N75 20838

HEAT FLOW AND GEOTHERMAL POTENTIAL OF THE EAST MESA KGRA, IMPERIAL VALLEY, CALIFORNIA

Chandler A. Swanberg*
U. S. Bureau of Reclamation
Boulder City, Nevada

The East Mesa KGRA (Known Geothermal Resource Area) is located in the southeast part of the Imperial Valley, California, and is roughly 150 km^2 in areal extent. A new heat flow technique which utilizes temperature gradient measurements across "best clays" is presented and shown to be as accurate as conventional methods for the present study area. Utilizing the "best clay" gradient technique, over 70 heat flow determinations have been completed within and around the East Mesa KGRA. Background heat flow values range from 1.4 to 2.4 hfu (1 hfu = 10^{-6} cal/cm^2-sec) and are typical of those throughout the Basin and Range province. Heat flow values for the northwest lobe of the KGRA (Mesa anomaly) are as high as 7.9 hfu, with the highest values located near gravity and seismic noise maxima and electrical resistivity minima. An excellent correlation exists between heat flow contours and faults defined by remote sensing and microearthquake monitoring. This correlation indicates a tectonic origin for this lobe of the KGRA. The 5-hfu contour, which roughly defines the area in which a successful geothermal well can be completed, includes 40 km^2 of the northwest lobe of the KGRA.

Heat flow data for the southeast lobe of the KGRA (Border anomaly) are less reliable than for the northwest lobe and meaningful contouring is not possible. Maximum values are in the range 5-7 hfu and encompass an area of about 15 km^2. The center of the anomalous heat flow zone is on strike with the NW-SE trending fault located on the northwest lobe of the KGRA on the basis of microseismic monitoring, but is about 5 km south of the anomaly as defined on the basis of seismic groundnoise and electrical resistivity.

Previously unpublished heat flow data are also available for the Alamo geothermal anomaly, located about 15-20 km southwest of the East Mesa KGRA. Heat flow values are as high as 4.6 hfu, with the highest values located on either side of the Imperial Fault near the international boundary.

---

*Presently at New Mexico State University, Las Cruces, New Mexico.

I. INTRODUCTION

Heat flow is defined by the equation

$$q = -K \frac{dT}{dZ}$$

where q is heat flow, K is thermal conductivity, dT/dZ is the geothermal gradient, and the negative sign implies that heat flows from high temperature regions to those of low temperature. Thus the determination of heat flow requires knowledge of the geothermal gradient and the thermal conductivity of the strata over which the geothermal gradient is measured. The standard techniques for measuring geothermal gradient, thermal conductivity and the methods of obtaining heat flow and assessing the associated errors are summarized by Beck (Ref. 1).

The Imperial Valley, however, provides some interesting problems which make the standard heat flow techniques very difficult to apply. Most of the rock material in the Imperial Valley consists of unconsolidated sand, silt, and clay material so that collection of samples for thermal conductivity analysis is very difficult. Core samples suitable for measurement with a divided bar apparatus (Ref. 2) are virtually nonexistent and even collection of well cuttings for transient measurement (Ref. 1) or steady-state measurement (Ref. 3) provide problems. For example, there is always a tendency to preferentially sample clays because of their more consolidated nature and the uphole sloughing of material can substantially contaminate a sample. Also, the best thermal conductivity results are always obtained when laboratory analyses are performed under in situ conditions (Ref. 4) and for saturated sediments from geothermal areas; such conditions are difficult to reproduce in the laboratory, particularly when in situ temperatures exceed 100°C.

Because of the nature of the sediments and the abundance of wells in the Imperial Valley which are available for temperature measurement but had no core material available for conductivity analysis, it was decided to search for a method of obtaining heat flow without the need to make laboratory analysis of thermal conductivity. In the following sections, the resulting heat flow technique will be described and some of the problems associated with its application will be discussed. Finally, an analysis of the distribution of heat flow at the East Mesa KGRA will be presented.

II. HEAT FLOW TECHNIQUE

The heat flow technique developed for use at the East Mesa KGRA utilizes an empirical relation between known heat flow and temperature gradient measured across the "best clay," a stratigraphic horizon herein defined as that 10-foot section of a given well associated with the maximum temperature gradient and physically consisting of poorly conductive clay minerals and interstitial water, but having a minimum amount of highly conductive quartz. Figure 1 shows the relation between temperature gradient and lithology as depicted by a gamma ray log for three wells drilled on the Mesa anomaly. Although these three wells are typical of those drilled at the Mesa anomaly, they were not selected for representation in Fig. 1 for that reason. Rather, these three wells were selected because they are the only wells on the Mesa anomaly for which gamma ray logs, detailed temperature gradient measurements, and heat flow data are all available, the latter having been independently determined by Combs (Ref. 5) using standard laboratory techniques. Notice the direct correlation between the plots of temperature gradient and gamma radiation in Fig. 1. The sands appear on both plots as lows, whereas the clays appear as highs. Numerical values of temperature gradients for several clays are shown in Fig. 1, and the "best clay" (i.e., the maximum gradient) is designated with lined pattern.

Figure 2 is the heat flow calibration chart and is the basis of the present heat flow technique. Plotted in Fig. 2 is known heat flow (Ref. 5) as a function of the "best clay" gradient (Fig. 1). The following steps then summarize the method used herein to determine heat flow in the sand-clay sequences of the Imperial Valley:

(1) Measure temperatures to an accuracy of 0.01°C at 10-foot intervals throughout the well.

(2) Calculate the temperature gradient for each 10-foot interval and designate the maximum gradient as the "best clay" gradient.

(3) Make use of available geophysical logs to insure that the maximum temperature gradient actually falls opposite a clay horizon and does not result from measurement error or groundwater circulation.

(4) Use the linear plot of Fig. 2 to convert the "best clay" gradient to heat flow.

The accuracy of the present heat flow technique can be assessed from the data in Fig. 2. As long as a straight line can be drawn to fit all data points to within the error limits of the heat flow values, the technique is working as well as conventional methods. For the present study, an error of 0.3 hfu is suggested, an error which primarily reflects the errors associated with the control heat flow values (Fig. 2), rather than the internal consistency of the present technique. A more accurate heat flow calibration chart based on additional measurements of thermal conductivity is currently in preparation (Ref. 6). This newer calibration will slightly affect the heat flow values shown in Fig. 4, but not to the extent of the above stated accuracy. Also plotted against heat flow in Fig. 2 are the average geothermal gradients. The scatter of data underscores the inherent limitations of average geothermal gradients as a geothermal exploration tool and emphasizes the increased resolution that results from the present technique.

There are several interesting features of Fig. 2 that bear special mention. The reason that heat flow is a linear function of "best clay" gradient and the success of the technique is due to the fact that all of the "best clays" have the same thermal conductivity. This is a rather stringent requirement, particularly over large geographic areas and emphasizes the danger in attempting to apply the calibration curve of Fig. 2 to widespread parts of the Imperial Valley.

However, the data in Fig. 2 clearly shows that this requirement is quite realistic over the limited area surrounding the East Mesa KGRA. Clearly the present heat flow technique cannot be applied to regions other than those comprised of sand, silt, and clay continental sediments, such as those in the Imperial Valley.

Figure 2 is a plot of heat flow against temperature gradient so that the slope of the heat flow calibration line must represent thermal conductivity. The slope of the line in Fig. 2 is 2.41 cal/cm-sec-°C, a very realistic conductivity value for clay material.

The "best clay" gradients in Fig. 2 represent average gradient over a 10-foot section of clay, and this measurement interval should be used in determination of heat flow using Fig. 2. Clearly, a calibration curve similar to Fig. 2 can be constructed for any measurement interval, simply by measuring temperatures at that interval and plotting the resulting "best clay" gradients against known heat flow. However, a larger interval, such as temperature measurements every 50 feet, requires rather thick clay horizons which may not exist in a given stratigraphic section (see following section), whereas a smaller interval, such as measurements every 2 feet, requires more accurate temperature measurements (particularly in nongeothermal areas) and additional field time to make the measurements. Although the smaller interval should result in a more accurate heat flow calibration, the calibration shown in Fig. 2 is sufficiently accurate for the present study in view of the rather large errors associated with the known heat flow values. A measurement interval of 10 feet was found to give the most satisfactory results of the several intervals examined.

III. DISCUSSION OF THE "BEST CLAY" HEAT FLOW TECHNIQUE

The greatest advantage of the present heat flow technique is that it does not require the time-consuming and costly laboratory determination of thermal conductivity and thus makes available for heat flow analysis the wealth of drill holes in the Imperial Valley which are available for temperature gradient measurements, but which have no associated core material for thermal conductivity analysis. There is also a logistical advantage in the present technique in that heat flow values can be obtained in the field and thus correlated directly with any geological observations that may pertain to geothermal studies.

Another important feature of the "best clay" approach is that maximum interpretative value of temperature data is obtained. Since all of the "best clays" have very nearly the same thermal conductivity, a contoured map of "best clay" gradients will have precisely the same form as a contoured heat flow map, the only difference being the numerical value and units of the contours. Thus, the "best clay" technique is a useful method of geothermal exploration even in areas where a lack of heat flow data precludes the construction of a heat flow calibration chart such as Fig. 2.

The principal drawback to the present technique is the difficulty in assessing the error associated with a given heat flow value. It is of little use to apply statistical methods to the data in Fig. 2 because any resulting standard deviation would reflect the error only if a "best clay" is present, and there is unfortunately no way to guarantee the presence of such a clay. Figure 3 shows a plot of temperature gradient against lithology as depicted by resistivity, lithologic, and gamma ray logs for well T. 16 S., R. 18 E., 23aaa, located several kilometers northeast of the East Mesa KGRA. The heat flow technique presented above does not yield a suitable estimate of heat flow for this well, and the reason is simply that a "best clay" does not exist. Examination of the lithologic log, for example, shows the entire well to consist of sand with only 5 clay stringers, ranging in thickness from 2-8 feet. These clays are contrasted with those present in wells 123-125 (Fig. 1), which are in excess of 50 feet thick. Further, the thickest clay in well 23aaa consists of 30 percent gravel, 10 percent quartz, along with appreciable calcite, so that in addition to having an insufficient thickness for the application of the "best clay" heat flow technique, the clays are also of the wrong composition. Since there is generally no way of determining the presence or absence of the required clay horizons from a temperature survey alone, it is imperative that a good suite of logs be available for correlation with temperature gradient data. If a suite of logs is available along with the temperature gradient data, it should be possible to determine the presence or absence of the required "best clay" and thus estimate the reliability of a given heat flow value. Of the more than 70 wells used in the present heat flow study, only two do not have the required clay horizons, and these are designated in Fig. 4 with a heat flow value of "low."

In the case of well 23aaa, the absence of suitable clay material and the failure of the "best clay" heat flow technique can be determined even without the associated geophysical and lithologic logs, although this is not always or even generally the case. As shown in Fig. 3, the "best clay" has a gradient of only 24°C/km. Using this value to obtain a heat flow value from Fig. 2 gives a heat flow value of very nearly zero. Such a value is obviously unrealistic so that an error somewhere is suspected. The excellent correlation between lithology and temperature gradient (Fig. 3) suggests that the hole is in thermal equilibrium, and problems such as groundwater circulation or measurement error are not responsible for the low heat flow value. In fact, the data in Fig. 3 shows quite clearly that the unreasonably low heat flow value results from the lack of a "best clay" and the associated failure of the present heat flow technique to apply to this well.

IV. HEAT FLOW AT THE EAST MESA KGRA

The distribution of heat flow values over and adjacent to the East Mesa KGRA is shown in Fig. 4. Background heat flow values range from 1.4 to 2.4 hfu (1 hfu = 10^{-6} cal/cm^2-sec) and are typical of those throughout the Basin and Range physiographic province (Ref. 7). Over the northwest part of the KGRA (Mesa anomaly) values are as high as 7.9 hfu, while over the southeast part of the KGRA (Border anomaly) values are as high as 7 hfu.

The three pronounced contours of Fig. 4 are the 3-, 5-, and 7-hfu contours. The 3-hfu contour roughly outlines the extent of anomalously high heat flow. Areas outside this contour are only marginally above the regional background and such areas cannot be expected to yield successful production wells, although such areas might well prove ideal for disposal of geothermal brine. The area within the 5-hfu contour can be considered the production area. Anywhere within this contour should yield a successful production well, provided, of course, that suitable producing horizons are encountered. For the East Mesa KGRA, roughly 55 km^2 or 21 square miles of land fall within this contour.

Also shown in Fig. 4 are the three faults postulated for the East Mesa KGRA. One of these faults (Ref. 8) is currently active and was located during microseismic monitoring at the Mesa anomaly. The correlation between the faults and the heat flow contours is obvious, and this correlation indicates a tectonic origin for both lobes of the East Mesa KGRA. That is, the faults act as conduits, allowing the rise of geothermal fluids from the deep igneous heat source into the geothermal reservoir. Note also that for the northwest lobe of the KGRA, heat flow values decrease with distance very rapidly west of the zone of maximum heat flow, but decrease very slowly to the east. This indicates that the northwest trending faults either dip to the east or alternately that the predominant flow of water in the geothermal system is to the east, away from the faults.

The heat flow values for the southeast lobe of the KGRA are shown in Fig. 4 with an order of magnitude lower accuracy than the remaining values. This lower accuracy is presented because several of the wells exhibit temperature reversals below 500 feet, and, since no deep geothermal wells have been drilled into this portion of the KGRA, the existence of a geothermal reservoir has not yet been established.

Also presented in Fig. 4 are heat flow values for the Alamo anomaly, a part of the Heber KGRA. The highest values are roughly 4.5 hfu and fall on opposite sides of the Imperial fault. These values are included to demonstrate that geothermal activity is also associated with the Imperial fault.

Figure 5 shows the maximum contours of all geothermal exploration techniques that have been applied to the East Mesa KGRA. From a standpoint of exploration, the northwest part of the KGRA is an ideal place to evaluate the reliability of various geothermal exploration techniques. Not only has every technique applied been successful, but each method gives essentially the same result, although they differ in detail. If production wells were to be located on the basis of heat flow, residual gravity, seismic noise, microearthquake epicenters, or electrical resistivity, the holes would all fall within a few hundred meters of one another and all would fall within the zone suitable for geothermal development as defined by the 5-hfu contour. Also note the 5-hfu heat flow contour agrees well with the anomalous zones defined by the dipole-dipole resistivity soundings. Resistivity is a difficult exploration technique to apply to the Imperial Valley because the contrast between geothermal areas and adjacent colder areas is so low. This low contrast may preclude reliable modeling on the basis of the resistivity data, but the information presented in Fig. 5 clearly indicates that resistivity is a valuable tool in the Imperial Valley for outlining zones of anomalously high subsurface temperatures.

REFERENCES

1. A.E. Beck, "Techniques of Measuring Heat Flow on Land," in *Terrestrial Heat Flow*, edited by W.H.K. Lee, *Am. Geophys. Mono.*, Vol. 8, pp. 24-57, 1965.

2. F. Birch, "Flow of Heat in the Front Range, Colorado," *Bull. Geol. Soc. Am.*, Vol. 61, pp. 567-630, 1950.

3. J.H. Sass, A.H. Lachenbruch, and R.J. Munroe, "Thermal Conductivity of Rocks from Measurements on Fragments and Its Application to Heat-Flow Determinations," *J. Geophys. Res.*, Vol. 76, pp. 3391-3401, 1971.

4. F. Birch, and H. Clark, "The Thermal Conductivity of Rocks and Its Dependence upon Temperature and Composition," *Am. J. Sci.*, Vol. 238, pp. 529-558 and 613-635, 1940.

5. J. Combs, "Thermal Studies," in *Cooperative Investigation of Geothermal Resources in the Imperial Valley Area and Their Potential Value for Desalting of Water and Other Purposes*, University of California, Riverside, Calif., pp. B1-B7, 1972.

6. J. Combs, and C.A. Swanberg, "Heat Flow on the East Mesa KGRA, Imperial Valley, California," *Geophys.*, in preparation.

7. R.F. Roy, D.D. Blackwell, and F. Birch, "Heat Generation of Plutonic Rocks and Continental Heat Flow Provinces," *Earth Planet. Sci. Lett.*, Vol. 3, pp. 1-12, 1968.

8. J. Combs, and D.M. Hadley, "Microearthquake Investigation of the Mesa Geothermal Anomaly, Imperial Valley, California," *EOS*, Vol. 54, pp. 1213-1214, 1973.

9. S. Biehler, "Gravity Studies in the Imperial Valley," in *Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California*, University of California, Riverside, Calif., pp. 29-42, 1971.

10. J. Combs, "Heat Flow and Geothermal Resource Estimates for the Imperial Valley," in *Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California*, University of California, Riverside, Calif., pp. 5-27, 1971.

BIBLIOGRAPHY

Babcock, E.A., "Detection of Active Faulting Using Oblique Infrared Aerial Photography in the Imperial Valley, California," in Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley Area of California, University of California, Riverside, Calif., pp. 143-153, 1971.

Rex, R.W., "Investigation of Geothermal Resources in the Imperial Valley and Their Potential Value for Desalination of Water and Electricity Production," Inst. Geophys. Planet. Phys., University of California, Riverside, Calif., 1970.

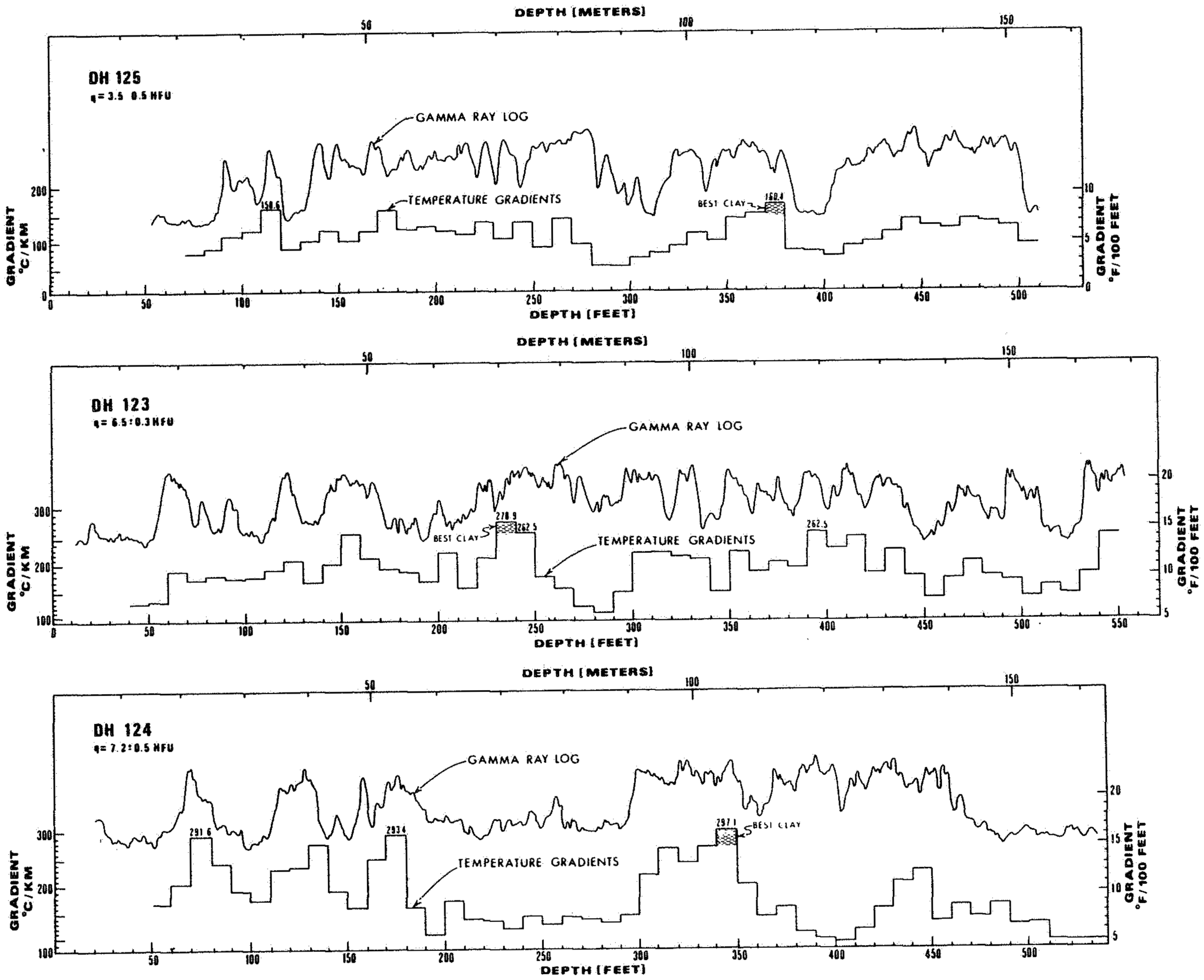

Fig. 1. Relation between temperature gradient and lithology as depicted by a gamma ray log for drill holes 123-125. The "best clays" are designated by the lined pattern.

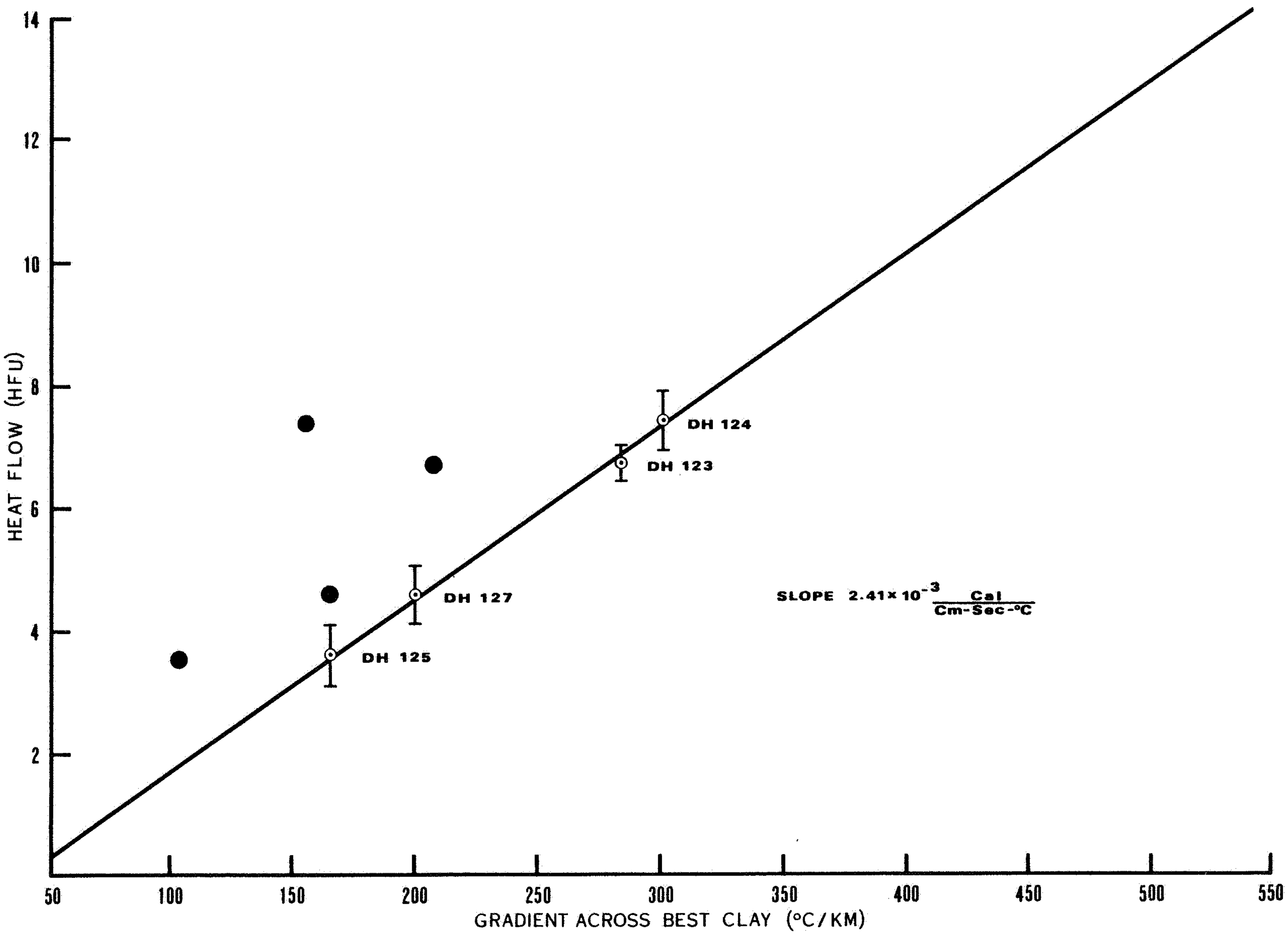

Fig. 2. Relation between heat flow and "best clay" temperature gradient. The solid dots represent the average gradient over the entire hole (see text).

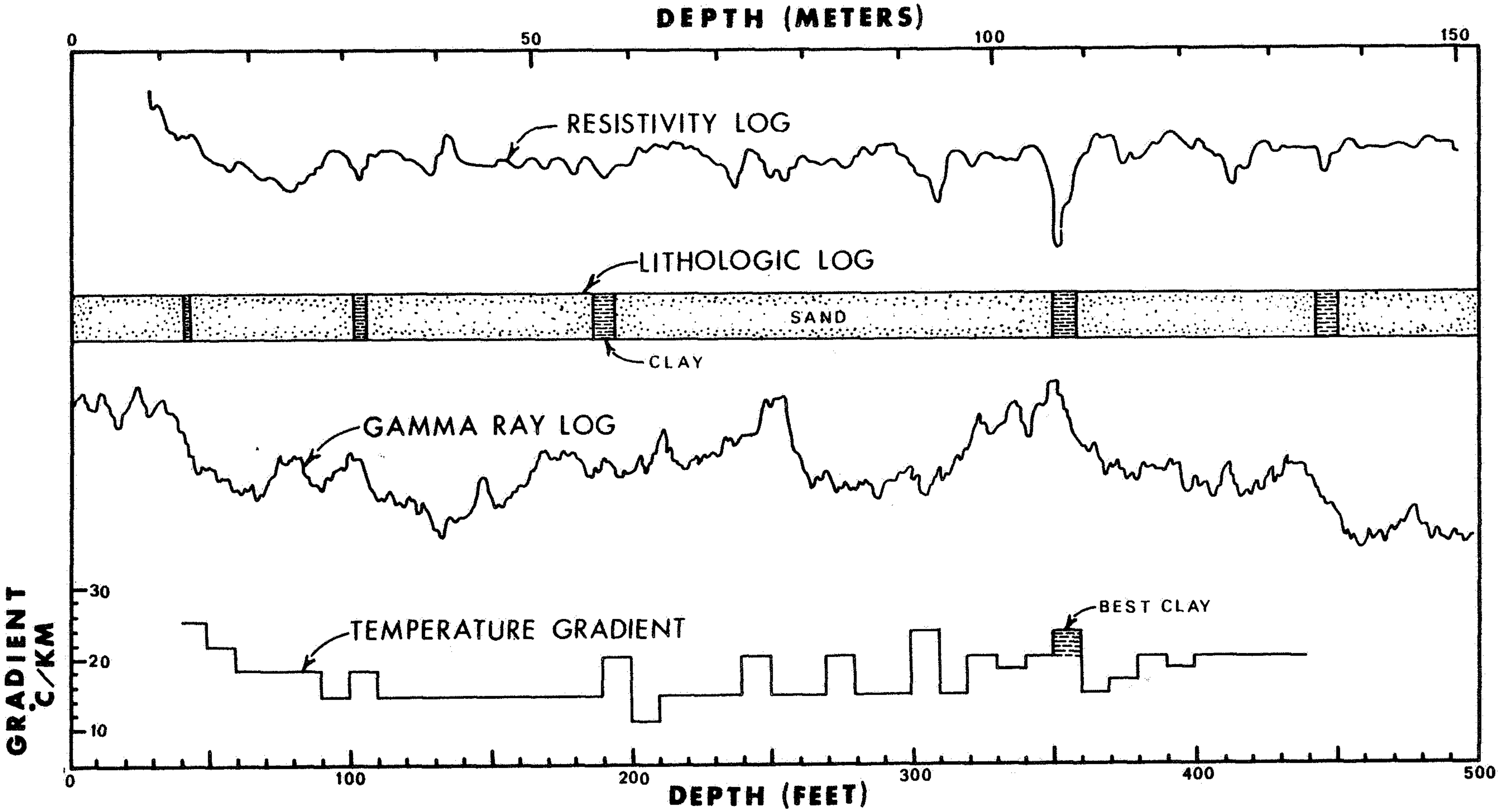

Fig. 3. Relation between temperature gradient and lithology for drill hole T. 16 S., R. 18 E., 23aaa. Note the failure of the present heat flow technique due to the lack of clay material.

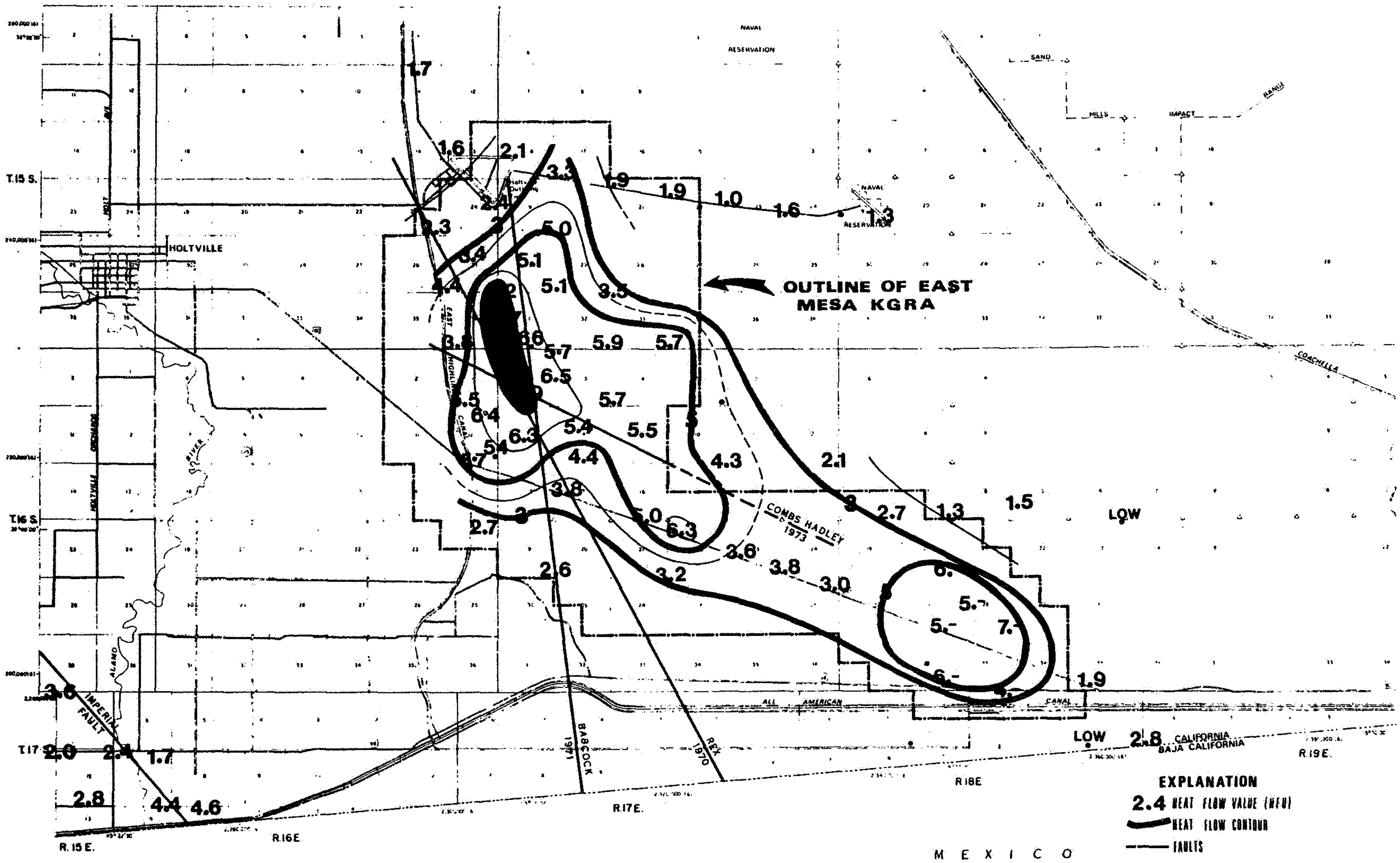

Fig. 4. Distribution of heat flow at the East Mesa KGRA.

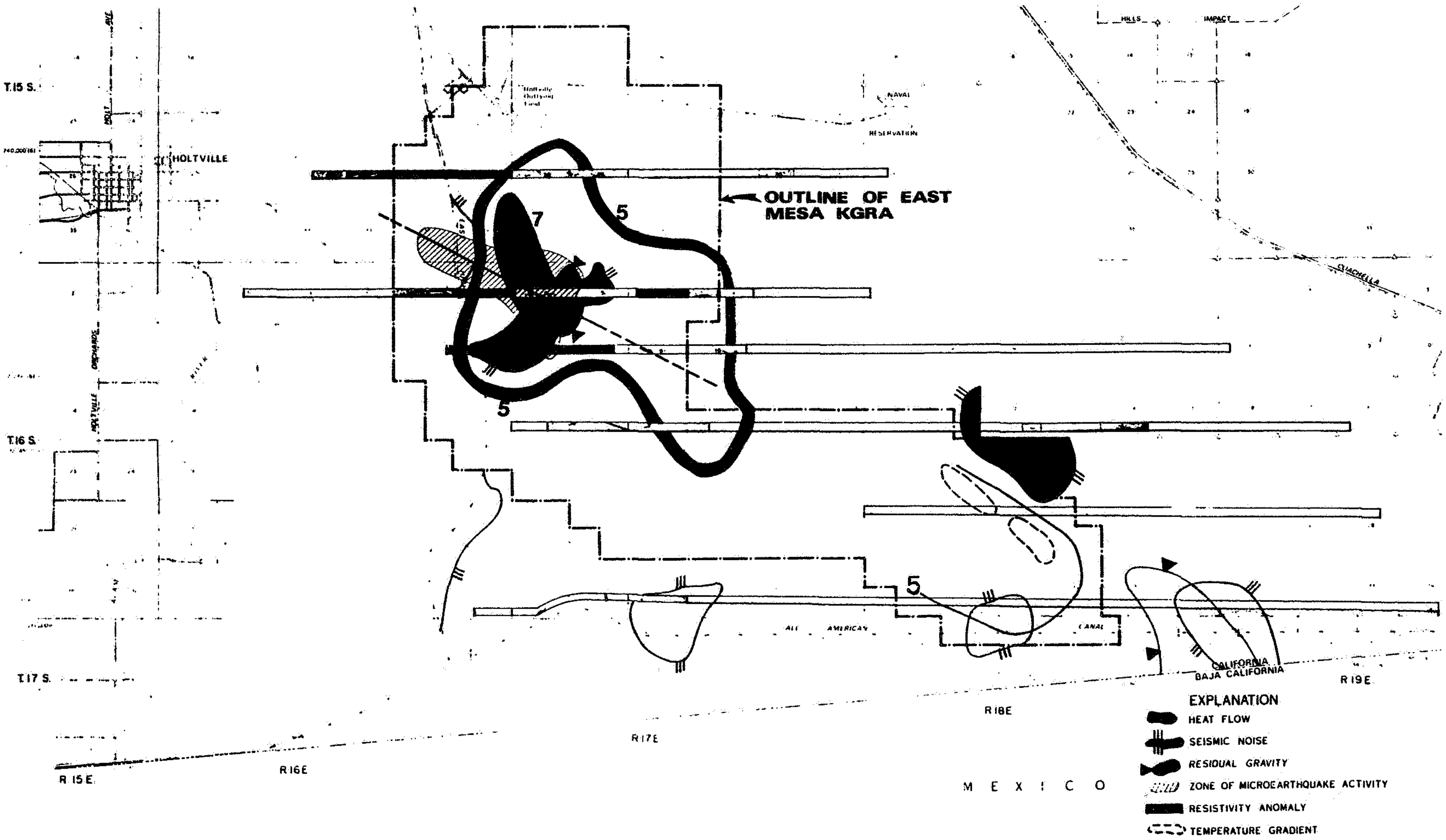

Fig. 5. Summary of geophysics at the East Mesa KGRA. Gravity data are from Biehler (Ref. 9) and shows maximum residual anomaly (solid with triangles) for the northwest lobe and maximum Bouguer gravity (open with triangles) for the southeast lobe of the KGRA. Seismic noise maxima (Teledyne-Geotech) are open when possibly related to cultural activity and solid when related to geothermal activity. Resistivity profiles (McPhar Geophysics) show confirmed anomalies (solid) and suspected anomalies (gray). Temperature gradient data is from Combs (Ref. 10) and microseismic data is from Combs and Hadley (Ref. 8).