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HEAT FLOW IN THE NORTHERN BASIN AND RANGE PROVINCE

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ABSTRACT

The heat flow in the Basin and Range province of northern Nevada is extremely complex. It is a product of superposition of the regional effects of extension and volcanism/intrusion modified by the local conductive effects of thermal refraction (complicated structural settings), variations in radioactive heat production, erosion and sedimentation. In addition to these conductive effects, groundwater flow, both on a local and a regional basis, affects heat-flow measurements. Typical heat-flow values for the Basin and Range province average 85 ± 10 mWm^{-2}. The higher estimates are probably based on biased sets of heat-flow measurements, and actual averages are on the order of 100 ± 10 mWm^{-2}. Geothermal systems appear to be related to deep fluid circulation in an active tectonic setting rather than to young silicic volcanic rocks. Young volcanoes occur along the borders of the Basin and Range province, but not in the part of northern Nevada discussed in this paper.

INTRODUCTION

The Basin and Range province of the western Cordillera of the United States is an exceedingly complex area resulting from the superposition of 600 million years of recurring tectonic and volcanic activity. In the late Cenozoic, the already highly fragmented geology of the Basin and Range was further disrupted by the subsidence and covering of approximately half the province by alluvial deposits in the valleys and by the exposure of different stratigraphic and structural levels in adjacent ranges. The heat flow in the Basin and Range province reflects this complicated tectonic development in both regional and detailed ways.

The object of this paper is to discuss the distribution of, and controls on, heat flow in the part of the Basin and Range province in northwestern Nevada from an observational point of view. Thermal variations may not have as distinctive an imprint as structural and stratigraphic evolution; however, certainly the varied thermal events during the mid and late Cenozoic have left their marks. Furthermore, the interaction between the present-day thermal background and the detailed structural and hydrologic settings is complex. Consequently, even with a relatively high density of heat flow data, compared to many areas of the earth, there are still many uncertainties and unknowns in the actual magnitude of the background, the detailed geographic and vertical distribution, and the way in which variations relate to structural geology, hydrology and volcanic history.

The history of heat flow studies in the Basin and Range province dates back to the late 1960s. Reconnaissance data in the Basin and Range were discussed by Roy et al. (1968b) and Sass et al. (1971). The most recent detailed heat flow map of northwestern Nevada was presented by Sass et al. (1981, Fig. 1). Sass et al. (1971) divided the Basin and Range province in Nevada into three heat flow regimes: a region of heat flow typical of the province average (surface heat flow values of about 85 ± 10 mWm^{-2}*); a region of above average heat flow (surface heat flow values of 100 + mWm^{-2}) which was designated the Battle Mountain Heat Flow High; an area of below average heat flow values which was named the Eureka Heat Flow Low (surface heat flow values of less than 60 mWm^{-2}). These heat flow subdivisions were maintained in later discussions by Lachenbruch and Sass (1977, 1978). In contrast, Blackwell (1978) argued that the highest overall energy loss within the Basin and Range province was along the eastern and western boundaries near the Wasatch and the Sierra Nevada Mountains, and not within the Battle Mountain Heat Flow High.

Extensive heat flow or subsurface temperature data have become available for many geothermal systems subsequent to the major discussions in 1978, especially in northern and northwestern Nevada. These data have yet to be integrated into the pre-existing regional data set. Neither space nor time permit the integration of these data in this paper, but some salient aspects of these studies which have a bearing on the current understanding of heat transfer in the Basin and Range province will be discussed. The order of the discussion in the paper proceeds more or less according to Table 1, a list of major effects on the heat flow pattern in the Basin and Range province. Following a brief summary of the

TABLE 1. THERMAL EFFECTS
Volcanism and Intrusion
Extension
Thermal Refraction-Structure
Radioactive Heat Production
Erosion and Deposition
Local Groundwater Flow
Geothermal Systems

* 41.84 $mWm^{-2} = 1 \times 10^{-6}$ cal/cm^2 sec = 1 HFU

observations, the regional effects on heat flow will be discussed. These regional effects are grouped as thermal effects related to extension and to volcanism. Following this discussion, the more local effects which may cause heat flow variations on the scale of a few kilometers will be discussed. The effects specifically to be discussed include the conductive effects of variation of basement radioactivity, effects of structure (i.e., lateral variations of thermal conductivity), erosion and deposition, and the effects of regional and local convective geothermal fluid-flow systems.

OBSERVED HEAT FLOW DISTRIBUTION

The regional heat flow data described by Sass et al. (1981) are shown in Figure 1. A total of 93 heat-flow measurements for the Nevada portion of the Basin and Range province are shown. The spacing of heat-flow stations is quite dense for a continental region, but as will subsequently become obvious, it is not dense enough to determine many of the characteristics of the heat-flow pattern. Superimposed on the heat-flow map are the contours of the Eureka Heat Flow Low and Battle Mountain Heat Flow High. Heat-flow values generally exceed 100 mWm^{-2} within the area identified as the Battle Mountain Heat Flow High. Elsewhere within the Basin and Range province, heat-flow values are typically 85 ± 10 mWm^{-2}. The thermal boundaries of the Basin and Range province are very sharp against the Wasatch Mountains-Colorado Plateau region on the east (Bodell and Chapman, 1982; Keller et al., 1979; Reiter et al., 1979) and the Sierra Mountains on the west (Roy et al., 1968b, 1972; Sass et al., 1971). To the north there is no distinct thermal boundary with the Columbia Plateau region and, in fact, contours of the Battle Mountain Heat Flow High include part of the High Lava Plains in Oregon, and the Snake River Plain region in Idaho (see Brott et al., 1978, 1981).

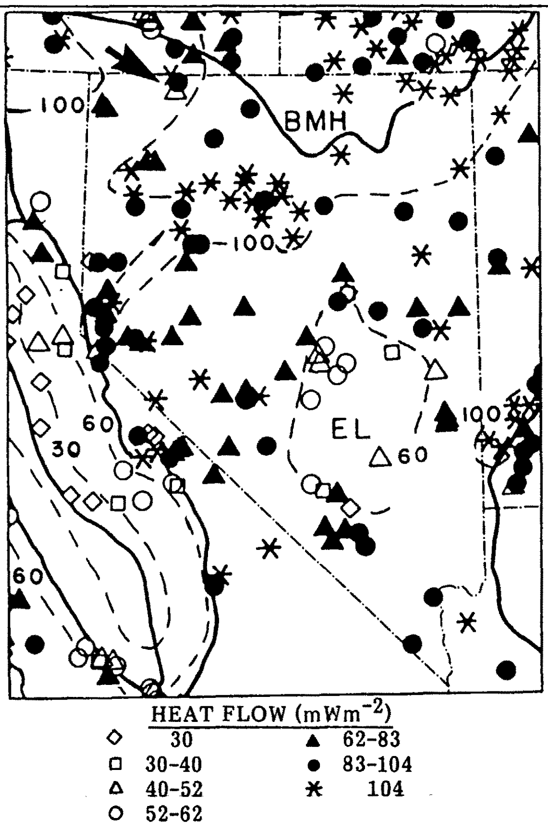

FIGURE 1. Heat flow in Nevada and surrounding areas, after Sass et al. (1978). Contours are from Lachenbruch and Sass (1978). Arrow in northwestern Nevada indicates three holes in granite discussed in text.

In addition to the "regional heat flow" data set, an extensive data set including 10 to 100 times as many holes as shown on Figure 1 is available from exploration activities associated with individual geothermal systems. In general, these data are not included in Sass et al. (1981), nor in earlier descriptions of heat flow in the Basin and Range province. The existence of this new data set gives an additional complexity to the heat-flow character, poses many interesting questions, and also opens the possibility of investigating in more detail local conditions affecting observation.

Most of the geothermal exploration drilling has been along the boundaries between a range and valley, or within a valley. On Figure 1, no "regional" heat flow data from the valleys are shown, so the two data sets do not overlap geographically or geologically, and it cannot necessarily be anticipated that the geothermal regimes will be the same in the ranges and in the valleys. Another important aspect of the geothermal systems is the maximum temperature of the system, which is controlled by the depth and rate of circulation. No systematic summary of such temperatures based on drilling has yet been described. Edmiston (1982) has presented a map showing the location of deep geothermal tests and the geothermal tests which have been successful (i.e., have found temperatures in excess of 200°C). Analysis and integration of the new data set with regional data will take effort, but has the potential to greatly refine our understanding of the heat flow distribution in the Basin and Range province.

REGIONAL CONTROLS ON HEAT FLOW

Introduction. The two dominant regional thermal effects are mechanical-thermal effects associated with the late Cenozoic extension, and the thermal effects of mid and late Cenozoic intrusion and volcanism. Although these two effects will be discussed separately, in fact they are interrelated, and individual components are difficult to identify separately.

Thermal Effects of Extension. There has been an emphasis on extension effects on the thermal pattern because the extensional activity is so prominent in the most recent history of the Basin and Range province. Lachenbruch and Sass (1977, 1978) have developed a model for the thermal regime in the Basin and Range province emphasizing extension. The primary thermal effect of extension is to move deeper, hotter material to shallower depths as the lithosphere is stretched. However, there are definite limits to the enhancement of surface heat flow by this mechanism if the spreading does not lead rapidly to ocean basin formation, so the favored models discussed by Lachenbruch and Sass (1978) actually depend on basalt intrusion to supply a large part of the high heat flow observed at the surface. Indeed, the Lachenbruch and Sass (1978) models have a one-to-one correlation between extension rate and intrusive emplacement. These models were also applied to areas of large-scale silicic volcanism such as Yellowstone and Long Valley. In these areas, much more of the anomalous surface heat flow is associated with intrusion than with extension!

Limits on the amount of extension are related to isostatic effects. As stretching occurs, continental crustal material is replaced by mantle material with a large increase in density and, consequently, subsidence. The subsidence is offset to some extent by thermal effects of extension. A comparison of these two quantities is shown in Table 2. The heat-flow model includes one-dimensionsal time-dependent stretching (Jarvis and McKenzie, 1980). Example extension rates, total extension associated with a 17 M.Y. period of extension in the form of ratios (βs), the amount of mechanical subsidence which would be associated with extension of an originally 40 km thick continental crust, the amount of thermal uplift, and the difference between the mechanical subsidence and the thermal uplift (a net subsidence) are shown in Table 2. The associated heat flow anomaly for each case is also shown. This model includes a time-dependency, so the heat flow values are slightly lower than would be the case if extension had occurred long enough for thermal equilibrium to be attained (see Figure 2). The 17 M.Y. period was chosen as it is the maximum period of time of extension in the northern Basin and Range province during the late Cenozoic, and was the period of time of extension assumed in the analysis of Lachenbruch and Sass (1978).

Typical extension proposed (Lachenbruch and Sass, 1978) ranges from 50 to over 100%, corresponding to β values of 1.5 to 2. Taking isostatic effects into account, a net subsidence of 1.5 to 2.4 km is associated with the required heat-flow anomaly of 40 to 60 mWm^{-2}. These observations can be compared to the mean topographic height of the Basin and Range province in Nevada at the present time (from 1.5 km in the Lahontan and Bonneville Basins to over 2 km in the center of the province), and the regional elevations of approximately 2 to 2.5 km in the Wasatch Range and the Sierra Nevada Mountains. Unless the Basin and Range province started at an extraordinarily great elevation, it seems unlikely that the total subsidence could exceed 0.5 km, as the Basin and Range province still stands at a high elevation. The results of this analysis suggest that extension is not the main mechanism responsible for high heat flow in the Basin and Range province.

Figure 2 shows more detail of the heat-flow contribution associated with a transient thermal event as summarized in Table 2. In this calculation, an initial lithospheric thickness of 94 km and a background heat flow of 40 mWm^{-2} were assumed. Extension rates in percent per million years are shown for each curve. The dashed line on the plot is the locus of points with a β value of 1.5.

These results may be compared to the various heat flow subregions in the Basin and Range province. A typical background heat flow in the Basin and Range is approximately 85 mWm^{-2}. The reduced or mantle heat flow (the heat flow from below the upper crustal radioactivity layer) is 59 mWm^{-2}, approximately 50% of

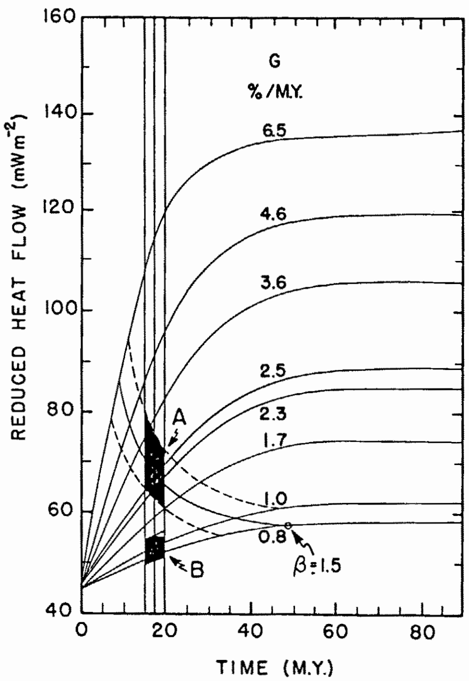

FIGURE 2. Thermal effect of extension calculated using model of Jarvis and McKenzie, 1980. Age range of extension in the Basin and Range province is shown by the vertical lines (17 ± 2 M.Y.). G is extensional strain rate in %/M.Y. Shaded area A is the region of the graph corresponding to reduced heat flow values typical of the Battle Mountain Heat Flow High. Shaded area B is the region of the graph consistent with present crustal thickness.

TABLE 2. COMPARISON OF MECHANICAL SUBSIDENCE AND THERMAL UPLIFT IN BASIN AND RANGE PROVINCE FOR 17 M.Y.

Extensional Strain Rate (%/M.Y.)	β (17 M.Y.)	Mechanical Subsidence (km)	Thermal Uplift (km)	Net Subsidence (km)	Surface Heat Flow (mWm^{-2})
0.8	1.14	0.67	0.24	0.43	78
1.7	1.29	1.33	0.54	0.79	84
2.5	1.43	1.83	0.73	1.10	93
3.6	1.61	2.43	0.91	1.52	104
4.6	1.78	2.87	1.02	1.85	117
5.6	1.95	3.25	1.11	1.11	128
6.5	2.11	3.54	1.17	2.37	140

which is anomalous with respect to a thermally "normal" continental lithosphere (Roy et al., 1968a, 1972). Heat flow values in the Battle Mountain Heat Flow High range from 100 to 150 mWm^{-2}, and the reduced heat flow in the Battle Mountain Heat Flow High according to Lachenbruch and Sass (1977, 1978) ranges from 85-100 mWm^{-2}, or approximately 30-45 mWm^{-2} in excess of the normal Basin and Range reduced heat flow, and 60-75 mWm^{-2} in excess of a "normal" continental reduced heat flow.

It is clear from the consideration of Table 2 and Figure 2 that the magnitude of heat flow observed in the Battle Mountain Heat Flow High cannot be associated with the thermal effects of extension alone. To add emphasis to this conclusion, it is clear that the present-day distribution of active earthquake zones in the Basin and Range province is not coincident with the highest heat flow. One zone of earthquake activity extends north through the Battle Mountain Heat Flow High, but much of the heat-flow high is essentially aseismic at the present time (Smith, 1978). Other zones of active seismicity along the Sierra Nevada-Basin and Range transition and along the Colorado Plateau-Basin and Range transition are not apparently characterized by quite as high surface heat flow (see Lachenbruch and Sass, 1978; Blackwell, 1978).

Thermal Effects of Intrusive and Volcanic Activity. There is no difficulty in generating high heat flow values in association with volcanic and intrusive activity, although many of the highest values are obviously associated with geothermal systems rather than with conductive heat flow from magma chambers. A correlation between the age of volcanic activity in a particular area and the heat flow, especially in the case of the continental crust characterized by rhyolitic volcanic activity, might be expected. A generalized volcanic age map for the area shown in Figure 1 is shown in Figure 3. The pattern has been discussed by many people, recently including Stewart and Carlson (1978) and Snyder et al. (1976). The areas of oldest, or lack of, Cenozoic volcanism are in southern Nevada and in east-central Nevada. Most of the rest of Nevada is characterized by volcanism in the age range 6-17 M.Y. and only along the margins of the province are younger, extensive silicic volcanic features found.

Various types of volcano/thermal models have been discussed, including the extension/intrusion models of Lachenbruch and Sass (1978). If volcanism is not associated one-to-one with extension, then the event will lead to some sort of heating of the crust followed by cooling after the end of the volcanic/intrusive event. The peak heat flow will depend on the actual distribution of magma within the crust and lithosphere. However, after 1-5 M.Y. or so of cooling, all models approach the same sort of behavior. The long time asymptote of the cooling depends on the assumption of the background heat flow. The general sort of behavior is shown in Figure 4. The curves in Figure 4 are shown to cool off to three different backgrounds, depending on the assumed steady-state mantle heat flow. These models are discussed in more detail by Blackwell (1978). On Figure 4, the typical heat flow in the Basin and Range province and the heat-flow range for the Battle Mountain Heat Flow High are shown. Based on these results, it would appear that the higher estimates of heat flow in the Battle Mountain Heat Flow High are too high to be explained by the volcanic model if no silicic volcanism in the area is

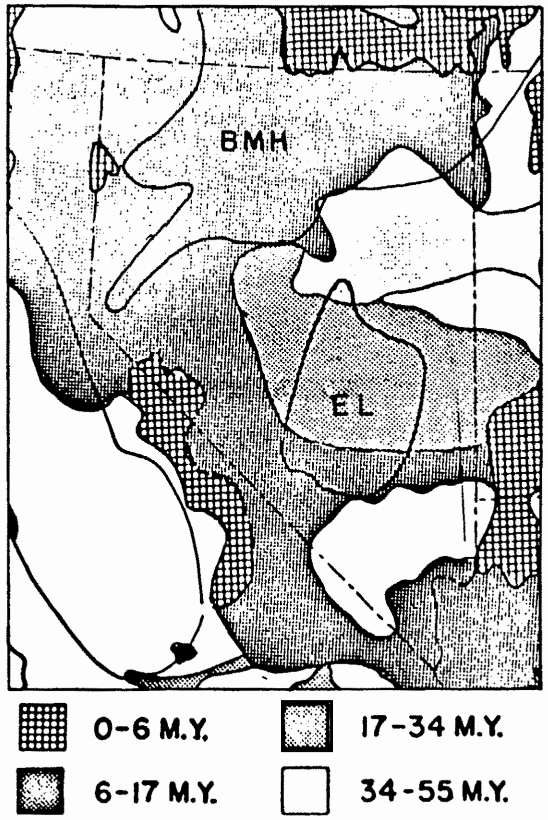

FIGURE 3. Age of silicic volcanism (generalized from Stewart and Carlson, 1978). Light lines are 60 mWm^{-2} heat-flow contours.

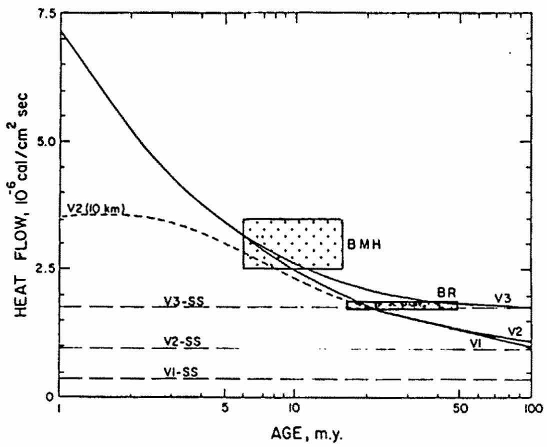

FIGURE 4. Thermal models for regional volcanic and intrusive events in the Basin and Range province. Observed heat-flow ranges for the models are explained by Blackwell (1978). SS indicates the steady-state asymptotic heat-flow values.

younger than 6 M.Y. Because the heat flow is also too high to be explained by extension, the apparent magnitude of the regional heat flow pattern is somewhat difficult to explain.

LOCAL CONDUCTIVE HEAT FLOW EFFECTS

Radioactive Heat Production. If the geology of the Basin and Range province were similar to the Sierra Nevada Mountains, and consisted of a large, homogeneous, relatively unfractured, granitic terrain, then the heat flow evaluation would be relatively straightforward. The surface heat flow within the granite would show a linear correlation with the local heat production of the rocks from uranium, thorium and potassium. In this simple case, local lateral heat-flow variations due to sub- and intracrustal sources, groundwater flow, thermal refraction and so forth, would not have significant effects on the heat flow distribution. Such linear arrays have been observed in many places throughout the world (Roy et al., 1968a; 1972). Early studies of heat flow versus heat production for the Basin and Range province indicated a regional linear relationship with an intercept heat flow of approximately 59 mWm^{-2} and a slope of approximately 9.4 km (Roy et al., 1968a). Subsequent studies of the relationship between heat flow and heat production in granitic rocks in the Basin and Range have led to a considerably more complicated pattern.

A summary of the available data is shown in Figure 5. This figure was presented by Lachenbruch and Sass (1978), but the detailed data on which this figure is based have not been published. It is difficult to identify a linear relationship between heat flow and heat production

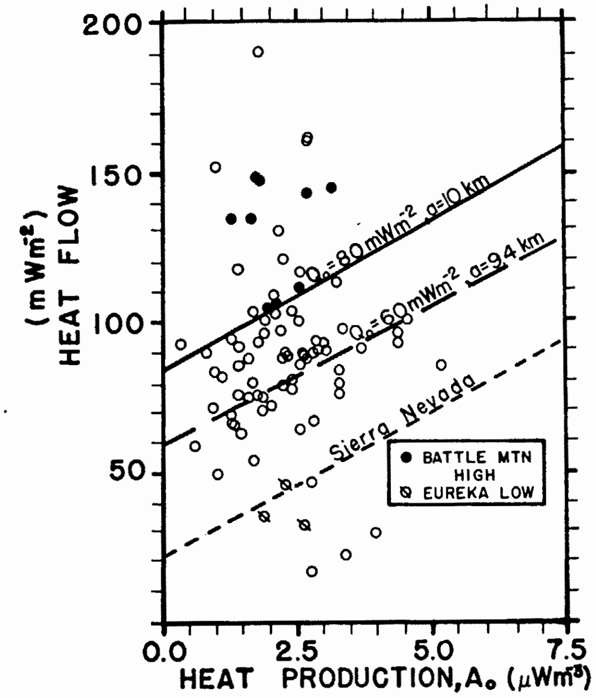

FIGURE 5. Surface heat flow as a function of surface heat production (after Lachenbruch and Sass, 1977).

in this data set, although most of the data lie between two lines with intercept values of 50 mWm^{-2} and 90 mWm^{-2} (with slopes of 9.4 to 10 km).

In the Basin and Range province, unlike the Sierra Nevada Mountains, it is not possible to avoid systematic effects on the heat flow data, even by drilling heat-flow holes only in granitic rocks, in large part because granitic rocks represent only a small fraction of the exposed bedrock of Nevada (2.8%, Archbold, 1972). Therefore, the data shown in Figure 5 have all sorts of extraneous (from the regional point of view) effects present in the measurements. The difficulties of attempting to use these data to determine regional quantities are illustrated by three points in granite in close proximity in north-central Nevada (see arrow in Figure 1). The radioactive heat production values are approximately the same for the three points, and yet the heat-flow values are respectively 45, 85 and 150 mWm^{-2}. These points are within a few km of one another, and all are in granite. If only one of the three holes were available, it might be inferred that this area had heat flow typical of (1) the Eureka Heat Flow Low, (2) normal Basin and Range, or (3) the Battle Mountain Heat Flow High.

The sites are close to the Baltazor geothermal system (Earth Power Prod. Co., 1980), and it is possible that there is some interaction between the fluid convection represented by the geothemal system and the extreme variation in heat-flow values shown by these three data points. Thus it seems quite clear that both high and low heat flow values are associated with convection systems, as concluded by Lachenbruch and Sass (1977).

Because of the very noisy data set, the heat flow-heat production relationship for various parts of Nevada and its relationship to other known continental patterns is not presently resolvable in an accurate way. It is clear that heat flow determinations in granitic rocks in Nevada, without considerable attention to each individual measurement, are insufficient for the determination of typical regional heat-flow values and heat-flow distribution in contrast to standard practice in some geologic terrains.

Thermal Effects of Structure: Refraction. In an ideal case, to avoid anomalies due to the spatial distribution of thermal conductivity, the thermal conductivity of the rocks should either be uniform or should vary only in the vertical direction. If there are variations only in the vertical direction, then a hole penetrating various units will show an inverse correlation between the thermal conductivity of the rock and the geothermal gradient, resulting in constant heat flow with depth. However, the geologic structure of the Basin and Range province is anything but layer cake. In order to investigate possible systematic effects of thermal conductivity on heat flow, determinations from the Battle Mountain Heat Flow High are plotted as a function of thermal conductivity in Figure 6. Most of the early heat-flow determinations in the Battle Mountain Heat Flow High were made in very high thermal conductivity sedimentary rocks. Average thermal conductivities at these sites are over 4 $Wm^{-1}K^{-1}$. The thermal conductivity of the granites where subsequent heat-flow values were obtained is typically about 3 $Wm^{-1}K^{-1}$ (Sass, personal communication, 1980). Typical thermal conductivities from some of the basins are 1-1.5 $Wm^{-1}K^{-1}$. The basin data are primarily from the Black Rock Desert, which has been extensively studied (Sass et al., 1979; Mase and Sass, 1980), and the Grass Valley area (Sass et al., 1976; Welch et al., 1981). A strong positive correlation between the heat flow and thermal conductivity is demonstrated in Figure 6. This correlation suggests that thermal refraction is important in the results; consequently, heat-flow values from any one geologic terrain may not represent true regional values.

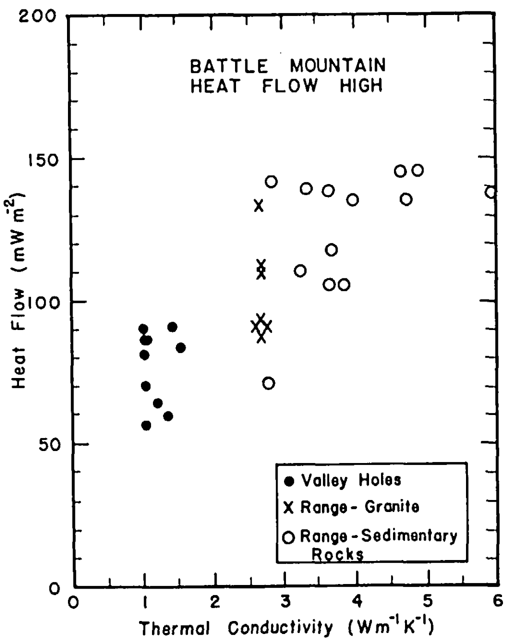

FIGURE 6. Comparison of heat flow and thermal conductivity from heat-flow sites in the Battle Mountain Heat Flow High. Data from reference in text and from J.H. Sass (personal communication, 1980).

Another way to investigate systematic effects between heat flow and thermal conductivity is to look at variations in gradient. Measurements in granite, in pre-Tertiary sedimentary rocks, and in valley fill are shown by separate patterns in Figure 7. The gradient distribution from both the granite and the sedimentary rock lithologies overlap, with the range of values being 25-40°C/km. The fact that there is a correlation between heat flow and thermal conductivity, but not between heat flow and gradient, also suggests that structural effects are controlling the variation of the heat-flow values. The reasoning proceeds as follows: if the measurements had been made in horizontal units of varying thermal conductivity (the ideal case), then the gradients would be inversely proportional to the thermal conductivity, there would be no correlation between heat flow and thermal conductivity, and there would be good correlation between gradient and conductivity. In fact, the reverse situation is observed in each case.

Also shown in Figure 7 is a histogram of gradient values from the Basin and Range province of Arizona. This data set includes values recently published by Shearer and Reiter (1981). The Basin and Range province in Arizona has a considerably larger percent of granitic bedrock, generally lower relief, fewer known geothermal systems, and older volcanic rocks. Thus some of the geologic complexities of the northern Basin and Range in Nevada are more subdued in the part of the Basin and Range province in Arizona. A histogram of gradients from the ranges in Arizona shows almost identical distribution to that in the Battle Mountain Heat Flow High, whereas an average of the heat flow values in the two provinces differs by 25 to 50% (lower in Arizona). Figure 8 shows a plot of thermal conductivity versus heat flow for the Arizona data. Included in this plot are the data from several holes in the valleys in Arizona which are, as in the case of Nevada, undersampled in the present data set. The correlation between thermal conductivity and heat flow is weak, and there is a large overlap between the data from the Battle Mountain Heat Flow High and from central Arizona, excluding the very high heat flow values in the high thermal conductivity sedimentary rocks in the northern Basin and Range province. The conclusion of this discussion is that there may be a bias in heat flow toward too-high values if data only from the ranges (including the high thermal conductivity sedimentary rocks) are used to calculate province average values.

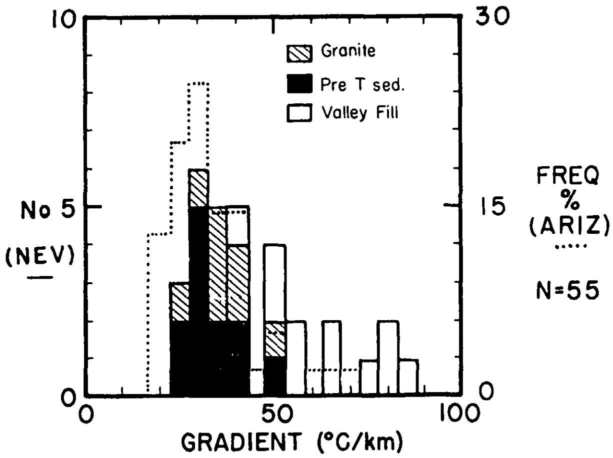

FIGURE 7. Histograms of gradient in Battle Mountain Heat Flow High and Arizona Basin and Range province (dotted lines). Arizona data from Shearer and Reiter (1981) and Sass et al. (1982).

Of course, detailed evaluation of the structural effects on heat flow has to be considered individually for each hole. However, there is one large-scale effect which needs to be considered in this discussion. This thermal effect is the large-scale distortion of heat flow by Basin and Range structure. In general, the valleys are 10-20 km wide and 1-2 km deep. They are generally filled with low thermal conductivity Cenozoic sedimentary rocks. In the ranges, older sedimentary, igneous and metamorphic rocks generally have thermal conductivity values two to three times greater. As a result of this contrast, heat flows preferentially into the ranges, resulting in systematically high values in the ranges, and systematically low values in the valleys with respect to the regional mean value. This large-scale effect of a valley is sometimes modeled as a single, semi-elliptical or semi-circular cylinder embedded in an otherwise uniform media (see Jaeger, 1965). In this case, for typical geometries observed in the Basin and Range province, there would be no appreciable expected effect of thermal refraction except in the immediate proximity of a range-bounding fault, where higher-than-normal values would be observed in the range side, and lower-than-normal values would be observed on the basin side. Two effects are not considered in this simple model. The first of these is that the basins and ranges repeat, so that it is not appropriate to consider only a single valley

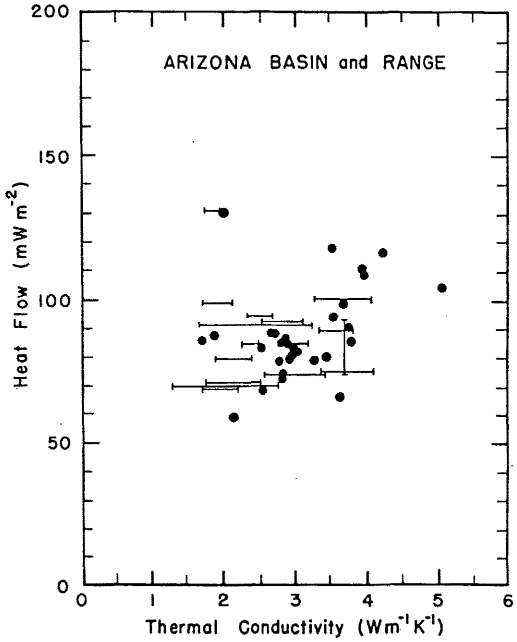

FIGURE 8. Comparison of heat flow and thermal conductivity at heat-flow sites in Arizona. The bars represent ranges of values as observed in specific holes or areas.

to consider only a single valley embedded in an otherwise semi-infinite media with conductivities typical of the ranges. The effect of repeated ranges and valleys is interaction (Lee and Henyey, 1974), so that larger refraction effects than calculated from the single ellipse model of Jaeger (1965) are observed.

Another complexity not considered in either of these models is the fact that the heat source is within the crust. The boundary condition for the models is that there is constant heat flow from "great depth" and the heat flow is allowed to adjust at great depths below the inhomogeneity. In the Basin and Range province the heat sources (extension effects and magma) may be in the mid- to upper levels of the crust, and there may be interaction between the heat source and the variations in thermal conductivity, with even more heat being forced through the ranges (and less heat forced through the valleys) than calculated assuming a constant heat flow at great depth. In the extreme limit, the model would be characterized more by constant temperature than by constant heat flow, in which case (except again in the immediate vicinity of the boundaries of the inhomogeneities) the mean heat flow would be simply proportional to the integrated thermal resistance from the constant temperature plane to the surface.

A typical model is shown in Figure 9. A Basin and Range valley filled with rocks having a thermal conductivity of 1.7 $Wm^{-1}K^{-1}$ is embedded in material with a conductivity of 3.35 $Wm^{-1}K^{-1}$. The geometry of the model is constant into and out of the paper, and repeats that shown side-to-side. In a steady-state case, it is assumed that the heat flow is uniform at great depth. If the average regional heat flow is assumed to be 72 mWm^{-2}, then the heat flow observed in the valley away from the bounding fault would be 60 mWm^{-2}, while the heat flow observed in the range away from the bounding fault would be 80 mWm^{-2}; this represents a 25% variation between the high and low heat-flow values and an error in regional heat-flow determination (if the range value is used) of about +12%. If heat-flow determinations were made in the ranges without avoiding areas close to the bounding fault, however, the mean observed heat flow would be 16% higher than the true mean. Therefore, based on this simple model, a random set of measurements in the ranges would be 16% higher than the regional average, and would be greater than 25% higher than the values measured in the adjoining valleys.

These results are consistent with the distribution of gradients shown in Figure 7, and to some extent with the distribution of heat-flow values shown in Figure 6, if the most thermally conductive sedimentary rocks are not considered typical and the values in the granites are used for comparison instead. It is iteresting to note that peak heat-flow values associated with the boundary of the range would be 96 mWm^{-2}, or 25% high with respect to the average in a steady-state case. Since the amount of the granitic exposure in the northern Basin and Range

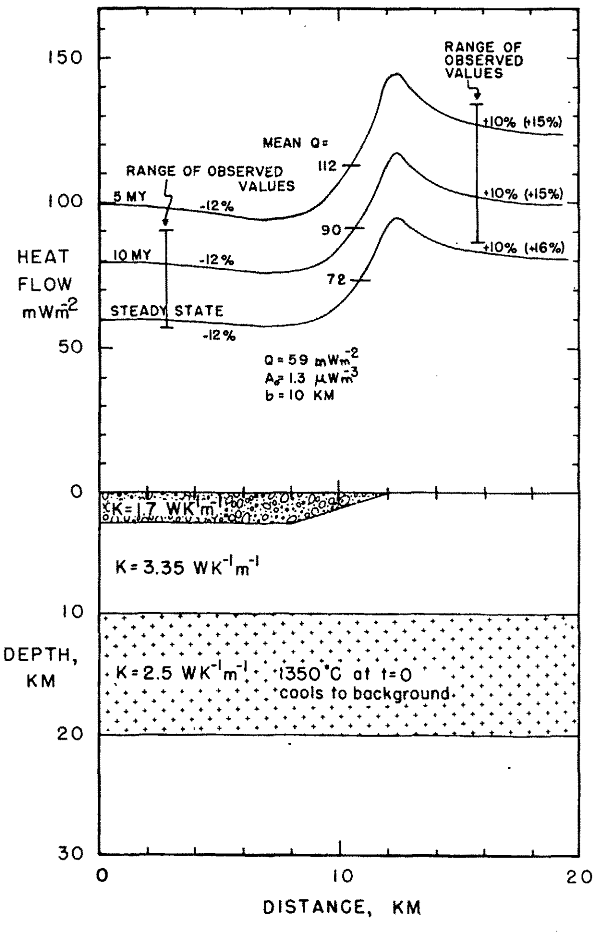

FIGURE 9. Surface heat flow effects of Basin and Range structure and a crustal intrusive. Range of observed values refers to Battle Mountain Heat Flow High.

province is so limited, it is argued that use of these sites for the determination of regional heat-flow values may have a large bias.

Effects of Erosion and Deposition. The thermal effects associated with erosion of mountain ranges and the deposition of sediments in basins have been discussed by numerous authors (including Jaeger, 1965; England and Richardson, 1980). The general effect is to decrease observed heat-flow values in the sedimenting basins as the colder sediments deposited in the basin are heated up, and to increase heat-flow values in the ranges as hotter rocks are exposed by erosion. In view of the great tectonic relief developed in the last few million years in the Basin and Range province, significant perturbations from these effects may exist in the heat-flow data set. Unfortunately, there are not sufficient data to estimate these corrections in general. However, it is possible that systematic effects of up to 10 or 20% of the observed values could be related to the systematic differences in the erosional and depositional environments of the ranges and valleys. These effects might or might not be superimposed on the refraction effects in an additive way, depending on the detailed timing of the development of the basins and ranges, and of the thermal conductivity contrast associated with various structural settings. The sense of these effects is in the same direction as the structural effects, i.e. values would appear to be higher than the true regional value in the ranges and lower than the true regional value in the valleys.

CONVECTIVE HEAT-FLOW EFFECTS

Shallow Groundwater Aquifers. The effects of subsurface water movement on heat flow can be many, complex, and on different scales. The most common effect is that of water table fluid flow, which is probably present in varying degrees at almost all sites. Water movement in very large aquifers may affect the heat flow so severely that it is virtually impossible to use holes of any reasonable depth to do classical heat-flow studies. An example of this situation is the Snake River Plain aquifer in Idaho, where heat flow values are much subnormal over an area 50 km wide by 200 km long (Brott et al., 1981). Because of the rapid flow rates in the aquifer (up to 1000 m/year), about 75% of the total amount of heat conducted into the bottom of the Snake Plain aquifer is advected out the end of the aquifer, leaving only about 25% of the heat to be measured by conductive heat-flow studies. On the other end of the scale, if the aquifer moves slowly enough that no heat is actually advected at the discharge zone of the aquifer, then the overall heat budget would remain the same as in the conductive heat-flow case, but the distribution would reflect the downflow and upflow parts of the system. This situation has been modeled by Domenico and Palciauskas (1973) and applied to basins in the Rio Grande rift by Morgan et al. (1981).

Mifflan (1968, 1983) has discussed in detail the hydrology of the Basin and Range province. The dominant hydrologic system in the Basin and Range province is a range-to-valley flow system. Aquifer heads are typically highest in the ranges and lowest in the valleys. As drill holes are deepened in the ranges, each successive aquifer usually has a lower head, and as drill holes are deepened in the valleys, each successive aquifer usually has a higher head. This observation implies recharge in the ranges and discharge in the valleys of the groundwater flow systems. Thus low heat-flow values would be observed in the ranges and high heat-flow values would be observed in the valleys, if this effect dominates the shallow heat transfer.

In the Battle Mountain Heat Flow High, no low heat-flow values which might be characteristic of recharge areas in the ranges have been described. Even if the regional heat flow is high, it seems likely that some evidence of local circulation would have been discovered, particularly in the sedimentary rocks.

Superimposed on the local hydrologic pattern are (in some situations) complex interbasin groundwater flow systems. These interbasin groundwater flow systems are particularly characteristic of the carbonate terrain in eastern and south-central Nevada. This phenomenon may be related to the existence of the Eureka Heat Flow Low (Sass et al., 1971).

Geothermal Systems. There is also abundant evidence, in the form of many geothermal anomalies, for large-scale water flow in northern Nevada. If water flow goes deep enough, high temperatures and a commercially attractive geothermal system may result. The depth of circulation required is a function of the permeability of the rocks (rate of fluid flow) and the background geothermal gradient. These geothermal convective systems can be local or they can be regional. Near many active volcanic and intrusive centers, the water flow systems may have lateral dimensions of only a few kilometers. On the other hand, some geothermal systems may involve fluid which moves across ranges and valleys (for example, the Desert Peak geothermal anomaly; Yeamans, 1983). The characteristics of some of the geothermal systems in the Basin and Range province have been discussed by Blackwell and Chapman (1977), Sass et al. (1976), Benoit et al. (1983), and Benoit and Butler (1983). Extensive thermal data are now available from many areas, in too great a number to be discussed in detail here. Many of these data were collected through DOE-Industry coupled geothermal programs, and are available from the Earth Science Laboratory of the University of Utah. Brief discussions of many of these areas are given in papers of the Geothermal Resources Council Transactions. References to discussions of thermal data from areas in northern Nevada are listed in Table 3.

Mase and Sass (1980) have discussed an extensive heat-flow study in the Black Rock Desert area of northern Nevada (Figure 10). This area includes several geothermal systems, one of which is Gerlach Hot Springs, but in addition areally extensive data outside the geothermal systems were also calibrated. Typical heat-flow values in the Black Rock Desert are 40-60 mWm^{-2} along the axis of the valley, rising to 80-100 mWm^{-2} at the margins of the valley. Several large high heat-flow anomalies are identified, particularly north of Gerlach along the east side of the Granite Range, along the southeast margin of the Black Rock Desert against Pahisupp Mountain, and along the west side of the Black Rock Range. In addition, MacFarlane's Hot Spring (Swanberg and Bowers, 1982) is just off the map to the east. The major gap in the data is that few values are available from the ranges to compare to the basin. A heat-flow value measured in the granite of Pahisupp Mountain was 188 mWm^{-2}, clearly much in excess of any possible regional value, and affected in some way by a geothermal system.

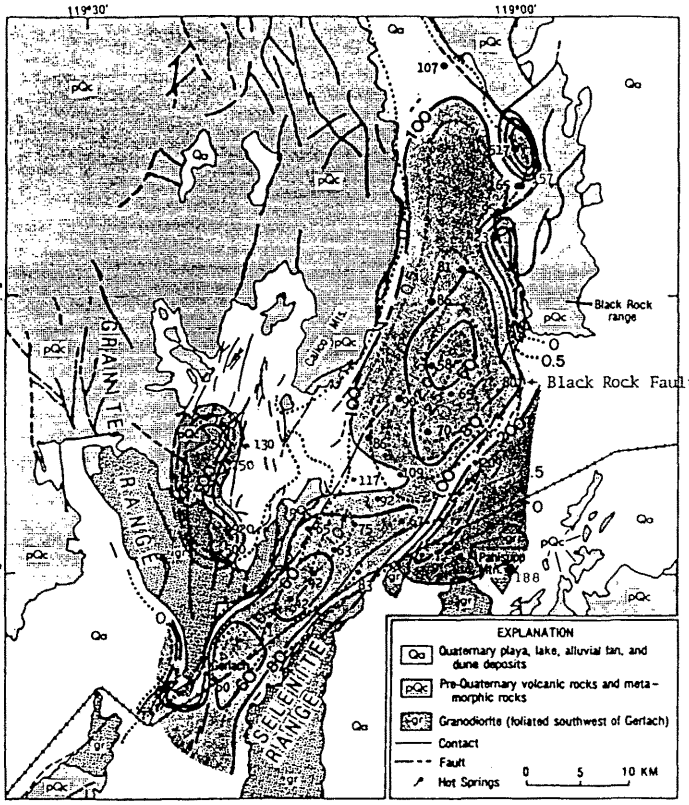

FIGURE 10. Heat-flow contours (solid line: 60, 80, 100, 200,300, 500 mWm^{-2}) and depth-to-basement contours (dotted line: 0,0.5, 1.0, 1.5, 2.0, 2.5 km) in the western Black Rock Desert. Location of heat-flow points (solid circles) for reference. Major normal faults are also indicated. After Mase and Sass (1980).

TABLE 3. Geothermal systems and published geothermal gradient/heat flow studies or data reports.

Location	Geothermal System	Reference
Black Rock Desert	McFarland H.S. Gerlach H.S.	Swanberg and Bowers, 1982 Sass *et al.*, 1979 Sass *et al.*, 1976
San Emedio Desert	San Emedio West	Mackelprang *et al.*, 1980
Humbolt Sink	Colado Humbolt House	Mackelprang, 1982
Carson Sink	Desert Peak Brady H.S. Stillwater Soda Lake Fallon-NAS	Benoit *et al.*, 1982 Hill *et al.*, 1979
Clan Alpine Mts.	McCoy	Olson *et al.*, 1979
Pueblo Mountains	Baltazor H.S.	Earth Power Prod. Co., 1980
Steamboat Hills	Steamboat H.S.	White, 1968
Buena Vista Valley	Kyle H.S.	McMannes *et al.*, 1981
Crescent Valley	Beowawe H.S.	Smith, 1983
Independence Valley	Tuscarora	Pilkington *et al.*, 1980
Grass Valley	Leach H.S. Parker Canyon	Sass *et al.*, 1977 Welch *et al.*, 1981 Mase and Sass, 1980
Buffalo Valley		Sass *et al.*, 1976

Superimposed on the heat-flow values are the depth-to-basement contours, also from Mase and Sass (1980). There is a good correlation between the heat-flow values and the depth to basement, with the lowest heat-flow values being associated with the deepest part of the basin. Mase and Sass (1980) suggested that regional downflow is occurring in the valleys with upflow along the margins of the valleys. The proposed hydrologic circulation would be counter to the "normal" hydrologic circulation pattern of downflow in the ranges and upflow in the valleys (Mifflan, 1968). Unfortunately, the lack of data in the ranges does not allow a complete test of the Mase and Sass (1980) hypothesis. Furthermore, geothermal systems are often associated with the contact between the valleys and the ranges and may be controlled by hydrologic barriers between the ranges and the valleys. In this case, if water flow were down in the range, it might be expected to come back up again along the bounding fault so that the whole system would be contained within the range. This particular circulation pattern seems to be characteristic of the Roosevelt area in southeastern Utah (Ward et al., 1978). The data of Mase and Sass (1980) not immediately adjacent to geothermal systems are included in Figure 6, and it is clear that the gradients and heat flow values in the Black Rock Desert are consistent with those observed in the Battle Mountain Heat Flow High, if an allowance is made for the refractive effect of the low thermal conductivity sedimentary basins, and no absorption of heat by fluid downflow in the basins is necessary to make the heat flow consistent with the inclusion of this area as part of the Battle Mountain Heat Flow High. Mase and Sass (1980) included this area in the Battle Mountain Heat Flow High based on addition of the total amount of energy lost in the geothermal systems to the actual observed heat-flow values in the valleys. If refractive effects are significant, as is implied by Figure 6, then the observed values are consistent with such an association, without hypothesizing any large-scale water flow effects on the heat-flow data. An additional complexity associated with the geothermal systems is that flow is usually transient. Temperature gradient reversals with depth in exploration holes are almost the rule rather than an exception (see Benoit et al., 1982). Ziagos and Blackwell (1980, 1983) have discussed modeling of temperature-depth curves where this phenomenon is observed, to determine aquifer characteristics and flow regimes.

There is no doubt that the fluid flow patterns are extremely complicated and have a major effect on heat flow at some locations in the Basin and Range province. However, the nature of these patterns remains to be sorted out, as in no place are there sufficient heat-flow data to thoroughly investigate the total geographic extent of a water flow system. There is evidence for many different kinds of flow patterns from the geothermal systems themselves. Many of the geothermal systems are associated with the range-valley contacts; however, some systems appear to be confined to the valley side, some to the range side, some to the faults, and some involve intrabasin/range fluid flow. Consequently, convective systems can be imagined which might involve flow in ranges only, valleys only, ranges and valleys, and perhaps even only along the normal faults. At the present time, neither the data nor the interpretations are sufficiently constrained to allow description of the nature of a "typical" geothermal flow system in the Basin and Range province.

DISCUSSION

The object of this paper has been to investigate the effects and interactions that make the thermal pattern in the Basin and Range province so complex. The basic observations of geothermal gradient (Figure 7) are probably the most reliable and useful information. The heat-flow pattern remains to be explained.

A very simple conceptual model of heat flow in a Basin and Range setting is shown in Figure 9. The model includes the effects of a crustal thermal disturbance and refraction in the Basin and Range setting. The thermal source is approximated by a body at a temperature of 1350°C emplaced between 10 and 20 km. The 1350°C includes the regional background, which was calculated for a Basin and Range heat flow of 80 mWm^{-2} at the surface, and a mantle heat flow of 59 mWm^{-2}. The temperature corresponds approximately to the emplacement temperature of basalt with some allowance for the latent heat effects. The model is similar to the one used for the western Snake River Plain by Brott et al. (1978). The model was designed to investigate the effects of refraction and a thermal anomaly.

Heat-flow values as a function of position are shown at 5 M.Y. and 10 M.Y. after emplacement of this sort of a body (Figure 9). The basic heat-flow pattern is not much affected by the source, even though it is within the crust. If such a source had been emplaced 5 M.Y. ago, then the mean heat flow would be 112 mWm^{-2}, with a variation from below 100 to over 120 mWm^{-2}, except in the vicinity of the range-bounding faults, where variations would be more extreme. If the intrusive has cooled for a period of 10 M.Y., then the mean heat flow drops to 90 mWm^{-2} while the heat flow varies from about 80 mWm^{-2} in the valleys to 100 mWm^{-2} in the ranges. The variation of observed heat-flow values for the valleys and the ranges in the Battle Mountain Heat Flow High, ignoring the extremely high heat-flow values in the sedimentary rocks and those that are certainly associated with geothermal systems, is shown on the plot. The heat-flow pattern associated with a cooling period of 10 ± 5 M.Y. would approximate the midpoint of the range of observed data. There is slightly larger variation in heat flow than is predicted by this model between the ranges and the valleys, which might suggest some superimposed small effects of fluid circulation. The calculated age has little significance because the model is very approximate, and if extension effects are superimposed on a magmatic effect, the heat flow might be maintained at high values for some period of time after it would ordinarily have dropped. At the same time less extension would be required to keep the heat flow at a high level.

The conclusion is that a reasonable heat-flow model for the northern Basin and Range province involves a background heat flow which in superposition of a late Cenozoic thermal (intrusive and extrusive) event followed by regional extension active to within the last 1 M.Y. In the northern Nevada region, intrusive or extrusive silicic rocks of young age are not involved with the geothermal systems. The actual distribution of values is profoundly affected by the thermal conductivity contrasts between the ranges and the valleys. A combination of a very high permeability crust (due to the extension) with relatively high gradients due to high regional heat flow results in the observed pattern of heat flow and geothermal systems. Geothermal manifestations are associated in many cases with range-bounding faults, although there is no simple relationship between the faults and the geothermal systems. Some of the geothermal systems are on the range side, some are on the valley side, some involve ranges and valleys, and some may be within the fault system itself. Although there are a lot of heat-flow data available, much analysis remains before we thoroughly understand the heat-flow pattern. Drilling in the geothermal systems has added a new set of data which gives information on areas which have not been previously included in the regional data set, and need to be included for complete understanding of the heat flow pattern. Future studies will need to thoroughly assimilate these data, so that a more realistic and accurate pattern of heat-flow distribution and the controls on that distribution in the Basin and Range province can be developed.

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REFERENCES

Archbold, N.L., 1972, Modified geologic map of Nevada, Nevada Bur. Mines and Geol. Map 44.

Benoit, W.R. and D. Butler, 1983 (this volume).

Benoit, W.R., J.E. Hiner and R.T. Forest, 1982, Discovery and geology of the Desert Peak geothermal field: a case history, Nevada Bur. Mines and Geol. Bull. 97, 81 pp.

Blackwell, D.D., 1978, Heat flow and energy loss in the western United States, pp. 175-208 in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Memoir 152, Smith, R.B. and G.P. Eaton (eds.), Geol. Soc. Amer., Boulder, Colorado.

Blackwell, D.D. and D.S. Chapman, 1977, Interpretation of geothermal gradient and heat flow data for Basin and Range geothermal systems, Trans. Geothermal Resources Council, 1, 19-20.

Bodell, J.M. and D.S. Chapman, 1982, Heat flow in the Northern Central Colorado Plateau, Jour. Geophys. Res., 87, 2869-2884.

Brott, C.A., 1978, Tectonic implications of the heat flow of the western Snake River Plain, Idaho, Geol. Soc. Amer. Bull., 89, 1697-1707.

Brott, C.A., D.D. Blackwell and J.P. Ziagos, 1981, Thermal and tectonic implications of heat flow in the eastern Snake River Plain, Jour. Geophys. Res., 86, 11709-11734.

Domenico, P.A. and V.V. Palciauskas, 1973, Theoretical analysis of forced convective heat transfer in regional ground-water flow, Geol. Soc. Amer. Bull., 84, 3803-3814.

Earth Power Prod. Co., 1980, Geochemical map, geologic cross section, sulfate map, microearthquake survey map, DOE Industry Coupled Program, Earth Science Laboratory of University of Utah Research Institute Open-File Rept. NV/BAL/EPP-7.

Edmiston, R.C., 1982, A review and analysis of geothermal exploratory drilling results in the northern Basin and Range geologic province of the USA from 1974 through 1981, Trans. Geothermal Resources Council, 6, 11-14.

England, P.C. and S.W. Richardson, 1980, Erosion and the age dependence of continental heat flow, Geophys. Jour. Royal Astr. Soc., 62, 421-437.

Hill, D.G., E.B. Layman, C.M. Swift and S.H. Yungul, 1979, Soda Lake, Nevada thermal anomaly, Trans. Geothermal Resources Council, 3, 305-308.

Jaeger, J.C., 1965, Application of the theory of heat conduction to geothermal measurements, pp. 7-23 in Terrestrial Heat Flow, Geophys. Mono. Ser., 8, Lee, W.H.K. (ed.), Amer. Geophys. Union.

Jarvis, G.T. and D.P. McKenzie, 1980, Sedimentary basin formation with finite extension rates, Earth Planet. Sci. Lett., 48, 42-52.

Keller, G.P., L.W. Braile and P. Morgan, 1979, Crustal structure, geophysical models, and contemporary tectonism of the Colorado Plateau, Tectonophysics, 61, 131-148.

Lachenbruch, A.H., and J.H. Sass, 1977, Heat flow in the United States and the thermal regime of the crust, pp. 626-675 in The Earth's Crust, Geophys. Mono. Ser., 20, Amer. Geophys. Union, Heacock, J.G. (ed.).

Lachenbruch A.H. and J.H. Sass, 1978, Models of extending lithosphere and heat flow in the Basin and Range province, pp. 209-250 in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Memoir 152, Smith, R.B. and G.P. Eaton (eds.), Geol. Soc. Amer., Boulder, Colorado.

Lee, T.C. and T.L. Henyey, 1974, Heat-flow retraction across dissimilar media, Geophys. Jour. Royal Astr. Soc., 39, 319-333.

Mackelprang, C.E., 1982, Interpretation of geophysical data from the Colado KGRA, Pershing County, Nevada, Univ. Utah Res. Inst. Rept. DOE/ID/12079-58, ESL-71, 27 pp.

Mackelprang, C.E., J.N. Moore and H.P. Ross, 1980, A summary of the geology and geophysics of the San Emedio KGRA, Washoe County, Nevada, Trans. Geothermal Resources Council, 4, 221-224.

Mase, C.W. and J.H. Sass, 1980, Heat flow from the western arm of the Black Rock Desert, Nevada, U.S. Geol. Surv. Open-File Rept. 80-1238, 38 pp.

McMannes, D., B. Quillin and D. Butler, 1981, Granite Mountain, Nevada geothermal prospect: a case history, Trans. Geothermal Resources Council, 5, 107-110.

Mifflan, M.D., 1968, Delineation of groundwater flow systems in Nevada, Desert Research Institute, Center for Water Resources Research Tech. Rept. Ser., Pub. 4.

Mifflan, M.D., 1983 (this volume).

Morgan, P., V. Harder, C.A. Swanberg and P.H. Daggett, 1981, A groundwater convection model for Rio Grande Rift geothermal resources, Trans. Geothermal Resources Council, 5, 193-196.

Olson, H.J., F. Dellechaie, H.D. Pilkington and A.L. Lange, 1979, The McCoy geothermal prospect, status report of a possible new discovery in Churchill and Louder Counties, Nevada, Trans. Geothermal Resources Council, 3, 515-518.

Pilkington, H.D., A.L. Lange and F.E. Barkman, 1980, Geothermal exploration of the Tuscarora prospect in Elko County, Nevada, Trans. Geothermal Resources Council, 4, 233-236.

Reiter, M., A.J. Mansure and C. Shearer, 1979, Geothermal characteristics of the Colorado Plateau, Tectonophysics, 61, 183-195.

Roy, R.F., D.D. Blackwell and F. Birch, 1968a, Heat generation of plutonic rocks and continental heat flow provinces, Earth Planet. Sci. Lett., 5, 1-12.

Roy, R.F., E.R. Decker, D.D. Blackwell and F. Birch, 1968b, Heat flow in the United States, Jour. Geophys. Res., 73, 5207-5221.

Sass, J.H., A.H. Lachenbruch, R.J. Munroe, G.W. Green and T.H. Moses, Jr., 1971, Heat flow in the western United States, Jour. Geophys. Res., 76, 6356-6431.

Sass, J.H., F.H. Olmsted, M.L. Sorey, H.A. Wollenberg, A.H. Lachenbruch, R.J. Munroe and S.P. Galanis, Jr., 1976, Geothermal data from test wells drilled in Grass Valley and Buffalo Valley, Nevada, U.S. Geol. Surv. Open-File Rept. 76-85.

Sass, J.H., J.P. Ziagos, H.A. Wollenberg, R.J. Munroe, D.E. diSomma and A.H. Lachenbruch, 1977, Application of heat-flow techniques to geothermal energy exploration, Leach Hot Springs area, Grass Valley, Nevada, U.S. Geol. Surv. Open-File Rept. 77-762, 125 pp.

Sass, J.H., M.L. Zoback and S.P. Galanis, Jr., 1979, Heat flow in relation to hydrothermal activity in the southern Black Rock Desert, Nevada, U.S. Geol. Surv. Open-File Rept. 79-1467, 39 pp.

Sass, J.H., R.J. Munroe and C. Stone, 1981, Heat flow from five uranium test wells in west-central Arizona, U.S. Geol. Surv. Open-File Rept. 81-1089, 42 pp.

Sass, J.H., D.D. Blackwell, D.S. Chapman, J.K. Costain, E.R. Decker, L.A. Lawver and C.A. Swanberg, 1981, Heat flow from the crust of the United States, pp. 503-548 in Physical Properties of Rocks and Minerals, McGraw-Hill/CINDAS Data Series on Material Properties, Vol. II-2, Touloukian, Y.S., W.R. Judd and R.F. Roy (eds.), McGraw-Hill.

Shearer, C. and M. Reiter, 1981, Terrestrial heat flow in Arizona, Jour. Geophys. Res., 87, 6249-6260.

Smith, C., 1983, Thermal hydrology and heat flow of Beowawe geothermal area, Nevada, Geophysics, 48, 618-626.

Smith, R.B., 1978, Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera, pp. 111-144 in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Memoir 152, Smith, R.B. and G.P. Eaton (eds.), Geol. Soc. Amer., Boulder, Colorado.

Snyder, W.S., W.R. Dickinson and M.L. Silberman, 1976, Tectonic implications of space-time patterns of Cenozoic magmatism in the Western United States, Earth Planet. Sci. Lett., 32, 91-106.

Stewart, J.H. and J.E. Carlson, 1978, Generalized maps showing distribution, lithology, and age of Cenozoic igneous rocks in the western United States, pp. 263-264 in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Memoir 152, Smith, R.B. and G.P. Eaton (eds.), Geol. Soc. Amer., Boulder, Colorado.

Swanberg, C.A. and R.L. Bowers, 1982, Downward continuation of temperature gradients at MacFarlane's Hot Spring, northern Nevada, Trans. Geothermal Resources Council, 6, 177-180.

Ward, S.H., W.T. Parry, W.P. Nash, W.R. Sill, K.L. Cook, R.B. Smith, D.S. Chapman, F.H. Brown, J.A. Whelan and J.R. Bowman, 1978, A summary of the geology, geochemistry and geophysics of the Roosevelt Hot Springs thermal area, Utah, Geophys., 43, 1515-1542.

Welch, A.H., M.L. Sorey and F.H. Olmsted, 1981, The hydrothermal system in southern Grass Valley, Pershing County, Nevada, U.S. Geol. Surv. Open-File Rept. 81-915, 193 pp.

White, D.E., 1968, Hydrology, activity and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada, U.S. Geol. Surv. Prof. Paper 458-C, 109 pp.

Yeamans, 1983 (this volume).

Ziagos, J.P. and D.D. Blackwell, 1981, A model for the effect of horizontal fluid flow in a thin aquifer on temperature-depth profiles, Trans. Geothermal Resources Council, 5, 221-224.

Ziagos, J.P. and D.D. Blackwell, 1983, A model for the transient temperature effects of horizontal fluid flow in geothermal systems, Jour. Geophys. Res., in press.