CHAPTER 1

NATURE AND DISTRIBUTION OF GEOTHERMAL ENERGY

Work Group

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(Chapter 1, continued)

FIGURES

ABSTRACT

Five major factors, either alone or in combination, are responsible for geothermal anomalies: 1) differences in regional heat flow, 2) range in value of thermal conductivity, 3) differences in concentrations of radioactive elements, 4) young magmatic intrusions, and 5) hydrothermal circulation. Geothermal exploration involves searching for positive geothermal anomalies, and geothermal production involves extraction of thermal water or steam from holes drilled into these anomalies. Favorable geothermal reservoirs require rocks of high natural transmissivity, but artificial fracturing shows some promise of allowing energy to be produced from hot rocks of low permeability. Important types of geothermal systems include 1) hydrothermal convection systems related to young igneous intrusions, 2) fault-controlled systems, 3) radiogenic heat sources beneath insulating sediments of low thermal conductivity, 4) geopressured-geothermal reservoirs, and 5) deep regional aquifers. The geologic environments of geothermal systems in the United States include volcanic belts, extensional environments, the northern Gulf of Mexico Basin, and the Atlantic Coastal Plain. The accessible resource base and the geothermal resource of the United States have been estimated in recent publications of the U.S. Geological Survey.

GEOTHERMAL GRADIENT, HEAT FLOW, AND GEOTHERMAL ANOMALIES

It is well known from drilling, observations in mines, and various geophysical studies that temperatures in the Earth increase with depth. This increase of temperature (T) with depth (Z) is termed the geothermal gradient ($\Delta T/\Delta Z$). At depths accessible to drilling (currently less than 6 miles--10 kilometers), the geothermal gradient usually is in the range of 5-25°F per 1000 ft (9-45°C per km), but in many areas of the United States it exceeds 25°F per 1000 ft (45°C per km). Differences in rock type, geologic setting, and hydrologic regime account for the wide range in geothermal gradient.

In response to this geothermal gradient, thermal energy moves toward the Earth's surface, either by conduction of heat through solid rock, by movement of molten rock (magma), or by movement of water. The vertical movement of thermal energy by conduction is termed heat flow (q) and is related to the geothermal gradient by the equation

$$q = K\ (\Delta T/\Delta Z) \qquad (1)$$

where K is the thermal conductivity.

A geothermal anomaly is an area beneath which, at some depth, temperatures are elevated or depressed relative 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 positive geothermal anomalies--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) and explained in terms of fundamental differences in heat flow at depths of up to 20 miles (32 km; 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 (Figure 1), intermediate in the eastern United States, and high in the Basin and Range province.

2. Range in value 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

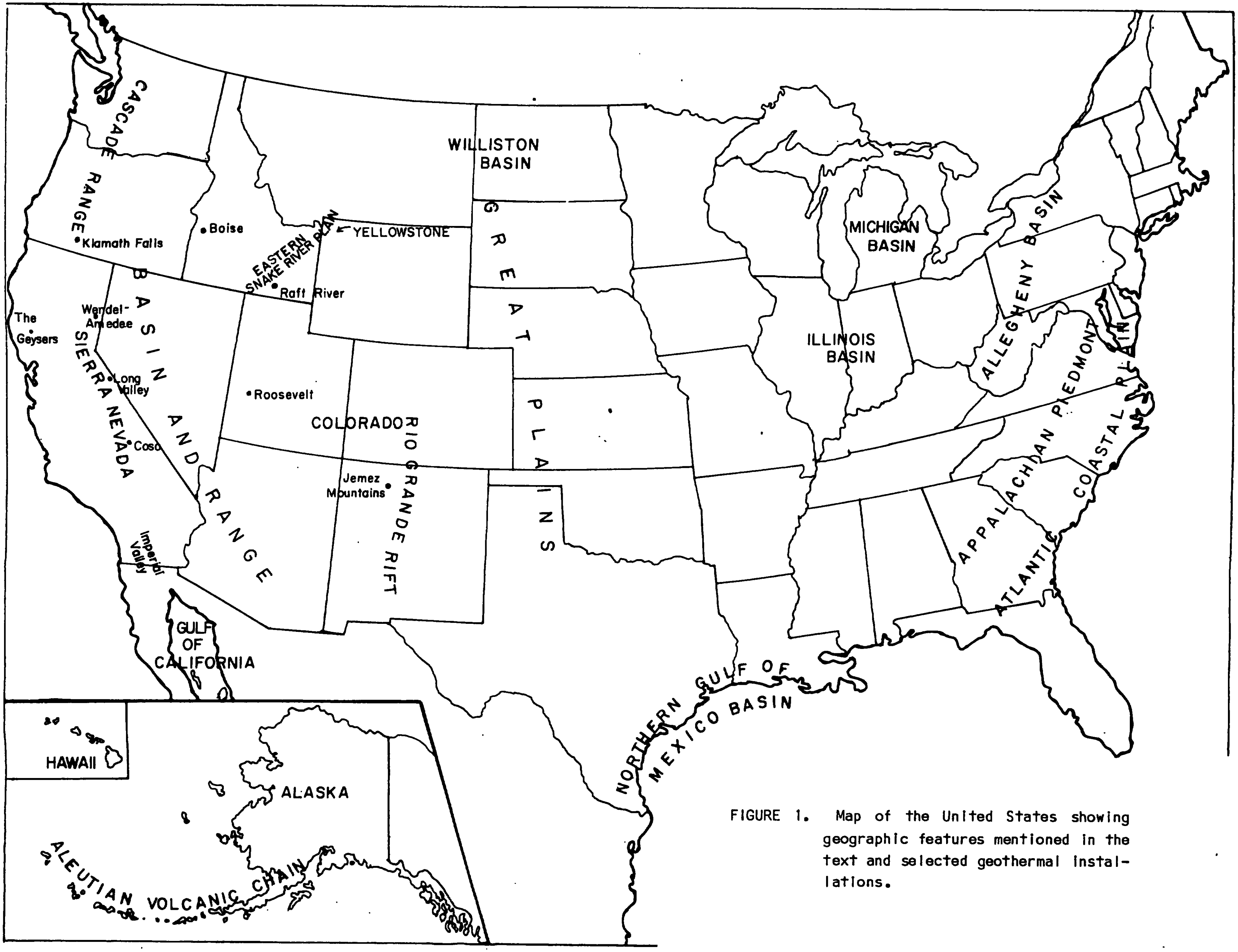

FIGURE 1. Map of the United States showing geographic features mentioned in the text and selected geothermal installations.

stratigraphic section. Hence, according to equation 1, the geothermal gradient must increase if thermal conductivity decreases. The thermal conductivity of common rocks ranges over a factor of at least 6 from unconsolidated clay 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 a heat-flow province, 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 from these rocks by the decay of radioactive isotopes of the 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 parts per million) and thorium (20-80 parts per million) 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 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). Upward movement of magma transfers heat toward the Earth's surface and can result in very high geothermal gradients. The positive geothermal anomalies produced in this manner by recent intrusion of magma may represent substantial geothermal resources. However, intrusive bodies older than several million years have had the chance to cool to ambient temperatures and no longer sustain a positive geothermal anomaly.

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. This hydrothermal circulation may be driven by heat from a young intrusive mass or may result merely from deep circulation of water in a region devoid of young igneous rocks. In either case, thermal energy is transported to shallow depths in the crust, and major positive 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 or permeability. Rocks such as fractured quartzite and limestone, brecciated volcanic rock, 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 transmissivity (the product of the hydraulic conductivity and the thickness of the cross-section of flow). Rocks of high transmissivity form the principal aquifers in groundwater systems and constitute the most productive geothermal reservoirs.

The long-term productivity of a geothermal reservoir is dependent on many interrelated factors. In addition to the aquifer transmissivity and storage coefficient, these factors include the volume and temperature of the reservoir, type of heat source, magnitude of regional heat flow, chemical nature of the geothermal fluid, and the presence or absence of recharge and discharge boundaries. Reliable evaluation of several of these factors may not be possible prior to actual production of fluid from the geothermal reservoir.

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 economics and common applicability remain 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 the fluid losses from the circulation loop are minimal. This procedure, commonly referred to as "hot dry rock technology," is presently in the experimental stage. 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 commonly allow the development of a hydrothermal convection 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, thus concentrating thermal energy in a near-surface geothermal reservoir (Figure 2). Geothermal reservoirs related to young igneous intrusions can have very high temperatures (300-660°F, 150-350°C) and have been developed for electrical generation and direct uses in a number of localities throughout the world.

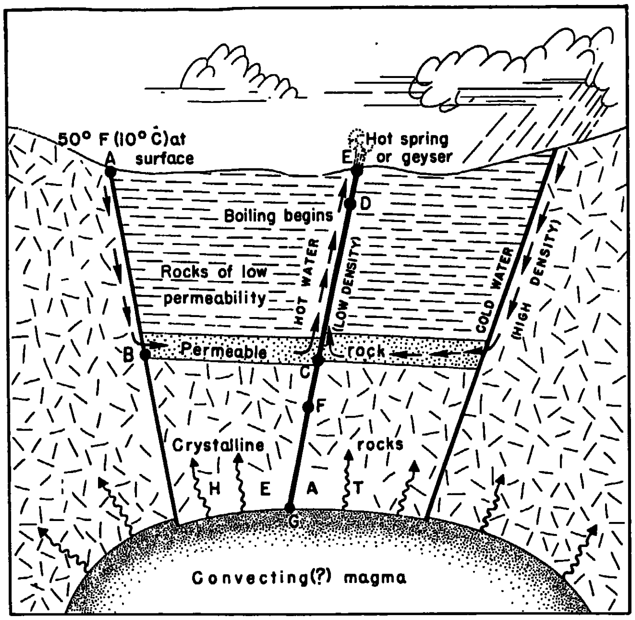

FIGURE 2. Schematic model of a hydrothermal convection system driven by an underlying young igneous intrusion (modified from White, 1968).

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 networks of faults and fractures (Figure 3). 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 may occur over both mountain areas and adjacent valleys. The types of fractures and faults could differ from those shown in the generalized model of Figure 3; the only requirement is that the faults or fractures be permeable enough to transmit the rising hot water.

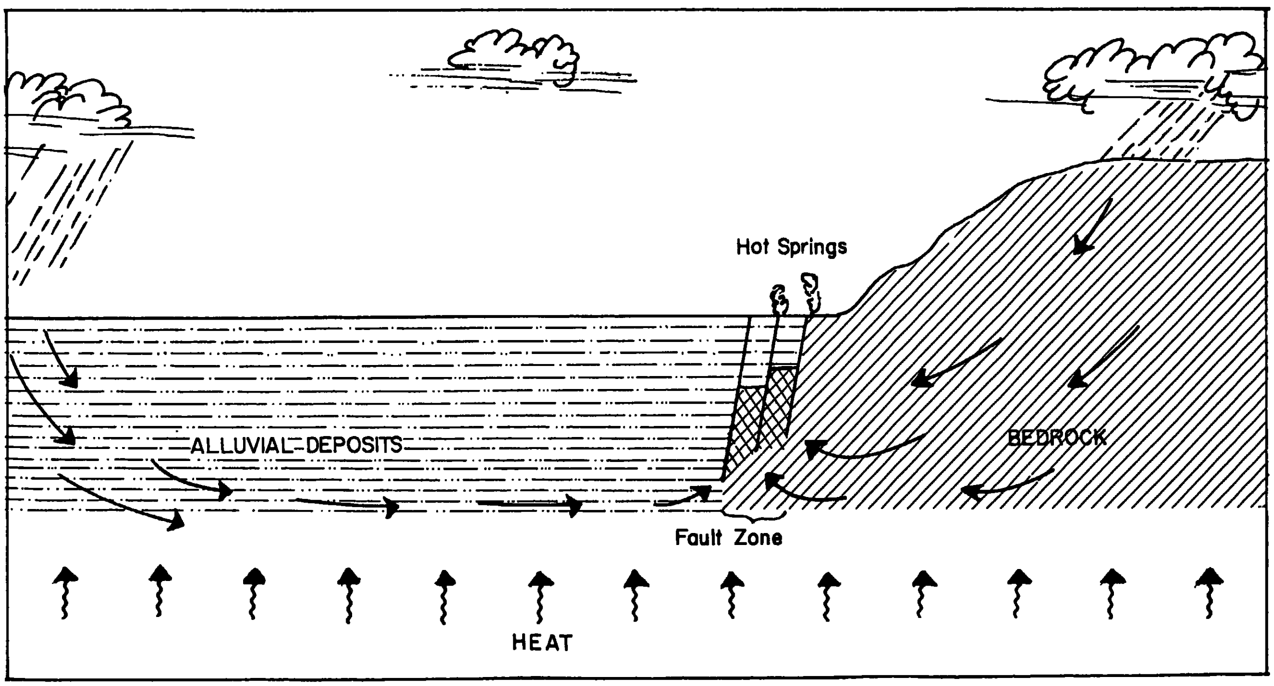

FIGURE 3. Schematic model of a hydrothermal convection system related to deep circulation of meteoric water without the influence of young igneous intrusions.

Deep regional aquifers

Down-warped troughs in the crust form sedimentary basins that collect and transmit groundwater 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 4).

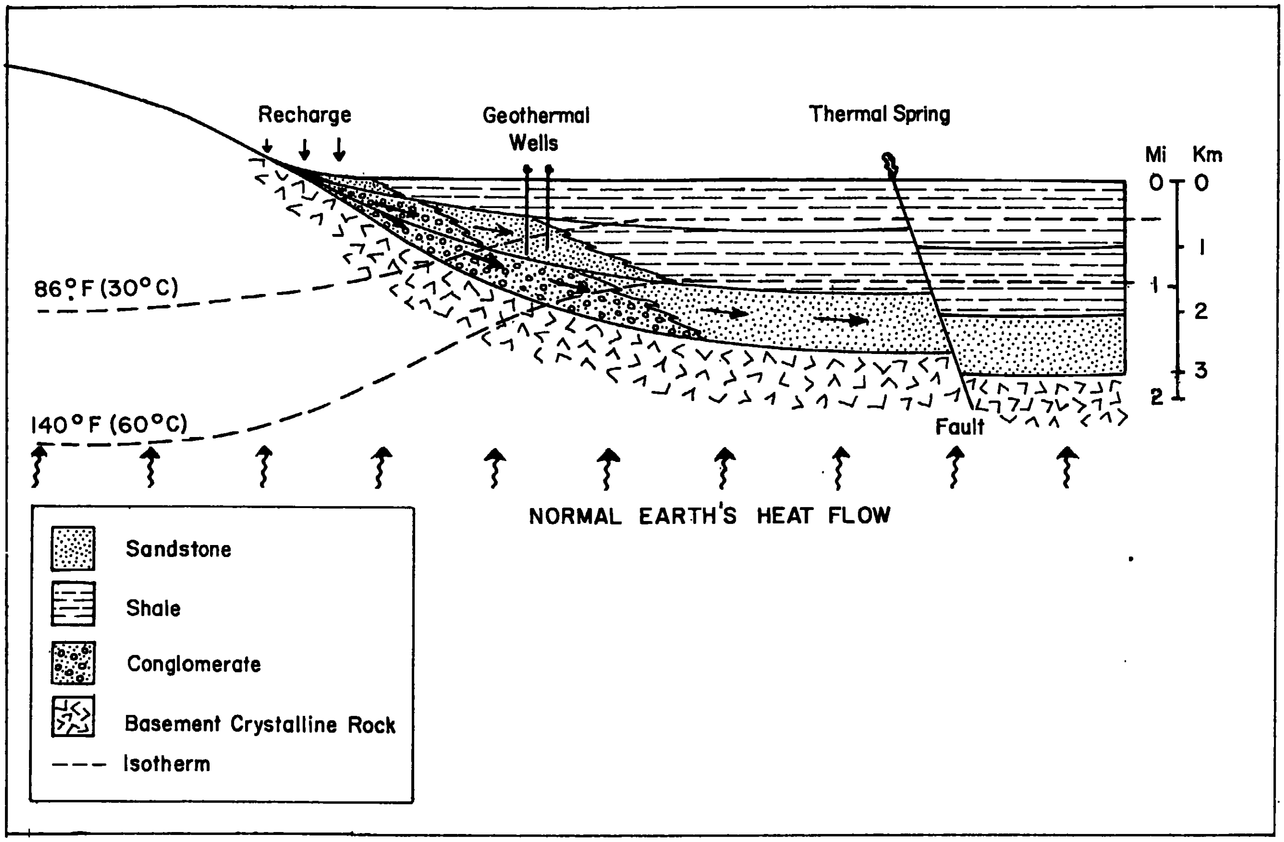

FIGURE 4. Schematic model of a geothermal reservoir in a deep regional aquifer.

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 4, 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 have been developed extensively for direct uses in France, Hungary, and the USSR. In the United States, deep regional aquifers having geothermal potential are 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 midwestern United States, areas such as the Allegheny, Michigan, and Illinois Basins (Figure 1) appear to offer similar opportunities for geothermal exploration.

Geopressured-geothermal reservoirs

Geopressured-geothermal reservoirs are aquifers whose fluids are under pressure exceeding the pressure of a water column (hydrostatic head) and approaching that caused by the weight of the

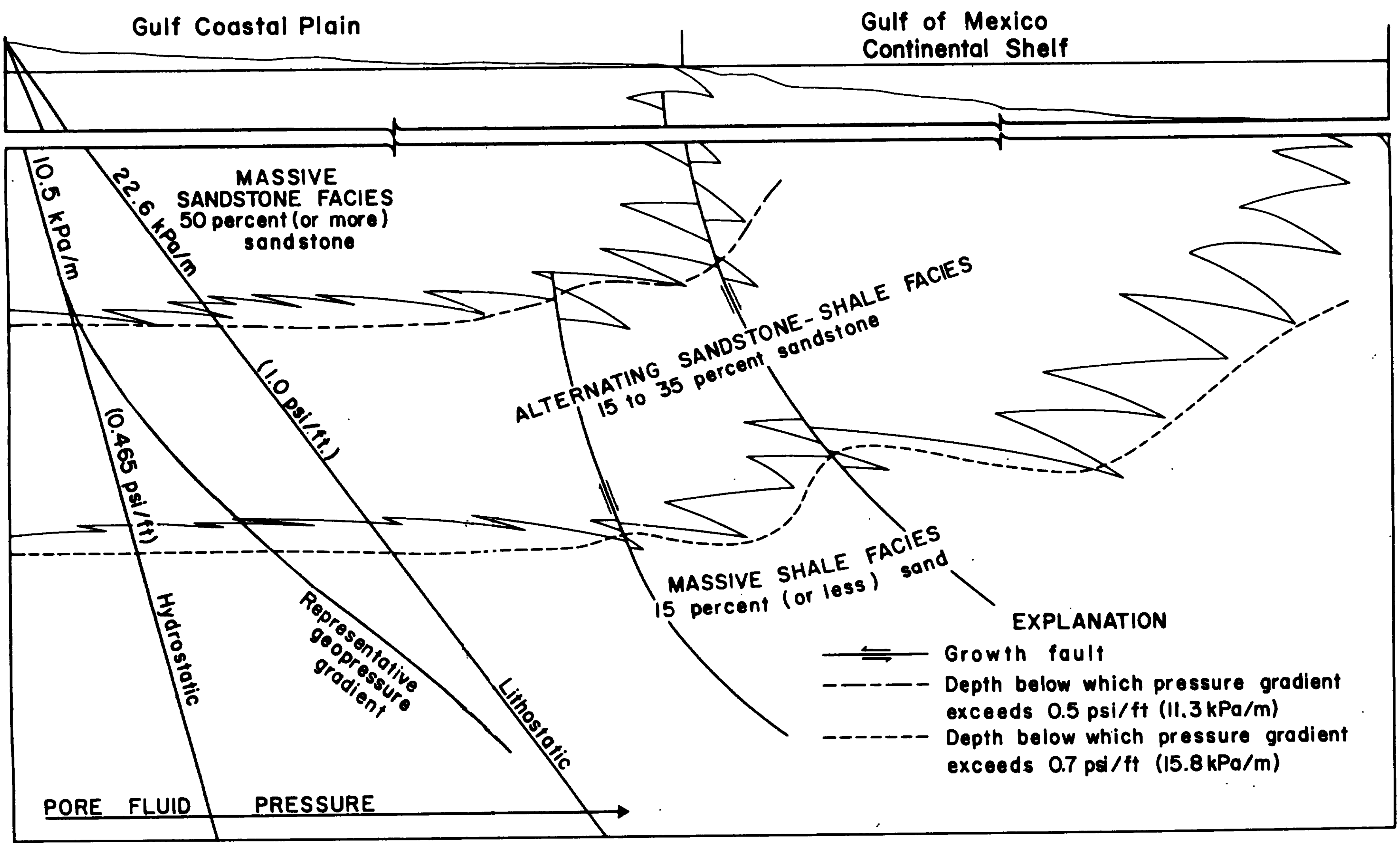

FIGURE 5. Generalized sedimentary model of the northern Gulf of Mexico basin, showing the relation of gross lithology to fluid-pressure gradient and growth faulting (modified from Wallace et al., 1979).

overlying rocks (lithostatic head). Less porous sediments that lie on top of geopressured-geothermal reservoirs prevent upward leakage of water that ordinarily would transport and lose the heat to the surface (Figure 5). 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 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. Therefore the development of these sorts of reservoirs will be restricted to organizations with substantial financial backing and will not be 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.

Radiogenic heat sources beneath insulating sediments of low thermal conductivity

Granitic plutonic rocks are relatively enriched in uranium and thorium. Radioactive disintegration of isotopes of these elements gives off heat. 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 6.) 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.

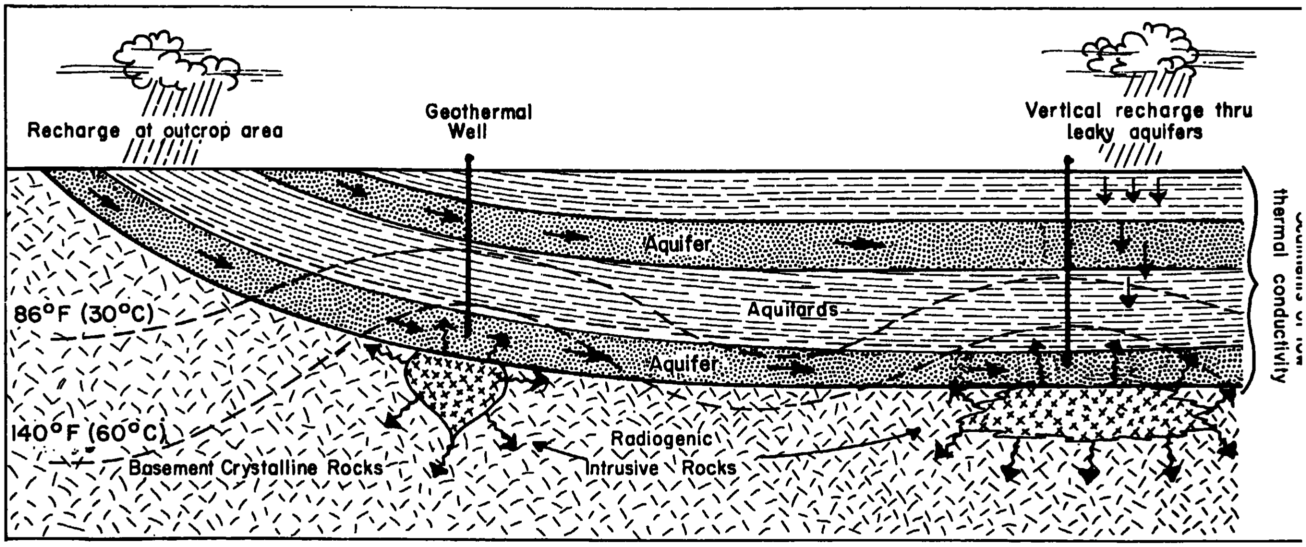

FIGURE 6. Schematic model of a geothermal reservoir in sedimentary rocks of low thermal conductivity overlying basement plutonic rocks enriched in uranium and thorium.

GEOLOGIC ENVIRONMENTS OF GEOTHERMAL SYSTEMS

Volcanic 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 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 do not necessarily indicate 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 1 and 2). Most voluminous are the volcanic rocks and associated intrusions of the Aleutian Volcanic Chain and of the Cascade Range (Figure 1), both related to converging margins of major plates. The Imperial Valley of Southern California is along the major spreading zone that extends northward from 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 commonly characterized by active faulting, relatively young mountain ranges, basins that have moderately thick unconsolidated to poorly consolidated sedimentary fill, and local sites of young volcanic activity.

In the United States, the Basin and Range province in Nevada and western Utah and the Rio Grande Rift 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.

Northern Gulf of Mexico basin

From thousands of oil wells drilled in the northern Gulf of Mexico basin (Figure 1) it has been determined 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 thick deposits of sediments has been trappped by the rapidly depositing overlying sediments of low permeability and low thermal conductivity. This trapping occurs at depths generally about 10,000 ft (3050 m), and the geopressured reservoirs may extend to depths as great as 50,000 ft (15,250 m). There is some possibility that there are geopressured geothermal energy areas in other deep sedimentary basins of the United States (Wallace et al., 1979; Fig. 26), but to date only the northern Gulf of Mexico basin 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 age that extends from New York to Florida. The sedimentary section is thickest (up to 10,000 ft—3050 m) along the coastline and consists of limestone, siltstone, sandstone, and conglomerate (Brown et al., 1972). The several major aquifers that are present beneath the Coastal Plain include the Tuscaloosa Formation (a thick Cretaceous sandstone) and the sandstones of the Potomac Group. Wells producing up to 3500 gallons (13,250 liters) per minute (220 l/s) 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 is most likely to occur in the Atlantic Coastal Plain where basement granitic rocks that contain moderate concentrations of radiogenic heat-producing elements are concealed beneath thick sedimentary sequences of low thermal conductivity. Geothermal gradients as high as 24°F per 1000 ft (44°C per km) 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 7).

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.

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). Both the 1975 and 1978 assessments estimate the accessible resource base to 30,000 ft (10 km) for regional conductive environments, approximately 22,500 ft (7 km) for geopressured-geothermal energy environments, and 10,000 ft (3 km) for hydrothermal convection systems. Geothermal resources are estimated only for geopressured-geothermal energy of the northern Gulf of Mexico basin and for hydrothermal convection systems $\geq$ 194°F (90°C). No quantitative estimates are made of the thermal energy in geothermal waters at temperatures less than 194°F (90°C), but areas favorable for discovery and development of these low-temperature waters are depicted on

Map 1 and in the text figures of Circular 790.

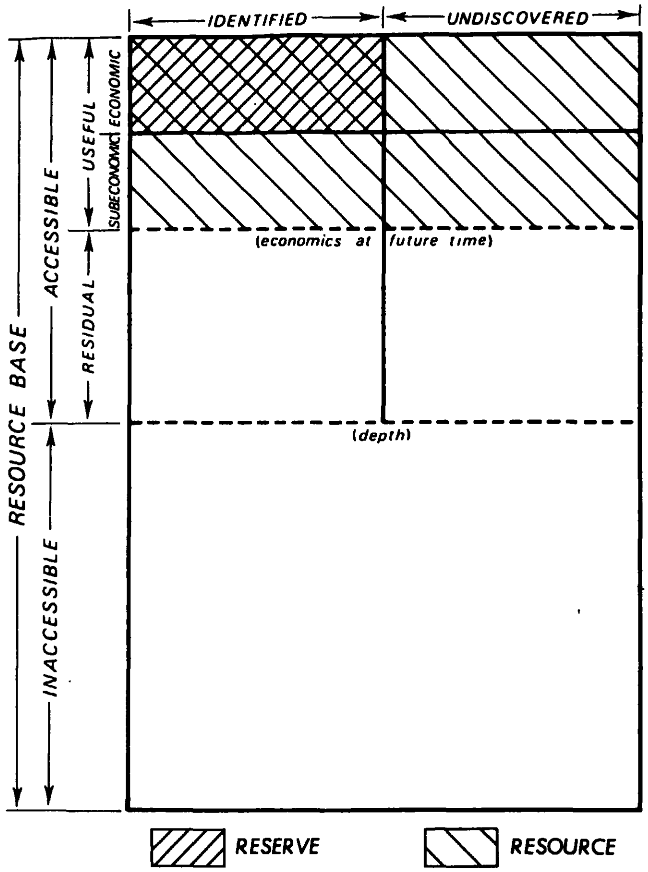

FIGURE 7. McKelvey diagram for geothermal energy showing derivation of the terms resource and reserve (from Muffler and Cataldi, 1979). Vertical axis is degree of economic feasibility; horizontal axis is degree of geologic assurance.

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