HEAT FLOW - THE TECHNIQUE FOR HOT DRY ROCK EXPLORATION AND EVALUATION

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Heat Flow Techniques for Hot Dry Rock Evaluation

In its idealization, the hot dry rock (HDR) concept involves location and exploitation of an area where the rocks are at a high enough temperature and are impermeable enough to allow artificial fracturing and exploitation of water circulated through the produced fractures. This low-permeability setting is also ideal for heat flow measurements. Heat flow is determined as a product of the geothermal gradient times the thermal conductivity. Geothermal gradients are obtained from measurements of temperature versus depth in a drill hole and the thermal conductivity is measured on cuttings or core samples from the hole. If thermal conductivity is uniform, then the geothermal gradient and heat flow vary together. In most areas, however, there are significant lateral and vertical variations in thermal conductivity and thus gradient measurements over a limited depth range will have little direct usefulness for HDR exploration as the gradients will vary within the borehole and laterally due to changes in lithology.

Recent attempts to compile regional gradient maps have had the objective of geothermal evaluation both for hydrothermal resources (Gaffanti and Nathanson, 1980) and HDR resources (Kron and Heiken, 1980). The maps prepared by these two groups bear little resemblance to one another, however (see Blackwell, 1981). The futility of evaluation using this technique is clearly demonstrated by a hole in Kansas (Fig. A-1, from Blackwell and Steele, 1981). The heat flow is constant in this hole at 1.4 cal/cm^2 sec, yet the geothermal gradient varies by a factor of 4 (from approximately 15°C/km in the bottom of the hole, to approximately 50°C/km in the upper part of the hole). The variation is solely related to changes in thermal conductivity so mere determination of a geothermal gradient over "some interval" for this locality contains little useful information, either for extrapolation to depth or evaluation of the temperature at a specific horizon. Another example is shown from Fig. A-2, also from Kansas. The intricate correlation of gradient with lithology is shown by a comparison of the gradient logs with the gamma and sonic velocity logs. If information is available on the thermal conductivity

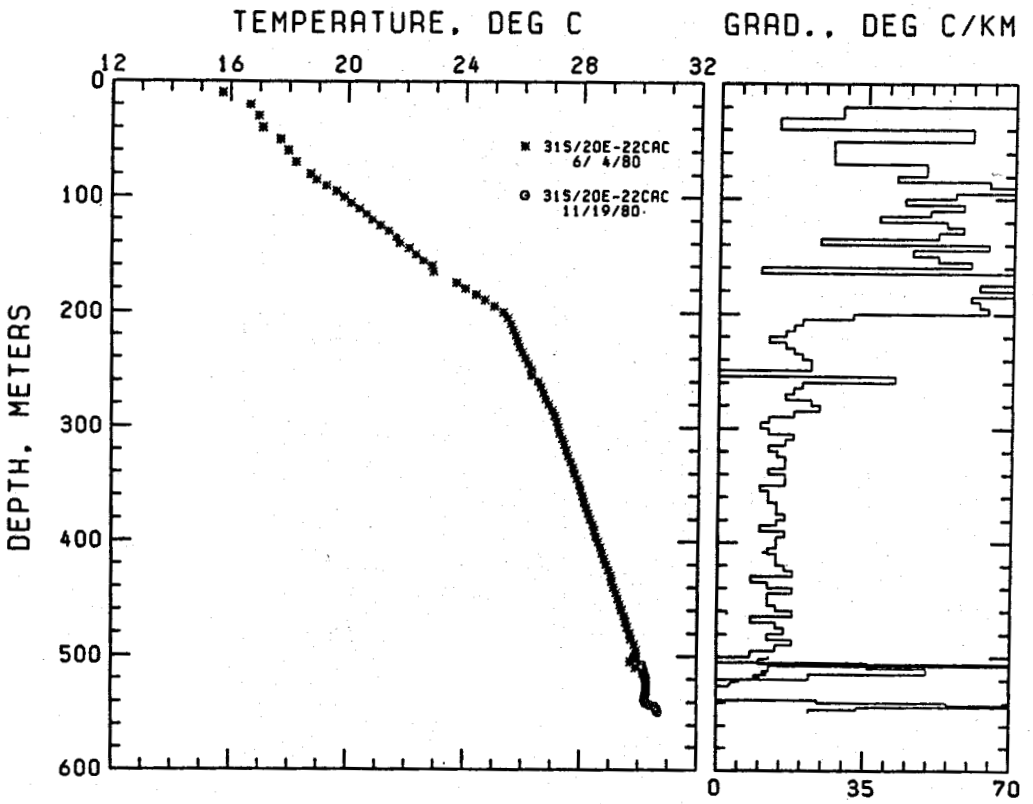

Fig. A-1.
Temperature-depth and gradient data for Kansas hole 31S/20E-22 cac (Blackwell and Steele, 1981).

of the geologic section involved, then a single gradient and thermal conductivity measurement and subsequent heat flow determination in a single interval is sufficient for calculation of the geothermal gradient in the remainder of the section (assuming that the heat flow is constant). Without such heat flow information however, a single measurement of temperature gradient is of little use. Therefore heat flow studies rather than gradient studies must be used in the HDR exploration.

Other geophysical techniques are used for geothermal exploration and evaluation. For HDR, however, it is questionable if such techniques have general applicability. As is the case with most exploration, the object in the HDR exploration program would be to locate the highest temperature at the shallowest depth in a given region. Temperature variations at depths of 2-5 km in regions of low permeability are likely to be virtually indetectable by gravity, seismic, electrical resistivity or magnetic studies unless there is an indirect relationship between temperature and some other property such as,

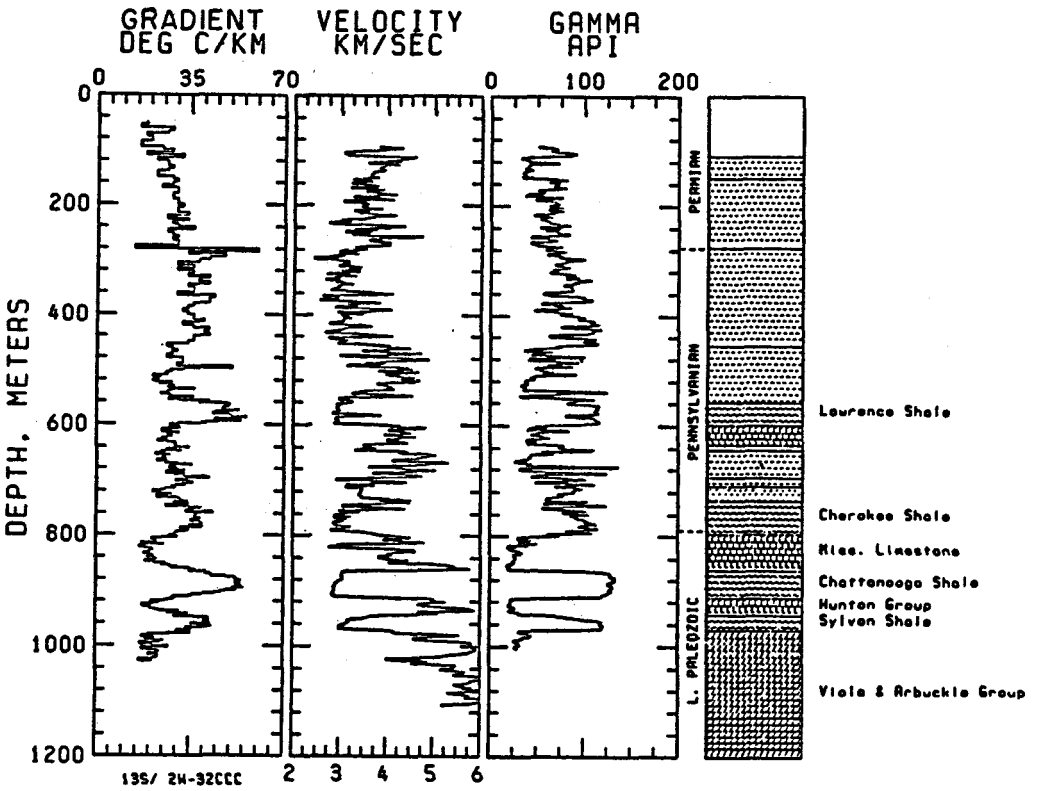

Fig. A-2.
Bar graphs of gradient, P-wave velocity, and natural gamma-ray activity and a generalized geologic section for Kansas hole 13S/2W-32 ccc.

for example, the correspondence of high radioactive areas (with consequent high heat flow) and low gravity anomalies as had been proposed for the eastern United States (Costain et al., 1980). Furthermore, most other geophysical techniques lose their resolution in the depth range 0.5-3 km and thus may not be useful in determining the deep thermal conditions (see Jiracek, 1981 for example). So the HDR exploration and evaluation program must emphasize heat flow techniques.

The main difficulty with the application of the heat flow technique is that in areas of complicated hydrology, it may not be easy to determine what the true heat flow is at depth. An example of this situation occurs at the site of the current HDR exploitation project. Apparently hot water flow laterally along the base of the Paleozoic section has progressed outward from the Valles Caldera. This causes the heat flow to be higher from the Paleozoic rocks, then from the basement. However, as discussed below, we have become much more proficient in recognizing locations for water disturbances on heat flow and have enough information for various areas in the U.S. to clearly

recognize when problems exist and even to use the information from problem areas to determine certain quantities of geologic interest. For example, analysis of temperature-depth curves from the EE holes suggests that water flow outward from the Valles Caldera has been in existence for a period of about 10,000 years. The water flow is responsible for the upper curvature observed in the gradients.

Recent Advances in Heat Flow Studies in the United States

Investigations supported by the Department of Energy (DOE)/state-coupled geothermal-direct-heat program have resulted in collection of extensive new heat flow data in the past three years. A small part of this data base is discussed by Sass et al., (1981) and many hundreds more data points will be published in the next year or two as these projects are completed. As a result we have made major advances in our understanding of the regional variations of heat flow and controls on subsurface temperatures, all of which are significant to HDR evaluation and exploration. At this point, regionalization of heat flow and temperature is fairly well understood at a scale of 10-100 km. Also, in most areas there are now deep enough holes for evaluation of the heat flow, and subsequent gradient, variations with depth. In general, most of the interpretations of the shallow heat flow data are borne out but the deeper holes allow a more complete analysis of the impact of such variables as regional water flow on the deeper thermal conditions.

Important changes in our regional understanding with specific reference to HDR have been the discovery of a very large area of high temperature and low permeability in the Oregon Cascade range. In this area, a region at least 150 km long and 30 km wide has a mean temperature gradient of 60°C/km, which is as high as gradients typically associated with igneous systems. The impermeability of much of this province suggests that it may be a prime target for HDR exploitation. Furthermore, it also appears that large areas of the Mid-continent have much higher temperatures at depth than anticipated, even though heat flow values are quite modest. Particularly, studies have shown temperatures at the basement surface of 80°C and possible temperatures of 150°C at depths as shallow as 4 or 5 km over large areas of Nebraska and possibly Colorado, North and South Dakota (Gosnold and Eversoll, 1981). Also, we now understand that there are large conductive haloes surrounding all the high-temperature hydrothermal systems, whether igneous related or not. This halo occurs because the circulation in the geothermal system can be very effective

at heating up the rocks surrounding the system. These areas are prime targets for the development of HDR geothermal energy because high temperatures occur at quite shallow depths. As more and more geothermal systems are discovered and evaluated, additional HDR regions will be discovered as well.

Summary

Heat flow rather than geothermal gradient must be used in HDR evaluation. Heat flow techniques are the most cost effective technique for exploring for HDR because of the specific nature of the technique, because of the extensive data base available, and because of the understanding of the controls on heat flow variations. Much new data has been developed through the DOE hydrothermal exploration programs and most of this data is directly applicable to the HDR program. Several large new areas of potential importance for HDR exploitation have been located. Many new local geothermal systems have been drilled that may be suitable for HDR exploitation as the technique is developed.

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