Regional Heat Flow and Temperature Gradients

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ABSTRACT

To assess the potential for low-temperature geothermal resources in regional conductive thermal environments, a knowledge of temperature gradients to depths of about 2 km is required. Regional variations in temperature gradient, which reflect corresponding regional variations in heat flow, thermal conductivity, or both, result in some uncertainties in the derivation of deep thermal-gradient data from near-surface (100-250-m depth) heat flows. A contour map of regional heat flow in the conterminous United States shows that heat flow in the West is generally higher than in the East. A temperature-gradient map, based on data from 240 drill holes generally deeper than 600 m, indicates the same sort of first-order variation in geothermal-resource potential as does the heat-flow map, although there also are some important differences between these two maps. Large areas are without data on both maps, but either map can be used to identify promising geothermal-resource areas or areas where more reconnaissance work is needed.

INTRODUCTION

For the assessment of low-temperature geothermal resources in the United States, regional heat flow and temperature gradients assume a much greater importance than for intermediate- and high-temperature resources. For low-temperature geothermal energy, a favorable combination of high regional heat flow, low thermal conductivity, and a good aquifer can result in an exploitable resource at depths of 2 km or less. However, the depths of occurrence for high-temperature geothermal energy derived from conductive thermal gradients without hydrothermal convection are so great that economical extraction becomes unlikely.

This chapter briefly reviews heat flow and temperature gradients to provide a background for presentation of maps of heat flow and deep temperature gradients in the United States and of a table of thermal conductivities. These maps help to delineate areas favorable for the occurrence of low-temperature geothermal resources and have been used to assign average temperature gradients for the estimation of reservoir temperatures for some geothermal systems (Sorey, Reed, and others, this volume).

BACKGROUND

The vertical conductive heat flow $\underline{q}$ given by

$$\underline{q}=\underline{k}\left(\frac{dT}{dz}\right), \qquad (1)$$

where $\underline{k}$ is the conductivity and $\underline{dT/dz}$ is the vertical temperature gradient. The temperature gradient is determined by measuring the temperature at various depths in a drill hole and calculating a gradient (for example, Sass and others, 1971). Thermal conductivities, which are commonly measured in the laboratory on core or cuttings, generally range from 1.7 to 3.5 W/m K for consolidated rocks, although values as low as 0.8 W/m K and as high as 8 W/m K also occur (Roy and others, 1981). Table 1 lists typical values for regional heat flow and temperature gradients in the United States.

Birch and others (1968) showed that for granitic plutonic rocks in the Northeastern United States, a plot of the measured surface heat flow $\underline{q}$ versus the measured radioactive heat production $\underline{A}$ defines a straight line:

$$\underline{q}=\underline{q}_r+\underline{DA}, \qquad (2)$$

where $\underline{D}$ is the slope of the line, in units of depth. The reduced heat flow $\underline{q}_r$ is the heat flow obtained by extrapolating the plot of $\underline{q}$ versus $\underline{A}$ to zero radioactive heat production. Typical values for

Table 1.—Typical values of heat flow and temperature gradient in parts of the conterminous United States

[All values assume a thermal conductivity of 2.5 W/m·K and a radioactive heat production of 2.1 $\mu W/m^3$ (after Lachenbruch and Sass, 1977)]

Region	Reduced heat flow (mW/m^2)	Heat-production thickness (km)	Heat flow (mW/m^2)	Temperature gradient (°C/km)
Sierra Nevada----------	17	10	38	15
Eastern United States--	34	7.5	49	20
Basin and Range--------	67	10	88	35
Battle Mountain high (part of the Basin and Range)	84	10	105	42

radioactive heat production in felsic crystalline-basement rocks range from 1 to 3 W/m^3, although values as high as 8 W/m^3 are also known. The q-A relation was interpreted by Birch and others (1968) to indicate that the heat flow measured at the surface is made up of one component of heat flow q_r from the mantle and lower crust and another component of heat flow DA due to the radioactivity of the upper crust. The parameter D can be related to the thickness of a layer of rock with constant heat production A below which heat flow is constant and equals the reduced heat flow q_r. Other distributions of radioactivity with depth also satisfy equation 2; a model in which A decreases exponentially with depth was proposed to maintain the validity of equation 2 under the effects of differential erosion (Lachenbruch, 1968, 1970).

Different regions have been found to have characteristic values of q_r and D (for example, Roy and others, 1968a, b; Lachenbruch, 1968), and on this basis the conterminous United States can be divided into regions of characteristic heat flow. Table 1 lists the values of q_r and D for these regions (Lachenbruch and Sass, 1977). Within most such regions, q_r remains constant, whereas the measured surface heat flow may vary from place to place owing to variations in radioactive heat production of the crust. The value used in table 1 for radioactively generated heat flow in the Eastern United States is 16 mW/m^2, which represents a substantial fraction of the measure surface heat flow. For the tectonically young parts of the Western United States, the data for q are quite high on the average, and the q-A data show considerable scatter (Lachenbruch and Sass, 1977), so that a linear q-A relation cannot be defined. Some of the heat flow in all the regions is attributable to crustal radioactivity, but other large-scale processes also are involved. The high mean value is most likely related to deep-seated tectonic processes, such as crustal extension and associated magmatism, whereas the large scatter is probably due to hydrothermal convection in the uppermost few kilometers of the crust, and to associated hot-spring activity.

DISTRIBUTIONS OF HEAT FLOW AND TEMPERATURE GRADIENTS IN THE UNITED STATES

The temperature-versus-depth relation in the upper 2 km of the crust can be estimated from either heat-flow or temperature-gradient data. In many areas, heat flows have been determined from data collected in drill holes less than 150 m deep, and although the measured gradients may appear to be conductive, some heat flows are probably affected by hydrothermal convection and ground-water flow below the drill hole. If, however, the conductive heat flow is representative of the region and if a model can be developed for the variation in thermal conductivity with depth, then temperatures to depths of 2 km can be predicted from shallow heat-flow measurements alone. In most of the conterminous United States, however, it is difficult to fulfill both these requirements, owing to an insufficient number of internally consistent heat-flow determinations or to incomplete knowledge of the thermal conductivity to the required depths.

A more direct method of estimating deep subsurface temperatures is by extrapolating measured gradients. However, if the depths of interest lie significantly below the depth for which temperature measurements are available, this extrapolation becomes uncertain, and variation in conductivity must be accounted for. When the thermal conductivity has not been measured or cannot be estimated with confidence, the temperature data should be from drill holes sufficiently deep that any changes in thermal conductivity between the bottom of the hole and the target depth will not be significant.

The heat-flow map (fig. 4) of Sass and others (1981, fig. 13.4) shows contours of surface heat flow based on more than 1,000 determinations. The specific data are not shown, but a map of them together with a fairly complete reference list may be found in Sass and others (1981). The United States east of the 100th meridian is generally characterized by a heat flow of 40 to 60 mW/m^2, with some local regions of higher heat flow in New England and on the Atlantic Coastal Plain. Heat flow west of the 100th meridian appears to vary more and to be higher overall than in the East; the mean heat flow in the West is about 80 mW/m^2. Within the West, areas of relatively low heat flow occur in the western Sierra Nevada, southern Nevada, and parts of the Colorado Plateaus, whereas heat flow greater than 100 mW/m^2 characterizes the Southern Cascade Mountains, the Battle Mountain high, and the Rio Grande Rift. On a regional scale it is unlikely that conductive heat flow can exceed 150 mW/m^2, and higher values indicate some form of hydrothermal convection.

An empirical approach to predicting heat flow in areas of little or no conventional heat-flow data was developed by Swanberg and Morgan (1978, 1980; see Sass and others, 1981), who discovered a statistical correlation between the silica geotemperature of ground waters and heat flow within 1-degree blocks of latitude and longitude for which silica geotemperature and heat flow are both well documented and have small scatter. They extended this empirical relation

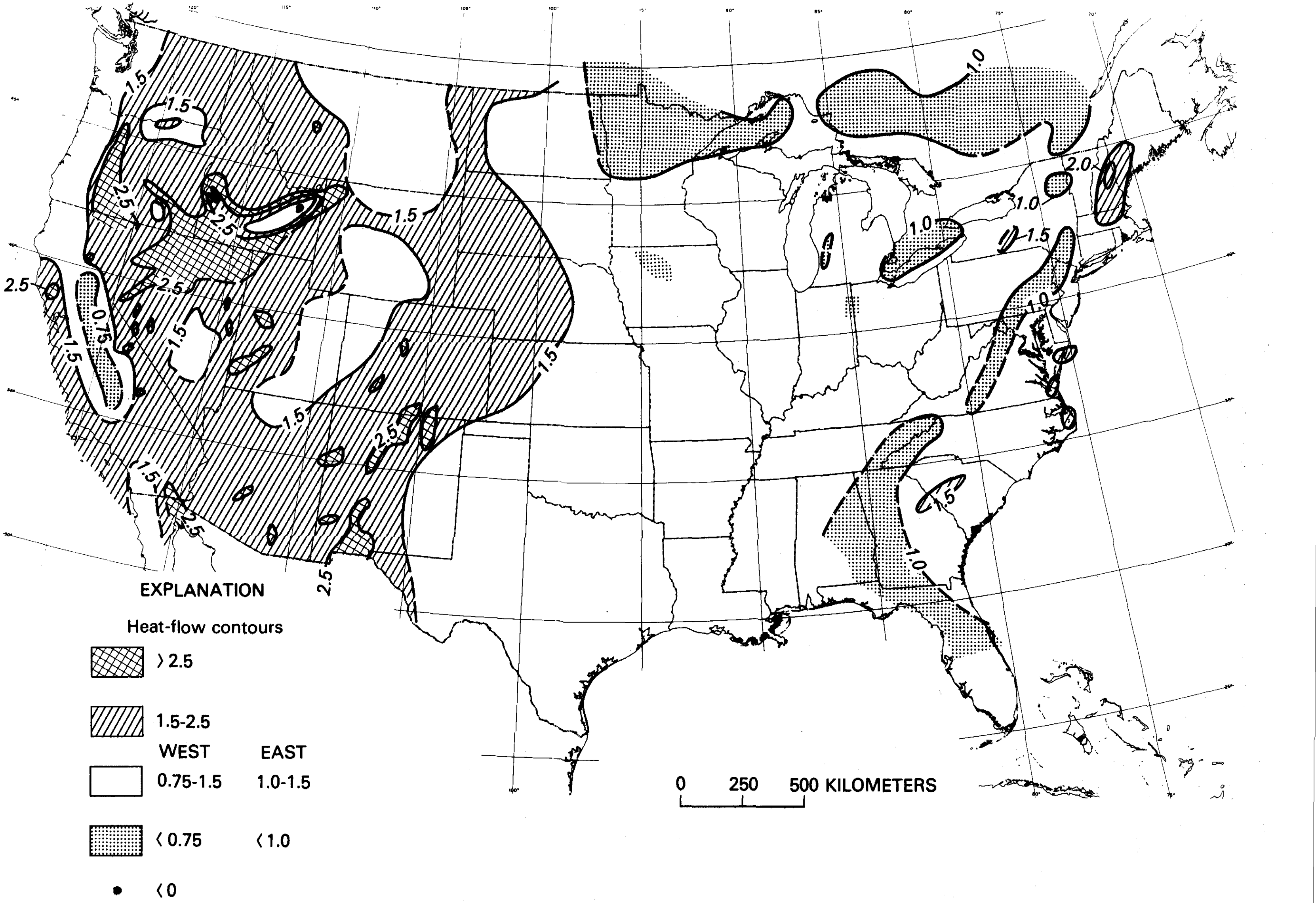

Figure 4.--Heat-flow map of the conterminous United States (from Sass and others, 1981, fig. 13.4). Contours are in heat-flow units.

to areas with few heat-flow measurements and predicted heat-flow anomalies for several such areas. Some of their predictions—namely, on the Atlantic Coastal Plain, in southeastern Utah, and in parts of Nebraska—have been confirmed by subsequent heat-flow measurements, whereas others (for example, in the Central Valley of California) appear to represent something other than high heat flow (see J. K. Costain, in Sass and others, 1981, p. 533-539; C. A. Swanberg and Paul Morgan, in Sass and others, 1981, p. 540-544). The silica-geotemperature/heat-flow relation has thus had some success in predicting heat-flow anomalies on a regional basis, and the anomalies predicted by this method are worth investigating with conventional techniques. However, because the method relies on a statistical approach involving data averaged over 1-degree blocks of latitude and longitude or larger areas, and because the physical basis of the relation has yet to be established, the silica-geothermometer/heat-flow method probably has only a limited applicability to reconnaissance exploration for low-temperature geothermal resources.

If thermal conductivities were more or less uniform or well known on a regional scale, the heat-flow map in figure 4 could be used to characterize temperature gradients. Table 2 lists representative values of the thermal conductivities of water-saturated rocks in various parts of the United States. The ranges and means are only approximate and have been generalized from various sources, including Clark (1966), Roy and others (1981), and J. H. Sass and R. J. Munroe (unpub. data, 1982).

Table 2.—Thermal conductivities of common rock types

[All values in watts per meter-Kelvin]

Rock type	Range	Mean
Andesite	1.35-4.86	3.7
Basalt	1.12-2.38	1.8
Dolomite	4.0-5.9	4.5
Gabbro	1.80-3.60	2.6
Gneiss	1.69-5.75	3.7
Granitic rocks	2.1 -5.0	3.6
Limestone	1.30-5.80	3.6
Marble	2.02-6.52	4.3
Quartzite	2.33-7.45	4.9
Rhyolite	1.58-4.33	3.0
Rock salt	5.3-7.2	5.4
Sandstone	1.5-4.3	2.9
Shale	1.2-2.9	2.0
Tuff	.91-3.20	2.1

Several observations should be made in relation to the data listed in table 2:

1. For most rock types, the thermal conductivity varies enormously. For some rock types in a given locality or region, however, most values may fall within a relatively narrow range of about 20 to 30 percent of the mean. Mean values commonly vary from region to region, and so the literature values used for estimates of heat flow and for derivation of temperature gradients must be chosen with care.
2. For quartz-rich rocks, the bulk thermal conductivity varies widely with the content of such low-conductivity minerals as feldspars and with the porosity, and so it is difficult to generalize regional means.
3. Literature values for shale are unreliable. Argillaceous sedimentary rocks represent possibly the most difficult media for the measurement of thermal conductivity. They are fissile and, in many places, poorly consolidated, and it is almost impossible to maintain them in their natural physical state after removal from the ground. They also are anisotropic, and so measurements of thermal conductivity on crushed samples or drill cuttings (the most common current method) will generally be in error because such measurements represent a geometrically weighted average conductivity rather than the actual vertical conductivity. Blackwell and others (1981) discussed some of the implications of this type of error to measured heat-flow values from the Great Plains. In the context of low-temperature geothermal resources, suspect literature values for the thermal conductivity of shale are irrelevant if the temperatures of interest are entirely within a shale section; however, if gradients are extrapolated from sand to shale or vice versa, the predicted temperatures can be greatly in error.
4. Generalized literature values of thermal conductivity can be used to estimate the variation in conductivity with depth and thus, as mentioned previously, to facilitate extrapolation of temperature gradients for most crystalline terranes and a restricted class of sedimentary terranes. For carbonate rocks, the ratio of limestone to dolomite in a given section must be known. In sand-shale sections, an accurate estimate of the sand/shale ratio is required, and in sedimentary basins where the sand/shale ratio varies laterally, gradients in these sections may vary by a factor of 2 for the same regional heat flow.

Several maps of temperature gradients in the United States have been constructed. The American Association of Petroleum Geologists and U.S.

Geological Survey (1976) prepared a map of gradients calculated primarily from temperature measurements at a single depth in oil, gas, and water wells and from assumed values of the mean annual air temperature (see Guffanti and Nathenson, 1980, fig. 2). Vaught (1980) used the data for Michigan to point out various problems with the accuracy of this data set in that area and thus showed that the map must be interpreted with care. Kron and Heiken (1980a, b) used data from the heat-flow literature for drill holes deeper than 50 m to construct a map of temperature gradients. Although they omitted data for any drill hole with temperatures that were obviously disturbed, some shallow drill holes with either high or low temperature gradients are most probably influenced by underlying hydrothermal convection. Although meaningful estimates of thermal budgets and deep temperatures can be obtained from groups of such shallow heat-flow data (for example, Sass and others, 1971; Brott and others, 1976), simple linear extrapolation of thermal gradients from such data generally is misleading.

Guffanti and Nathenson (1980, fig. 1) constructed a temperature-gradient map based on data from drill holes generally deeper than 600 m, using data that appeared to represent conductive heat transfer, to obtain a representation of regional, background thermal gradients. Data from drill holes at sites in or adjacent to known hydrothermal-convection systems were omitted. In drill holes where the gradient varied with depth, an overall gradient was chosen as the average of straight-line segments, approximately weighted by depth interval. Although, this value may not exactly reflect the temperatures at all depths, it can be a good approximation of these temperatures, provided the temperature-gradient contrasts over large depth intervals are not too great. As part of their study, Guffanti and Nathenson (1981) made a systematic search of the compilation by Spicer (1964) to extract the deepest, least disturbed, and most areally representative temperature logs.

Figure 5 shows the map of Guffanti and Nathenson (1980) but with added data from Blackwell and Steele (1981), Dashevsky and McClung (1980), M. C. Gardner (written commun., 1981), Hodge and others (1981), Jessop and Judge (1971), Judge and Beck (1973), W. S. Keys and D. E. Eggers (written commun., 1980), Leonard and Wood (1980), McClung (1980), Perry and others (1980), Roy and others (1980), Sass and others (1981), J. H. Scott and J. J. Daniels (written commun., 1980), Shearer (1979), and Urban and others (1978). An important characteristic of these deep temperature gradients is that few of the high gradients shown on the map by Kron and Heiken (1980b) are confirmed by the deeper data. In part, this difference reflects the smaller number of deep drill holes used by Guffanti and Nathenson (1980), but it also reflects the improbability of very high gradients persisting to depths of 600 m except in geothermal areas, as well as the local-areal extent of most high-temperature thermal anomalies. It should be emphasized that the map (fig. 5) is highly generalized and that in areas between temperature-gradient contours, both higher and lower values may be measured on a local scale, especially at shallow (less than 300 m) depths.

The temperature-gradient map (fig. 5) reflects the combined effects of heat flow and thermal conductivity. Comparison with the heat-flow map (fig. 4) shows a general coincidence of temperature gradients with heat flow. Gradients less than 25°C/km and heat flow less than 63 mW/m^2 (1.5 HFU) predominate east of the 100th meridian, whereas gradients greater than 25°C/km and a heat flow greater than 63 mW/m^2 are common in the West. Within the East, part of the southern Appalachians region stands out as a thermal low in terms of both heat flow and temperature gradients, whereas in parts of the Atlantic Coastal Plain, higher than average heat flow is expressed by higher temperature gradients. High temperature gradients in the Northwestern United States and in parts of Colorado and Wyoming approximately correspond to areas of high heat flow. Virtually no heat-flow determinations exist on which a comparison can be based in western Texas, where temperature gradients are low, or in the Gulf Coastal Plain, where inland gradients are high.

This general correspondence between heat flow and temperature gradients suggests that thermal conductivities cluster around some average value on a regional scale, despite smaller scale variations in lithology. Some variations in conductivity, however, are related to regional geologic features, and some temperature-gradient anomalies mirror geologic environments but not heat flow. For example, relatively high temperature gradients occur in western Pennsylvania and West Virginia, primarily owing to the low thermal conductivity of the thick sequence of Devonian shale in those States; however, this is not a region of high heat flow except for a small area in south-central New York. Some anomalous temperature gradients are related to local thermal-conductivity extremes that are not significant on a regional scale; for example, a 13°C/km gradient in eastern Utah relects the local presence of high-conductivity salt.

LOW-TEMPERATURE GEOTHERMAL-RESOURCE ASSESSMENT

Low-temperature geothermal resources are defined partly in relation to regional background values of heat flow and temperature gradient. The low-temperature geothermal resources assessed in this volume occur in permeable aquifers that have temperatures greater than those defined by a minumum of 10°C above the local mean annual air temperature at the surface, increasing by 25°C/km with depth to a maximum of 90°C (see Reed, this volume, fig. 1). The value of 25°C/km corresponds to the temperature gradient based on an average heat flow of 63 mW/m^2 and a thermal conductivity of 2.5 W/m·K for felsic crystalline rocks. This thermal regime is appropriate for stable continental environments and is an upper limit for large areas of the Eastern United States, as depicted on the temperature-gradient map (fig. 5).Gradients higher than 25°C/km occur in regions of high heat flow and in areas of normal heat flow containing a thick sequence of such low-conductivity rocks as shale and basalt. The low-temperature limit used in this assessment screens from consideration geologic environments with

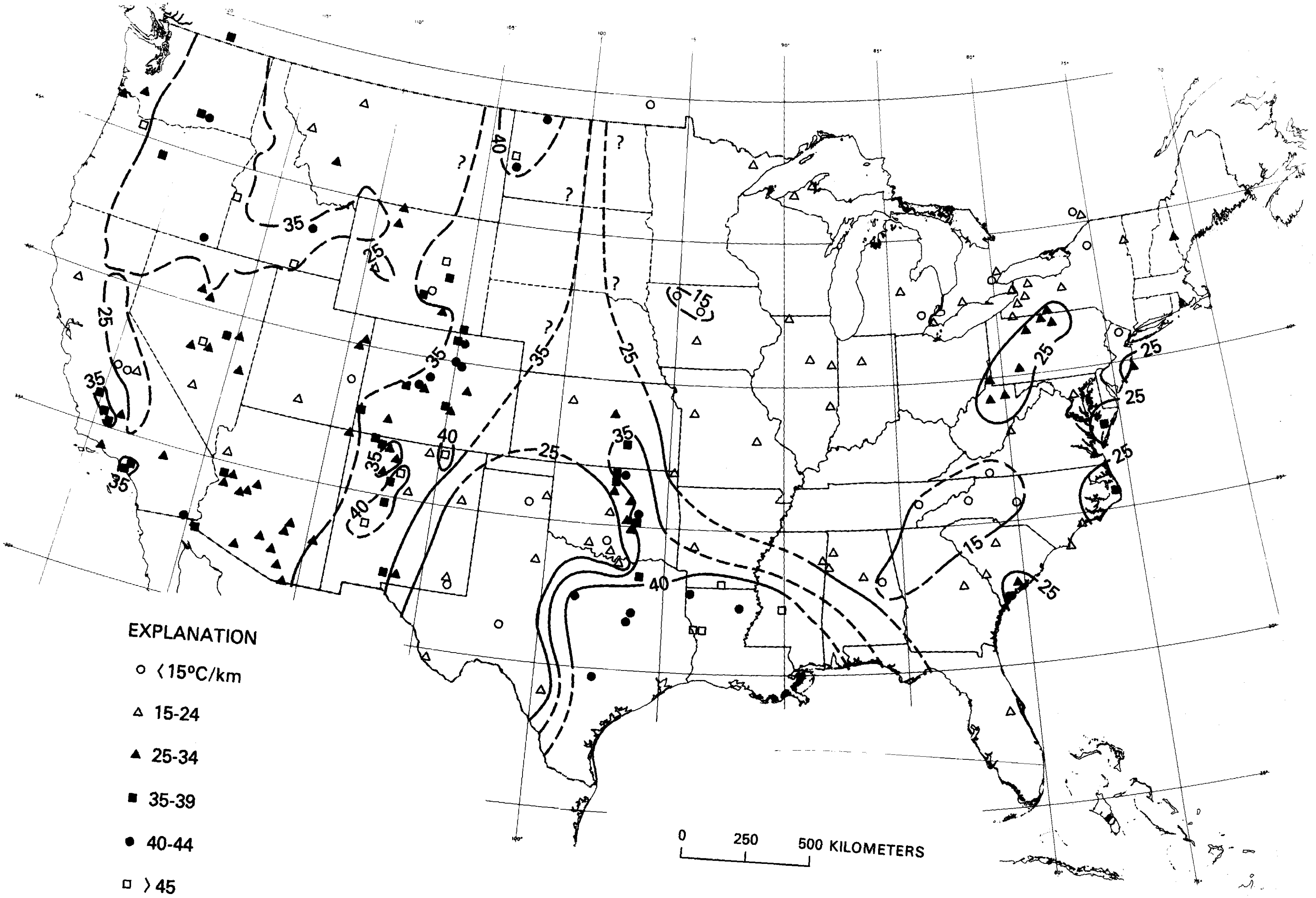

Figure 5.—Temperature-gradient map of the conterminous United States (based on Guffanti and Nathenson, 1980, fig. 1).

normal heat flow and average conductivity, and thus excludes areas containing vast amounts of relatively cool shallow ground water; it also constrains to reasonable values the drilling depths required to reach adequate temperatures for nonelectrical uses.

The temperature-gradient map (fig. 5) broadly highlights areas with gradients greater than 25°C/km where useful temperatures can be found at drillable depths. East of the 100th meridian, an area in western Pennsylvania, parts of the Atlantic Coastal Plain, and areas inland of the Gulf of Mexico coast all have higher than average temperature gradients. Much of the West has high gradients, although depths to basement are shallow in many places; obvious exceptions are the San Joaquin Valley and the Los Angeles basin in California, the Williston basin in North Dakota, and smaller basins in Wyoming, Colorado, and New Mexico.

To be considered a resource, not only must the temperatures be adequate, but also there must be indication of sufficient permeability to supply long-term production (Sorey, Nathenson, and Smith, this volume). Mariner and others (this volume) and Sorey, Reed, and others (this volume) survey the available hydrologic data to estimate reservoir thicknesses, transmissivities, and confining-bed properties for aquifers that exceed the minimum-temperature criterion. For most aquifers, actual temperature data were used; however, for some areas the data shown on the temperature-gradient map (fig. 5) were used to assign average gradients for an estimation of reservoir temperatures.

Superimposed on the regional gradients are anomalies caused by hydrothermal convection. The low-temperature resources identified by Mariner and others (this volume) include some that have hot springs at the surface and are clearly associated with hydrothermal-convection systems. Other resources are defined by high temperatures in wells; for these resources, the heat-flow and temperature-gradient maps (figs. 4, 5) are useful for deciding whether the system reflects regional conductive heat flow and temperature gradients, or is likely to require convection to give the temperatures measured in wells at the depth shown.

REFERENCES CITED

American Association of Petroleum Geologists and U.S. Geological Survey, 1976, Geothermal gradient map of North America: Washington, U.S. Government Printing Office, scale 1:5,000,000.

Birch, Francis, Roy, R. F., and Decker, E. R., 1968, Heat flow and thermal history in New England and New York, in Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., eds., Studies of Appalachian geology: northern and maritime: New York, Interscience, p. 437-451.

Blackwell, D. D., and Steele, J. L., 1981, Heat flow and geothermal potential of Kansas: Kansas State Agency Contract 949 final report, 69 p.

Blackwell, D. D., Steele, J. L., and Steeples, D. W., 1981, Heat flow determinations in Kansas and their implications for Midcontinent heat flow patterns abs.: Eos (American Geophysical Union Transactions), v. 62, no. 17, p. 392.

Brott, C. A., Blackwell, D. D., and Mitchell, J. C., 1976, Heat flow study of the Snake River Plain region, Idaho, pt. 8 of Geothermal investigations in Idaho: Idaho Department of Water Resources Water Information Bulletin 30, 195 p.

Clark, S. P., Jr., 1966, Thermal conductivity, in Clark, S. P., Jr., ed., Handbook of physical constants: Geological Society of America Memoir 97, p. 459-482.

Dashevsky, S. S., and McClung, W. S., 1980, Summary of temperature logging of Crisfield, Maryland geothermal test hole, in Costain, J. K., Glover, Lynn, III, and Sinha, A. K., eds., Evaluation and targeting of geothermal energy resources in the southeastern United States: July 1-September 30, 1979: Blacksburg, Virginia Polytechnic Institute and State University Report VPI-SU-78ET-27001-7, p. A22-A32.

Guffanti, Marianne, and Nathenson, Manuel, 1980, Preliminary map of temperature gradients in the conterminous United States: Geothermal Resources Council Transactions, v. 4, p. 53-56.

——1981, Temperature-depth data for selected deep drill holes in the United States obtained using maximum thermometers: U.S. Geological Survey Open-File Report 81-555, 100 p.

Hodge, D. S., De Rito, R., Hifiker, K., Morgan, P., and Swanberg, C. A., 1981, Investigations of low-temperature geothermal potential in New York state: Los Alamos National Laboratory Report LA-8960-MS, 74 p.

Jessop, A. M., and Judge, A. S., 1971, Five measurements of heat flow in southern Canada: Canadian Journal of Earth Sciences, v. 8, no. 6, p. 711-716.

Judge, A. S., and Beck, A. E., 1973, Analysis of heat-flow data—several boreholes in a sedimentary basin: Canadian Journal of Earth Sciences, v. 10, no. 10, p. 1494-1507.

Kron, Andrea, and Heiken, Grant, 1980a, Geothermal gradient map of the United States: Geothermal Resources Council Transactions, v. 4, p. 69-71.

——1980b, Geothermal gradient map of the United States: Los Alamos Scientific Laboratory Map LA-8476-MAP, scale 1:5,000,000.

Lachenbruch, A. H., 1968, Preliminary geothermal model of the Sierra Nevada: Journal of Geophysical Research, v. 73, no. 22, p. 6977-6989.

——1970, Crustal temperatures and heat production: Implications of the linear heat-flow relation: Journal of Geophysical Research, v. 75, no. 17, p. 3291-3300.

Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, in Heacock, J. G., ed., The Earth's crust: American Geophysical Union Geophysical Monograph 20, p. 626-675.

Leonard, R. B., and Wood, W. A., 1980, Geothermal gradients in the Missoula and Bitteroot valleys, west-central Montana: U.S. Geological Survey Water-Resources Investigations 80-89, 15 p.

McClung, W. S., 1980, Temperature logs of observation wells in the Coastal Plain of Georgia, in Costain, J. K., and Glover, Lynn, III, Evaluation and targeting of geothermal energy resources in the southeastern United States, October 1, 1979-March 31, 1980: Blacksburg, Virginia Polytechnic Institute and State University Report VPI-SU-78ET-27001-8, p. B22-B30.

Perry, L. D., Higgins, G. P., and McKinney, M. M., 1980, Heat flow and heat generation in the Atlantic Coastal Plain, in Costain, J. K., and Glover, Lynn, III, eds., Evaluation and targeting of geothermal energy resources in the southeastern United States: October 1, 1979-March 31, 1980: Blacksburg, Virginia Polytechnic Institute and State University Report VPI-SU-78ET-27001-8, p. B114-B153.

Roy, R. F., Beck, A. E., and Touloukian, Y. S., 1981, Thermophysical properties of rocks, chap. 12 of Toulokian, Y. S., Judd, W. R., and Roy, R. F., eds., Physical properties of rocks and minerals: New York, McGraw-Hill, p. 409-502.

Roy, R. F., Blackwell, D. D., and Birch, Francis, 1968a, Heat generation of plutonic rocks and continental heat-flow provinces: Earth and Planetary Science Letters, v. 5, no. 1, p. 1-12.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, Francis, 1968b, Heat flow in the United States: Journal of Geophysical Research, v. 73, no. 16, p. 5207-5221.

Roy, R. F., Taylor, B., Pyron, A. J., and Maxwell, J. C., 1980, Heat-flow measurements in the state of Arkansas: Final report: Los Alamos Scientific Laboratory Report LA-8569-MS, 15 p.

Sass, J. H., Blackwell, D. D., Chapman, D. S., Costain, J. K., Decker, E. R., Lawver, L. A., and Swanberg, C. A., 1981, Heat flow from the crust of the United States, chap. 13 of Touloukian, Y. S., Judd, W. R., and Roy, R. F., eds., Physical properties of rocks and minerals: New York, McGraw-Hill, p. 503-548.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., Jr., 1971, Heat flow in the western United States: Journal of Geophysical Research, v. 76, no. 26, p. 6376-6413.

Sass, J. H., Munroe, R. J., and Stone, Claudia, 1981, Heat flow from five uranium test wells in west-central Arizona: U.S. Geological Survey Open-File Report 81-1089, 42 p.

Shearer, C. R., 1979, A regional terrestrial heat-flow study in Arizona: Socorro, New Mexico Institute of Mining and Technology, Ph. D. thesis, 184 p.

Spicer, H. C., 1964, A compilation of deep earth temperature data, U.S.A., 1910-1945: U.S. Geological Survey Open-File Report [64-147].

Swanberg, C. A., and Morgan, Paul, 1978/79, The linear relation between temperatures based on the silica content of groundwater and regional heat flow: A new heat flow map of the United States: Pure and Applied Geophysics, v. 117, p. 227-241.

——1980, The silica heat flow interpretation technique: Assumptions and applications: Journal of Geophysical Research, v. 85, no. B12, p. 7206-7214.

Urban, T. C., Diment, W. H., and Nathenson, Manuel, 1978, East Mesa geothermal anomaly, Imperial County, California: Significance of temperatures in a deep drill hole near thermal equilibrium: Geothermal Resources Council Transactions, v. 2, pt. 2, p. 667-670.

Vaught, T. L., 1980, Temperature gradients in a portion of Michigan: A review of the usefulness of data from the AAPG geothermal survey of North America: U.S. Department of Energy Report DOE/NV/10072-1, 39 p.