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THE NATURE AND GEOLOGIC CHARACTERISTICS OF GEOTHERMAL RESOURCES

by

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ABSTRACT

Geothermal resources occur where heat is concentrated in the upper levels of the earth's crust, ranging between the surface and about 5 km in depth. Such resources can be broadly divided into those with naturally occurring water, the so-called "hydrothermal" resources, and those without naturally occurring water, the so-called "hot rock" resources. At the present stage of geothermal resource development, we know by far the most about the hydrothermal resource type because this is the only type that can be economically developed today. Little deep drilling has been done in areas which would give us access to the hot rock resources.

Hydrothermal systems are found in many different geologic environments, and to a considerable extent, the characteristics of the environment determine those of the resource. In igneous and volcanic terranes, the hydrologic relationships are complex, and several reservoirs with different fluid compositions may be present. Fluid compositions depend on many factors, including temperature, rock type, origin of the fluids, residence time in the reservoir, boiling, mixing, cooling, fluid/rock interaction and mineral deposition. Heating of the fluids may be the result of nearby intrusive rock containing residual heat or may simply be the result of deep circulation and heating due to the earth's normal geothermal gradient. Permeability is usually controlled by faults, fractures and contacts between different rock types. These hydrothermal systems are usually volumetrically small and confined to a local area of heating and/or enhanced permeability. Typical areal sizes range from 0.1 sq km to 100 sq km.

The U.S. Geological Survey has assessed the geothermal resource base in the United States, and finds that the amount is large. Evaluation of volume and temperature data available in 1978 indicated that 1650 E18 joules of energy are present in 215 identified hydrothermal systems having temperatures greater than 90 deg C to depths of 3 km, excluding energy in National Parks. This is believed to be a minimum figure, but a more accurate estimate is not possible without more information. Electrical energy estimated to be producible from these resources is 23,000 megawatts for 30 years. The energy in the hot rock resources is very poorly known at the present time, but is probably at least two orders of magnitude more than the hydrothermal resource base. It is apparent that geothermal energy development can help replace the use of petroleum as that resource becomes more scarce and costly.

INTRODUCTION

Geothermal energy is heat that originates within the earth. At our current stage of technology, economic development of geothermal heat can be accomplished in a few areas where the heat is concentrated by geological processes. Approximately 4,733 megawatts of electricity (MWe) are currently being generated in 17 countries from geothermal energy, and about 10,000 thermal megawatts (MWt) are being used for direct heat applications. The United States produces 2,006 MWe of electrical power and uses 400 MWt in direct applications. While this is small compared to our use of an estimated 8.4 million MW of fossil energy (1), it nevertheless saves the consumption of 111 million barrels of oil per year worldwide and 35 million barrels per year in the U.S.

It is difficult to estimate the ultimate potential contribution of geothermal energy to mankind's needs for three reasons: 1) future energy costs are uncertain, and many lower-grade geothermal resources would become economic at higher energy prices; 2) only preliminary estimates of the worldwide resource base have been made, and; 3) technology is not yet available for using magma, hot rock, geopressured, radiogenic, and normal thermal-gradient resources, whose potential contributions are large.

The Earth's Internal Heat

Many large-scale geological processes are powered by redistribution of internal heat as it flows from inner, hotter regions to outer, cooler regions. Although the variations with depth in the earth of density, pressure and seismic velocity are well known, the temperature distribution is uncertain. We know that temperature within the earth increases with increasing depth (Figure 1), at least for the first few tens of kilometers, and we hypothesize a steadily increasing temperature to the earth's center. Plastic or partially molten rock at temperatures between 700 deg C and 1,200 deg C is postulated to exist everywhere beneath the earth's surface at depths of 100 km, and the temperature at the earth's center, nearly 6,400 km deep, may as much as 6,000 deg C.

Because the earth is hot inside, heat flows steadily outward and is permanently lost by radiation into space. The mean value of surface heat flow is 82 E-3 watts/m2. Since the surface area of the earth is 5.1 E+14 m2, the rate of heat loss is about 42 million megawatts (1). White (2) estimates the total thermal energy above surface temperature to a depth of 10 km at 1.3 E+27 J, equivalent to burning 2.3 E+17 barrels of oil. The outward heat flux is about 5,000 times smaller than the flux of solar heat, and the earth's surface temperature is, thus, controlled by the sun and not by internal heat (3).

Two sources of internal heat are most important among several contributing alternatives: 1) heat released throughout the earth's 4.7 billion-year history by decay of radioactive isotopes of uranium, thorium, potassium and other elements; and, 2) heat released during formation of the earth by gravitational accretion and during subsequent mass redistribution when heavier material sank to form the earth's core. The relative contribution to the surface heat flow of these two mechanisms is not resolved.

GEOLOGICAL PROCESSES

The genesis of geothermal resources lies in the geological transport of anomalous amounts of heat near enough to the surface for access. Thus, the distribution of geothermal areas is not random but is governed by geological processes of global, regional and local scale. Figure 2 shows the principal areas of known geothermal occurrences on a world map. Also indicated are areas of young volcanos and currently active geological structures. It is readily observed that geothermal resources occur in areas that have volcanic and other geological activity.

Geothermal resources commonly have three components: 1) an anomalous concentration of heat, i.e. a heat source; 2) fluid to transport the energy from the rock to the surface; and, 3) permeability in the rock for the plumbing system. We will consider these elements in turn.

Heat Sources

In geothermal areas, higher temperatures are found at shallower depths than is normal. This condition usually results from either 1) intrusion of molten rock from great depth to high levels in the earth's crust, 2) higher-than-average surface heat flow, with an attendant high temperature gradient with depth (Figure 1), 3) ascent of ground water that has circulated to depths of 2 to 5 km, or 4) anomalous heating of shallow rock by decay of radioactive elements. Most high-temperature resources appear to be caused by the first mechanism.

A schematic cross section of the earth is shown in Figure 3. A solid layer, the lithosphere, extends from the surface to a depth of about 100 km. The lithosphere is composed of an uppermost layer called the crust and of the uppermost regions of the mantle, which lies below the crust. Mantle material below the lithosphere behaves plastically, flowing very slowly under sustained stress. The crust and mantle are composed of minerals whose chief building block is silica (SiO2). The outer core is believed to be composed of a liquid iron-nickel-copper mixture while the inner core is a solid mixture of these metals.

Plate Tectonics. One geological process that generates shallow crustal heat sources in several different ways is known as plate tectonics (Figure 4). Outward heat flux from the deep interior is hypothesized to form convection cells in the mantle in which hotter material slowly rises, spreads out under the solid lithosphere, cools and descends again. The lithosphere cracks above areas of upwelling and is dragged apart along arcuate structures called "spreading centers", or "rift zones". These spreading plate boundaries are typically thousands of kilometers long, several hundred kilometers wide and coincide with the world's mid-oceanic mountain system (Figures 2 and 4). Crustal plates on each side of the rift separate a few centimeters per year, and molten mantle material rises in the crack, where it solidifies to form new crust. The upwelling of molten material brings large quantities of heat to shallow depths.

The laterally spreading plates press against adjacent plates, some of which contain the imbedded continental land masses, and in most locations the oceanic plates are thrust beneath the continental plates. These zones of under-thrusting, where crust is consumed, are called "subduction zones". They are marked by the world's deep ocean trenches, formed as the sea floor is dragged down by the subducted oceanic plate.

The subducted plate descends into the mantle and is warmed by the surrounding warmer material and by frictional heating. At the descending plate's upper boundary, temperatures become high enough in places to cause partial melting. The molten or partially molten rock bodies (magmas), ascend buoyantly through the crust (Figures 4 and 5) along zones of structural weakness, carrying their heat to within 1.5 to 20 km of the surface. They give rise to volcanos if part of the molten material escapes to the surface through fractures. Since the subducted plate descends at an angle of about 45 degrees, crustal intrusion and volcanos occur on the landward side of oceanic trenches 50 to 200 km inland. This is the process that causes the volcanos in the Cascade Range of California, Oregon and Washington, for example, and in many other parts of the globe as well.

Figure 2 shows where these processes of spreading, formation of new oceanic crust and subduction of oceanic plates are currently operating. Oceanic rises, where new crustal material is formed, occur in all major oceans. The East Pacific Rise, the Mid-Atlantic Ridge and the Indian Ridges are examples. In places, the ridge crest is offset by large faults that result from variations in the rate of spreading along the ridge. Such faults are called "transform faults".

Magmatic Intrusions and Intrusive Rocks. An ascending body of molten material may cease to rise at any level in the earth's crust and may or may not vent through erupting volcanos (Figure 5). Intrusion of magmas into the upper crust has occurred throughout geologic time. We see evidence for this in the occurrence of volcanic rocks of all ages and in the small to very large areas (hundreds of square miles) of crystalline, granitic rock, now exposed at the surface by erosion, that result when magmas cool slowly at depth.

Volcanic rocks extruded at the surface and crystalline rocks that have cooled at depth are known collectively as igneous rocks. They have a range of chemical and mineral compositions. At one end of the compositional range are rocks that are relatively poor in silica (SiO_2 about 50%) and relatively rich in iron (Fe_2O_3 + FeO about 8%) and magnesium (MgO about 7%). The volcanic variety of this rock is basalt and an example can be found in the rocks that compose the Hawaiian Islands. At the other end of the range are rocks that are relatively rich in silica (SiO_2 about 64%) and poor in iron (Fe_2O_3 + FeO about 5%) and magnesium (MgO about 2%). The volcanic variety of this rock, rhyolite, is usually lighter in color than black basalt and occurs mainly on land. The plutonic variety is granite. Magmas that result in basalt are termed "mafic" or "basic" whereas magmas that result in rhyolite or granite are termed "felsic" or "acidic".

The upper portions of the mantle are believed to be basaltic in composition. The great outpourings of basalt found on the ocean ridges and in places like the Hawaiian Islands seem to indicate a more or less direct pipeline from the upper mantle to the surface.

The origin of granites is a subject of controversy. Felsic magma can be derived by progressive segregation of the melt fraction from a basaltic magma as it cools and begins to crystallize. However, the chemical composition of granites is much like the average composition of the continental crust, and some granites also result from melting of crustal rocks due to heating by upwelling basaltic magmas. Basaltic magmas melt at a higher temperature and are more fluid than granitic magmas. Occurrence of felsic volcanic rocks of very young age (less than 1 million years and preferably less than 50,000 years) is a sign of good geothermal potential in an area because they may indicate a large body of viscous magma at depth to provide a strong heat source. On the other hand, occurrence of young basaltic rocks is not as encouraging because the basalt, being fairly fluid, could simply ascend along narrow conduits from the mantle directly to the surface without need for a shallow magma chamber (4).

Mantle Plumes. Another important source of volcanic rocks are point sources of heat in the mantle. It has been hypothesized that the upper mantle contains local areas of upwelling, hot material called "plumes". As crustal plates move over these hot spots, a linear or arcuate sequence of volcanos is developed. Young volcanic rocks occur at one end of the chain with older ones at the other end. The Hawaiian Island chain is an example. The youngest volcanic rocks on the island of Kauai on the northwest end have been dated through radioactive means at about 4 million years, whereas the volcanos Mauna Loa and Mauna Kea on the island of Hawaii at the southeast end of the chain are forming today and are in almost continual eruptive activity. To the northwest, the Hawaiian chain continues beyond Kauai for more than 2,000 miles to Midway Island, where the last volcanic activity was about 16 million years ago. The trace of the island chain is consistent with the motions of the Pacific plate as postulated by geophysicists from other data.

Thin Crust. Not all geothermal resources are caused by near-surface intrusion of molten rock bodies. Certain areas have a higher than average rate of increase in temperature with depth (high geothermal gradient) without shallow magma being present. Much of the western United States contains areas that have an anomalously high heat flow (100 E-3 watt/m2) and an anomalously high geothermal gradient (40 to 60 deg C/km). The typical geothermal gradient in the continental interior is 20 to 30 deg C/km. In the West, geologic evidence suggests that the crust is thinner than normal, accounting for upwarping of mantle isotherms and high measured geothermal gradients.

Fluids

For geothermal resources to be developed economically, an efficient means of bringing large quantities of heat to the surface is needed. Fortunately, nature provides water, which normally pervades fractures, pores and other open spaces in rocks. Water has a high heat capacity and a high latent heat of vaporization. Thus, it is an ideal heat-transfer fluid.

The density and viscosity of water both decrease as temperature increases. Water heated at depth is lighter than cold water in surrounding rocks, and is therefore subjected to buoyant forces. If heating is great enough for buoyancy to overcome the flow resistance of the rock, heated water will rise toward the earth's surface. As it rises, cooler water moves in to replace it. In this way, natural convection is set up in the groundwater around and above a source of heat such as an intrusion. Convection brings large quantities of heat within the reach of wells, and is, thus, responsible for the most economically important class of geothermal resources, the convective hydrothermal resources.

In some convective hydrothermal resources, the temperature never reaches the boiling point because of rapid water flux, and the system does not generate steam. However, in other systems pressure release (perhaps through sudden venting) causes the local boiling point to be reached, and steam is produced. The steam ascends and meets cooler rocks where it partially condenses while heating the rocks, and the pressure drop due to condensation brings up more steam. In this way, steam convection is set up. If venting exceeds recharge, the steam zone grows and steam will accumulate in the reservoir. The temperature and pressure in such a steam reservoir vary slowly with depth. At Larderello, Italy, the reservoir temperature and pressure are 240 deg C and 35 bars, values that appear to be typical of other vapor-dominated systems.

Permeability

Permeability is a measure of a rock's capacity to transmit fluid as a result of pressure differences. The flow takes place in pores between mineral grains and in open spaces created by fractures and faults. Porosity is the term given to the fraction of void space in a volume of rock. Interconnected porosity provides flowpaths for the fluids, and creates permeability, although there is no simple relationship between porosity and permeability.

Permeability and porosity can be primary or secondary, i.e. formed with the rock or subsequently. Primary permeability in sedimentary rocks originates from intergranular porosity and it usually decreases with depth due to compaction and cementation. In volcanic sequences, primary intergranular porosity and permeability exist, but primary permeability also exists in open spaces at contacts between individual flows and within the flows themselves. Secondary permeability occurs in open fault zones, fractures and fracture intersections, along dikes and in breccia zones produced by hydraulic fracturing (5) and (6). Permeabilities in rocks range over 12 orders of magnitude. Permeabilities in pristine, unfractured crystalline rock are commonly on the order of E-6 darcy or less. However, in-situ measurements at individual sites may vary by as much as 4 to 6 orders of magnitude, and zones of >100 millidarcy are commonly encountered. These higher permeabilities are due to increased fracture density.

Most geothermal systems are structurally controlled, i.e., the magmatic heat source has been emplaced along zones of structural weakness in the crust. Permeability may be increased around the intrusion from fracturing and faulting in response to stresses involved in the intrusion process itself and in response to regional stresses. Thus, an understanding of the geologic structure in a resource area can lead not only to evidence for the location of a subsurface magma chamber, but also to inferences about areas of higher permeability at depth. Such areas would be prime geothermal exploration targets. Regarding exploration for hydrothermal systems, the key problem appears to be more in locating permeable zones than in locating high temperatures. Fractures sufficient to make a well a good producer need be only a few millimeters in width, but must be connected to the general fracture network in the rock in order to sustain large fluid volumes.

CLASSIFICATION OF GEOTHERMAL RESOURCES

Geothermal resources can be classified as shown in Table 1, modeled after (7). To describe resources, we resort to simplified geologic models. A given model is often not acceptable in all details to all geologists. In spite of disagreement over details, however, the models presented below are generally acceptable and facilitate our thinking.

Geothermal resource temperatures range upward from the mean annual ambient temperature (10 to 30 deg C) to over 350 deg C (Figure 6). For convenience, geothermal temperatures are arbitrarily divided into high, intermediate or moderate, and low temperatures, corresponding to the ranges T > 150 deg C, 90 < T < 150 deg C, and T < 90 deg C, respectively.

Convective Hydrothermal Resources

Convective hydrothermal resources are geothermal resources in which the earth's heat is carried upward by convective circulation of naturally occurring hot water or steam. Underlying some high-temperature hydrothermal resources is presumably an intrusion of still-molten or recently solidified rock whose temperature ranges between 300 and 1,100 deg C. Other convective resources result from circulation of water down fractures to depths where the rock temperature is elevated even in the absence of an intrusion, with heating and buoyant transport of the water to the surface.

Vapor-Dominated Systems. Figure 7 (8) shows a conceptual model of a hydrothermal system where steam is the pressure-controlling fluid phase, a so-called "vapor-dominated" geothermal system. Convection of deep saline water brings heat upward to a level where boiling can take place. Boiling removes the latent heat of vaporization, thereby cooling the rock and water and allowing more heat to rise from depth. Steam moves upward through fractures and is possibly superheated by the hot surrounding rock. At the top and sides of the system, heat is lost from the vapor and condensation results, with the condensed water moving downward to be vaporized again. Within the vapor-filled part of the reservoir, temperature is nearly uniform due to rapid steam flux. If an open fracture penetrates to the surface, steam may vent or may heat the shallow ground water to boiling. Pressure within the reservoir is controlled by the vapor phase and increases slowly with depth. Because the surrounding rocks typically contain ground water under hydrostatic pressure, a large horizontal pressure differential exists between the steam in the reservoir and the water in adjacent rocks, and a significant question revolves around why the adjacent water does not move in and inundate the reservoir. We postulate that permeability at the boundaries of the reservoir is low either as a result of pre-existing geological features such as impermeable beds or faults, or that it has been decreased by deposition of minerals in the fractures and pores to form a sealed zone. The formation of a vapor-dominated system appears to require venting of steam at a rate in excess of water recharge to prevent flooding of the reservoir (8).

Vapor-dominated systems may be formed from pre-existing water-dominated systems through special geological conditions. In fact, a hydrothermal system that is basically water dominated can have one or more natural zones which are vapor dominated, and vapor-dominated zones can result from production of fluids from a well if local water recharge is insufficient to keep pace with production.

The Geysers geothermal area in California is an example of this type of resource. Other producing vapor-dominated resources occur at Lardarello and Monte Amiata, Italy, and at Matsukawa, Japan.

Water-Dominated Systems. Figure 8 (after Mahon and others, 1980) illustrates a high-temperature, hot-water dominated geothermal system. Models for such systems have been discussed by (8), (9), (10), and (11), among others. The heat source is probably molten rock or rock that has solidified only in the last few tens of thousands of years, lying at a depth of perhaps 3 to 10 km. Ground water circulates downward in open fractures and removes heat from these deep, hot rocks. Rapid convection produces uniform temperatures over large volumes of the reservoir. In some places, boiling may occur and a two-phase region may exist, but the pressure is controlled by water. Recharge takes place at the margins. Escape of hot fluids is often minimized by a near-surface sealed zone or cap-rock formed by precipitation of minerals in fractures and pore spaces. Surface manifestations include hot springs, fumaroles, geysers, travertine deposits, chemically altered rocks, or alternatively, no surface manifestation at all. If there are no surface manifestations, discovery is difficult and requires sophisticated geology, geophysics, geochemistry and hydrology.

Isotopic studies of hydrothermal fluids show that the bulk of the water and steam is derived from meteoric water (rain or snow), with the exception of those few systems where the fluids are derived from seawater or connate brines (12). Only a small percentage of the water comes from the intrusive rocks at depth. As the fluids move through the reservoir rocks, the compositions of both the fluids and the rocks are modified by the dissolution of primary minerals and the precipitation of secondary minerals. The entire hydrothermal convection system (rocks and fluids) is, in fact, a large-scale chemical reactor with interactions that are not completely understood today. The waters generally become enriched in NaCl and depleted in Mg. Salinities of high-temperature geothermal fluids range from less than 10,000 ppm total dissolved solids in some volcanic systems to over 250,000 ppm total dissolved solids in basin environments such as the Salton Sea, California (13) and (14). Table 2 shows some typical chemical analyses for hydrothermal fluids.

The pressure and temperature in most high-temperature hydrothermal convection systems lie near the curve of boiling point versus depth for saline water, and sporadic, local boiling occurs in many systems. Because boiling concentrates acidic gases (CO_2 and H_2S) in the steam, the oxygenated meteoric water overlying a boiling reservoir is heated and acidified. These acidic waters interact with the near-surface rocks to form certain hydrothermal minerals, typically clays, that can be used to help locate zones of subsurface boiling.

Hydrothermal Reservoirs. At this point, it is desirable to discuss the term "reservoir". The reservoir is the volume containing hydrothermal fluids at a useful temperature. The porosity of the reservoir rocks determines the total amount of fluid available, whereas the permeability determines the rate at which fluid can be produced. One must not envisage a large bathtub of hot water that can be tapped at any handy location, however. Both porosity and permeability vary over wide ranges at different points in the reservoir. A typical well encounters tight, hot rocks with steam or hot water inflow mainly along a few open fractures or over a restricted stratigraphic interval. Apertures of producing fractures may be as little as a few millimeters. Areas where different fracture or fault sets intersect or where fractures intersect favorable stratigraphic units may be especially favorable for production of large volumes of fluid. The longevity of a well depends upon how completely the producing zones are connected to the local and reservoir-wide network of porosity. If this inter-zone permeability is poor, the local open spaces are drained quickly and fluid production drops. However, if the well intersects a thoroughgoing geologic structure such as a major fault or fracture, the local producing volume around the well is recharged continuously, and fluid production can be maintained for many years.

Virtually all of industry's geothermal exploration effort in the United States is presently directed at locating vapor- or water-dominated hydrothermal systems having temperatures above 200 deg C. A few of the highest grade resources are capable of commercial electrical power generation today, and the majority of the growth in geothermal energy production is expected to come from hydrothermal resources until well into the next century.

Intermediate- and Low-Temperature Systems. The fringe areas of high-temperature vapor- and water-dominated hydrothermal systems often produce water of low and intermediate temperature. These lower-temperature fluids are suitable for direct-heat applications and may also be used for electrical power production as new binary conversion technology becomes available. Low- and intermediate- temperature waters can also result from deep water circulation in areas where heat conduction and the geothermal gradient are merely average, as previously discussed.

Sedimentary Basins and Regional Aquifers

Some basins are filled to depths of 10 km or more with sedimentary rocks that have intergranular permeability. Such basins often contain accumulations of oil and gas. In some of the sedimentary units, circulation of ground water can be very deep. Vertical permeability is usually provided by faults. Water in deep rock units may be heated in a normal or enhanced geothermal gradient and may then either return to the near-surface environment or remain trapped at depth. Basin fluids range in chemical composition from relatively fresh water to highly saline. It is believed that many basin fluids were originally connate waters (trapped in the rocks at the time of formation) of seawater composition (15). Chemical interaction of these waters with rocks in the basin along their flowpaths leads to changes in the chemistry of the brine. Basins often contain evaporite beds of salts that dissolve easily in the basin fluids, bringing them to high salinities. An understanding of the chemistry of basin waters can sometimes lead to the identification of areas of upwelling fluids which may be thermally anomalous. Most basin waters are too low in temperature for the generation of electricity but may be used for direct applications such as space heating and greenhousing.

The Madison carbonate rock sequence of widespread occurrence in North and South Dakota, Wyoming, Montana, and northward into Canada contains warm waters that are currently being tapped by drill holes for space heating and agricultural purposes. In a similar application, space-heating systems installed in France use warm water contained in the Paris basin (16). Many other occurrences of this resource type are known worldwide.

Geopressured Resources

Geopressured resources also occur in basin environments. They consist of deeply buried fluids contained in permeable sedimentary rocks warmed in a normal or anomalous geothermal gradient by their great burial depth. The fluids are tightly confined by surrounding impermeable rock and bear pressure much greater than hydrostatic, that is, the fluid pressure supports a portion of the weight of the overlying rock column as well as the weight of the water column (Figure 9). A large amount of geopressured fluid is found in the Gulf Coast of the U.S. (Figure 12), where it generally contains dissolved methane. Therefore, three sources of energy are actually available from these resources: 1) heat, 2) mechanical energy due to the great pressure with which these waters exit the borehole, and 3) recoverable methane.

The U.S. Department of Energy, is currently sponsoring research to develop a better understanding of geopressured resources and exploitation technologies. Activities include the testing of geopressured wells to determine the nature and extent of the resource, its production characteristics and the potential environmental effects of long-term production. The research also includes the design and analysis of a total energy recovery system. These resources will probably contribute during the mid to late 1990s or the next century.

Radiogenic Resources

Research has been done that could lead to development of radiogenic geothermal resources in the eastern U.S. (17). The coastal plain of the East is blanketed by a layer of thermally insulating sediments. In places beneath these sediments, rocks occur that have an anomalously high rate of heat production due to decay of natural radioactive isotopes of uranium, thorium and potassium. These radioactive rocks represent old granitic intrusions, long since cooled. Methods for locating radiogenic rocks beneath sedimentary cover have been partly developed, and very limited drill testing of the geothermal target concept (Figure 11) has been completed under DOE funding, although no such research is being conducted by the federal government today.

Hot Dry Rock Resources

Hot dry rock resources are defined as heat stored in rocks within about 10 km of the surface from which the energy cannot be economically extracted by natural hot water or steam. These hot rocks have few pore spaces or fractures, and therefore contain little water and little or no interconnected permeability. The feasibility and economics of extraction of heat from hot dry rock has, for the past decade, been the subject of a $150 million research program at the Department of Energy's Los Alamos National Laboratory in New Mexico (18). Batchelor (19) describes similar research in England. Both projects indicate that it is technologically feasible to induce an artificial fracture system in hot, tight rocks at depths of about 3 km through hydraulic fracturing from a deep well. During formation of the fracture system, its dimensions, location and orientation are mapped using geophysical techniques. A second borehole is located and drilled such that it intersects the hydraulic fracture system. Water can then be circulated down one hole, through the fracture system where it removes heat from the rocks, and up the second hole (Figure 10).

The principal aim of the research at Los Alamos is to develop the engineering data needed for industry to evaluate the economic viability of candidate resources. The current plans are for a one-year flow test of the existing two-well system in order to determine production characteristics of the artificially created fracture system and its thermal drawdown and rate of water loss. Hot dry rock energy may contribute to our energy mix in the 1990s or in the next century.

Molten Rock (Magma) Resources

Experiments are underway at the Department of Energy's Sandia National Laboratories in Albuquerque, New Mexico to learn how to extract heat energy directly from molten rock. Techniques for locating a shallow, crustal magma body, drilling into it and implanting heat exchangers or possibly direct electrical converters are being developed (20). In Iceland, where geothermal energy was first used for space heating in 1928, technology has been demonstrated for economic extraction of thermal energy from young lava flows (21). A heat exchanger constructed on the surface of the 1973 lava flow on Heimaey recovers steam which results from downward percolation of water applied at the surface above hot portions of the flow. A space heating system which uses this energy has been operating successfully for over ten years.

GEOTHERMAL RESOURCES IN THE UNITED STATES

Figure 12 displays the distribution of known geothermal resources in the United States. Information for this figure was taken mainly from Muffler et al. (22) and Reed (23). Not shown are locations of hot dry rock or magma resources because very little is known. In addition, it should be emphasized that the present state of knowledge of geothermal resources of all types is limited.

Most of the hydrothermal resources and all of the presently known resources capable of electric power generation occur in the West. Large areas underlain by warm waters in sedimentary rocks exist in Montana, North and South Dakota, and Wyoming (the Madison Group of aquifers). Another important large area of low-temperature water is the north east-trending Balcones zone in Texas. The geopressured resource areas of the Gulf Coast and surrounding states are also shown. Resource areas indicated in the eastern states are highly speculative. Low temperature resources are much more plentiful than are high-temperature resources. Muffler et al. (22) and Reed (23) conclude that the cumulative frequency of occurrence increases exponentially as reservoir temperature decreases (Figure 13).

Let us consider the known geothermal occurrences in a bit more detail, beginning in the Western U. S. Figure 14 shows a physiographic map of the U.S. to help in locating the areas discussed, and Table 3 lists the geologic time scale.

Salton Trough/Imperial Valley, CA

The Salton Trough lies along the landward extension of the Gulf of California. It is composed of the Imperial Valley in the U.S. and the Mexicali Valley in Mexico. The area is one of complex, currently active plate tectonic processes. The crest of the East Pacific Rise spreading center is offset repeatedly northward up the Gulf of California by transform faulting (Figure 2). Both the rise crest and the transform faults come onto the continent under the delta of the Colorado River (Figure 15) and the structure of the Salton Trough suggests that they underlie the trough.

The Salton Trough has been an area of subsidence since Miocene times (7-23 million years before present, mybp). Sedimentation in the tough has paced subsidence, with debris from the Colorado River predominating. At present, 3 to 5 km of poorly-consolidated sedimentary material overlie a basement of Mesozoic crystalline rocks that intruded Paleozoic and Precambrian sedimentary rocks. Detailed analysis of drilling data and of surface and downhole geophysics indicates that at least some of the known geothermal occurrences (Cerro Prieto, Brawley and the Salton Sea) are underlain by pull-apart basins apparently caused by crustal spreading above a local section of the East Pacific Rise crest (24). Very young volcanic activity has occurred at Cerro Prieto where a rhyolitic volcanic cone is known, and along the southern margin of the Salton Sea where rhyolite domes occur. The Salton Sea domes are approximately 60,000 years old (25).

The Cerro Prieto hydrothermal field provides an example of a Salton Trough resource type. This field is water-dominated producing from depths of 1.5 to over 3 km. Fluid temperatures range from about 200 deg C to over 350 deg C (26). The rocks are composed of an upper layer of unconsolidated silts, sands and clays, and a layer of consolidated sandstones and shales overlying the crystalline basement (27). Two principal reservoir horizons occur in sandstones within the consolidated sequence. Enhanced production has been noted in the vicinity of faults, indicating that fracture permeability is important, although intergranular permeability due to dissolution of minerals by the geothermal fluids is believed to be important also (28). Reservoir recharge is apparently from the northeast and east and consists partly of Colorado River water (29). A conceptual model of fluid flow at Cerro Prieto (Figure 16) has been developed by Halfman et al. (30). They conclude that water flows upward from depth within permeable sandstone units that have a shallow dip. The permeable units are overlain by impermeable shales, and the water gains access to permeable units higher in the section through breaks in the shales.

The geothermal fluid from Cerro Prieto, after steam separation, contains about 25,000 ppm total dissolved solids. This figure is much lower than some of the other resources in the Salton Trough. For example, the Salton Sea hydrothermal field contains 20 to 30 percent by weight by solids.

The Geysers, CA

The Geysers geothermal area is the world's largest producer of electricity from geothermal fluids with about 1,800 MWe from 22 plants on line and an additional 800 MWe scheduled. This area lies about 150 km north of San Francisco. The portion of the resource being exploited is a vapor-dominated field having a temperature of 240 deg C. The ultimate potential of the vapor-dominated system is not known. Associated with the vapor-dominated field are believed to be several unexploited hot water-dominated reservoirs whose volumes and temperatures are unassessed (Figure 17).

The geology of The Geysers area is complex, especially structurally. Reservoir rocks consist mainly of fractured greywackes, which are sandstone-like rocks consisting of poorly sorted fragments of quartzite, shale, granite, volcanic rocks and other rocks. Fracturing has created the reservoir permeability. Overlying the reservoir rocks is a series of impermeable metamorphosed rocks (serpentinite, geenstone, melange and metagranite) that forms a cap on the system.

The presently known steam field is confined between the Mercuryville fault zone on the southwest and the Collayomi fault zone on the northeast (Figure 18). The northwest and southeast margins of the steam field are not definitely known. Surface manifestations of the steam field include two small areas, the largest one being known as The Big Geysers, an area of hot springs, fumaroles and hydrothermal alteration. The extent of surface manifestations is curiously small compared to the large size of the underlying steam resource.

To the east and northeast lies the extensive Clear Lake volcanic field composed of dacite, rhyolite, andesite and basalt. The interval of eruption for these volcanics extends from 2 million to 10,000 years ago, with ages progressively younger northward (31). The Clear Lake volcanics are very porous and soak up large quantities of surface water. It is believed that recharge of a deep, briny hot-water reservoir comes from water percolating through the Clear Lake volcanics, and that this deep reservoir supplies steam to the vapor-dominated system through boiling (Figure 17), although the deep water table has never been intersected by drilling. Geophysical surveys indicate the presence of a large magma chamber underlying the Clear Lake volcanic rocks and centered on Mt. Hanna, immediately northeast of the Collayomi fault zone (32).

Basin and Range

The Basin and Range province extends northward from Mexico into southern Arizona, southwestern New Mexico and Texas on the south, through parts of California, Nevada and Utah, and becomes ill-defined beneath the covering volcanic flows of the Columbia Plateau and the Snake River plain on the north (Figure 14). The northern portion of this area contains abundant geothermal resources of all temperatures. Resources along the eastern and western margins of the province appear to be both more abundant and of higher temperature.

Electrical power is presently being generated from Roosevelt Hot Springs (20 MWe) and Cove Fort/Sulphurdale (3.2 MWe) in Utah; from Beowawe (17 MWe), Desert Peak (9 MWe), Wabuska (0.6 MWe), and Steamboat Springs (5.4 MWe) in Nevada; and from Coso Hot Springs (30 MWe) in California. Exploration is being or has been conducted at probably 20 or more sites. Direct application of geothermal energy for industrial process heating and space heating are currently operating in this area at several sites including Brady Hot Springs (vegetable drying), Reno (space heating) and Salt Lake City (greenhouse heating).

The reasons for the abundance of resources in the Basin and Range seem clear. This area, especially at its margins, is an active area geologically. Volcanism only a few hundred years old is known from tens of areas. The area is also active seismically and faulting that causes the uplift of mountain ranges also serves to keep pathways open for deep fluid circulation.

As an example of a Basin and Range hydrothermal system, we will discuss Roosevelt Hot Springs, although it should not be supposed to be typical of all high-temperature occurrences in this province. The oldest rocks exposed (Figures 19 and 20) are Precambrian sedimentary rocks that have been extensively metamorphosed. These rocks were intruded during Miocene time (7-23 mybp) by granitic rocks (33) and (34). Rhyolite volcanic flows and domes were emplaced during the interval 800,000 to 500,000 years ago. The area has been complexly faulted by north- to northwest-trending high-angle faults and by east- west high-angle faults. The Negro Mag fault is such an east-west fault that is an important controlling structure in the north portion of the field. The north- trending Opal Mound fault apparently forms the western limit of the system. The oldest fault system is a series of low-angle denudation faults (Figure 20) along which the upper plate has moved west by about 600 m and has broken into a series of discrete blocks. Producing areas in the southern portion of the field are located in zones of intersection of the upper-plate faults with the Opal Mound and other parallel faults. Producing zones in the northern part of the region are located at the intersection of north-south and east-west faults. The permeability is obviously fracture controlled.

Cascade Range and Vicinity

The Cascade Range of northern California, Oregon, Washington and British Columbia is comprised of a series of volcanos, 12 of which have been active in historic times. The May 18, 1980 eruption of Mount St. Helens attests to be the youth of volcanic activity here. The Cascade Range lies above the zone of subduction of the Juan de Fuca plate beneath the North American plate, (Figure 2) and magma moving into the upper crust has transported large amounts of heat upward. In spite of the widespread, young volcanism, however, geothermal manifestations are not as plentiful as expected. High rainfall and snowfall in the Cascades are believed to suppress surface geothermal manifestations through downward percolation of the cold surface waters in the highly permeable volcanic rocks. In the absence of surface manifestation, discovery becomes much more difficult.

No producible high-temperature hydrothermal systems have yet been located in the Cascades. A vapor-dominated system is present at Lassen Peak in California, but it lies within a national park, and will not be developed. A hydrothermal system having temperatures greater than 200 deg C has been located at Newberry Caldera in Oregon through research drilling sponsored by the U. S. Geological Survey (35), but the known portion of the system lies within the caldera and will not be exploited for environmental reasons.

Industry's exploration efforts have increased somewhat in the last several years. The Department of Energy is currently sponsoring a cost-shared drilling program with industry to encourage more subsurface exploration and to help develop research data for devising new exploration techniques. To date, two holes have been drilled at Newberry volcano by GEO Operator Corporation, and one hole has been completed by Thermal Power Company north of Mt. Jefferson. A third research hole has been started on the southeast slope of Mt. Mazama, the volcano whose summit consists of the Crater Lake caldera. This hole has found interesting temperatures at shallow depths (+100 deg C at 1300 feet), but the hole remains unfinished at this writing.

The use of geothermal energy for space heating at Klamath Falls, Oregon is well established (36), and numerous hot springs and wells occur throughout the Cascades. Potential for discovery of resources in all temperature categories is great (37).

Snake River Plain

The basalt flows and other volcanic deposits of the Snake River Plain are an extension of the Columbia Plateau eastward across southern Idaho to the border with Wyoming. The Plain is divided into a western part and an eastern part. Thermal waters occur in numerous wells and springs in the western portion, especially on or near the edges of the plain. Geochemically indicated resource temperatures exceed 150 deg C at Neal Hot Springs and Vale, Oregon and Crane Creek, Idaho, but indicated temperatures for most resources are lower. Younger volcanic rocks occur in the eastern part of the plain, but no high-temperature resources are yet identified. This part of the plain is underlain by a high-flow, cold-water aquifer that is believed to mask surface geothermal indications.

The ages of volcanic eruptions decrease from west to east along the Snake River Plain, apparently reflecting the arcuate track of a mantle plume as the North American plate moved westward. Recent volcanic activity has taken place at Yellowstone, under which the hot spot currently lies. Future violent eruptions in the area are possible. The vapor- and water-dominated hydrothermal systems at Yellowstone will not be developed because they lie within a national park, but surrounding areas are highly prospective.

Direct use of hydrothermal energy for space heating is famous at Boise, Idaho, where the Warm Springs district has been heating homes geothermally for almost 100 years (38). Also, near this area, but lying in the Basin and Range, is the Raft River site where the Idaho National Engineering Laboratory of DOE constructed and operated a 5 MWe binary demonstration plant on a hydrothermal resource whose temperature is 147 deg C. This project is currently inoperative and the plant has been sold.

Rio Grande Rift

The Rio Grande Rift is a north-trending tectonic feature that extends from Mexico through central New Mexico and ends in central Colorado. It is a down-dropped area that has been filled with volcanic rocks and erosional debris from the bordering plateaus and mountains. The rift began to form in late Oliogocene times (23-38 mybp), and volcanic and seismic activity have occurred subsequently to the present.

There are several low- and intermediate-temperature hydrothermal convection systems in this area, but the only high-temperature system that has been drill tested to any significant extent and where production is proven is a hot water-dominated system in the Valles caldera (39) and (40). Deep drilling has encountered a hydrothermal convection system in fractured Tertiary volcanic, Paleozoic sedimentary and Precambrian granitic rocks at an average depth of 2 to 3 km. Temperatures as high as 300 deg C have been recorded. An attempt by DOE, Union Geothermal and Public Service Company of New Mexico to build a demonstration plant at that location failed when the steam supply proved to be inadequate. Recent research drilling, sponsored by DOE under the Continental Scientific Drilling Program, has developed an improved understanding of the area. Geologists believe that the area contains an important, undiscovered hydrothermal resource capable of electrical power generation. Also located near the caldera is the site of Los Alamos National Laboratory's DOE sponsored hot dry rock experiment at Fenton Hill.

Madison and other Aquifers

Underlying a large area in western North and South Dakota, eastern Montana and northeastern Wyoming are a number of aquifers that contain thermal waters. These aquifers have developed in carbonates and sandstones of Paleozoic and Mesozoic age. The permeability is both intergranular and fracture controlled in the case of the sandstones (e.g. the Dakota Sandstone) and fracture and solution cavities in the carbonates (e.g. the Madison Limestone). Some of the aquifers produce under artesian pressure. Depths to production vary widely but average perhaps 2,000 ft. Temperatures are 30 to 80 deg C (41) in the Madison but are lower in other shallower aquifers such as the Dakota. Direct use of the thermal water is being made at a few locations today (42), and it is evident that the potential for further development is substantial.

Balcones Zone, TX

Thermal waters at temperatures generally below 60 deg C occur in a zone that trends northeasterly across central Texas. Many of the large population centers are in or near this zone, and there appears to be significant potential for geothermal development in spite of the rather low temperatures.

An initial assessment of the geothermal potential has been documented by Woodruff and McBride (43). The thermal waters occur in a band broadly delimited by the Balcones fault zone on the west and the Luling-Mexia-Talco fault zone on the east. In many locations the thermal waters are low enough in content of dissolved salts to be potable, and indeed many communities already tap the warm waters for their municipal water supplies.

The geothermal aquifers are mostly Cretaceous (65-140 mybp) Sandstone units, although locally thermal waters are provided from Cretaceous limestones and Tertiary sandstones. The thermally anomalous zone coincides with an ancient zone of structural weakness dating back more than 200 million years. The zone has been a hinge line with uplift of mountain ranges to the north and west and downwarping to the south and east. Sediments have deposited in the area of downwarping, and the rate of sedimentation has kept pace with sinking, keeping this area close to sea level. Structural deformation of the sediments, including faulting and folding, and interfingering of diverse sedimentary units have resulted in the complex aquifer system of today. The source of the anomalous heat is not known with certainty.

Hawaiian Islands

The chain of islands known as the Hawaiian archipelago stretches 2,500 km in a northwest-southeast line across the Pacific Ocean from Kure and Midway Islands to the Big Island of Hawaii. Built of basaltic volcanic rocks, this island chain boasts the greatest volcanic masses on earth. The volcano Kilauea rises 9,800 m above the floor of the ocean, the world's largest mountain in terms of elevation above its base. The Kilauea, Mauna Loa and other vents on the big island are in an almost continual state of eruptive activity, but by contrast volcanos on the other islands have shown little recent activity. Haleakala on the island of Maui is the only other volcano in the state that has erupted in the last few hundred years, and the last eruption there was in 1790 (44).

Several of the Hawaiian islands are believed to have geothermal potential. The only area where exploration has proceeded far enough to establish the existence of a hydrothermal reservoir is in the Puna district on the Big Island near Kapoho along the so-called "East Rift", a fault zone on the east flank of Kileaua. Here a well was completed to a depth of 1965 m (45) with a bottom- hole temperature of 358 deg C. A 3 MWe generator is currently being operated at the site. Exploration is underway by several companies in areas adjacent to the operating plant. Elsewhere on the islands, potential for occurrence of low- to moderate-temperature resources has been established at a number of locations on Hawaii, Maui and Oahu, although little drilling to prove resources has been completed (46).

Alaska

Little geothermal exploration work has been done in Alaska. A number of geothermal occurrences are located on the Alaska Peninsula and the Aleutian Islands and in central and southeast Alaska. The Aleutians and the Peninsula overlie a zone of active subduction (Figure 2), and volcanos are numerous. A hydrothermal system was located at Makushin volcano on the island of Unalaska (47) and the island of Adak is also believed to have good discovery potential.

Low- and moderate-temperature resources are indicated in a number of locations in Alaska by occurrence of hot springs (22). One area that has been studied in more detail and has had limited drilling is Pilgrim Hot Springs (48). This site is 75 km north of Nome, Alaska. Initial drilling has confirmed the presence of a hot water reservoir about 1 sq km in extent that has artesian flow rates of 200-400 gallons per minute of 90 deg C water.

POTENTIAL FOR GEOTHERMAL DEVELOPMENT IN THE U.S.

Muffler et al. (22) have dealt with the problem of how much accessible resource exists in the U. S. both at known sites and those that are undiscovered. They conclude that about 1650 EH8J of energy are present in reservoirs of 215 identified hydrothermal systems in the U.S. having temperatures greater than 90 deg C and excluding national parks. Recoverable thermal energy at the surface from these systems is estimated to be 400 EH8J, which is sufficient to produce 23,000 megawatts of electricity for 30 years and to produce 42 EH8J of direct heat. The undiscovered hydrothermal resource base is estimated to be about five times greater than the known resources. These figures do not include possible hot dry rock or other more speculative resources. Table 4 is a summary of the current estimate of the geothermal resource base as taken from Muffler et al. (22). This table demonstrates our lack of resource knowledge through the ranges and relative amounts of undiscovered resources and through the many missing numbers. We can conclude, however, that the geothermal resource base is large in the U.S.

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Table 1

Geothermal Resource Classification

Resource Type	Temperature Characteristics
Convective Hydrothermal Resources	
Vapor dominated	~ 240°C
Hot-water dominated	~ 30°C to 350°C+
Other Hydrothermal Resources	
Sedimentary basins/Regional aquifers (hot fluid in sedimentary rocks)	~ 30°C to 150°C
Geopressured (hot fluid under pressure that is greater than hydrostatic)	~ 90°C to 200°C
Radiogenic (heat generated by radioactive decay)	~ 30°C to 150°C
Hot Rock Resources	
Part still molten	higher than 600°C
Solidified (hot, dry rock)	90° to 650°C

Table 3

Geologic Time Scale

(millions of years)
(from van Eysinga, 1978)

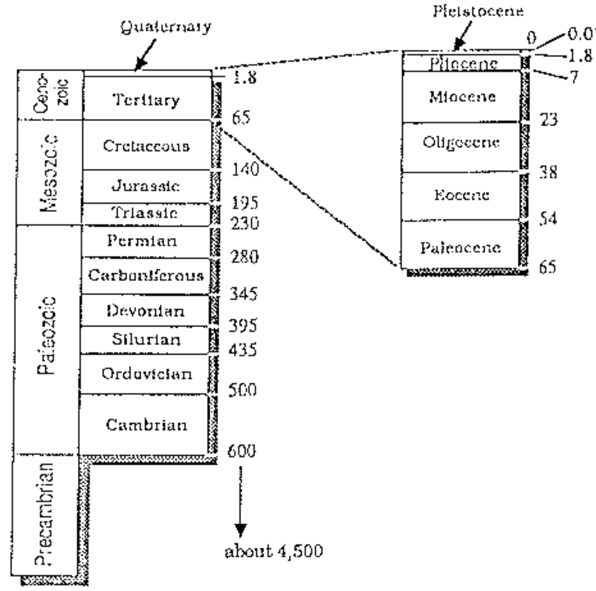


Table 2

Representative Analyses of Geothermal Fluids

Sample #		1	2	3	4	5	6
Temp. °C		42	89	255	<260	292	316
pH			7.9	8.4			
SiO_2	(ppm)	52	293	690	563	705	400
Ca	(ppm)	257	5	17	8	592	28,000
Mg	(ppm)	17	.8	.03	<2	.6	54
Na	(ppm)	578	653	1,320	2,320	6,382	50,400
K	(ppm)		71	255	461	1,551	17,500
Li	(ppm)	.5	.7	14.2	25.3	14.5	215
HCO	(ppm)		305		232	28	7,150
SO	(ppm)	932		36	72	<3.5	5
Cl	(ppm)	625	865	2,260	3,860	11,918	155,000
F	(ppm)	2.8	1.8	8.3	6.8		15
B	(ppm)	2.6	4.9			13.4	390
As	(ppm)		2.7	4.8	4.3		12

Sample Descriptions:

1. Hot spring, Monroe, UT.
2. Hot spring, Steamboat, NV.
3. Well 44, Wairakei, New Zealand.
4. Brine discharged from well 54-3, Roosevelt Hot Springs, UT.
5. Analyses calculated from flashed brine, well M-26, Cerro Prieto, Mex.
6. Brine discharged from well 11D, Salton Sea Geothermal Field, CA.

Table 4

Geothermal Energy of the United States

After Muffler et al. (1978) Table 20

RESOURCE TYPE	ELECTRICITY (MWe for 30 yr)	BENEFICIAL HEAT (10^{18} joules)	RESOURCE (10^{18} joules)
Hydrothermal			
Identified	23,000	42	400
Undiscovered	72,000-127,000	184-310	2,000
Sedimentary Basins	?	?	?
Geopressured (N. Gulf of Mexico)			
Thermal			270-2800
Methane			160-1600
Radiogenic	?	?	?
Hot Rock	?	?	?

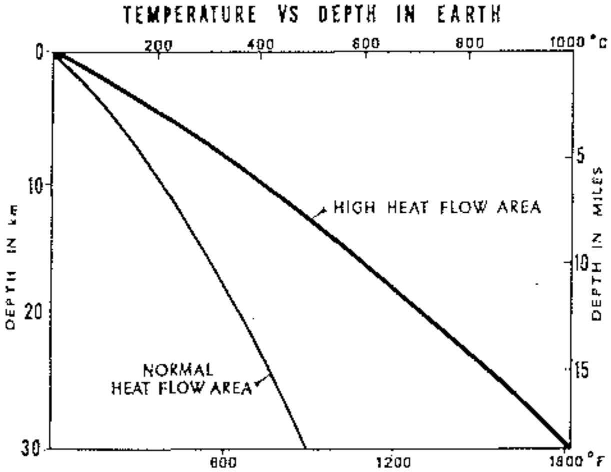


FIGURE 1

INTERIOR OF THE EARTH

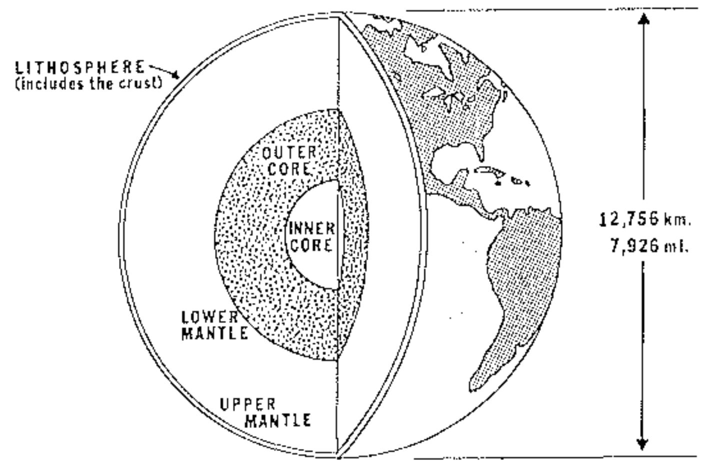
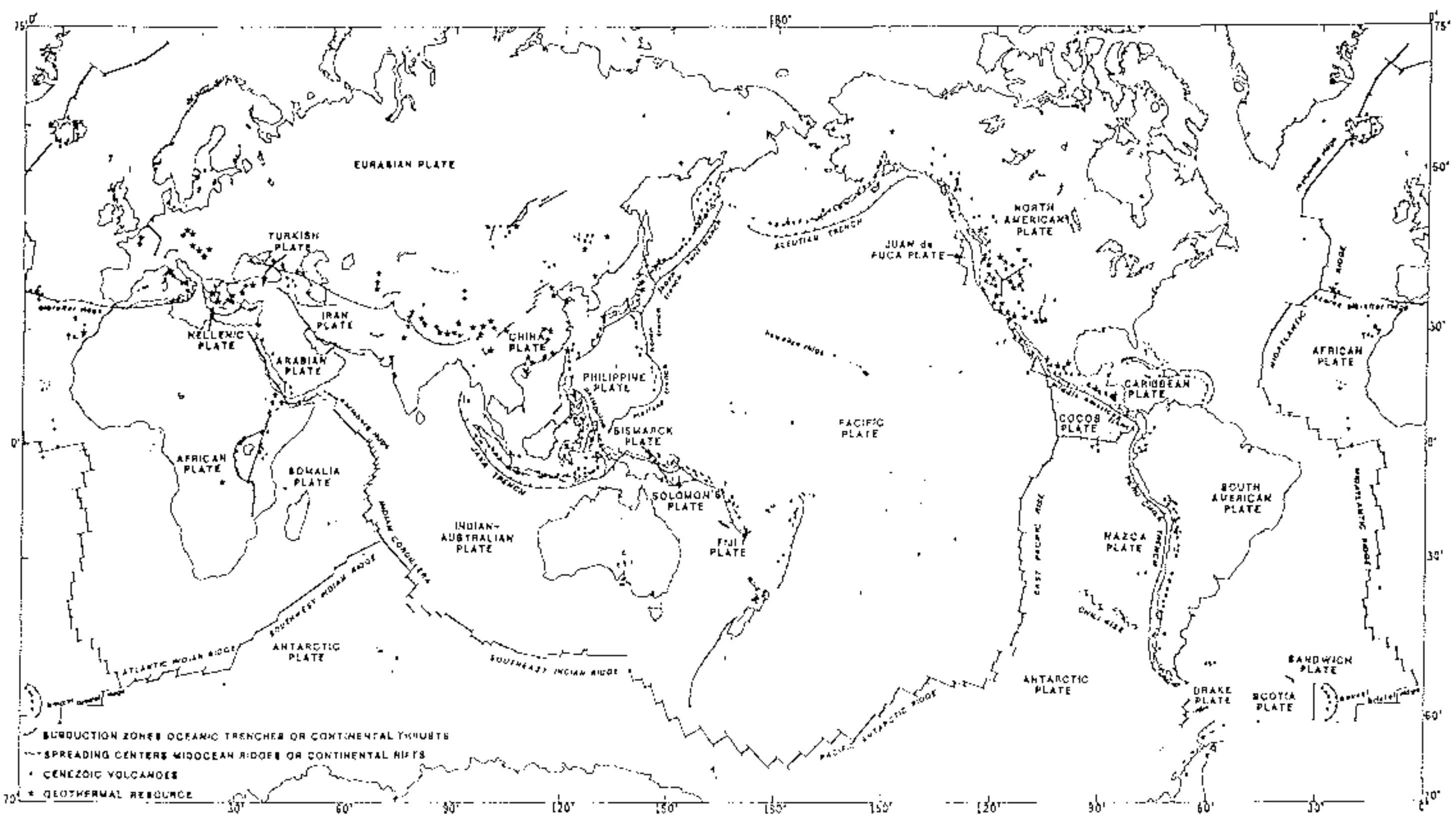


FIGURE 3



GEOTHERMAL RESOURCES AND PLATE TECTONIC FEATURES

FIGURE 2

CONCEPT OF PLATE TECTONICS

(NOT TO SCALE)

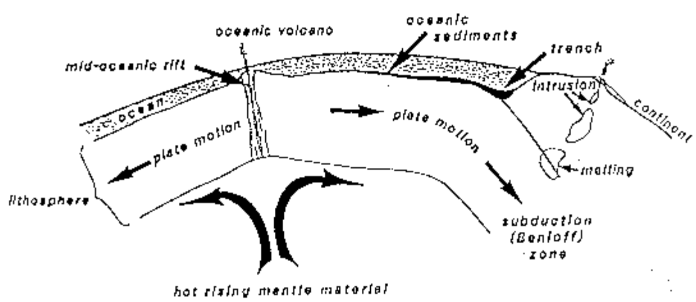


FIGURE 4

Geothermal Temperatures

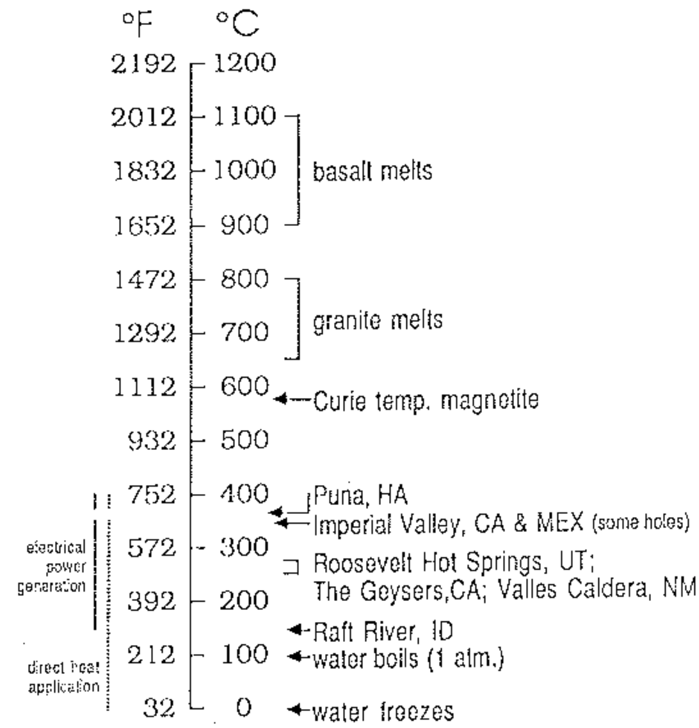


Figure 6

CRUSTAL INTRUSION

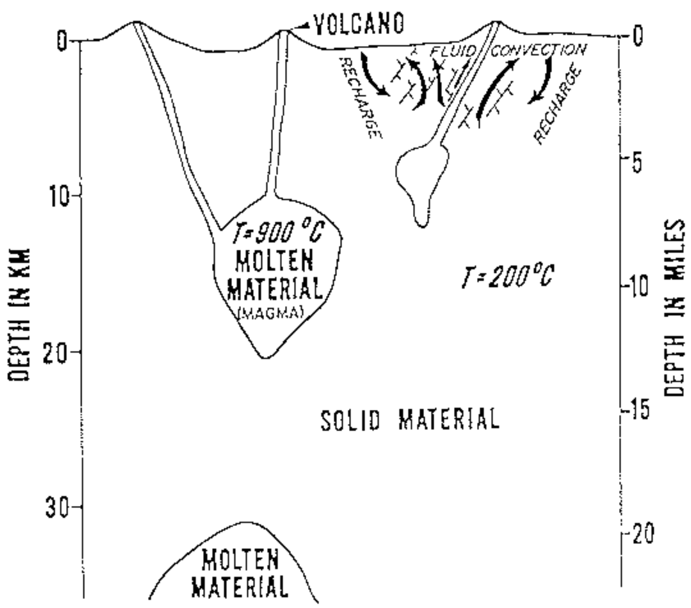


FIGURE 5

VAPOR DOMINATED GEOTHERMAL RESERVOIR

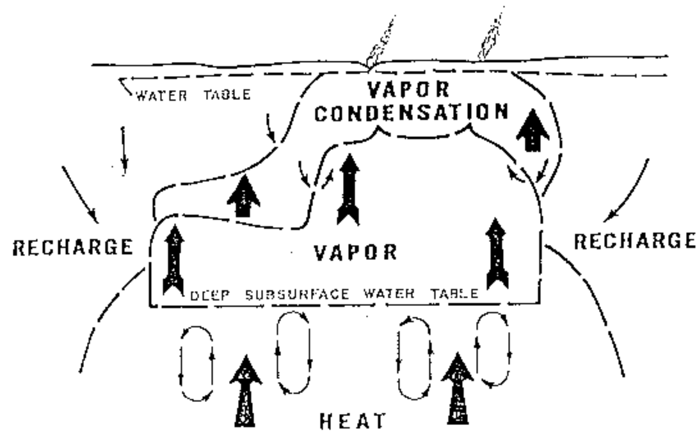


FIGURE 7

HYDROTHERMAL SYSTEM IN VOLCANIC TERRANE

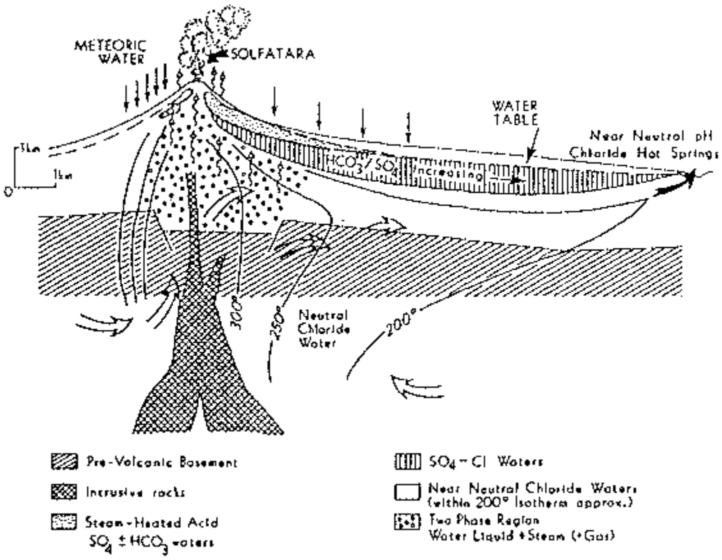
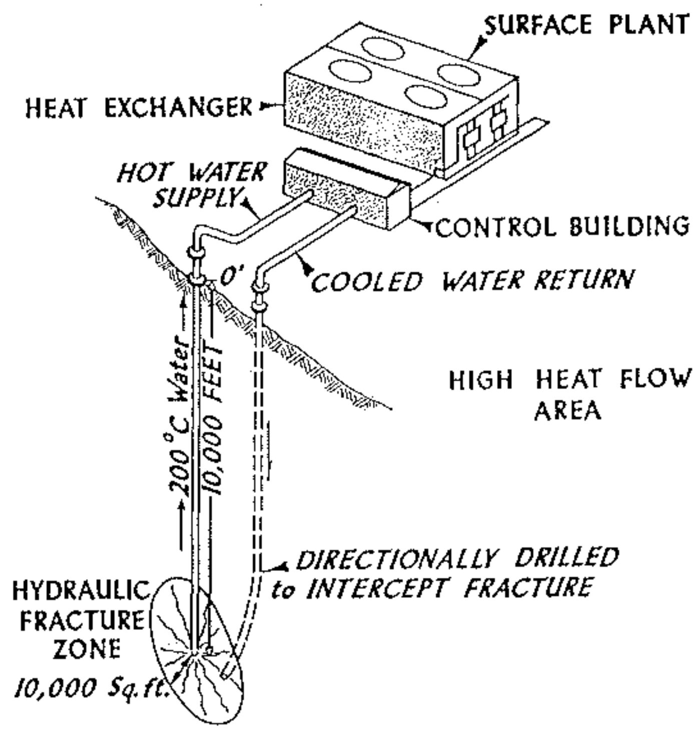


FIGURE 8



HOT DRY ROCK GEOTHERMAL RESOURCE

FIGURE 10

GEOPRESSURED GEOTHERMAL RESOURCES

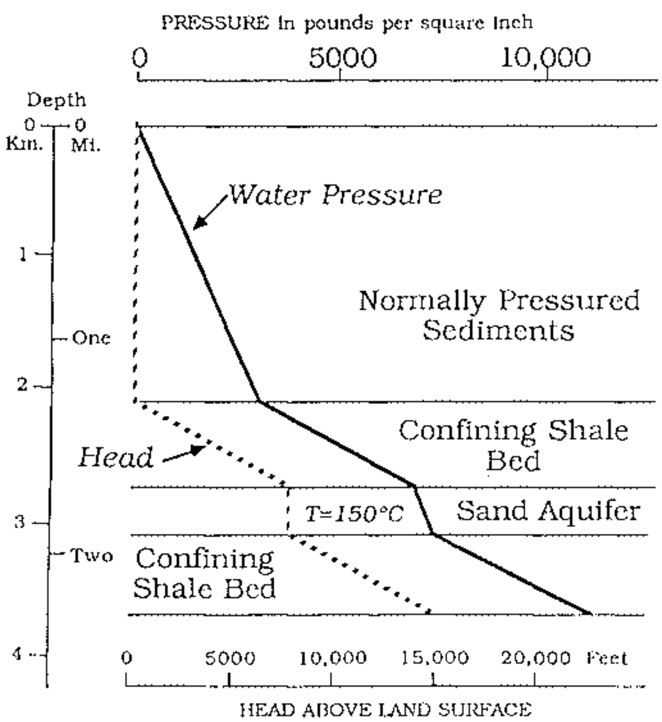


FIGURE 9

RADIOGENIC GEOTHERMAL RESOURCE

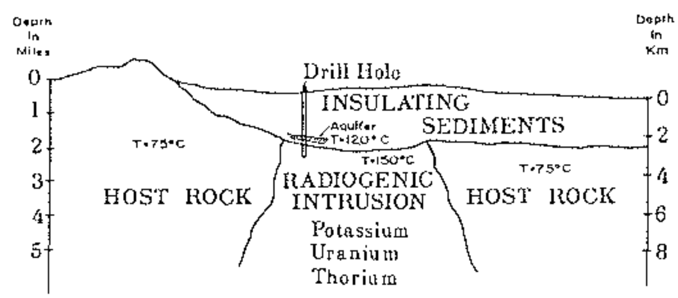


FIGURE 11

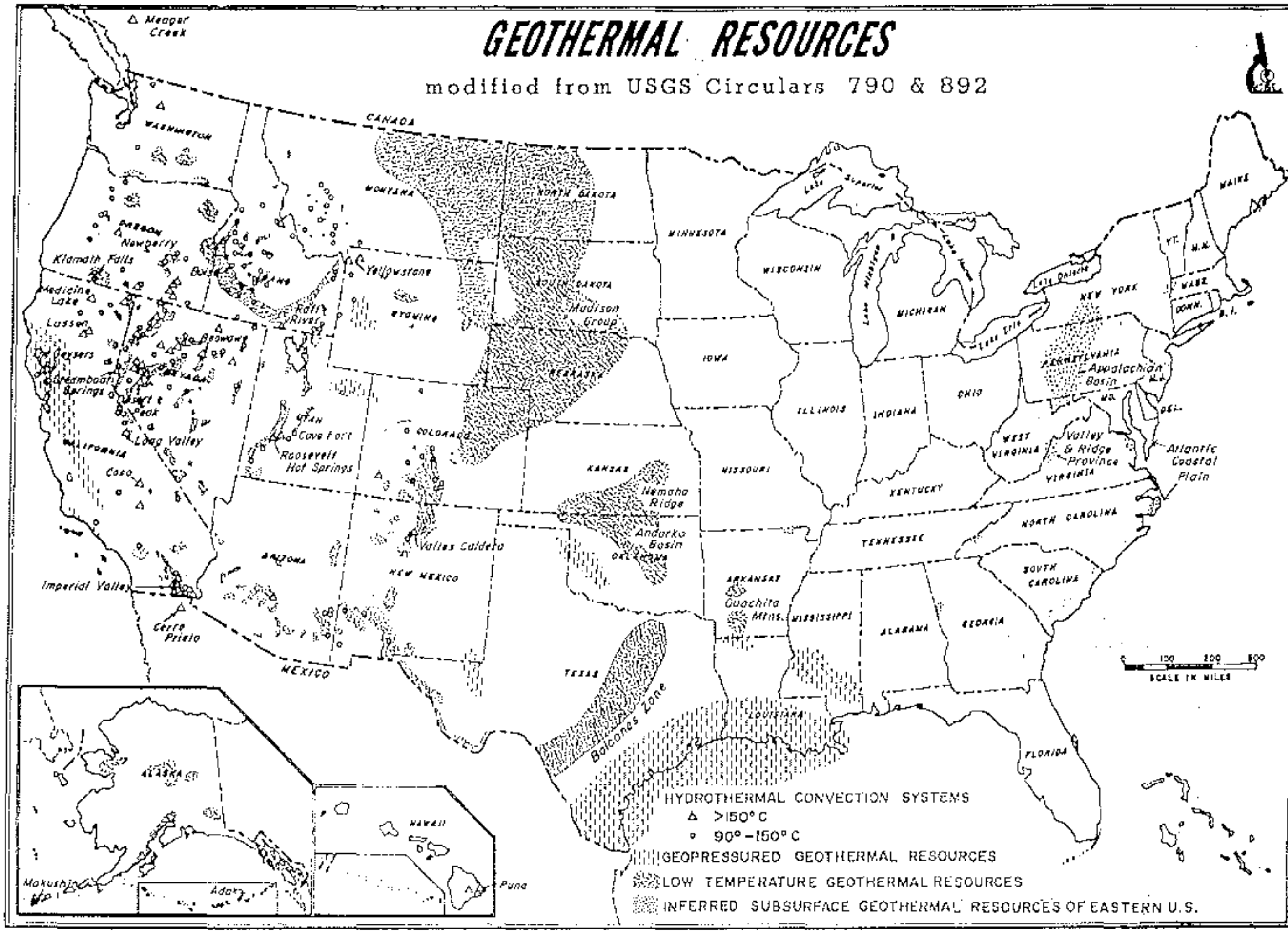
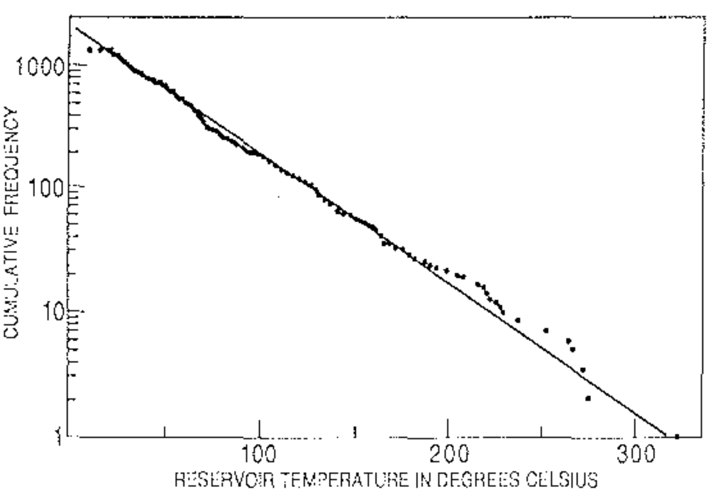
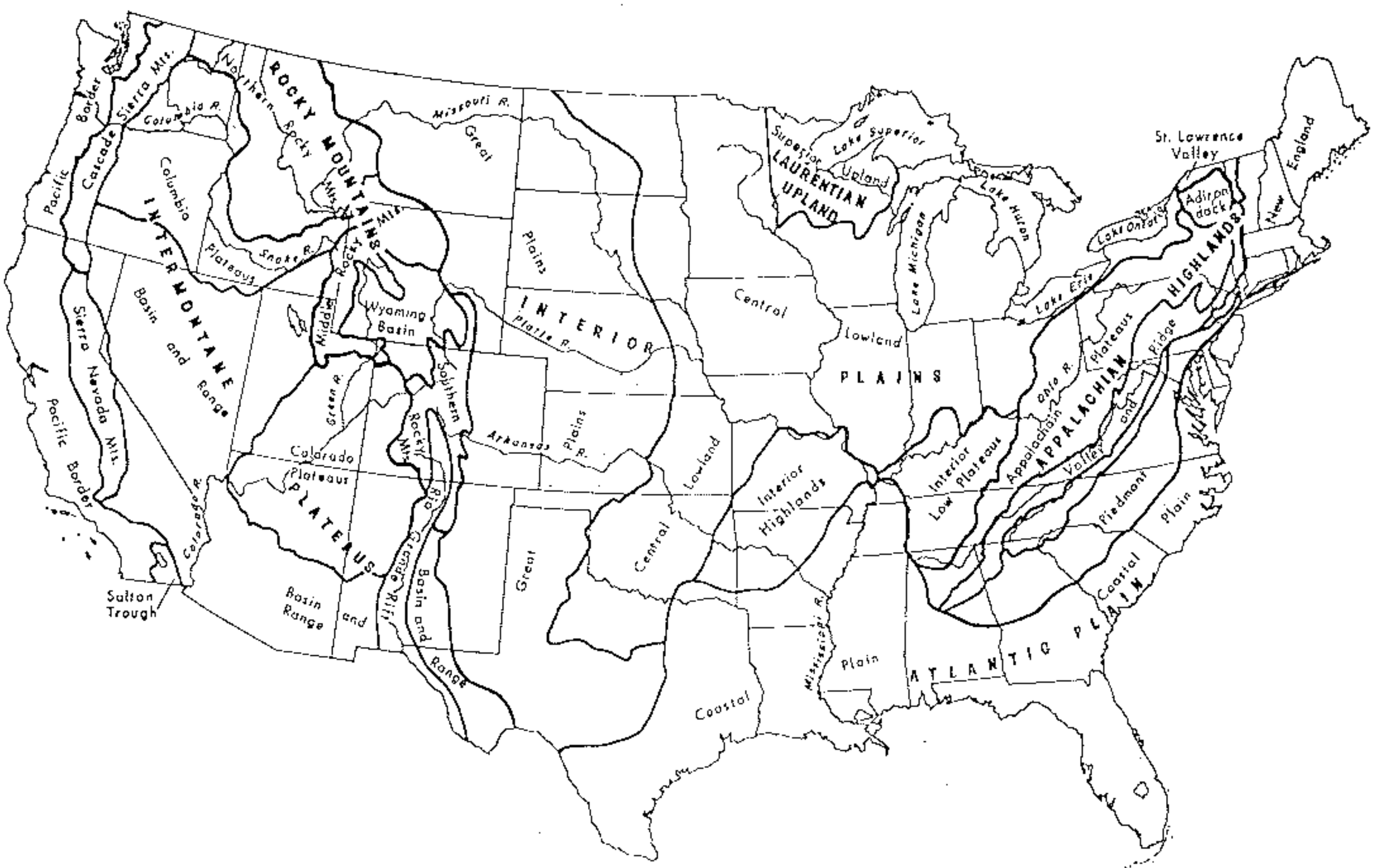


FIGURE 12



(after Reed, 1982)

FIGURE 13

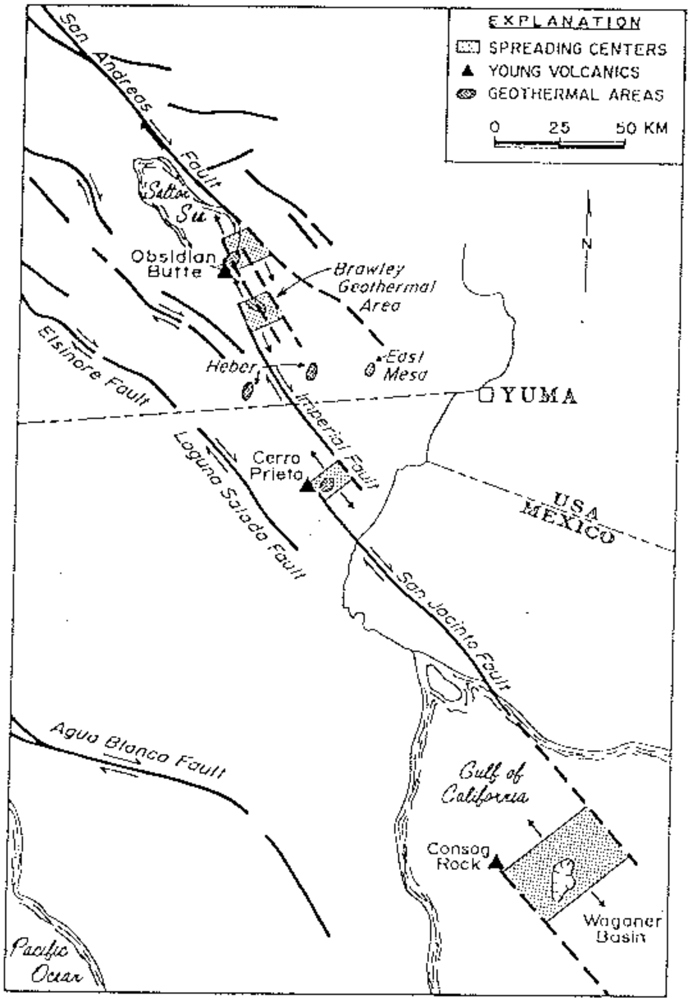


PHYSIOGRAPHIC MAP of USA

(after Fenneman, 1928)

SCALE
0 100 200 300 400 MILES
0 200 400 600 KILOMETERS

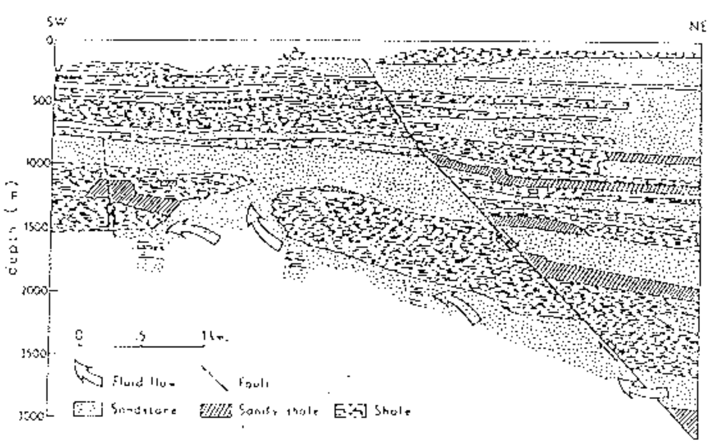
FIGURE 14



MAJOR STRUCTURES OF SALTON TROUGH

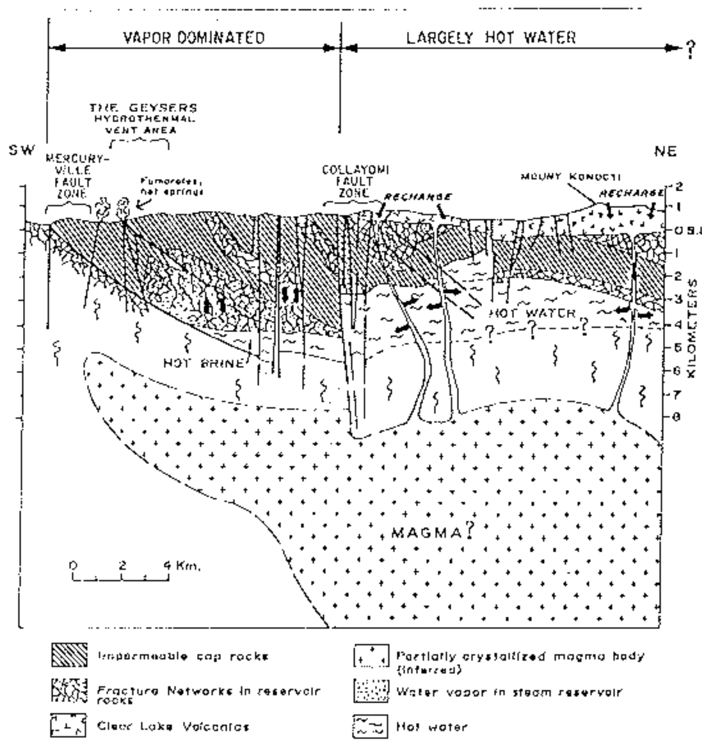
(after Palmer et al., 1975)

FIGURE 15



FLUID FLOW MODEL OF CERRO PRIETO, MEXICO

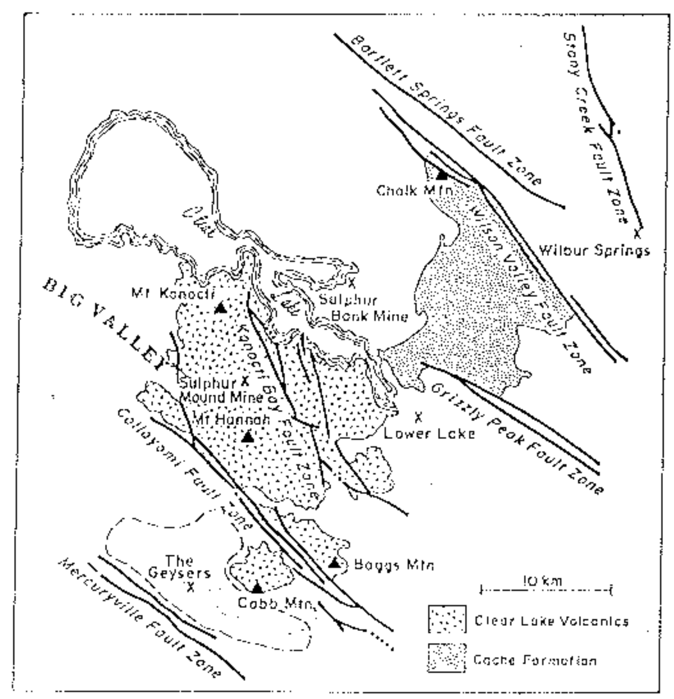
FIGURE 16



CRUSTAL MODEL FOR THE GEYSERS - CLEAR LAKE AREA, CA.

(after McLaughlin, 1977)

FIGURE 17

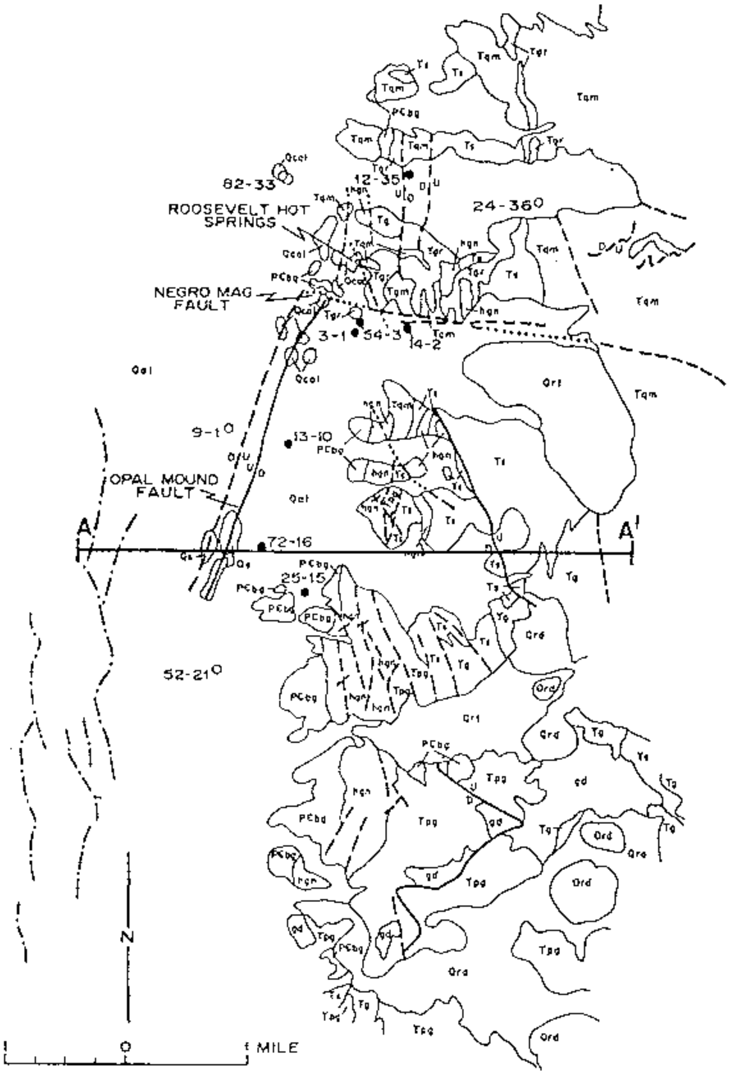


MAJOR STRUCTURES in

THE GEYSERS-CLEAR LAKE AREA

(After Goff, 1980)

FIGURE 18



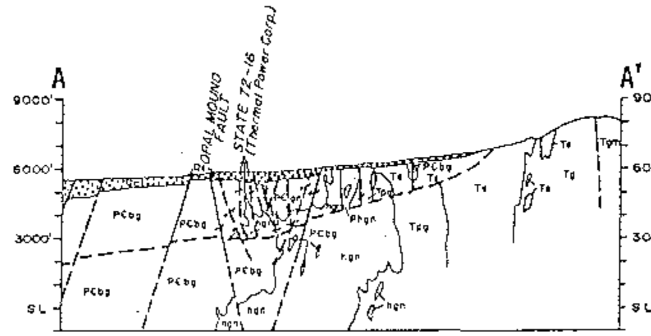
GEOLOGIC MAP
ROOSEVELT HOT SPRINGS, UTAH

(from Nielson et al., 1978)

FIGURE 19

GEOLOGIC CROSS SECTION
ROOSEVELT HOT SPRINGS, UTAH

(from Nielson et al., 1978)



E X P L A N A T I O N

Qal – alluvium	Tg – granite
Qcal – silicified alluvium	Ts – syenite
Qs – siliceous sinter	Tpg – porphyritic granite
Qrd – rhyolite domes	Tqm – quartz monzonite
Qra – pyroclastic deposits	gd – biotite diorite
Qrf – rhyolite flows	hgn – foliated hornblende granodiorite
Tgr – fine-grained granite	PЄbg – banded gneiss

FIGURE 20