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NATURE AND DISTRIBUTION OF GEOTHERMAL ENERGY

by

Working Group I

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GEOTHERMAL GRADIENT, HEAT FLOW, AND GEOTHERMAL ANOMALIES

The increase of temperature with depth, defined as the geothermal gradient, is usually in the range of 5°F per 1000 ft to 25°F per 1000 ft, but in many areas of the United States, it exceeds 25°F per 1000 ft. Differences in the geologic setting and differences in rock types account for this wide range in geothermal gradient. In a conductive regime, geothermal gradient ($\Delta T/\Delta Z$) is related to heat flowing towards the Earth's surface (q) by the equation

$$q = K (\Delta T/\Delta Z)$$

where K is the thermal conductivity.

A geothermal anomaly is an area beneath which, at some depth, temperatures are elevated with respect to adjacent terrain; these areas may range in size from the environs of a single hot spring to a region of thousands of square kilometers. Because of the high cost of drilling, developing, and maintaining wells that will produce warm or hot water, geothermal exploration involves searching for these locations where relatively high temperatures will be encountered at the shallowest possible depths. Accordingly, it is important to understand the five major factors that cause geothermal anomalies in various geologic settings:

1. Differences in regional heat flow: Regional "heat flow provinces"

have been defined (Birch _et_ _al_., 1968; Diment, _et_ _al_., 1975; Sass and Lachenbruch, 1979) and interpreted to suggest that fundamental differences in heat flow exist at depths of about 20 miles (the base of the continental crust). For example, heat flow near the base of the crust (commonly termed the "reduced heat flow") is very low beneath the Sierra Nevada, intermediate in the eastern United States, and high in the Basin and Range province.

2. Relatively low values of thermal conductivity: Conductive heat flow (in the absence of heat sources such as radiogenic heat-producing elements) must be the same at any depth in a sedimentary section, irrespective of rock type. Since at constant q, if thermal conductivity (K) decreases, the geothermal gradient $\Delta T/\Delta Z$) must increase. The thermal conductivity of common rocks varies by a factor of at least 6 from unconsolidated dry sand to quartzite (essentially all SiO_2) (Clark, 1966). Correspondingly, at constant heat flow, geothermal gradients can range over a factor of at least 6 owing to different thermal conductivities alone. Lateral changes in rock type from high to low thermal conductivity thus can produce striking geothermal anomalies.

3. Differences in concentrations of radioactive elements: Within heat flow provinces, additional factors influence the magnitude of the geothermal gradient. Radiogenic elements are concentrated in the upper crust and tend to be concentrated even further in granitic intrusive rocks. Such concentrations increase the magnitude of heat flow at shallow crustal levels. It is now known that up to two-thirds of the heat flow in some granitic rocks is the result of heat continually released by the decay of the radioactive elements uranium, thorium, and potassium (Birch _et_ _al_., 1968). Of these,

uranium and thorium are about equal in importance, and contribute approximately 80-90 percent of the heat associated with radioactive decay. It is worth noting that only modest amounts of uranium (5-10 ppm) and thorium (20-80 ppm) in granites have a significant effect on the elevation of subsurface temperatures, if the volume of granite is large enough. Thus, within a given heat flow province, lateral variation in concentration of radiogenic elements will result in differences in the geothermal gradient, even in crystalline rocks of uniform thermal conductivity.

4. Young magmatic intrusions: The theory of plate tectonics (Le Pichon et al., 1973) has successfully explained, for the most part, the geographic occurrence of young centers of magmatic activity. Magma generation takes place along spreading ridges, along zones of plate convergence, and at intraplate melting anomalies (such as Hawaii or Yellowstone). Movement of magma upward through the crust transfers heat towards the Earth's surface and can result in very high geothermal gradients. The resulting intense geothermal anomalies may represent substantial geothermal resources.

5. Hydrothermal circulation: In many areas of the United States, heat is transported relatively rapidly by fluid flow along permeable sedimentary beds, faults, fissures, or fracture zones. The hydrothermal circulation may be driven by heat from a young intrusive mass or may result merely from circulation of water to depth in a region devoid of young igneous rocks. In either case, thermal energy is transported to shallow depths in the crust, and major geothermal anomalies can result. At places where the thermal waters rise to the land surface, hot springs occur. At other places, the thermal waters may be within reach of shallow wells.

PRODUCTION OF GEOTHERMAL ENERGY

Geothermal energy of the Earth's crust is stored predominantly in rock, and only subordinately in water, steam, or other fluids that fill pores or fractures within the rock. This diffuse energy must be collected from large volumes of rock and transported to a discharge point in order to make the energy available for practical uses. The water contained in nearly all rocks within the upper few kilometers of the Earth's crust provides the transfer mechanism by which this collection and discharge is accomplished.

In order to permit the economic extraction of water and its contained thermal energy, the rocks through which the water moves must store significant amounts of water and transmit it freely. The capacity of a rock to store water is termed the storage coefficient, and the ability of a rock to transmit water is termed the hydraulic conductivity. Rocks such as fractured quartzite and limestone, brecciated volcanic rocks, or uncemented sand and gravel generally have moderately high storage coefficients and hydraulic conductivities, and may be expected to produce fairly large amounts of water per unit cross-sectional area. Where these rocks have large thicknesses, they are said to have high transmissivities (transmissivity is the product of the hydraulic conductivity and the thickness of the cross-section of flow). Rocks of high transmissivity, therefore, form the principal aquifers in ground-water systems and constitute the most productive geothermal reservoirs. In order to insure long-term productivity, these aquifers must also be areally extensive and be hydraulically connected to adequate recharge areas.

The productivity of low-permeability reservoirs theoretically can be enhanced by various fracturing techniques (for example, hydrofracturing, explosives, or chemical treatment). To date, such techniques have been used only rarely in geothermal settings, and their common applicability remains to be demonstrated.

Extraction of energy from rock of very low porosity and permeability can be accomplished by the establishment of a confined circulation loop consisting of two wells connected by a network of fractures induced by hydraulic or other means (Smith, 1978). Cold water is pumped down one well, heated by conduction as it flows through the induced fractures, and extracted as hot water through the second well. Implicit is the requirement that rocks adjacent to the fractured volume remain impermeable, so that fluid losses from the circulation loop are minimal. This procedure, commonly referred to as "hot dry rock technology", is presently in the experimental stage, and its widespread applicability and its economics have yet to be demonstrated. Hot dry rock is one end-member of a series of hydrologic environments that extend, with increasing permeability, to conventional reservoirs or aquifers (Muffler, 1979, p. 160). Indeed, most rock in the Earth's crust is likely to be intermediate in this series; that is, too permeable to support a confined circulation loop but not permeable enough to produce contained fluids at economically acceptable rates.

TYPES OF GEOTHERMAL SYSTEMS

Hydrothermal convection systems related to young igneous intrusions

The most spectacular evidence of the heat of the Earth is a volcanic eruption. Although the lavas that may be extruded from such an eruption will cool on the Earth's surface in a relatively short time, the chamber in the Earth's crust from which these lavas came will contain molten or still hot rock for many thousands of years. At present it is not practical to tap these magma chambers directly by drilling. However, fractures and faults around the intrusion may allow the development of a hydrothermal circulation system--that is, circulating ground water that reaches down to or near the cooling intrusion, absorbs some of the heat, and returns to or near the Earth's surface. The density difference between hot and cold water causes the heated water to rise, just as in a tea kettle over a gas burner. Figure 1 illustrates this sort of geothermal system.

Fault-controlled systems

Most hydrothermal convection systems are not located in areas where young igneous intrusions have been identified. Instead, these geothermal systems derive their heat from large volumes of rock by deep circulation of water along permeable zones, which may be either stratigraphic beds or fault and fracture networks (figure 2). The temperature attained by the water is primarily dependent upon the magnitude of the regional heat flow and the depth to which the water circulates. Recharge to the downward-circulating limb of the hydrothermal convection system from occur~~s~~ over both mountain areas and adjacent valleys. The fractures and faults could ~~can~~ be ~~may~~ be of different types than the generalized model shown in figure 2; the only requirement is that the faults be permeable enough to transmit the rising hot water.

Radiogenic heat sources concealed beneath insulating sediments of low thermal conductivity

Granitic plutonic rocks are relatively enriched in uranium and thorium. Radioactive disintegration of these elements gives off heat, and thus heat flow in a radiogenic pluton is higher than that in the adjacent country rock into which it was intruded. If the granitic rocks are blanketed by sediments of low thermal conductivity, then relatively high temperatures can occur at the base of the sedimentary section over the radiogenic source (figure 3). The areal extent of the geothermal anomaly depends on the shape and thickness of the radiogenic source, the concentration of uranium and thorium in the radiogenic source, and the thermal conductivity and thickness of the overlying sediments. ~~Figure 3 illustrates the geologic setting~~.

Geopressured-geothermal reservoirs

Geopressured-geothermal reservoirs are aquifers that are under pressure exceeding the pressure of a water column (hydrostatic head) and approaching that caused by the weight of the overlying rocks (lithostatic head). The less porous sediments that lie on top of the geopressured-geothermal zone prevent upward leakage of water that ordinarily would transport and lose the heat to the surface (figure 4). Water in the geopressured sediments thus contains an anomalous amount of heat as well as substantial amounts of dissolved methane (the chief constituent of natural gas).

The technology for producing the geothermal energy from geopressured-geothermal reservoirs, along with the dissolved methane, is still being perfected, but basically it involves the use of the same tools and techniques required in very deep oil drilling. This is a costly undertaking, and therefore the development of these sorts of reservoirs will be restricted to organizations with substantial financial backing, and is not an endeavor into which smaller firms or individuals can readily enter. Also, at present the hot water alone does not seem to be an economically justifiable target, but combined with the associated methane, the development of these geopressured-geothermal energy reservoirs may become economic.

Deep regional aquifers

Downwarped troughs in the crust form sedimentary basins that collect and transmit ground water from recharge areas in adjacent highlands. This water moves down-dip through the sedimentary deposits and is heated in the Earth's geothermal gradient (figure 5).

At places in these basins where hydraulic conductivities are unusually high or where fractures allow water to move vertically under artesian pressure, geothermal water may occur within economic reach of drill holes. If artesian pressures are sufficiently great, the thermal water may flow at land surface. As shown in figure 5, the upwarping of isotherms in sediments of low thermal conductivity may also aid in making geothermal water available at fairly shallow depths.

Deep regional aquifers having geothermal potential are currently known to occur in the Williston Basin in the northern Great Plains, and may also occur in other large basins of the north-central and western United States. In the eastern and mid-western United States, areas such as the Allegeny Basin of western Pennsylvania and New York, and the Michigan and Ohio Basins, appear to offer similar opportunities for geothermal exploration.

GEOLOGIC ENVIRONMENTS OF GEOTHERMAL SYSTEMS

Volcanic belts

Volcanic belts provide a major ~~and very important~~ location for the occurrence of hydrothermal systems. Most of the world's geothermal regions now under development are in this sort of setting. It seems certain that many more geothermal developments will take place in these very extensive volcanic mountain belts.

Volcanic belts of the United States are the loci of major geothermal anomalies and contain substantial geothermal energy (Smith and Shaw, 1979). This energy exists in magma, in low-permeability igneous and country rock, and in associated hydrothermal convection systems. In general, volcanoes less than one million years old have the best chance of being sites of good economic geothermal systems. Older volcanic areas are less favorable, but it should be kept in mind that the volcanic rocks at the Earth's surface are not necessarily an indication of the age of rocks that may be cooling beneath the surface. That is, younger intrusions that have no surface expression may occur at depth and may support hidden (or "blind") geothermal systems.

Young volcanic belts are concentrated in the western United States (Smith and Shaw, 1979, maps 2 and 3). Most voluminous are the volcanic rocks and associated intrusions of the Aleutian Chain and of the Cascades, both related to converging margins of major plates. The Imperial Valley of Southern California is along the major spreading zone that extends up the Gulf of California, whereas Hawaii, the eastern Snake River Plain, and Yellowstone are related to intraplate melting anomalies. Other young volcanic belts occur along the east and west margins of the northern Basin and Range Province, along the Rio Grande Rift, and along the southwest margin of the Colorado Plateau.

Extensional environments

Environments where the crust of the Earth is under tensional stress are favorable geologic settings for the presence of hot water. These areas are often characterized by active faulting, relatively young mountain ranges, basins that have moderately thick unconsolidated to poorly consolidated sedimentary fill, and local [illegible] young volcanic activity.

In the United States, the Basin and Range province in Nevada and western Utah and the Rio Grande Rift area of central New Mexico and southern Colorado are two areas of active extension that contain large amounts of geothermal water. Heat in extensional environments typically comes from elevated regional heat flow, which can be an important source of heat for a large region, or from young igneous intrusions, which can be locally important as sources of heat. Hot water in both these environments typically circulates through faults and fractures, but in areas where thick sequences of basin-fill sediments are present, the hot water may be encountered in the sediments themselves.

Gulf Coast region

From thousands of oil wells drilled in the Gulf Coast region of the United States it has long been known that extensive areas (both onshore and offshore) contain large geopressured-geothermal reservoirs (Jones, 1970; Papadopulos *et al*., 1975; Wallace *et al*., 1979). The geological circumstances which combined to produce these reservoirs are complex, but suffice it to say that heat coming into the lower portions of the very thick deposits of sediments has been trapped by the rapidly depositing overlying sediments of low permeability and low thermal conductivity. This trapping occurs at depths generally about 10,000 feet, and the geopressured reservoirs may extend to as depths as great as 50,000 feet. There is some possibility that there are other geopressured-geothermal energy areas in certain other deep sedimentary basins of the United States (Wallace *et al*., 1979, fig. 26), but to date only the Gulf Coast region has been clearly identified as containing this sort of reservoir.

Atlantic Coastal Plain

The Atlantic Coastal Plain is underlain by a wedge of sediments of Cretaceous and younger ages that extends from New York to Florida. The sediments are thickest (up to 10,000 ft) along the coastline, and consist of limestone, siltstone, sandstone, and conglomerate (Brown *et al*., 1972). The several major aquifers that are present within the Coastal Plain sediments include the Tuscaloosa Formation (a thick Cretaceous sand) and the sands of the Potomac Group. Wells producing up to 3500 gallons per minute have been reported (Siple, 1975).

Granitic rocks crop out over a large area of the central and southern Appalachian Piedmont and presumably extend eastward beneath the sedimentary cover of the Atlantic Coastal Plain.

Development of low-temperature geothermal energy in the eastern United States will probably occur where basement granitic rocks that contain moderate concentrations of radiogenic heat-producing elements are concealed beneath thick sequences of sediments of low thermal conductivity of the Atlantic Coastal Plain. Geothermal gradients as high as 14°F per 1000 ft have been observed in Coastal Plain sediments and are presumed to be associated with concealed granitic radiogenic rocks (Costain et al., 1979).

GEOTHERMAL RESOURCE ASSESSMENT

Geothermal resource assessment is the process of estimating how much geothermal energy might become available for use at a specified time, under some set of generalized technologic and economic assumptions (Muffler and Cataldi, 1979). The process is analogous to the methods of estimating mineral and petroleum resources, except that the results are given in units of thermal energy rather than in tons of ore or barrels of oil. Also, geothermal energy figures must be given relative to a reference temperature, normally taken by convention to be mean annual temperature.

The terminology for geothermal resource assessment has been adapted from the petroleum and mineral industries (Muffler, 1973; Muffler and Cataldi, 1979). The term geothermal resource base is adapted from Schurr and

Netschert (1960) to refer to all the thermal energy in the Earth's crust beneath a given area, referenced to mean annual temperature. The *accessible resource base* is defined by Muffler and Cataldi (1979) as that part of the resource base which is accessible to drilling; the depth limit of drilling must be specified in each situation. The accessible resource base is then divided into *useful* and *residual* components, with the useful component being that fraction of the accessible resource base that can be extracted and used at some future time under reasonable technologic and economic assumptions. The useful accessible resource base is termed the *resource* and is further divided into *identified* and *undiscovered* components. Still in a manner analogous to the mineral and petroleum industries, *reserve* is defined as that part of the resource which is identified and can be produced under present-day economics. These terms can be illustrated on a McKelvey diagram (figure 6).

It must be emphasized that the geothermal resource constitutes only a fraction of the accessible resource base. For favorable hydrothermal convection systems, the ratio of resource to accessible resource base (i.e., the "recovery factor") may be as much as 25 percent (Nathenson, 1975; Nathenson and Muffler, 1975). For most geologic environments, however, the recovery factor is likely to be far less, perhaps only a fraction of 1 percent for large volumes of low-permeability rock in regional conductive environments.

SOURCES OF GEOTHERMAL INFORMATION

National and regional data

The regional distribution of geothermal resources of the United States is discussed and depicted in U.S. Geological Survey Circular 790 (Muffler, 1979). This report is a refinement and update (to June, 1978) of U.S. Geological Survey Circular 726 (White and Williams, 1975), and can be obtained free-of-charge from Branch of Distribution, U.S. Geological Survey, 1200 South Eads St., Arlington, VA 22202.

Both the 1975 and 1978 assessments discuss the occurrence of geothermal energy in the United States, estimate the accessible resource base (to 30,000 ft for regional conductive environments, approximately 22,500 ft for geopressured-geothermal energy environments, and 10,000 ft for hydrothermal convection systems), and estimate geothermal resources for geopressured-geothermal energy of the northern Gulf of Mexico basin and for hydrothermal convection systems. The 1978 data are illustrated on three colored maps: the conterminous western United States (at 1:2,500,000), Alaska (at 1:5,000,000) and Hawaii (at 1:2,500,000), and the northern Gulf of Mexico basin (at 1:1,000,000).

Sources of data in individual states

Some state agencies are sources of information about local geothermal areas. Geological surveys or divisions of mines may have data on the geologic setting of geothermal sites within each state; departments of water resources or water rights may be able to provide information about water temperatures, quality, and potential flow rates; departments of energy may be able to provide assistance in contacting local sources of information. In addition, the District Offices of the U.S. Geological Survey Water Resources Division often are sources of data and information on geothermal areas in their respective states. Finally, an elaborate collation of data in individual states is being carried out by the Western States Cooperative Direct Heat Geothermal Program of the Department of Energy (Wright et al., 1978).

Miscellaneous geothermal data

A yearly compendium of ongoing activities in geothermal exploration and evaluation is provided by the Transactions of the Geothermal Resources Council. Each volume contains several hundred four-page summaries of geothermal papers submitted to the annual meeting of the Geothermal Resources Council.

Current drilling information is provided on a weekly basis in the National Geothermal Report, a publication of Petroleum Information, Inc., P.O. Box 2612, Denver, CO 80201.

In addition, several scientific and engineering periodicals deal wholly or in part with the nature and distribution of geothermal energy. These include:

Geothermics (Pergamon Press, Inc., Fairview Park,
Elmsford, NY 10523)

Journal of Volcanology and Geothermal Research
(Elsevier Scientific Publishing Company, 52 Vanderbilt Ave.,
New York, NY 10017)

Geothermal Energy Magazine (18014 Sherman Way, Suite
169, Reseda, CA 91335)

The National Technical Information Service (NTIS) is a major source for the public sale of U.S. and foreign government-sponsored research, development, and engineering reports. Publications related to geothermal energy are classified in category UC-66, with various sub-classifications:

a. Resource development
b. Exploration technology
c. Drilling technology
d. Utilization technology

e. Environmental research

f. Experimental and commercial electricity production from geothermal resources

g. Direct application of heat from geothermal resources

h. Legal and other institutional aspects of geothermal energy exploitation

i. Economic and financial aspects of geothermal energy exploitation

j. Federal energy plans.

Write or call the National Technical Information Service, Dept. of Commerce, Springfield, VA 22161; (804) 557-4650.

Available from NTIS on a subscription basis is the monthly Geothermal Energy Update (NTIS UB/D/47), which contains abstracts of reports, articles, conference proceedings, etc. on geothermal subjects.

Results of many investigations of the U. S. Geological Survey into the geology, geophysics, geochemistry, and hydrology of geothermal systems are published at USGS Bulletin~~g~~s, Professional Papers, maps, and Open-File Reports. New issues are listed monthly in the periodical New Publications of the Geological Survey, available free from the U. S. Geological Survey, 329 National Center, Reston, VA 22092.

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