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NATURE AND OCCURRENCE OF GEOTHERMAL RESOURCES IN THE UNITED STATES

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INTRODUCTION

Geothermal energy is heat energy that originates within the earth. Under suitable circumstances a small portion of this energy can be extracted and used by man. So active is the earth as a thermal engine that many of the large-scale geological processes that have helped to form the earth's surface features are powered by redistribution of internal heat as it flows from inner regions of higher temperature to outer regions of lower temperature. Such seemingly diverse phenomena as motion of the earth's crustal plates, uplifting of mountain ranges, occurrence of earthquakes, eruption of volcanoes and spouting of geysers all owe their origin to the transport of internal thermal energy.

In the United States and in many other countries, geothermal energy is used both for generation of electrical power and for direct applications such as space heating and industrial process energy. Although the technical viability of geothermal energy for such uses has been known for many years, the total amount of application today is very small compared with the potential for application. Availability of inexpensive energy from fossil fuels has suppressed use of geothermal resources. At present geothermal application is economic only at a few of the highest-grade resources. Development of new techniques and equipment to decrease costs of exploration, drilling, reservoir evaluation and extraction of the energy is needed to make the vastly more numerous lower grade resources also economic.

The objective of this paper is to present an overview of the geology of geothermal resources. It was written specifically with the non-geologist in mind. The use of highly technical geological language is avoided where possible, and the terms that are used are also defined. Emphasis is on resources in the United States, but the geological principles discussed have world-wide application. We will see that geothermal resources of high temperature are found mainly in areas where a number of specific geologic processes are active today and that resources of lower temperature are more widespread. We will present a classification for observed resource types and briefly describe the geology of each type. The geology of the United States will then be summarized to provide an appropriate background for consideration of the occurrence of geothermal resources. Finally we will be able to reach the conclusion that the accessible geothermal resource base in the United States is very large and that the extent of development over the next decades will be limited by economics rather than by availability.

THE EARTH'S INTERNAL HEAT

Although the distribution with depth in the earth of density, pressure and other related physical parameters is well known, the temperature distribution is extremely uncertain. We do know that temperature within the earth increases with increasing depth (Fig. 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 estimated temperatures between 700°C and 1200°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 6400 km deep, may be more than 4000°C. Using present technology and under good conditions, holes can be drilled to depths of about 10 km, where temperatures range upward from about 150°C in areas underlain by cooler rocks to perhaps 600°C in exceptional areas.

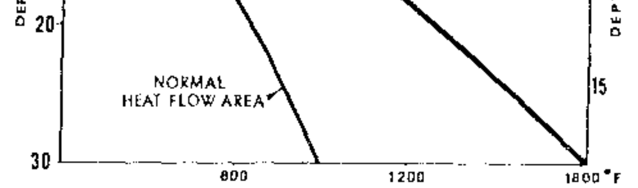


Figure 1

Because the earth is hot inside, heat flows steadily outward over the entire surface, where it is permanently lost by radiation into space. The mean value of this surface heat flow for the world is about 60 X 10^{-3} watts/m^2 (White and Williams, 1975) and since the mean surface area of the earth is about 5.1 X 10^{14} m^2, the rate of heat loss is about 32 X 10^{12} watts (32 million megawatts) or about 2.4 X 10^{20} calories/year, a very large amount indeed. At present only a small portion of this heat, namely that concentrated in what we call geothermal resources, can be captured for man's benefit. The mean surface heat flux of 60 milliwatts/m^2 is about 20,000 times smaller than the heat arriving from the sun when it is directly overhead, and the earth's surface temperature is thus controlled by the sun and not by heat from the interior (Goguel, 1976).

Two ultimate sources for the earth's internal heat appear to be most important among a number of contributing alternatives: 1) heat released throughout the earth's 4.5 billion-year history by radioactive decay of certain 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 much of the heavier material sank to form the earth's core (Fig. 2). The relative contribution to the observed surface heat flow of these two mechanisms is not yet resolved. Some theoretical models of the earth indicate that heat produced by radioactive decay can account for nearly all of the present heat flux (MacDonald, 1965). Other studies (Davis, 1980) indicate that, if the earth's core formed by sinking of the heavier metallic elements in an originally homogeneous earth, the gravitational heat released would have been sufficient to raise the temperature of the whole earth by about 2000°C. An appreciable fraction of today's observed heat flow could be accounted for by such a source. However, the distribution of radioactive elements within the earth is poorly known, as is the earth's early formational history some 4 billion years ago. We do know that the thermal conductivity of crustal rocks is low so that heat escapes from the surface slowly. The deep regions of the earth retain a substantial portion of their original heat, whatever its source, and billions of years will pass before the earth cools sufficiently to quiet the active geological processes we will discuss below.

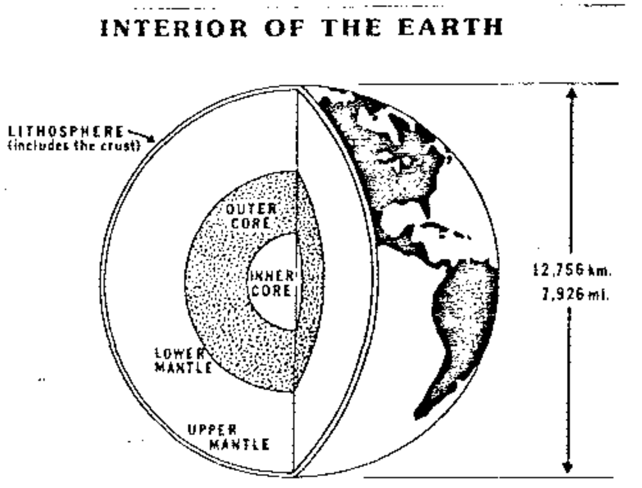


Figure 2

GEOLOGICAL PROCESSES

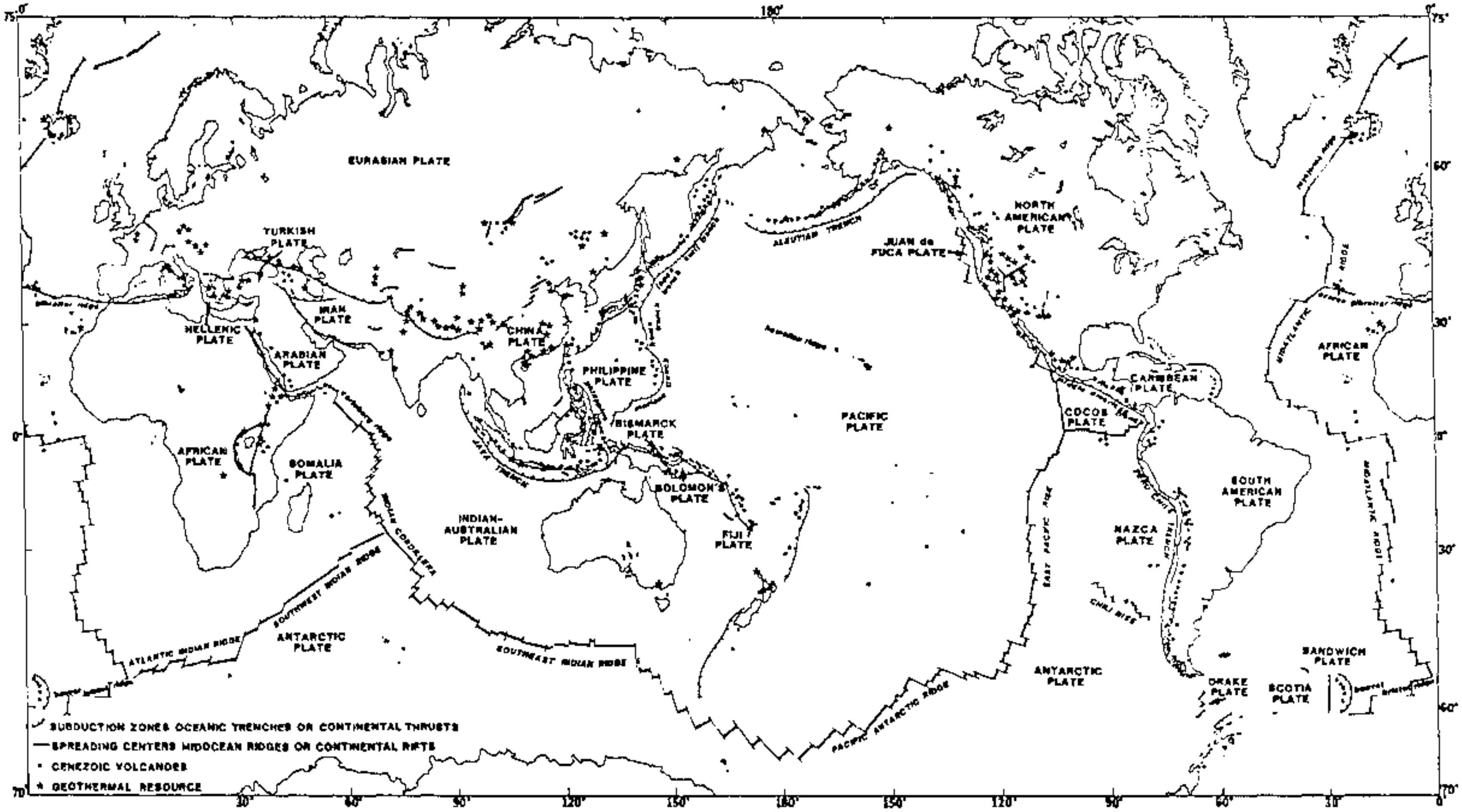
Geothermal resource areas, or geothermal areas for short, are generally those in which higher temperatures are found at shallower depths than is normal. This condition usually results from either 1) intrusion of molten rock to high levels in the earth's crust, 2) higher-than-average flow of heat to the surface with an attendant high rate of increase of temperature with depth (geothermal gradient) as illustrated in Figure 1, often in broad areas where the earth's crust is thin, 3) heating of ground water that circulates to depths of 2 to 5 km with subsequent ascent of the thermal water near to the surface, or 4) anomalous heating of a shallow rock body by decay of an unusually high content of radioactive elements. We will consider each of these phenomena in more detail below.

In many geothermal areas heat is brought right to the surface by circulation of ground water. If temperature is high enough, steam may be produced, and geysers, fumaroles, and hot springs are common surface manifestations of underlying geothermal reservoirs.

The distribution of geothermal areas on the earth's surface is not random but instead is governed by geological processes of global and local scale. This fact helps lend order to exploration for geothermal resources once the geological processes are understood. At present our understanding of these processes is rather sketchy, but, with rapidly increasing need for use of geothermal resources as an alternative to fossil fuels, our learning rate is high.

Figure 3 shows the principal areas of known geothermal occurrences on a world map. Also indicated are areas of young volcanoes and a number of currently active fundamental geological structures. It is readily seen that many geothermal resource areas correspond with areas that now have or recently have had volcanic and other geological activity. To understand why this is true we must consider some of the geologic processes going on in the earth's interior.

A schematic cross section of the earth is shown in Figure 2. A solid layer called 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 lie below



GEOTHERMAL RESOURCES AND PLATE TECTONIC FEATURES the crust. Mantle material below the lithosphere is less solid than the overlying lithosphere and is able to flow very slowly under sustained stress. The crust and the mantle are composed of minerals whose chief building block is silica (SiO_2). The outer core is a region where material is much denser than mantle material, and it is believed to be composed of a liquid iron-nickel-copper mixture. The inner core is believed to be a solid metallic mixture.

One very important group of geological processes that cause geothermal resources is known collectively as "plate tectonics". (Wyllie, 1971). It is illustrated in Figure 4. Outward flow of heat from the deep interior is hypothesized to cause formation of convection cells in the earth's mantle in which deeper, hotter mantle material slowly rises toward the surface, spreads out parallel to the surface under the solid lithosphere as it cools and, upon cooling, descends again. The lithosphere above the upwelling portions of these convection cells cracks and spreads apart along linear or arcuate zones called "spreading centers" that are typically thousands of kilometers long and coincide, for the most part, with the world's mid-oceanic ridge or mountain system (Figs. 3 and 4). The crustal plates on each side of the crack or rift move apart at rates of a few centimeters per year, and molten mantle material rises in the crack and solidifies to form new crust. The laterally moving oceanic lithospheric plates impinge 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, called subduction zones, are marked by the world's deep oceanic trenches which result from the crust being dragged down by the descending oceanic plate. The oceanic plate descends into regions of warmer material in the mantle and is warmed both by the surrounding warmer material and by frictional heating as it is thrust downward. At the upper boundary of the descending plate, temperatures become high enough in places to cause partial melting. The degree of melting depends upon the amount of water contained in the rocks as well as upon temperature and pressure and the upper layers of the descending plate often contain oceanic sediments rich in water. The molten or partially molten rock bodies (magmas) that result then ascend buoyantly through the crust, probably along lines of structural weakness (Fig. 5) and carry their contained heat to within 1.5 to 15 km of the surface. They give rise to volcanoes if part of the molten material escapes to the surface through faults and fractures in the upper crust.

Figure 3 shows where these processes of crustal spreading, formation of new oceanic crust from molten mantle material and subduction of oceanic plates beneath adjacent plates, are currently operating. Oceanic rises, where new crustal material is formed, occur in all of the major oceans. The East Pacific Rise, the Mid-Atlantic Ridge and the Indian ridges are examples. The ridge or rise crest is offset in places by large transform faults that result from variations in the rate of crustal spreading from place to place along the ridge. Oceanic crustal material is subducted or consumed in the trench areas. Almost all of the world's earthquakes result from these large-scale processes, and occur either at the spreading centers, the transform faults or in association with the subduction zone (Benioff zone), which dips underneath the continental land masses in many places. We thus see that these very active processes of plate tectonics give rise to diverse phenomena, among which is the generation of molten rock at shallow depths in the crust both at the spreading centers and above zones of subduction. These bodies of shallow molten rock provide the heat for many of the world's geothermal resources.

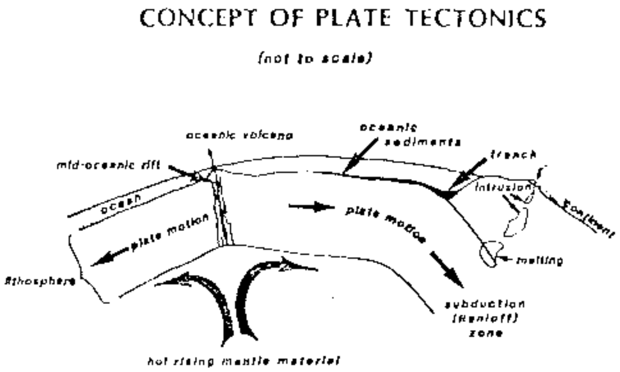


Figure 4

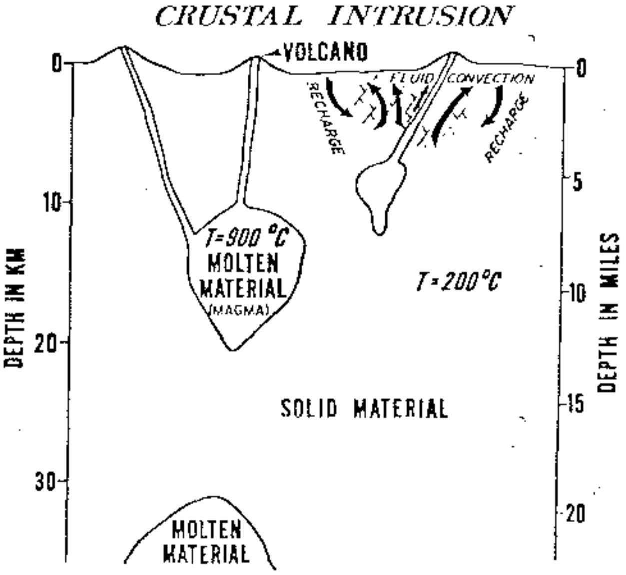


Figure 5

Before going on, let us discuss a bit more the processes of development of a crustal intrusion, illustrated in Figure 5. An ascending body of molten material may cease to rise at any level in the earth's crust and may or may not vent to the surface in volcanoes. Intrusion of molten magmas into the upper parts of the earth's crust has gone on throughout geological time. We see evidence for this in the occurrence of volcanic rocks of all ages and in the small to very large areas of crystalline, granitic rock that result when such a magma cools slowly at depth.

Volcanic rocks that have been extruded at the surface and crystalline rocks that have cooled at depth are known collectively as igneous rocks. They vary over a range of chemical and mineral composition. At one end of the 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 is the black rocks of the Hawaiian Islands. The crystalline, plutonic variety of this rock that has consolidated at depth is known as gabbro. 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 the black basalt and it occurs mainly on land. The plutonic variety of this rock is granite, although the term "granitic" is sometimes used for any crystalline igneous rock. Magmas that result in basalt or gabbro are termed "basic" whereas magmas that result in rhyolite or granite are termed "acidic"; however these terms are misleading because they have nothing to do with the pH of the magma.

The upper portions of the mantle are believed to be basaltic in composition. The great outpourings of basalt seen in places like the Hawaiian Islands and on the volcanic plateaus of the Columbia and Snake rivers (Fig. 16) seem to indicate a more or less direct pipeline from the upper mantle to the surface in places. The origin of granites is a subject of some controversy. It can be shown that granitic magmas could be derived by differential segregation from basaltic magmas. However, the chemical composition of granites is much like the average composition of the continental crust, and some granites probably result from melting of crustal rocks by upwelling basaltic magmas whereas others probably result from differentiation from a basaltic magma. In any case, basaltic magmas are molten at a higher temperature than are granitic magmas (see Fig. 6) and more importantly for our discussion basaltic magmas are less viscous (more fluid) than are granitic magmas. Occurrence of rhyolitic volcanic rocks of very young age (less than 1 million years and preferably less than 50,000 years) is generally taken as a sign of good geothermal potential in an area because presumably a large body of viscous magma may be indicated at depth to provide a geothermal heat source. On the other hand, occurrence of young basaltic magma 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 that would provide a geothermal heat source. In many areas both basaltic and rhyolitic volcanic rocks are present and often the younger eruptions are more rhyolitic, possibly indicating progressive differentiation of an underlying basaltic magma in a chamber like those illustrated in Figure 5.

A second important source of volcanic rocks results from hypothesized point sources of heat in the mantle as contrasted with the rather large convection cells discussed above. It has been hypothesized that the upper mantle contains local areas of upwelling, hot material called plumes, although other origins for the hot spots have also been postulated. As crustal plates move over these local hot spots, a linear or arcuate sequence of volcanoes is developed. Young volcanic rocks occur at one end of the volcanic chain with older ones at the other end. The Hawaiian Island chain is an excellent example. Volcanic rocks on the island of Kauai at the northwest end of the chain have been dated through radioactive means at about 6 million years, whereas the volcanoes Mauna Loa and Mauna Kea on the island of Hawaii at the southeast end of the chain are in almost continual activity, at the present time having an interval between eruptions of only 11 months. In addition, geologists speculate that Yellowstone National Park, Wyoming, one of the largest geothermal areas in the world, sits over such a hot spot and that the older volcanic rocks of the eastern and western Snake River plains in Idaho are the surface trace of this mantle hot spot in the geologic past (see Fig. 16 and the discussion below).

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 mean heat flow (100 mwatt/m^2) and an anomalously high geothermal gradient (50°C/km). Geophysical and geological data indicate that the earth's crust is thinner than normal and that the isotherms are upwarped beneath this area. Much of the western U.S. is geologically active, as manifested by earthquakes and active or recently active volcanoes. Faulting and fracturing during earthquakes help to keep fracture systems open, and this allows circulation of ground water to depths of 2 km to perhaps 5 km. Here the water is heated and rises buoyantly along other fractures to form geothermal resources near surface. Many of the hot springs and wells in the western United States and elsewhere owe their origin to such processes.

GEOTHERMAL RESOURCE TYPES

We have seen that the fundamental cause of many geothermal resources lies in the transport of heat near to the surface through one or more of a number of geological processes. We have also seen that the ultimate source of that heat is in the interior of the earth where temperatures are much higher than they are at the surface. We will now turn to an examination of various geothermal resource types.

All geothermal resources have three common components:

1) a heat source
2) permeability in the rock, and
3) a heat transfer fluid.

In the foregoing we have considered some of the possible heat sources, and we will discuss others presently. Let us now consider the second component, permeability.

Permeability is a measure of how easily fluids flow through rock as a result of pressure differences. Of course fluid does not flow through the rock matrix itself but rather it flows in open spaces between mineral grains and in fractures. Rocks in many, but not all, geothermal areas are very solid and tight, and have little or no interconnected pore space between mineral grains. In such rocks the only through-going pathways for fluid flow are cracks or fractures in the rock. A geothermal well must intersect one or more fractures if the well is to produce geothermal fluids in quantity, and it is generally the case that these fractures can not be located precisely by means of surface exploration. Fractures sufficient to make a well a good producer need only be a few millimeters in width, but must be connected to the general fracture network in the rock in order to carry large fluid volumes.

The purpose of the heat transfer fluid is to remove the heat from the rocks at depth and bring it to the surface. The heat transfer fluid is either water (sometimes saline) or steam. Water has a high heat capacity (amount of heat needed to raise the temperature by 1°C) and a high heat of vaporization (amount of heat needed to convert 1 gm to steam). Thus water, which naturally pervades fractures and other open spaces in rocks, is an ideal heat transfer fluid because a given quantity of water or steam can carry a large amount of heat to the surface where it is easily removed.

Geothermal resource temperatures range upward from the mean annual ambient temperature (usually 10-30°C) to well over 350°C. Figure 6 shows the span of temperatures of interest in geothermal work.

The classifications of geothermal resource types shown in Table I is modeled after one given by White and Williams (1975). Each type will be described briefly with emphasis on those that are presently nearest to commercial use in the U.S In order to describe these resource types we resort to simplified geologic models. A given model is often not acceptable to all geologists, especially at our rather primitive state of knowledge of geothermal resources today.

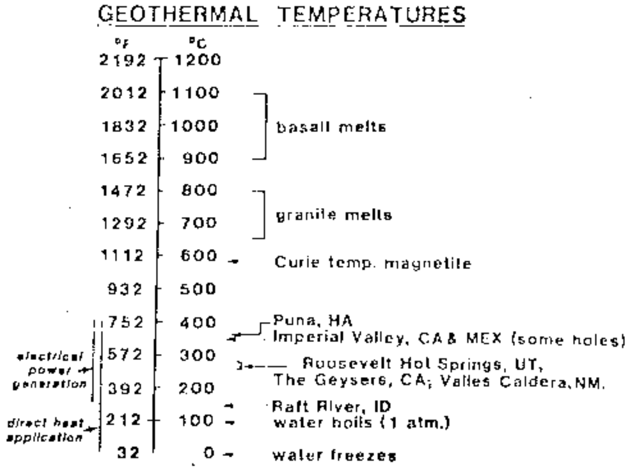


Figure 6

TABLE 1

GEOTHERMAL RESOURCE CLASSIFICATION
(After White and Williams, 1975)

Resource Type	Temperature Characteristics
1. Hydrothermal convection resources (heat carried upward from depth by convection of water or steam)	
a) Vapor dominated	about 240°C
b) Hot-water dominated	
i) High Temperature	150°C to 350°C+
ii) Intermediate	90°C to 150°C
iii) Low Temperature	less than 90°C
2. Hot rock resources (rock intruded in molten form from depth)	
a) Part still molten	higher than 600°C
b) Not molten (hot dry rock)	90°C to 650°C
3. Other resources	
a) Sedimentary basins (hot fluid in sedimentary rocks)	30°C to about 150°C
b) Geopressured (hot fluid under high pressure)	150°C to about 200°C
c) Radiogenic (heat generated by radioactive decay)	30°C to about 150°C

Hydrothermal Resources

Hydrothermal convection resources are geothermal resources in which the earth's heat is actively carried upward by the convective circulation of naturally occurring hot water or its gaseous phase, steam. Underlying some of the higher temperature hydrothermal resources is presumably a body of still molten or recently solidified rock (Fig. 6) that is very hot (300°C-1100°C). Other hydrothermal resources result simply from circulation of water along faults and fractures or within a permeable aquifer to depths where the rock temperature is elevated, with heating of the water and subsequent buoyant transport to the surface or near surface. Whether or not steam actually exists in a hydrothermal reservoir depends, among other less important variables, on temperature and pressure conditions at depth.

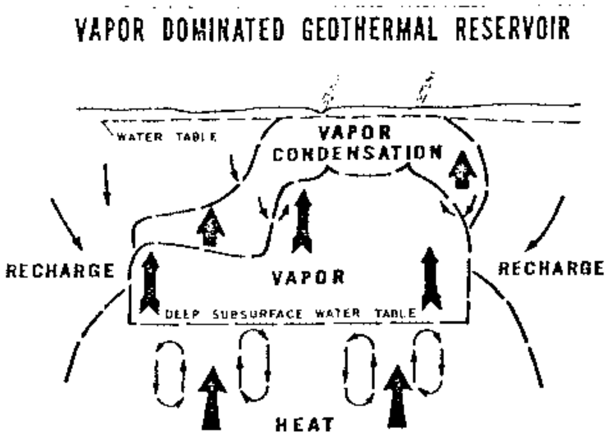


Figure 7

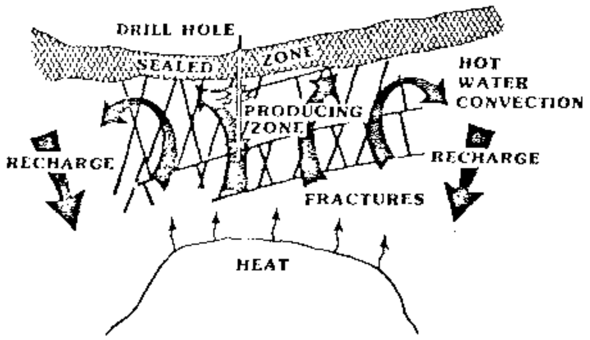
Figure 7 (after White et al., 1971) shows a conceptual model of a hydrothermal system where steam is present, a so-called vapor-dominated hydrothermal system (Ia of Table I). Convection of deep saline water brings a large amount of heat upward from depth to a level where boiling can take place under the prevailing temperature and pressure conditions. Steam moves upward through fractures in the rock and is possibly superheated further by the hot surrounding rock. Heat is lost from the vapor to the cooler, near-surface rock and condensation results, with some of the condensed water moving downward to be vaporized again. Within the entire vapor-filled part of the reservoir, temperature is nearly uniform due to rapid fluid convection. This whole convection system can be closed, so that the fluid circulates without loss, but if an open fracture penetrates to the surface, steam may vent. In this case, water lost to the system would be replaced by recharge, which takes place mainly by cool ground water moving downward and into the convection system from the margins. The pressure within the steam-filled reservoir increases much more slowly with depth than would be the case if the reservoir were filled with water under hydrostatic pressure. Because the rocks surrounding the reservoir will generally contain ground water under hydrostatic pressure, there must exist a large horizontal pressure differential between the steam in the reservoir and the water in the adjacent rocks, and a significant question revolves around why the adjacent water does not move in and inundate the reservoir. It is postulated that the rock permeability at the edges of the reservoir and probably above also, is either naturally low or has been decreased by deposition of minerals from the hydrothermal fluid in the fractures and pores to form a self-sealed zone around the reservoir. Self-sealed zones are known to occur in both vapor-dominated and water-dominated resources.

A well drilled into a vapor-dominated reservoir would produce superheated steam. The Geysers geothermal area in California (see Fig. 17 and the discussion below) is an example of this type of resource. Steam is produced from wells whose depths are 1.5 to 3 km, and this steam is fed to turbine generators that produce electricity. The current generating capacity at The Geysers is 908 MWe (megawatts of electrical power, where 1 megawatt = 1 million watts), and 880 MWe of additional generating capacity is scheduled to come on line by 1986.

Other vapor-dominated resources that are currently being exploited occur at Lardarello and Monte Amiata, Italy, and at Matsukawa, Japan. The famous Yellowstone National Park in Wyoming contains many geysers, fumaroles, hot pools and thermal springs, and the Mud Volcanoes area is believed to be underlain by a dry steam field.

There are relatively few known vapor-dominated resources in the world because special geological conditions are required for their formation (White et al., 1971). However, they are eagerly sought by industry because they are generally easier and less expensive to develop than the more common water-dominated system discussed below.

Figure 8 schematically illustrates a high-temperature, hot-water-dominated hydrothermal system (Ib(i) of Table I). The source of heat beneath many such systems 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. Normal ground water circulates in open fractures and removes heat from these deep, hot rocks by convection. Fluid temperatures are uniform over large volumes of the reservoir because convection is rapid. Recharge of cooler ground water takes place at the margins of the system through circulation down fractures. Escape of hot fluids at the surface is often minimized by a near-surface sealed zone or cap-rock formed by precipitation from the geothermal fluids of minerals in fractures and pore spaces. Surface manifestations of such a geothermal system might include hot springs, fumaroles, geysers, thermal spring deposits, chemically altered rocks, or alternatively, no surface manifestation may occur at all. If there are no surface manifestations, discovery is much more difficult and requires sophisticated geology, geophysics, geochemistry and hydrology. A well drilled into a water-dominated geothermal system would likely encounter tight, hot rocks with hot water inflow from the rock into the well bore mainly along open fractures. Areas where different fracture sets intersect may be especially favorable for production of large volumes of hot water. For generation of electrical power a portion of the hot water produced from the well is allowed to flash to steam within the well bore or within surface equipment as pressure is reduced, and the steam is used to drive a turbine generator.


WATER DOMINATED GEOTHERMAL SYSTEM

FLOW CONTROLLED BY FRACTURES

Figure 8

Examples of this type of geothermal resource are abundant in the western U.S. and include Roosevelt Hot Springs, Utah, and the Valles Caldera area, New Mexico. Approximately 50 areas having potential for containing such a resource have been identified (Muffler and others, 1978) so far in the West, with Nevada having a disproportionately large share.

A second type of hot-water dominated system is shown in Figure 9. Here the reservoir rocks are sedimentary rocks that have intergranular permeability as well as fracture permeability. Geothermal fluids can sometimes be produced from such a reservoir without the need to intersect open fractures by a drill hole. Examples of this resource type occur in the Imperial Valley of California, in such areas as East Mesa, Heber, Brawley, the Salton Sea, and at Cerro Prieto, Mexico. In this region the East Pacific Rise, a crustal spreading center, comes onto the North American continent. Figure 3 shows that the rise is observed to trend northward up the Gulf of California in small segments that are repeatedly offset northward by transform faults. Although its location under the continent cannot be traced very far with certainty, it is believed to occur under and be responsible for the Imperial Valley geothermal resources. The source of the heat is upwelling, very hot molten or plastic material from the earth's mantle. This hot rock heats overlying sedimentary rocks and their contained fluids and has spawned volcanoes. The locations of specific resource areas appear to be controlled by faults that presumably allow deep fluid circulation to carry the heat upward to reservoir depths.

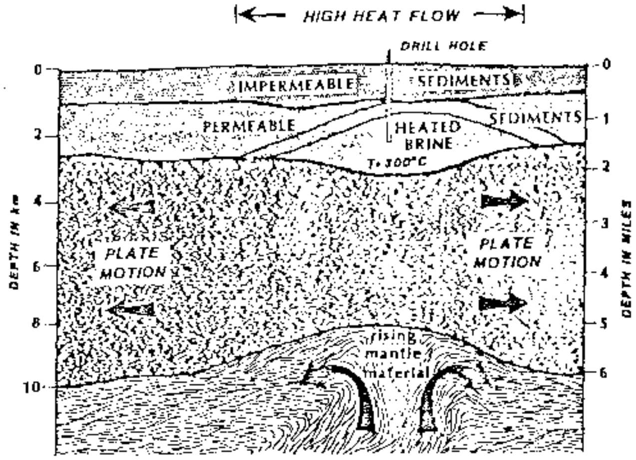
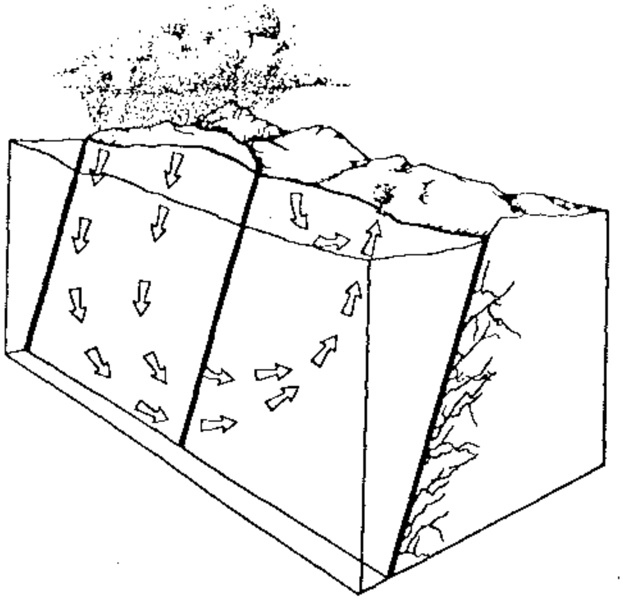

IMPERIAL VALLEY, CALIFORNIA GEOTHERMAL RESOURCE

Figure 9

Virtually all of industry's geothermal exploration effort in the United States is presently directed at locating vapor- or water-dominated hydrothermal systems of the types described above having temperatures above 200°C. A few of these resources are capable of commercial electrical power generation today. Current surface exploration techniques are generally conceded to be inadequate for discovery and assessment of these resources at a fast enough pace to satisfy the reliance the U.S. may ultimately put upon them for alternative energy sources. Development of better and more cost-effective techniques is badly needed.

The fringe areas of high-temperature vapor- and water-dominated hydrothermal systems often produce water of low and intermediate temperature (1b(ii) and 1b(iii) of Table 1). These lower temperature fluids are suitable for direct heat applications but not for electrical power production. 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. Waters circulated to depths of 1 to 5 km are warmed in the normal geothermal gradient and they return to the surface or near surface along open fractures because of their buoyancy (Fig. 10). There need be no enhanced gradient or magmatic heat source under such an area. Warm springs occur where these waters reach the surface, but if the warm waters do not reach the surface they are generally difficult to find. This type of warm water resource is especially prevalent in the western U.S. where active faulting keep conduits open to depth.



MODEL OF DEEP CIRCULATION HYDROTHERMAL RESOURCE

Figure 10

Sedimentary Basins

Some basins are filled to depths of 10 km or more with sedimentary rocks that have intergranular and open-space permeability. In some of these sedimentary units, circulation of ground water can be very deep. Water 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 (3a of Table 1). The Madison group 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 in a few places for space heating and agricultural purposes. In a similar application, substantial benefit is being realized in France from use of this type of resource for space heating by production of warm water contained in the Paris basin. Many other areas of occurrence of this resource type are known worldwide.

Geopressured Resources

Geopressured resources (3b of Table 1) consist of deeply buried fluids contained in permeable sedimentary rocks warmed in a normal or anomalous geothermal gradient by their great burial depth. These fluids are tightly confined by surrounding impermeable rock and thus bear pressure that is 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 11 (from Papadopulos, 1975) gives a few typical parameters for geopressured reservoirs and illustrates the origin of the above-normal fluid pressure. These geopressured fluids, found mainly in the Gulf Coast of the U.S. (Fig. 17), generally contain dissolved methane. Therefore, three sources of energy are actually available from such resources: 1) heat, 2) mechanical energy due to the great pressure with which these waters exit the borehole, and 3) the recoverable methane.

Industry has a great deal of interest in development of geopressured resources, although they are not yet economic. The U.S. Department of Energy (DOE), Division of Geothermal Energy, is currently sponsoring development of appropriate exploitation technology.

GEOPRESSURED GEOTHERMAL RESOURCE

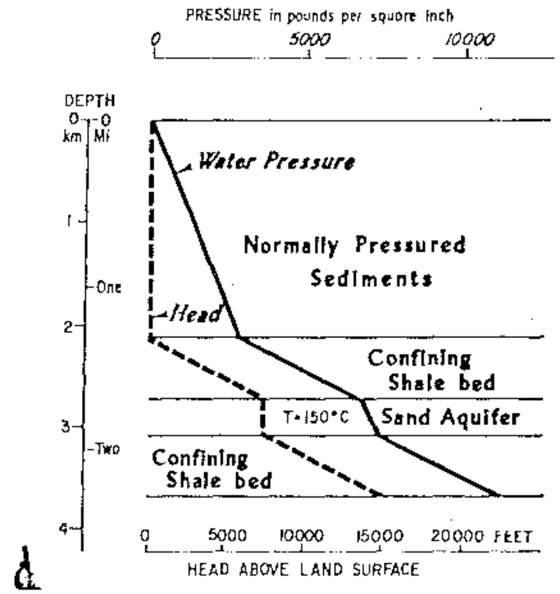


Figure 11

Radiogenic Resources

Research that could lead to development of radiogenic geothermal resources in the eastern U.S. (3c of Table 1) is currently underway following ideas developed at Virginia Polytechnic Institute and State University. The eastern states coastal plain is blanketed by a layer of thermally insulating sediments. In places beneath these sediments, rocks having enhanced heat production due to higher content of radioactive elements are believed to occur. These rocks represent old intrusions of once molten material that have long since cooled and crystallized. Geophysical and geological methods for locating such radiogenic rocks beneath the sedimentary cover are being developed, and drill testing of the entire geothermal target concept (Fig. 12) is currently being completed under DOE funding. Success would most likely come in the form of low- to intermediate-temperature geothermal waters suitable for space heating and industrial processing. This could mean a great deal to the eastern U.S. where energy consumption is high and where no shallow, high-temperature hydrothermal convection systems are known. Geophysical and geological data indicate that radiogenically heated rock bodies may be reasonably widespread.

RADIOGENIC GEOTHERMAL RESOURCE

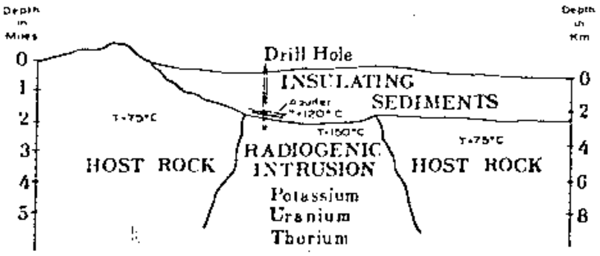
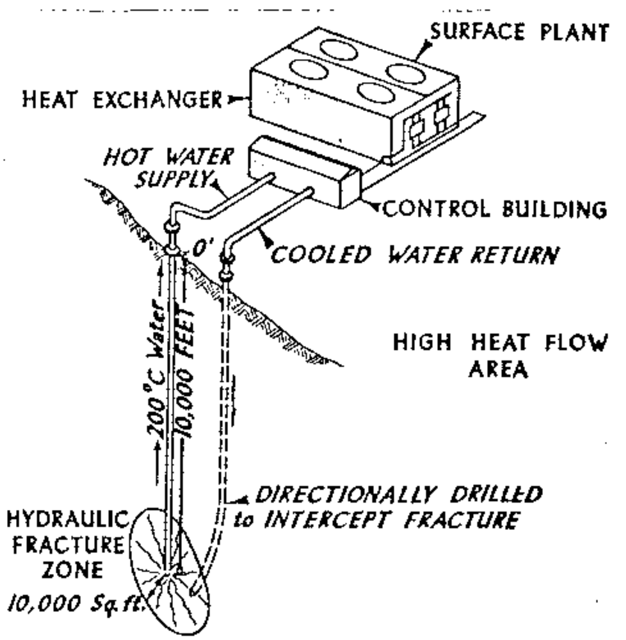


Figure 12

Hot Dry Rock Resources

Hot dry rock resources (2b of Table 1) 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. The feasibility and economics of extraction of heat for electrical power generation and direct uses from hot dry rocks is presently the subject of intensive research at the U.S. Department of Energy's Los Alamos National Laboratory in New Mexico (Smith et al., 1975; Tester and Albright, 1979). Their work indicates that it is technologically feasible to induce an artificial fracture system in hot, tight crystalline rocks at depths of about 3 km through hydraulic fracturing from a deep well. Water is pumped into a borehole under high pressure and is allowed access to the surrounding rock through a packed-off interval near the bottom. When the water pressure is raised sufficiently, the rock cracks to form a fracture system that usually consists of one or more vertical, planar fractures. After the fracture system is formed, its orientation and extent are mapped using geophysical techniques. A second borehole is sited and drilled in such a way that it intersects the fracture system. Water can then be circulated down the deeper hole, through the fracture system where it is heated, and up the shallower hole (Fig. 13). Fluids at temperatures of 150°C to 200°C have been produced in this way from boreholes at the Fenton Hill experimental site near the Valles Caldera, New Mexico. Much technology development remains to be done before this technique will be economically feasible.



HOT DRY ROCK GEOTHERMAL RESOURCE

Figure 13

Molten Rock

Experiments are underway at the Department of Energy's Sandia National Laboratory in Albuquerque, New Mexico to learn how to extract heat energy directly from molten rock (2a of Table 1). These experiments have not indicated economic feasibility for this scheme in the near future. Techniques for drilling into molten rock and implanting heat exchangers or direct electrical converters remain to be developed.

HYDROTHERMAL FLUIDS

The processes causing many of today's high temperature geothermal resources consist of convection of aqueous solutions around a cooling intrusion. These same basic processes have operated in the past to form many of the base and precious metal ore bodies being currently exploited, although ore forming processes differ in some aspects from hydrothermal convection processes as we understand them at present. The fluids involved in geothermal resources are complex chemically and often contain elements that cause scaling and corrosion of equipment or that can be environmentally damaging if released.

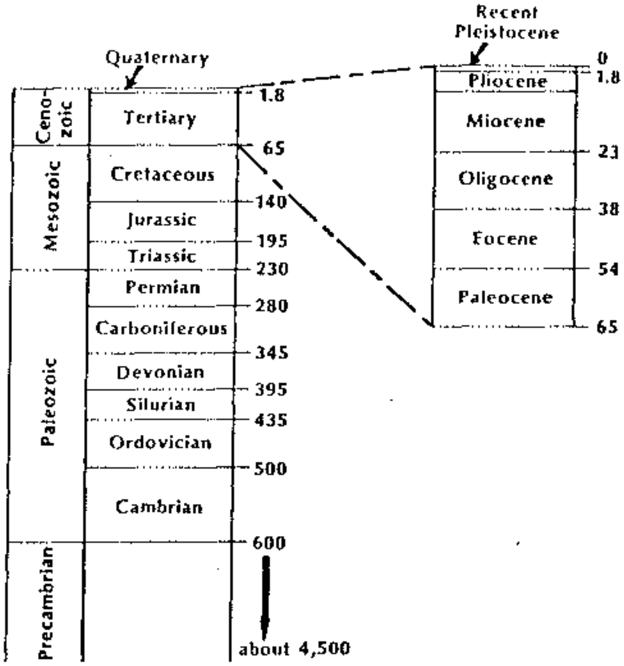
Geothermal fluids contain a wide variety and concentration of dissolved constituents. Simple chemical parameters often quoted to characterize geothermal fluids are total dissolved solids (tds) in parts per million (ppm) or milligrams per liter (mg/l) and pH. Values for tds range from a few hundred to more than 300,000 mg/l. Many resources in Utah, Nevada, and New Mexico contain about 6,000 mg/l tds, whereas a portion of the Imperial Valley, California resources are toward the high end of the range. Typical pH values range from moderately alkaline (8.5) to moderately acid (5.5). A pH of 7.0 is neutral at normal ground water temperature--neither acid nor alkaline. The dissolved solids are usually composed mainly of Na, Ca, K, Cl, SiO_2, SO_4, and HCO_3. Minor constituents include a wide range of elements with Hg, F, B and a few others of environmental concern. Dissolved gases usually include CO_2, NH_4 and H_2S, the latter being a safety hazard (Hartley, 1980). Effective means have been and are still being developed to handle the scaling, corrosion and environmental problems caused by dissolved constituents in geothermal fluids.

GEOLOGY OF THE CONTINENTAL UNITED STATES

Before going on to a more detailed discussion of the occurrence of geothermal resources in the United States, let us turn to a summary of the geology of the U.S. This will form an appropriate context for consideration of the known and suspected geothermal occurrences.

Like all continental land masses, North America has had a long and eventful geologic history. The oldest rocks are dated at more than 2.5 billion years before present using radioactive dating methods. During this time the continent has grown through accretion of crustal material, mountain ranges have been uplifted and subsequently destroyed by erosion, blocks of rock have been displaced by faulting, both on a large scale as evidenced, for example, by the currently active San Andreas fault in California, and on the scale of an individual geothermal prospect, and volcanic activity has been widespread. In the discussion below some of these events will be described and will be keyed in time to the geological time scale, shown in Figure 14.

The U.S. can be divided into several distinct regions on the basis of geology. One way to do this is illustrated in Figure 15, which shows the major tectonic, or structural, divisions in the U.S. (Eardley, 1951). Areas of long-time stability are differentiated from areas of orogenic activity that has consisted of crustal downwarping accompanied by filling of basins with thick deposits of eroded sediments, mountain building with attendant faulting and folding of the rock strata, metamorphic changes of existing rocks by heat and pressure due to great depth of burial, intrusion of molten igneous rock bodies, some of great extent (batholiths), and eruption of volcanic rocks at the surface. A summary of these events, following Eardley (1951) closely will be given below for each of the tectonic divisions.


GEOLOGICAL TIME SCALE

Millions of Years

(from von Eysinga, 1978)

Figure 14

A second way to view the U.S. is in terms of present land forms or physiography as shown in Figure 16. This map will help the reader to correlate the discussion to follow with current names for various physiographic division. By reference to Figures 14, 15 and 16 this discussion will be more meaningful.

Canadian Shield

For the last billion years, the Canadian shield has been the great stable portion of the North American continent. It consists mainly of pre-Cambrian granitic intrusions and metamorphosed volcanic and sedimentary rock. A few occurrences of Paleozoic strata indicate that the Paleozoic formations were once much more widespread over the shield than now, and that they have been stripped off by a long interval of erosion during the Mesozoic and Cenozoic eras.

Central Stable Region

The central stable region consists of a foundation of pre-Cambrian crystalline rock, which is a continuation of the Canadian shield southward and westward, covered by a veneer of sedimentary sandstone, limestone and shale. The veneer varies greatly in thickness from place to place, and several broad basins, arches, and domes, developed chiefly in Paleozoic times, are present. Many of these basins have been the site of oil accumulation, and some contain aquifers having geothermal potential.

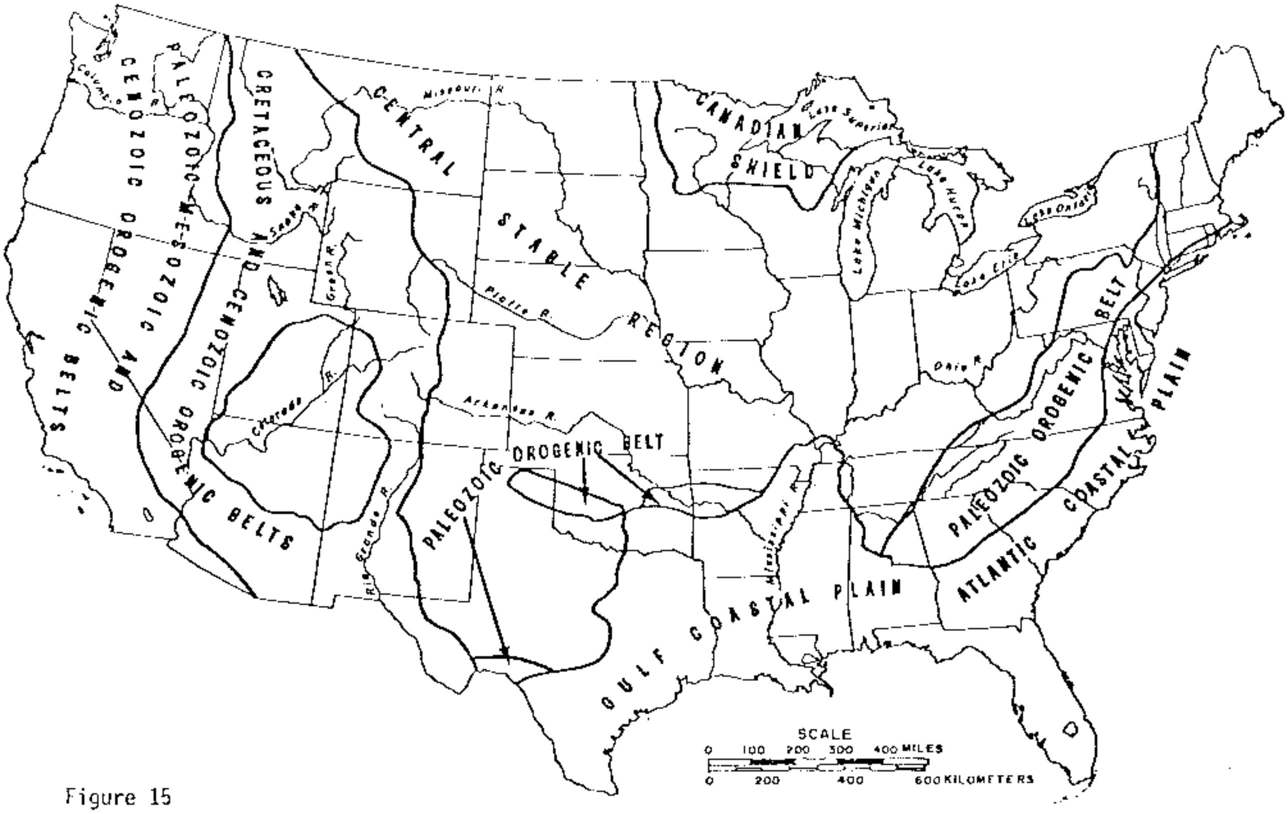


Figure 15

MAJOR TECTONIC DIVISIONS OF USA

(After Eardley, 1951)

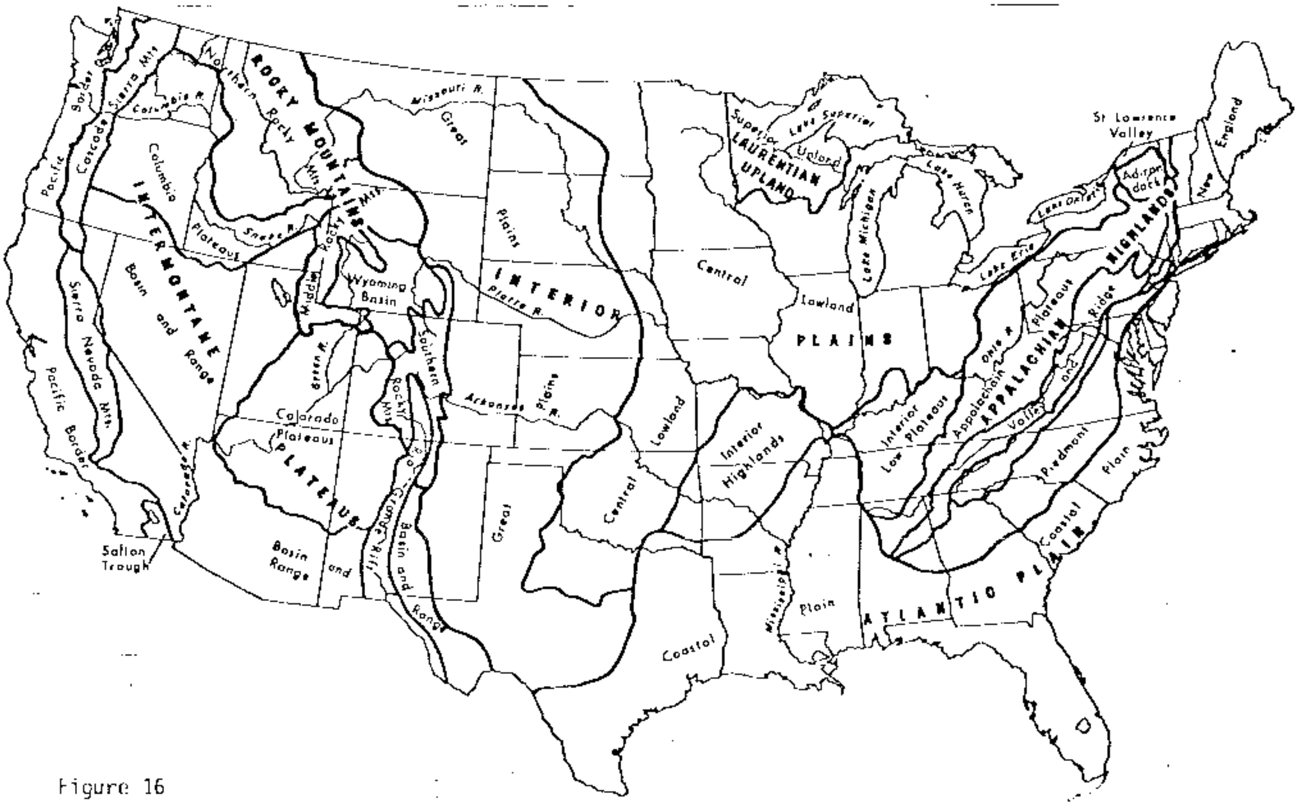


Figure 16

PHYSIOGRAPHIC MAP of USA

(after Fenneman, 1928)

In the southwestern corner of the central stable region, a system of ranges was elevated in Carboniferous time, and then during the Permian and Mesozoic it was largely buried. The ranges are known as the Ancestral Rockies in Colorado and New Mexico, and as the Wichita mountain system in Kansas, Oklahoma, and Texas. The late Cretaceous and early Tertiary Laramide orogenic belt was partly superposed on the Ancestral Rockies in Colorado and New Mexico, and a fragment of the central stable region was dismembered in the process to form the Colorado Plateau.

Orogenic Belts of the Atlantic Margin

The Paleozoic orogenic belts of the Atlantic margin bound effectively the southern, as well as the eastern, continental margin. The major belt is known as the Appalachian, and it consists of an inner folded and faulted division, the Valley and Ridge, and an outer compressed, metamorphosed, and intruded division, the Piedmont. Volcanic rocks and great intrusions of crystalline rock (batholiths) are important components of the outer division, but the inner folded and faulted belt is comparatively free of them. Both divisions are made up of very thick sequences of sedimentary rocks that have been metamorphosed.

The orogenic belt bordering the southern margin of the stable interior is mostly concealed by overlapping coastal plain deposits, but where exposed, it is a folded and faulted complex, somewhat similar to the inner Appalachian division.

The eastern extent or breadth of the Appalachian orogenic system and the nature and condition of the crust that lies east of it are not known, because of the cover of Atlantic Coastal plain sediments. The continental margin had begun to subside at least by early Cretaceous time, if not before. The gently sloping surface on the crystalline rocks has been traced eastward under this Cretaceous and Tertiary sedimentary cover to a depth of 10,000 feet, which is near the margin of the present continental shelf. Most units of the Coastal Plain sediments dip gently and thicken like a wedge oceanward as far as they have been traced by deep drilling and by seismic traverses. The Gulf coastal plain is continuous with the Atlantic coastal plain, and counting its shallowly submerged portions, it nearly encloses the Gulf of Mexico.

Orogenic Belts of the Pacific Margin

The great complex of orogenic belts along the Pacific margin of the continent evolved through a very long time. The oldest strata recognized are Ordovician. In Paleozoic time, the Pacific margin of the continent was a volcanic archipelago in appearance, and internally was a belt of profound compression and igneous intrusion. Inward from the archipelago, much volcanic material was deposited in a sagging trough and admixed with other sediments. The Permian, Triassic, and Jurassic were times of volcanism, and represent a continuation of essentially the same Paleozoic conditions well into the Mesozoic. In late Jurassic and early Cretaceous time, intense folding preceded batholithic intrusions (Nevadan orogeny) and the results of this great geologic activity now constitute large parts of the Coast Range of British Columbia, the ranges along the international border in British Columbia, Washington, and Idaho, the Klamath Mountains of southwestern Oregon and northern California, the Sierra Nevada Mountains of California, and the Sierra of Baja California. It is probable that this orogeny was caused by compression due to subduction of an oceanic plate beneath the western margin of the continent.

Following the Nevadan orogeny, a new trough of accumulation and a new volcanic archipelago formed west of the Nevadan belt, and a complex history of deformation and sedimentation carries down through the Cretaceous and Tertiary to the present, to result in the Coast Ranges of Washington, Oregon, and California. It is believed that subduction was active in this area until the last few million years (Dickinson and Snyder, 1979). Volcanism is active today in the Cascade Range.

The Columbia Plateau is a complex of flat-lying basaltic lava flows and airfall deposits that cover much of eastern Washington and Oregon. The main period of volcanism was Miocene, but the deposits merge smoothly eastward with the flows of the Snake River plain in Idaho where volcanism has been active in places in the past few hundred years. The volcanic rocks were deposited in a downwarped area and range in thickness up to perhaps 2 km. They were deposited on sedimentary rocks of Paleozoic and Mesozoic age. It is likely that the Basin and Range Province extends under the plateaus.

Orogenic Belts of the Rocky Mountains

During the complex and long orogenic history of the Pacific margin, the adjacent zone inward was one of gentle subsidence and sediment accumulation, comparatively free of volcanic materials during the Paleozoic.

The Paleozoic and all the Mesozoic sediments except the Upper Cretaeous of the Rocky Mountains may be divided into thick basin sequences on the west and fairly thin shelf sequences on the east. The line dividing the two lies approximately along the west side of the Colorado plateau and runs northward through western Wyoming and Montana to western Alberta. The shelf sequences were part of the central stable region until the late Cretaceous and early Tertiary (Laramide) orogeny. The eastern Laramide belt of folding and faulting extended through the shelf region of central and eastern Wyoming, central Colorado, and central New Mexico, forming the eastern Rocky Mountains and cutting off the Colorado plateau from the central stable region.

Following in the middle Tertiary, well after

Figure 17

Wright

the compressional Nevadan and Laramide orogenies of western North America, an episode of high-angle faulting occurred that created the Basin and Range physiographic province and gave sharp definition to many of its mountain ranges. The high-angle faults were superposed on both the Nevadan and Laramide belts; most of them are late Tertiary in age and some are still active. In many areas of the Basin and Range, volcanism occurred throughout the Tertiary and, especially along its eastern and western margins, it continues to the present time. Active volcanoes existed as recently as a few hundred years ago in parts of Idaho, Utah, Nevada, California, Arizona and New Mexico.

GEOTHERMAL RESOURCES IN THE CONTINENTAL UNITED STATES

Figure 17 displays the distribution of the various resource types in the 48 contiguous states. Information for this figure was taken mainly from Muffler et al. (1978), where a more detailed discussion and more detailed maps can be found. Not shown are locations of hot dry rock 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 poor. Because of the very recent emergence of the geothermal industry, insufficient exploration has been done to define properly the resource base. Each year brings more resource discovery, so that Figure 17 will rapidly become outdated.

Figure 17 shows that most of the known hydrothermal resources and all of the presently known sites that are capable or believed to be capable of electric power generation from hydrothermal convection systems are in the western half of the U.S. The preponderance of thermal springs and other surface manifestations of underlying resources is also 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), but the extent and potential of these resources is poorly understood. Another important large area much of which is underlain by low-temperature resources, is the northeast-trending Balcones fault 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 because almost no drilling has been done to actually confirm their existence, which is only inferred at present.

Regarding the temperature distribution of geothermal resources, low- and intermediate-temperature resources are much more plentiful than are high-temperature resources. There are many, many thermal springs and wells that have water at a temperature only slightly above the mean annual air temperature, which is the temperature of most non-geothermal shallow ground water. Resources having temperatures above 150°C are infrequent, but represent important occurrences. Muffler et al. (1978) show a statistical analysis of the temperature distribution of hydrothermal resources and conclude that the cumulative frequency of occurrence increases exponentially as reservoir temperature decreases (Fig. 18). This relationship is based only on data for known occurrences having temperatures 90°C or higher. It is firmly enough established, however, that we can have confidence in the existence of a very large low-temperature resource base, most of which is undiscovered.

FREQUENCY OF OCCURRENCE VS TEMPERATURE

FOR GEOTHERMAL RESOURCES

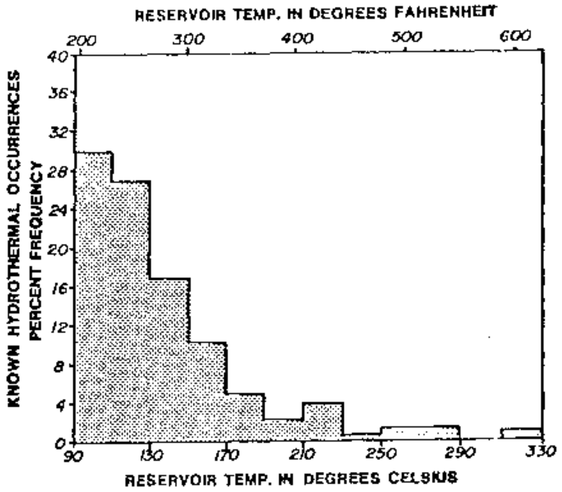


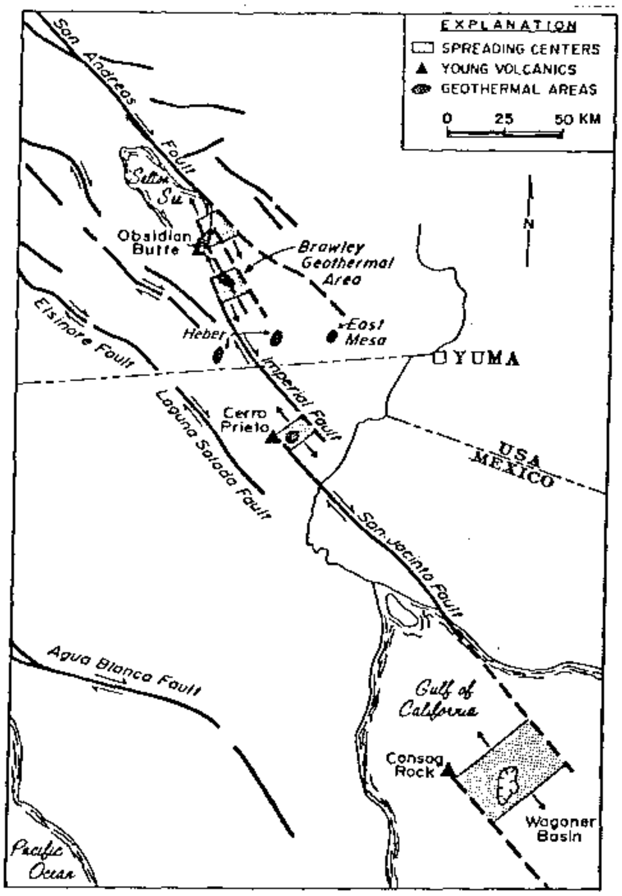
Figure 18

Let us consider the known geothermal occurrences in a bit more detail, beginning in the Western U.S.

Salton Trough/Imperial Valley, CA

The Salton Trough is the name given an area along the landward extension of the Gulf of California. It is an area of complex, currently active plate tectonic geologic processes. As shown on Figure 3, the crest of the East Pacific Rise spreading center is offset repeatedly northward, up the Gulf of California, by transform faulting. Both the rise crest and the transform faults come onto the continent under the delta of the Colorado River (Fig. 19) and the structure of the Salton Trough suggests that they underlie the trough. The offsetting faults trend northwest, parallel to the strike of the well-known San Andreas fault.

The Salton Trough has been an area of subsidence since Miocene times. During the ensuing years sedimentation in the trough has kept pace with subsidence, with shallow water sediments and debris from the Colorado River predominating. At present, 3 to 5 km of poorly-consolidated sediment overlies 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 (Elders, 1979). Very young volcanic activity has occurred at Cerro Prieto where a rhyodacite cone is known, and along the southern margin of the Salton Sea where rhyolite domes occur. The domes have an approximate age of 60,000 years (Muffler and White, 1969). The Cerro Prieto volcano has been difficult to date but may be about 10,000 years old (Wollenberg et al., 1980). Faulting is occurring at the present time as evidenced by the many earthquakes and earthquake swarms recorded there (Johnson, 1979).



MAJOR STRUCTURES OF SALTON TROUGH
(after Palmer et al., 1975)

Figure 19

The Cerro Prieto field is the best understood geothermal occurrence in the Salton Trough because of the drilling done there. We may take it as an example of a Salton Trough resource type. This field currently produces 150 MWe and there are plans by the Comision Federal de Electricidad in Mexico to enlarge its capacity to 370 MWe by 1985. The field is water-dominated and the more than 60 wells produce from depths of 1.5 to over 3 km. Fluid temperatures range from about 200°C to over 350°C (Alanso, et al., 1979). 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 (Puete Cruz and de la Pena, 1979). Two principal reservoir horizons occur in sandstones within the consolidated sequence, and 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 (Lyons and Van de Kamp, 1980). Reservoir recharge is apparently from the northeast and east and consists, at least partly, of Colorado River water (Truesdell et al., 1980).

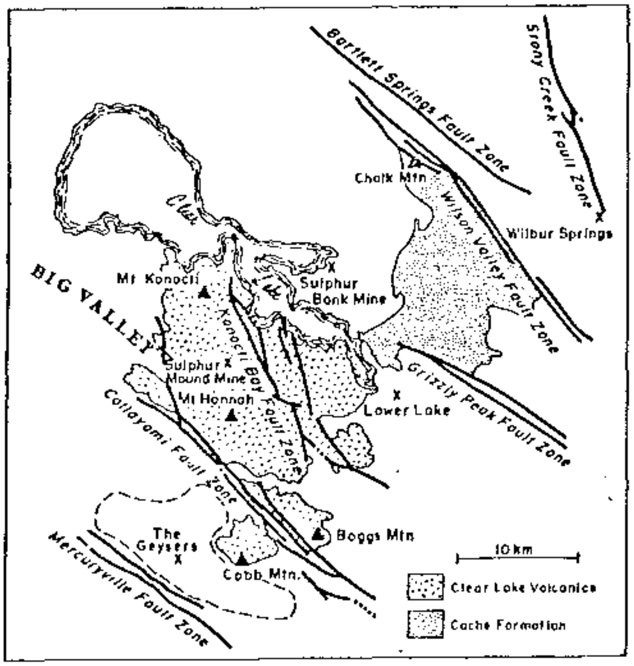
The geothermal fluid from Cerro Prieto, after steam separation, contains about 25,000 ppm total dissolved solids. This figure is much lower than some of the other resources in the Salton Trough. For example, the Salton Sea area contains 20 to 30 percent by weight by solids (Palmer, 1975). Primarily because of problems associated with this high salinity, no significant use has been made of Salton Sea fluids to date.

The heat source(s) for the several Salton Trough resources are unknown. Hot, partly molten rock at shallow depth (5-15 km) could underly at least some of the resource areas, or alternatively the active faulting could provide a mechanism where water could circulate to depths great enough to be heated by the enhanced geothermal gradient.

The Geysers, CA

The Geysers geothermal area is the world's largest producer of electricity from geothermal fluids with 908 MWe on line and an additional 880 MWe scheduled by 1986. 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°C, as previously discussed. The ultimate potential of the vapor-dominated system is presently believed to be around 2000 MWe. Associated with the vapor-dominated field are believed to be several unexploited hot water-dominated reservoirs whose volume and temperature are unknown.

The geology of The Geysers area is complex, especially structurally. Reservoir rocks consist mainly of fractured greywackies, sandstone-like rocks consisting of poorly sorted fragments of quartzite, shale, granite, volcanic rocks and other rocks). The fracturing has created the permeability necessary for steam production in quantities large enough to be economically exploitable. Overlying the reservoir rocks, as shown in Figure 21, is a series of impermeable metamorphosed rocks (serpentinite, greenstone, melange and metagrahite) that form a cap on the system. These rocks are all complexly folded and faulted. They are believed to have been closely associated with and perhaps included in subduction of the eastward-moving plate (Fig. 3) under the continent. This subduction apparently ended 2 to 3 million years ago.



MAJOR STRUCTURES in
THE GEYSERS-CLEAR LAKE AREA
(After Goff, 1980)

Figure 20

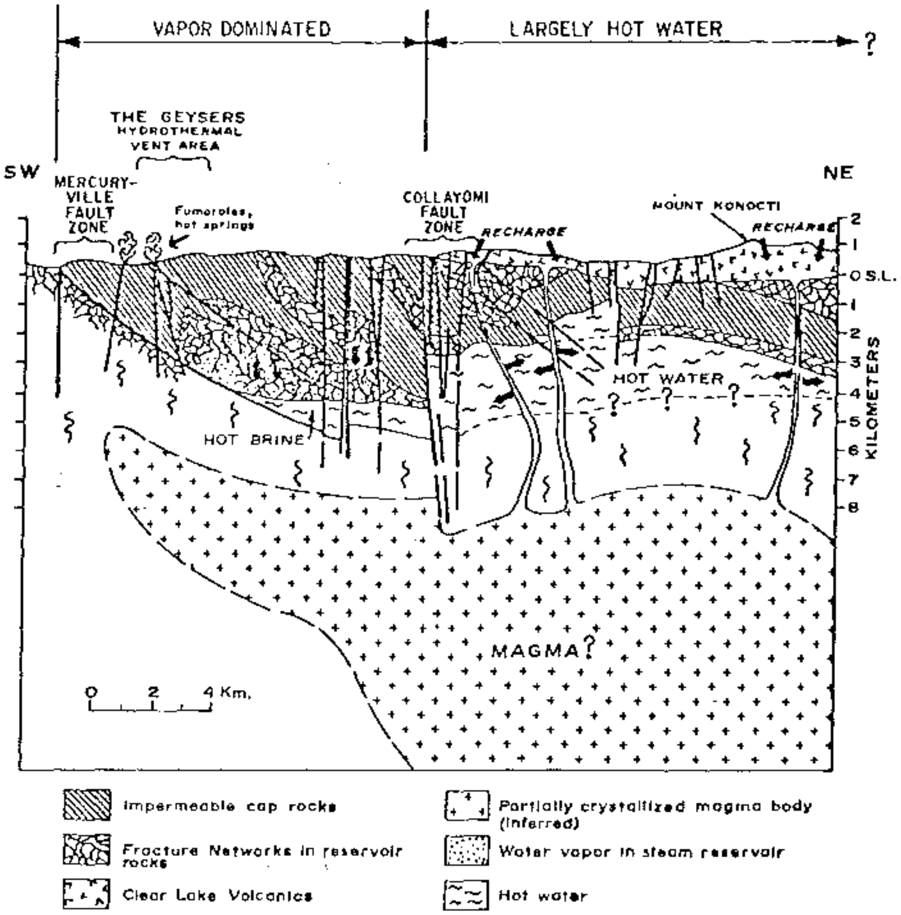
As shown in Figure 20, the presently known steam field is confined between the Mercuryville fault zone on the southwest and the Collayomi Fault zone on the northeast. The northwest and southeast margins are not defintely known. To the east and northeast lies the extensive Clear Lake volcanic field composed of dacite, rhyolite, andesite and basalt. The interval of eruption for these volcanics extends from 2 million years ago to 10,000 years ago, with ages progressively younger northward (Donnelly, 1977). 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 may supply steam to the vapor-dominated system through boiling (Fig. 21) although these ideas are not universally supported by geologists and the deep water table has never been intersected by drilling.

The postulated water-dominated geothermal reservoirs do not occur everywhere in the Clear Lake volcanics. At several locations drill holes have found temperatures of 200°C at depths of only 2000 m, but the rocks are tight and impermeable (Goff, 1980). Fractured areas apparently host the water-dominated reservoirs at the Wilbur Springs district (Thompson, 1979), the Sulphur Bank Mine (White and Roberson, 1962) and other smaller occurrences. Potential in The Geysers area for discovery of additional exploitable resources is good.

The Basin and Range

The Basin and Range province extends 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 on the north (Fig. 16). This area, especially the northern portion, contains abundant geothermal resources of all temperatures and is perhaps the most active area of exploration in the U.S. outside of the Imperial Valley and The Geysers areas. Resources along the eastern and western margins of the province are both more abundant and of higher temperature. Although no electrical power is presently being generated from geothermal resources in this area, plans have been announced to develop 20 MWe from Roosevelt Hot Springs in Utah and 10 MWe from an area yet to be selected in Nevada. Candidate sites in Nevada include Steamboat Springs, Dixie Valley, Desert Peak and Beowawe. Exploration is being conducted at probably 20 or more sites in the Basin and Range, including, in addition to those named above, Cove Fort, Utah; Tuscarora, McCoy, Baltazor, Leach Hot Springs, San Emidio, Soda Lake, Stillwater, and Humboldt House, Nevada; and Surprise Valley, Long Valley Caldera and Coso, California. 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, including parts of west central Utah on the east (Nash and Smith, 1977) and Long Valley caldera on the west (Rinehart and Huber, 1965). The area is also active seismically and faulting that causes the uplift of mountain ranges in this area also serves to keep pathways open for deep fluid circulation at numerous locations. Rocks in the Basin and Range consist of Paleozoic and Mesozoic sandstones, limestones and shales that lie on Precambrian metamorphic and intrusive rocks. These rocks were deformed, complexly in some places, during the Nevadan and Laramide orogenies, as discussed above, and some base and precious metal deposits were formed. Beginning in mid-Tertiary times volcanic activity increased many fold with both basaltic and rhyolitic rocks being erupted. Extentional stresses also began to operate and a sequence of north-south mountain ranges were formed which separate valleys that have been filled with erosional debris from the mountains (Eardley, 1951). In some places more



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

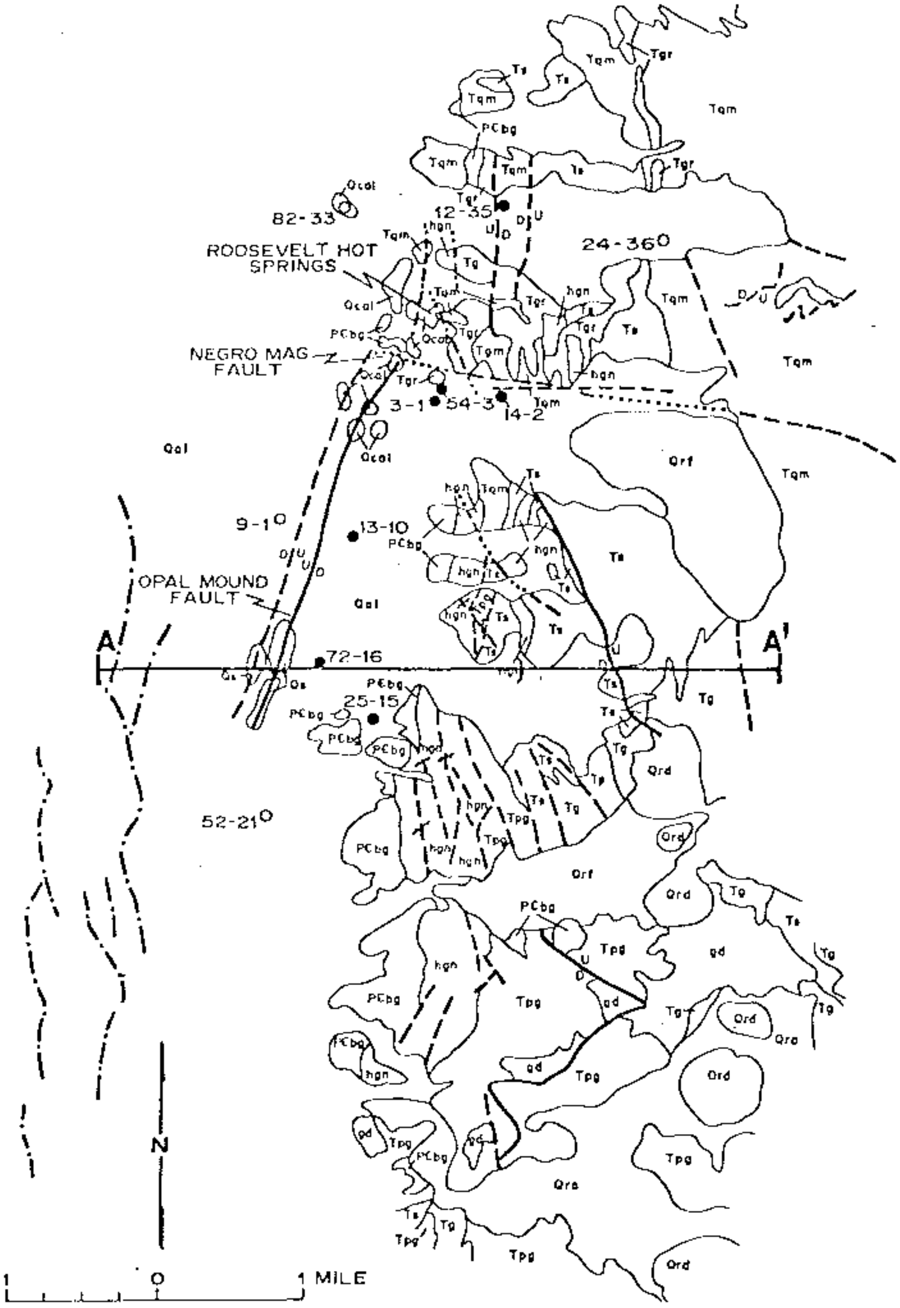
(after McLaughlin, 1977)

Figure 21

than 2 km offset has occurred along range-front faults, and the valleys may contain a hundred to as much as 3,000 m of unconsolidated erosional debris. This activity persists to the present time.

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. This geothermal area has been studied in detail for the past six years (Nielson et al., 1978; Ward et al., 1978). The oldest rocks exposed (Figs. 22 and 23) are Precambrian sedimentary rocks that have been extensively metamorphosed. These rocks were intruded during Miocene time by granitic rocks (diorite, quartz monzonite, syenite and granite). 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 (Fig. 23) 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 fault zones 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.

Seven producing wells have been drilled in the area (Fig. 22). Fluid temperature is about 260°C and the geothermal system is water-dominated. Average well production is perhaps 318,000 kg/hr (700,000 lbs./hr). Initial plans are for a 20 MWe power plant with two 50 MWe plants to be installed as knowledge of reservoir performance increases.



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

GEOLOGIC MAP
ROOSEVELT HOT SPRINGS, UTAH
(from Nielson et al., 1978)

Figure 22

GEOLOGIC CROSS SECTION
ROOSEVELT HOT SPRINGS, UTAH
(from Nielson et al., 1978)

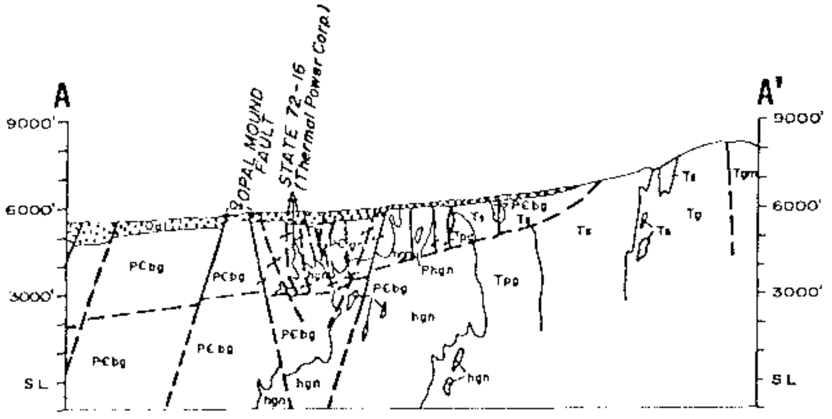


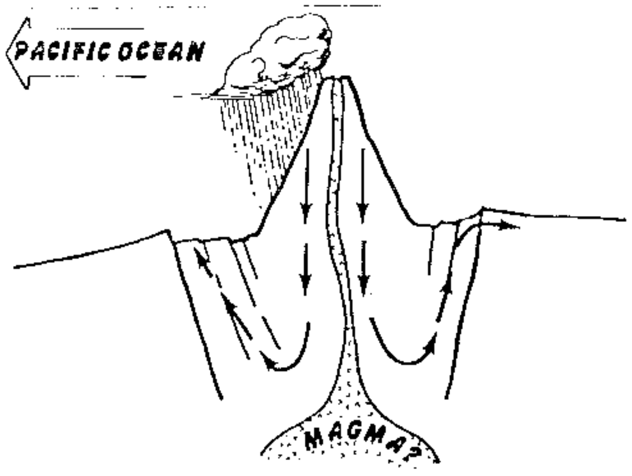
Figure 23

Cascade Range and Vicinity

The Cascade Range of northern California, Oregon, Washington and British Columbia is comprised of a series of volcanoes, 12 of which have been active in historic times. The May 18, 1980 eruption of Mount St. Helens attests to the youth of volcanic activity here. The Cascade Range probably lies over a subduction zone (Fig. 3) 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 one would suppose they should be (Fig. 17). Figure 24 illustrates in schematic form that the 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 of these resources becomes much more difficult.

No producible high-temperature hydrothermal systems have yet been located in the Cascades, although they are belived to exist. Geological and geochemical evidence indicates that a vapor-dominated system is present at Lassen Peak in California, but it lies within a national park, and will not be developed. Elsewhere hydrothermal systems having predicted temperatures greater than 150°C are postulated at Newberry Caldera in Oregon and Gamma Hot Springs in Washington, but drill evidence has not been obtained (Muffler et al., 1978). Industry's exploration effort so far in this area has been minimal.

The use of geothermal energy for space heating at Klamath Falls, Oregon is well known (Lund, 1975; Lund, 1980), and numerous hot springs and wells occur in both Oregon and Washington. Potential for discovery of resources in all temperature categories is great.



CASCADES GEOTHERMAL ENVIRONMENT

Figure 24

Columbia Plateaus

The Columbia Plateaus area is an area of young volcanic rocks, mostly basalt flows, that cover much of eastern Washington and Oregon and continue in a curved pattern into Idaho, following the course of the Snake River (see below).

There are no hydrothermal resources having temperatures >90°C known through drilling in this area. However, there are numerous warm springs and wells that indicate the presence of geothermal resources potentially suitable for direct heat uses.

Snake River Plain

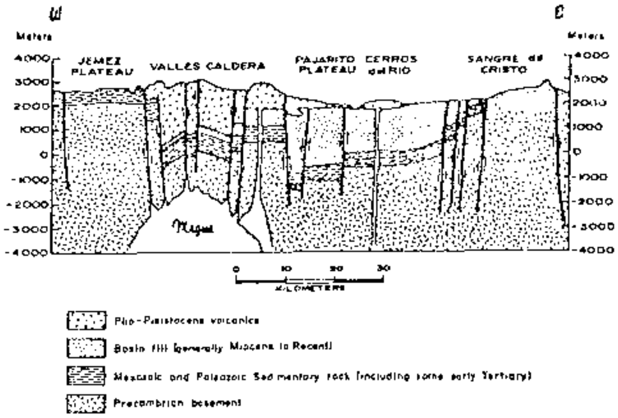
The basalt flows and other volcanic deposits of the Snake River Plain are an extension of the Columbia Plateau eastward across southern Idaho to the border with Wyoming. The plain is divided into a western part and an eastern part. Thermal waters occur in numerous wells and springs in the western portion, especially on or near the edges of the plain. Geochemically indicated resource temperatures exceed 150°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 (T>150°C) are yet identified, although numerous areas have warm wells and springs. This part of the plain is underlain by a high-flow cold-water aquifer that is believed to mask surface geothermal indications.

Direct use of hydothermal energy for space heating is famous at Boise, where the Warm Springs district has been heating homes geothermally for almost 100 years (Mink et al., 1977). Also in this area is the Raft River site where DOE is currently constructing a 5 MWe binary demonstration plant on a hydrothermal resource whose temperature is 147°C.

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 (Figs. 16 and 17). It is a down-dropped area that has been filled with volcanic rocks and erosional debris from the bordering plateaus and mountains (Fig. 25). The rift began to form in late Oligocene times, and volcanic and seismic activity have occurred subsequently to the present. Young volcanism, faulting and high heat flow characterize the area today.

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 (Dondanville, 1978). Surface manifestations at the Baca No. 1 location in the caldera include fumaroles, widely distributed hot springs and gas seeps. Hydrothermal alteration extends over 40 km^2. 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°C have been recorded and the average production temperature will likely be 260°C. There are current plans for a 50 MWe flash steam plant at this location. Also located near the caldera is the site of Los Alamos National Laboratory's hot dry rock experiment at Fenton Hill. Both the hot dry rock site and the hydrothermal convection system probably derive their heat from magma that has provided the material for the several episodes of volcanism that created the caldera structure.



SCHEMATIC CROSS SECTION
RIO GRANDE RIFT, NM
(after Eichelberger and Westrich, 1980)

Figure 25

Elsewhere in the Rio Grande Rift, there are numerous hot springs and wells. Discovery potential is high, although there are no known sites where discovery of fluids in excess of 150 to 170°C is indicated by present data (Harder et al., 1980).

The 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 been 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 open spaces in the carbonates (e.g. the Madison Limestone). At least some of the aquifers will produce under artesian pressure. Depths to production vary widely but average perhaps 2,000 ft. Temperatures are 30-80°C (Gries, 1977) in the Madison but are lower in other shallower aquifers such as the Dakota.

The U.S. Geological Survey is completing an intensive study of these aquifers, and the results will form a much firmer basis for hydrothermal development than presently exists. Direct use of the thermal water is being made at a few locations today, and it is evident that the potential for further development is substantial.

The Balcones Zone, Texas

Thermal waters at temperatures generally below 60°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 (1979). 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 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 been 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 but several postulates are (Woodruff and McBride, 1979): 1) deep circulation of ground waters along faults; 2) upwelling of connate waters, originally trapped in sediments now deeply buried; 3) stagnation of deep ground waters owing to faults that retard circulation; 4) local hot spots such as radiogenic heat sources (intrusions) within the basement complex, or; 5) other loci of high heat flow.

A minor amount of direct use is being made of these waters at present, and potential for further development is good.

Other Areas--Eastern Half of U.S.

Hydrothermal resources in other areas of the continental U.S. besides those mentioned above are very poorly known. There is believed to be potential for thermal waters of about 100°C at a number of locations along the Atlantic Coastal plain associated with buried intrusions that are generating anomalous heat through radioactive decay of contained natural uranium, thorium and potassium. Examples of such areas are shown at Savannah-Brunswick, Charleston, Wilmington, Kingston-Jacksonville and the mid-New-Jersey Coast. One drill test of such an area (Delmarva Penninsula near Washington, D.C.) has been conducted with inconclusive results regarding amount of thermal water that could be produced. This is the only geothermal test well so far in the east. Less than a dozen warm springs and wells are known at present. The Allegheny Basin is outlined on Figure 17 because it has potential for thermal fluids in aquifers buried deeply enough to be heated in a normal earth's gradient. Parts of Ohio, Kansas, Nebraska, and Oklahoma as well as other states are belived to have potential for low-temperature fluids. No drill tests have been conducted, however.

Hawaiian Islands

The chain of islands known as the Hawaiian archipelago stretches 2500 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 9800 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 activity, but by contrast volcanoes 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 (MacDonald and Hubbard, 1975).

Several of the Hawaiian islands are believed to have geothermal potential. The only area where exploration has proceeded for enough to establish the existence of a hydrothermal reservoir is in the Puna district 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 (Helsley, 1977) with a bottom-hole temperature of 358°C. Little is known in detail of the reservoir at present, but it is believed to be fracture-controlled and water-dominated. A 3 MWe generator is currently being installed and is scheduled for start-up in mid-1981. Success of this project would undoubtedly spur further development at this site.

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 no drilling to establish existence of a resource has been completed (Thomas et al., 1980).

Alaska

Very 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 overly a zone of active subduction (Fig. 3), and volcanoes are numerous. None of the identified hydrothermal convection systems here have been studied in detail.

Low- and moderate-temperature resources are indicated in a number of locations in Alaska by occurrence of hot springs (Muffler et al., 1978). One area that has been studied in more

TABLE 2

GEOTHERMAL ENERGY OF THE UNITED STATES
After Muffler et al. (1979) 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	?	?	?

detail and has had limited drilling is Pilgrim Hot Springs (Turner et al., 1980). This site is 75 km north of Nome, Alaska. Initial drilling has confirmed the presence of a hot water reservoir about 1 km^2 in extent that has artesian flow rates of 200-400 gallons/minute of 90°C water. Geophysical data suggest that the reservoir is near the intersection of two inferred fault zones. Further exploration work will be required to determine the potential of this reservoir.

POTENTIAL FOR GEOTHERMAL DEVELOPMENT

A small industry exists in the U.S. that is beginning the development of high-temperature hydrothermal resources for electrical power production. Developers involved are mainly large petroleum companies and potential users of the hydrothermal fluids are electric utilities. Exploration for high-temperature resources is being conducted at a rather low level, mainly because development of geothermal resources is not yet economic.

There is virtually no industry activity to develop geothermal resources for direct heat uses in the U.S. Good inventories of low- and moderate-temperature resources are only now becoming available in map form through efforts of the Federal geothermal program. And there has been very little drill testing that is necessary to prove resource viability so that money could be obtained for construction of utilization systems.

Muffler et al. (1978) 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 the undiscovered resource base is on the order of 3 to 5 times greater than the resources known today. These figures do not include possible hot dry rock or other more speculative resources. Table 2 is a summary of the current estimate of the geothermal resource base as taken from Muffler et al. (1978). 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

The amount of geothermal energy that will be in use at various times in the future is a topic of much discussion. It is no trivial exercise to estimate this number. Table 3 shows the best current estimates (Anon., 1980; Anon., 1981a; Anon., 1981b).

TABLE 3

GEOTHERMAL DEVELOPMENT POTENTIAL

	Estimated Use by Year 2000	
	ELECTRICAL (MW)	DIRECT HEAT (10^{15} BTU)
Hydrothermal	12,800	0.57
Geopressured	2,000	3.0 (methane)
Hot Dry Rock	700	0.007

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