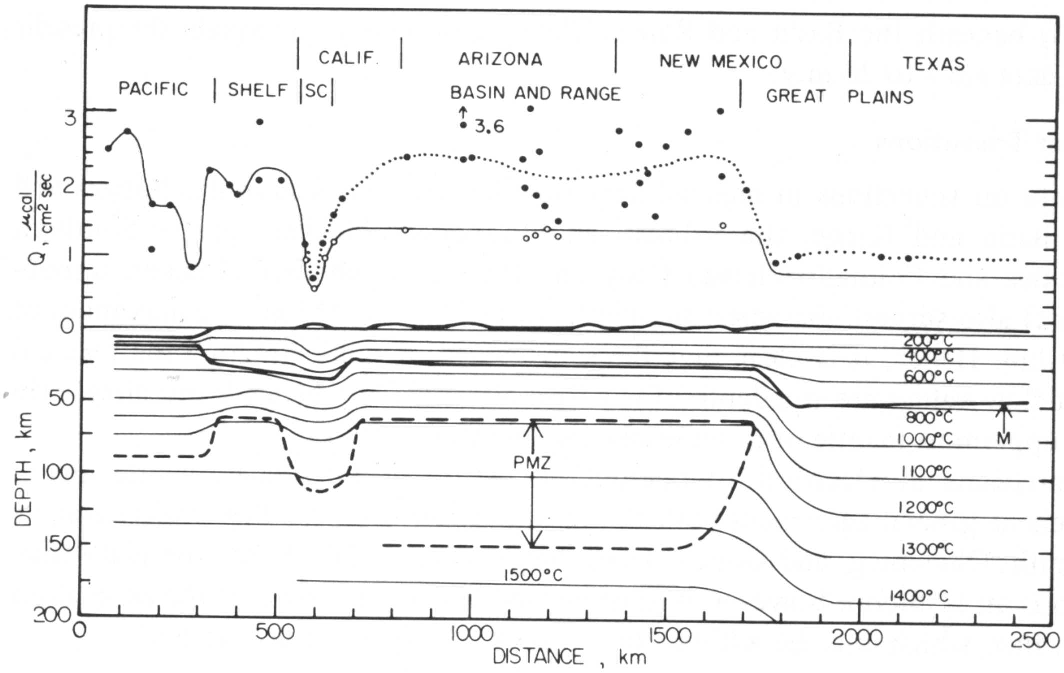

Fig. 18. Cross section across the southwestern United States and part of northern Mexico at approximately 32°N latitude. This cross section shows heat flow, crustal structure, and calculated temperatures. Solid dots represent observed heat flow at the surface and open circles, reduced heat flow. Data points have been projected to the section as much as 100 km. PMZ is the inferred Partial Melt Zone. *M* represents the Mohorovicic discontinuity. The region denoted by SC is the remarkable narrow zone of low heat flow in the Peninsular Ranges of Southern California, USA, and northern Baja California, Mexico. The temperature contours and PMZ boundaries west of the Basin and Range region are smoothed and on this scale do not attempt to fit the complex pattern of heat flow observed at the surface.

Heat Flow

The observed heat flow values have been plotted as solid dots and the trends indicated by a dotted line. This curve is the sort one might get from treating the observed values only, with no input of geological or other geophysical information. Reduced heat flow data were plotted as open circles and connected by a solid line. Aside from transition zones and the complex provinces along the Pacific Coast, all the points in the western United States are within ± 0.2 x 10^{-6} cal/cm^2 sec of the intercept of values of either the Sierra Nevada or Basin and Range heat flow-heat production lines. The solid and dotted curves merge in the oceans where as yet an analogous reduction for near surface heat sources has not been devised.

In contrast to the dotted line connecting the raw data, the solid line connecting the reduced heat flow values was drawn to emphasize a point previously made. At every heat flow transition where we have data, the transition is sharp and the total effect (within the limits of our precision)

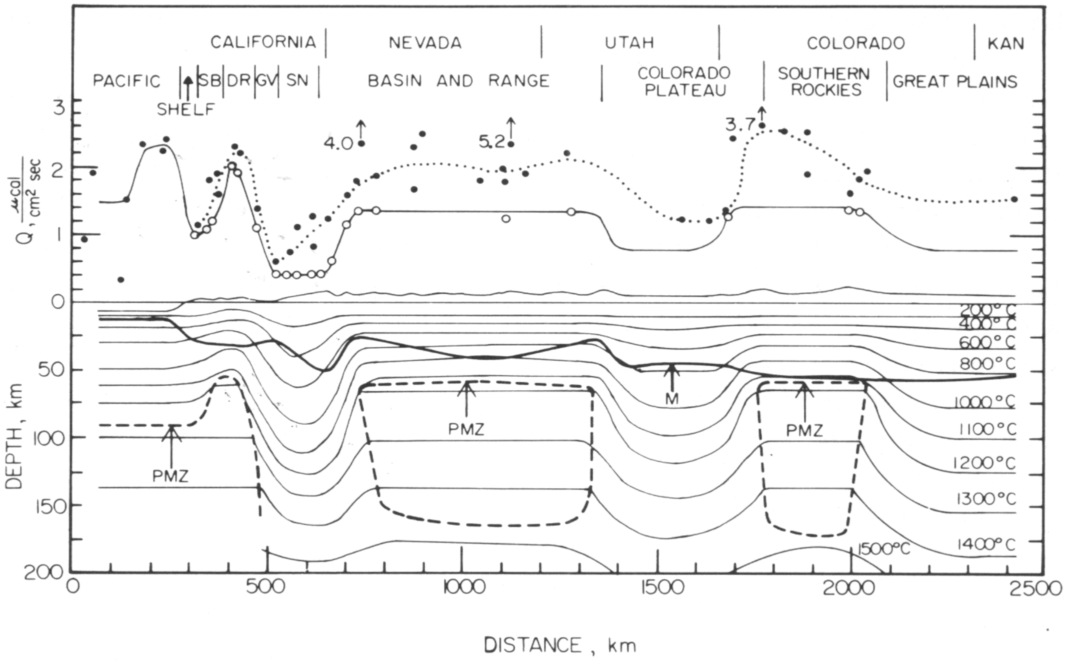

Fig. 19. Cross section across the western United States at approximately 38°N latitude. General notation and comments are the same as for Fig. 18. The abbreviations for the Pacific Coast provinces are: SB–Salinian Block, DR–Diablo Range, GV–Great Valley, SN–Sierra Nevada.

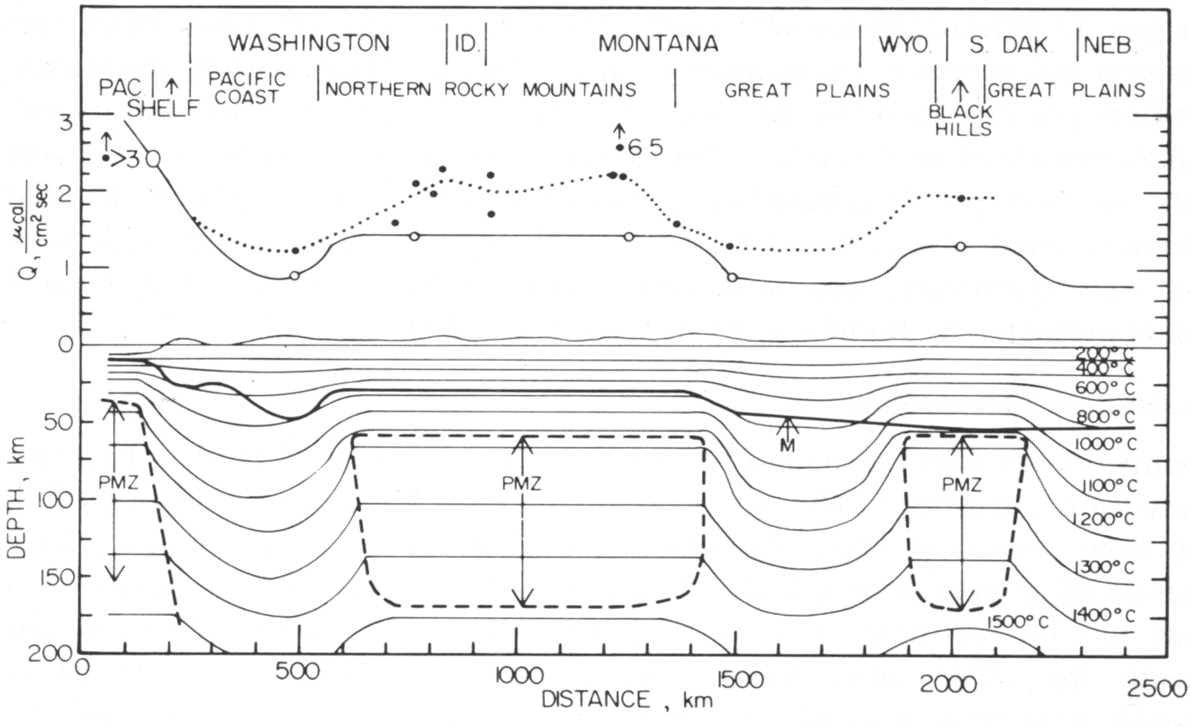

Fig. 20. Cross section across the western United States at approximately 47°N latitude. General notation and comments are the same as for Fig. 18.

occurs within 100 km (the half widths are 50 km or less). Therefore, at each place on the cross sections where we infer a transition in heat flow from the mantle, the solid curve has been drawn to indicate a sharp transition, whether or not we have data for that specific transition. Thus the solid line consists of sections of almost constant mantle heat flow separated by narrow regions of rapid variations of heat flow. We repeat that for many of the transitions this is hypothesis rather than observation.

Crustal and Upper Mantle Structure

The crustal structure determined by seismic refraction surveys for the various heat flow provinces has already been mentioned. In a few places, it was necessary to extrapolate known crustal structure into unknown areas. When this extension was necessary the extrapolation was guided in large part by the mantle heat flow province involved. An example of this is the inference that a thin crust is characteristic of southwestern New Mexico; the crustal structure for the rest of the southern profile is based on published data from Warren (1969) and the references cited above. Crustal structure along the central profile has been extensively investigated and, in addition to the references already cited, is based on data presented by Hamilton, Ryall and Berg (1964).

Temperature Calculations

Temperatures were calculated for one- and two-dimensional models assuming steady-state conditions. The temperatures beneath the central portions of all heat flow provinces were calculated using one-dimensional models. Two-dimensional models were calculated across the transitions we have discussed in detail and the unstudied transitions that appear to be similar. The isotherms beneath the other unstudied transitions were calculated by interpolations between isotherms beneath the heat flow provinces on each side of the transition. Because of the uncertainties of temperatures calculated in this manner and because of the large variations of upper mantle heat flow in the Pacific Coast provinces, distributions of isotherms west of the Sierra Nevada are largely diagramatic.

Temperature depth curves for models with an upper layer of constant radioactivity as shown in Figs. 16 and 17 are given in Roy, Blackwell, and Birch (1968). The models shown in Figs. 18, 19, and 20 were calculated assuming four layers of different conductivity and two layers with exponentially decreasing heat sources with depth.

Layer 1 (the “granitic” layer) was assumed to have a constant conductivity of 6.5 mcal/cm sec °C and to extend to a depth equal to twice the slope of the heat flow, heat production curve for that province. Thus the layer varied in thickness from 20 km in the Sierra Nevada to 15 km in the Mid-Continent. At the bottom of layer 1 the heat production is assumed to be 0.68×10^{-13} cal/cm^3 sec. Layers 2, 3, and 4 were assumed to all be part of the same heat production layer with an A_0 of 0.68×10^{-13} cal/cm^3 sec and an exponential decrement of 80 km, thus 0.4 *u*cal/cm^2 sec was generated in this layer. In regions of high heat flow, an additional layer with high radioactivity was placed near the base of the crust to simulate a shallow heat source. In all models approximately 0.4 pcal/cm2sec was assumed to come from below 400 km.

Layer 2 (the “gabbroic” layer) was assumed to extend from the base of layer 1 to the M-discontinuity, whose depth for a given province was taken from seismic refraction data. A constant conductivity of 5.0 mcal/cm sec°C was assumed for layer 2.

Layer 3 extends from the base of the crust to the I 000°C isotherm with a constant conductivity of 10 mcal/cm sec°C. Below the 1000°C isotherm the conductivity was assumed to increase 1.6 meal/cm sec°C for each temperature increment of 100°C.

The model for temperatures beneath the Basin and Range province was also constrained such that the zone of partial melting was consistent with limits suggested by the upper mantle *P* wave profiles of Archambeau, Flinn, and Lambert (1969). Similar models were assumed for zones of partial melting beneath the Northern and Southern Rocky Mountains. The melting point curve assumed for determinations of temperature at the partial melt zone boundaries increases at a rate of 3°C/km from 1050°C at 1 bar and corresponds to the melting curve of a slightly wet peridotite (Ito and Kennedy, 1967; Kushiro, Syono, and Akimoto, 1968).

The two biggest gaps in the data are the Colorado Plateau and the Pacific Coast in the northwestern United States. The Colorado Plateau was assumed to have the same heat flow-heat production curve as the eastern United States, based on inferences from long period magnetic variations which suggest the same electrical conductivity structure as in the Great Plains (Porath, Oldenberg, and Cough, 1970). The heat flow and temperatures along the Pacific coast in the northwestern United States are assumed to be about the same as in the eastern United States, but could be somewhat lower if a slab of cold oceanic lithosphere is sinking beneath the coastline (Silver, 1969). The heat flow in this area and in the Colorado Plateau are the two most important areas for new data in the western United States.

DISCUSSION

So far our treatment of heat flow in the United States has been largely descriptive. In this section, we will consider briefly some thoughts on the origin of that heat flow pattern.

The most impressive feature on the map of reduced heat flow (Fig. 12) is the large region of high heat flow corresponding to the Basin and Range province (in a broad sense, i.e., Blackwell’s Cordilleran Thermal Anomaly Zone). This region is similar in dimensions to the high heat flow in the Sea of Japan described by Vacquier et al. (1966). The superficial explanation of the high heat flow in the Basin and Range is that the upper mantle is partially molten near the base of the crust. The immediate cause of these high temperatures we attribute to local convection, i.e., diapiric intrusions of hot, solid and liquid material from deeper in the mantle to a position near the base of the crust as indicated in Figs. 18, 19, and 20.

Less impressive in areal extent on Fig. 12 but at least as important to the interpretation of recent tectonic history of the western United States are the low values of heat flow in the Sierra Nevada and Peninsular Ranges. There are many different types and origins of heat sources that could be invoked to explain high values of heat flow. The low values in the Sierra Nevada present a more difficult interpretational problem, as heat sinks are less common than sources. Because there are fewer possible explanations, we believe the Sierra Nevada anomaly may be the key to explaining the origin of the mantle heat flow pattern in the western United States. So, what is the origin of the anomaly?

Several possibilities have been considered (Roy, Blackwell, and Birch, 1968). The model that envisioned complete depletion of the lower crust and upper mantle of radioactive heat sources seems unlikely at the present time. Recent heat flow determinations in the Mid-Continent suggest that heat flow values over basaltic basement such as the bedrock beneath the Mid-Continent Gravity High (Fig. 10) have values of 0.8 to 1.1 (Combs and Simmons, 1970; Williams and Roy, 1970; Blackwell, in preparation), which are the values expected if the parameters of Eq. (1) for the eastern United States apply. We have concluded that a transient heat sink is necessary and that the sink is low temperatures in the Sierra Nevada crust and uppermost mantle, which are a byproduct of recent sea floor spreading.

Current dogma on continental drift has the North American continent moving away from the Mid-Atlantic ridge toward the East Pacific Rise during much of the Cenozoic (Bullard, Everett, and Smith, 1965). Within the past few million years the continent and the East Pacific rise have closely approached, and the interaction of plates has become quite complicated. Papers too numerous to cite have discussed the nature of the interaction of the continental and oceanic plates and the resultant effect on the Cenozoic geologic history of the western United States (see, for example, Atwater and Menard, 1970; McKenzie and Morgan, 1969). We believe that the heat flow pattern described above is a definitive test of most of these hypotheses. Our general conclusions are that corollaries of the basic sea floor spreading hypothesis and plate tectonics explain the pattern we observe in the coastal areas almost uniquely and further inland as only one of several possibilities.

We summarize here briefly our hypothesis for the late Mesozoic and Cenozoic tectonic history of the western United States. During the late Mesozoic, a sinking slab of oceanic lithosphere existed at the site of the Franciscan terrain in western California (Ernst, 1970). Inland from the trench, about 100 to 200 km, the batholiths of the Peninsular Ranges, Salinian Block, Sierra Nevada, Klamath Mountains, Coast Ranges in Canada, etc., were being generated and emplaced in the crust. Here, incidentally, is geologic evidence from the observed low temperature assemblages in the Franciscan terrain and the high temperatures in the Sierra Nevada of a sharp transition in regional heat flow during the late Mesozoic. 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 under the Sierra Nevada began to be cooled by the "cold conveyor belt" passing underneath, and the heat flow decreased to less than 0.4 $u$cal/cm^{2}sec. The high heat flow in the Basin and Range was probably established with something near its present boundaries by early Oligocene.

High temperatures near the top surface of the underthrust plate have been attributed to friction, stress heating, shear strain heating, (McKenzie, 1969; McKenzie and Sclater, 1968; Minear and Toksoz, 1970; Oxburgh and Turcotte, 1968, 1970; Turcotte and Oxburgh, 1968). In addition to these mechanisms of mechanical-thermal energy conversion, we would like to suggest that radioactive heat sources in a slab of undifferentiated oceanic lithosphere maybe important. If we take, for example, an oceanic plate with A_0=0.7 x 10^{-13} cal/cm^3 sec and b=100 km (a popular dimension for slabs of oceanic lithosphere), the steady-state heat flow at the surface would be 0.7. Add to this a heat flow of approximately 0.4 from deep in the mantle, and we have the average heat flow observed in deep ocean basins (far from ridges) and the average heat flow on continents (excluding thermal anomaly regions such as the Basin and Range).

A 100-km-thick plate with the middle at a depth of 100 km and an internal heat generation of 0.7 x 10^{-13} cal/cm^3 sec would raise the surface heat flow by only 0.1 $u$cal/cm2 sec in 10^8 years (Carslaw and Jaeger, 1959, p. 80). In 30 m.y., however, the temperature in the slab would rise about 200°C above the temperatures produced by heat conduction into a cold plate without radioactive heat sources. Partial melting of large portions of the descending slab thus becomes quite plausible. We find this suggestion attractive for three reasons: (1) it becomes possible to derive the intrusives and extrusives of quartz diorite to granodiorite composition now found at the surface directly from the mantle; (2) it is consistent with the low initial

Sr ratios that are found in these rocks (Hedge and Peterman, 1969; Menzer and Jones, 1969); (3) it is the simplest explanation of the equality of oceanic and continental heat flow. The abrupt transitions between the high and low heat flow provinces are secondary effects because of rapid upward convection of the partially molten mantle material and do not reflect the distribution of sources actually responsible for the anomaly. Such effects would not be apparent in the first-order theories of mechanical-thermal energy conversion referenced above.

At some time in the middle Cenozoic, portions of the North American plate completely overrode the Cocos plate and abutted the Pacific plate (Atwater and Menard, 1970). The first such point was probably between the Mendocino and Murray fracture zones. At this time, the portion of the North American plate west of the San Andreas fault was welded to the Pacific plate and the San Andreas fault originated as a transform fault connecting the two remaining ends of the rise (Atwater and Menard, 1970). When the last vestige of the Cocos plate north of the southern tip of Baja California was trampled beneath the continent, the heat flow from the mantle beneath the Sierra Nevada and Peninsular Ranges ceased to be held down by the “cold conveyor belt” and the blocks began to warm up. The higher values in the Peninsular Ranges could be a result either of the fact that the block is narrower than the Sierra Nevada block (75 versus 150 km) and thus heated up more quickly or that the Peninsular Ranges are on a different time portion of the transient recovery.

We emphasize that whatever the explanation for the Sierra Nevada and Peninsular Range anomalies, the presence of these well-determined regions of low heat flow between the Basin and Range province and the coast rejects the hypothesis that the continent has simply drifted over the East Pacific Rise. There is no reasonable way we can devise to drop the heat flow to the present low values in the Penninsular Ranges and the Sierra Nevada subsequent to passing over an extensive rise system.

Attempts to extend the subduction model to explain the zone of high heat flow in the Southern Rocky Mountains and Black Hills encounter difficulties with the inferred zone of normal heat flow in the Colorado Plateau-Wyoming Basin-Middle Rocky Mountain region. There are only two values of reduced heat flow in this region (one of which is typically Basin and Range), 0.9 in the Beartooth Plateau and 1.3 near the eastern edge of the Colorado Plateau. If the Colorado Plateau is indeed a continuous zone of normal heat flow as inferred from the seismic and electrical resistivity data, then other mechanisms must be sought to explain the high mantle heat flow in the Southern Rocky Mountains. Clearly, the Colorado Plateau is one of the most important areas for further studies of heat flow and basement radioactivity in the United States.

Our general model implies that on the landward side of a subduction zone there will be a zone of low heat flow similar to the Sierra Nevada with a region of high heat flow still further inland. Some obvious areas to test this hypothesis are in the granitic plutons of the Klamath and Northern Cascade Mountains in the United States, the Sierra Madre del Sur in Mexico, and the coastal batholiths of Peru and Chile.

Note added in proof: Since the submission of this manuscript, a number of important papers on plate margin tectonics, subduction, and thermal structure of the western United States have appeared. Among these are: Atwater, 1970: Dickinson, 1970: Lipman et al., 1971: Porath et al., 1970; and Reitzel et al., 1970. The conclusions drawn in these and other papers, although based largely on petrology, plate tectonics, and electrical resistivity arguments, are generally in excellent agreement with the views expressed in this paper.

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