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.

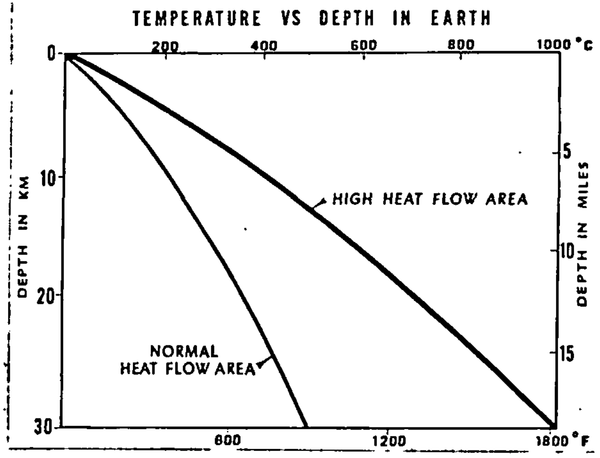


Figure 1

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 (Gogue1, 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.

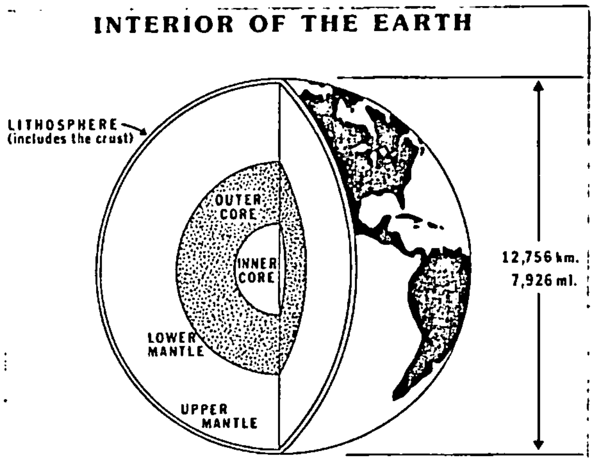


Figure 2

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.

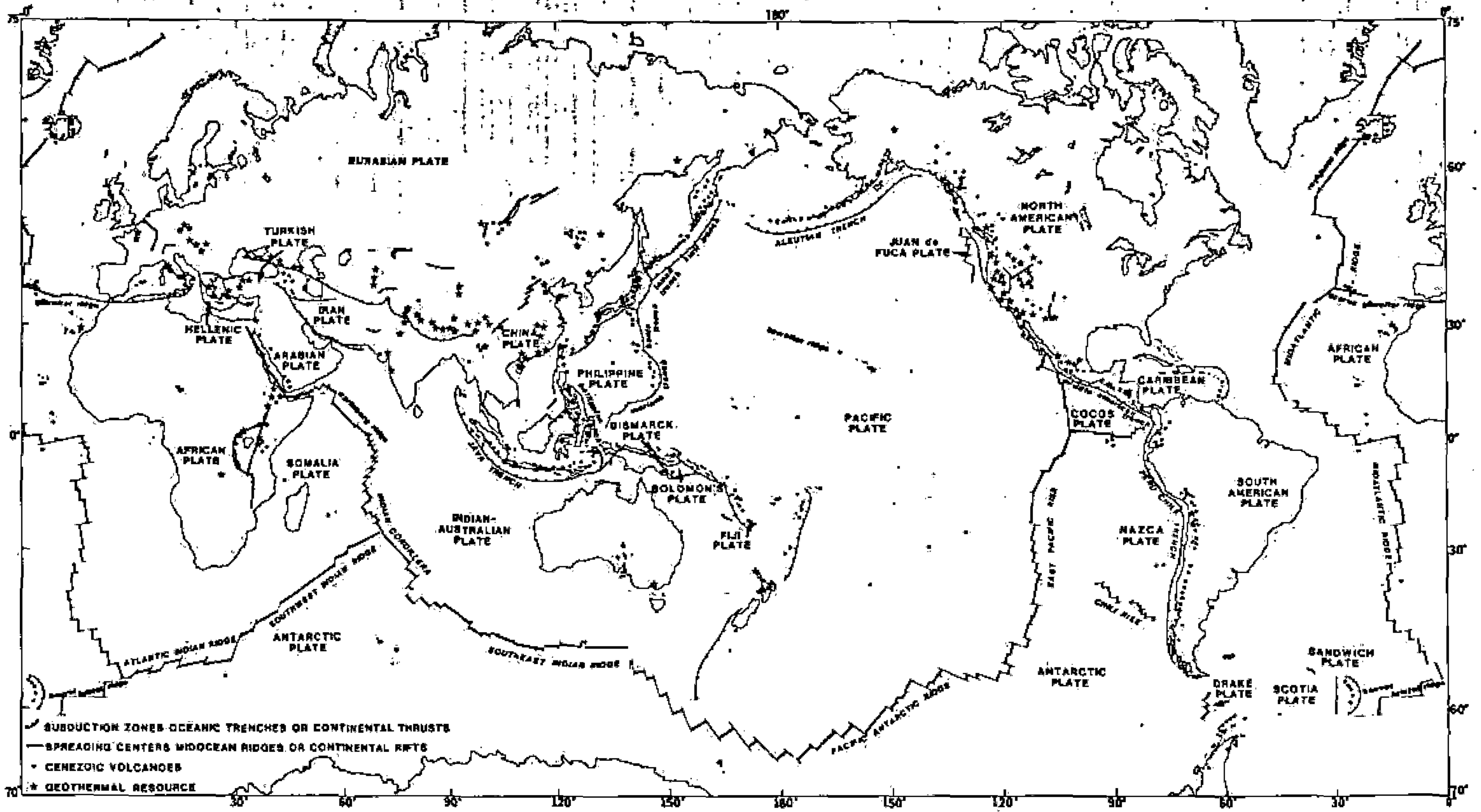
In many geothermal areas heat is brought right to the surface by circulation of ground water. If temperature is high enough, steam may be produced, and geysers, fumaroles, and hot springs are common surface manifestations of underlying geothermal reservoirs.

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

Figure 3



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.

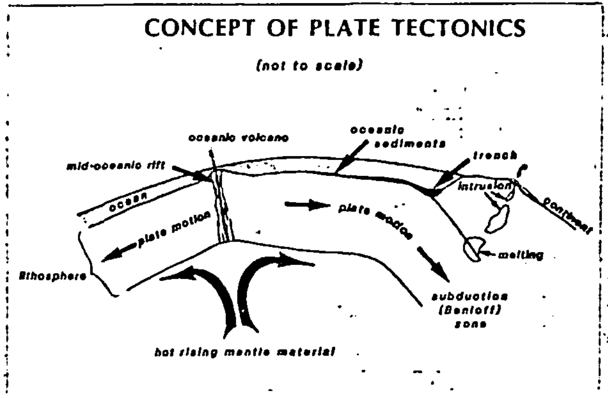


Figure 4

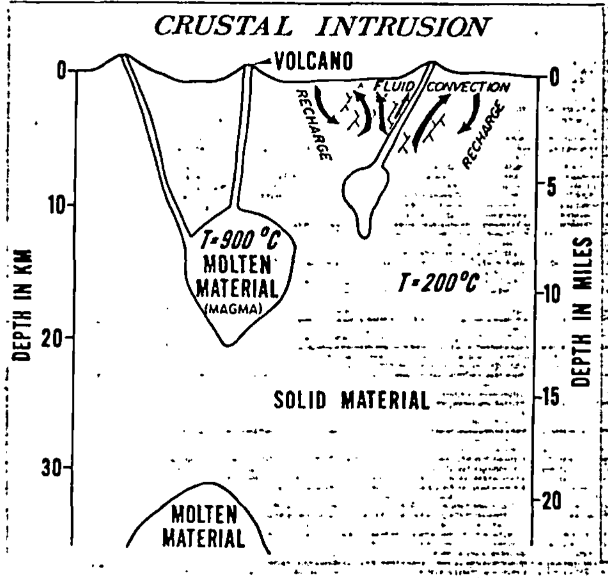


Figure 5

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.

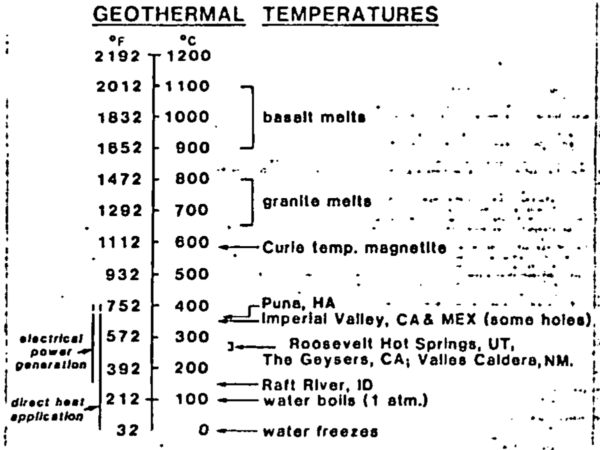


Figure 6

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.

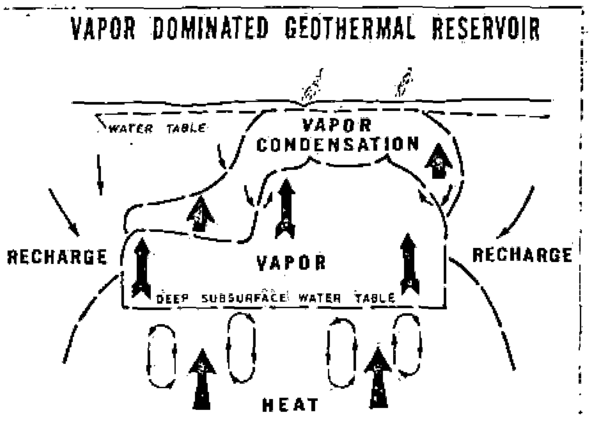


Figure 7

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.

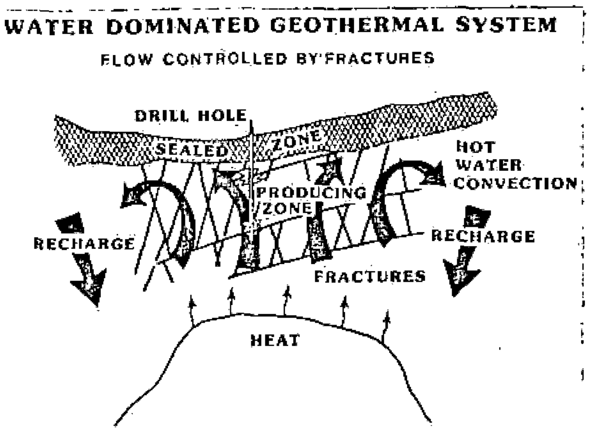


Figure 8

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 et al., 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.

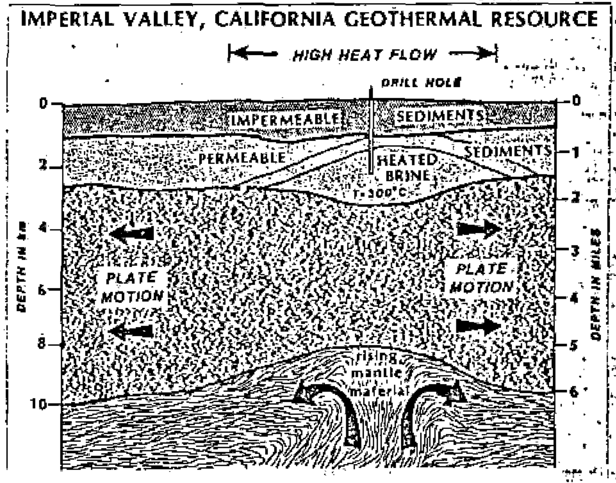
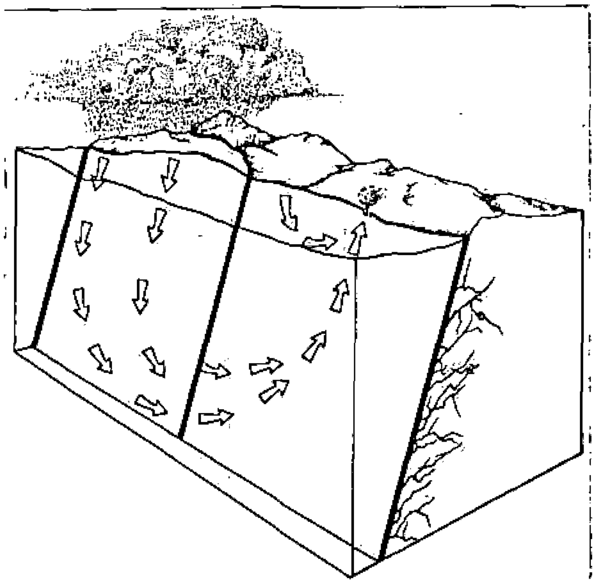


Figure 9

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 keeps 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

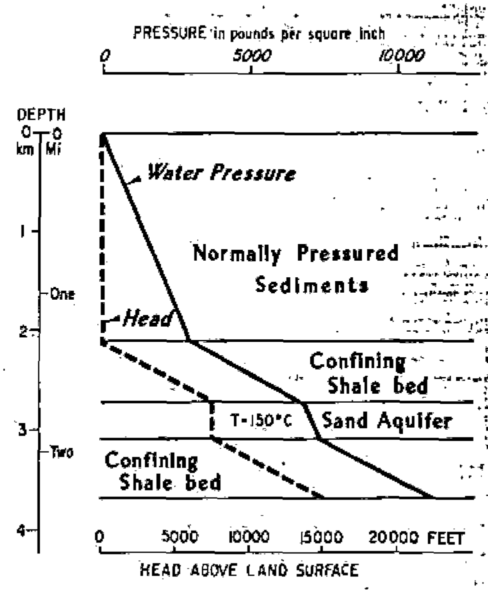


Figure 11

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.

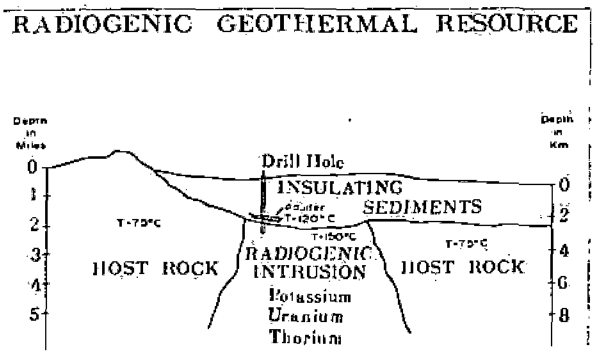


Figure 12

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.

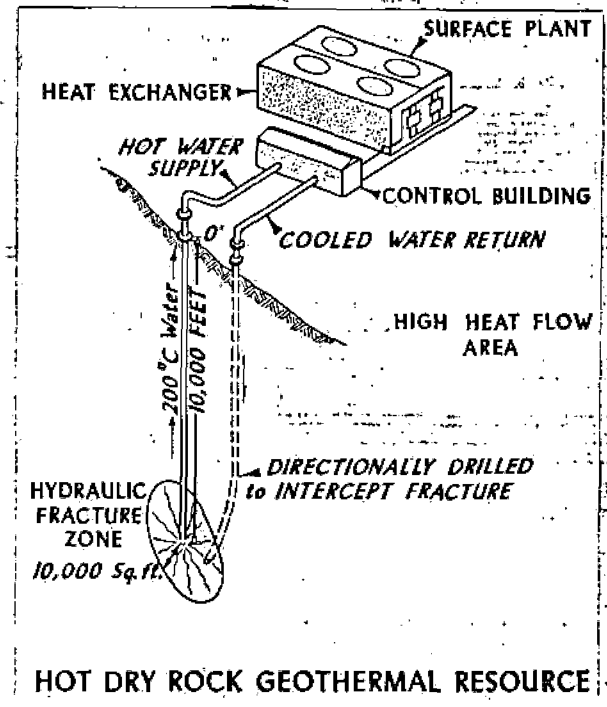


Figure 13

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.

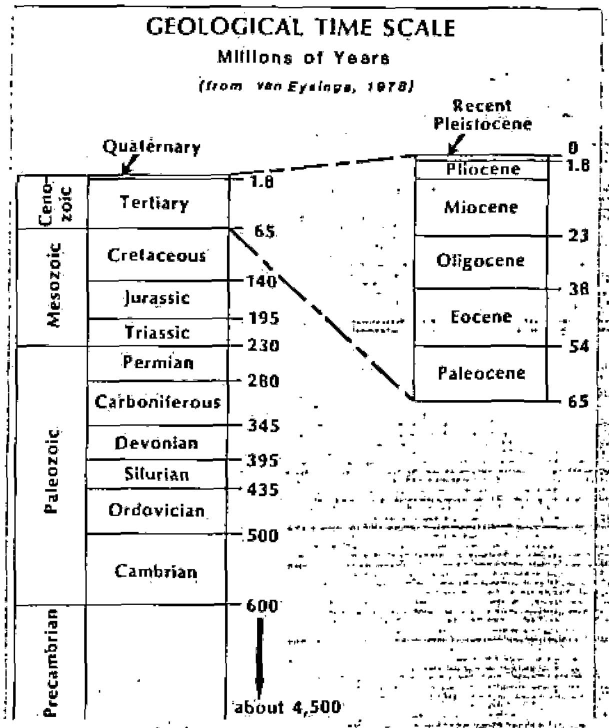


Figure 14

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.

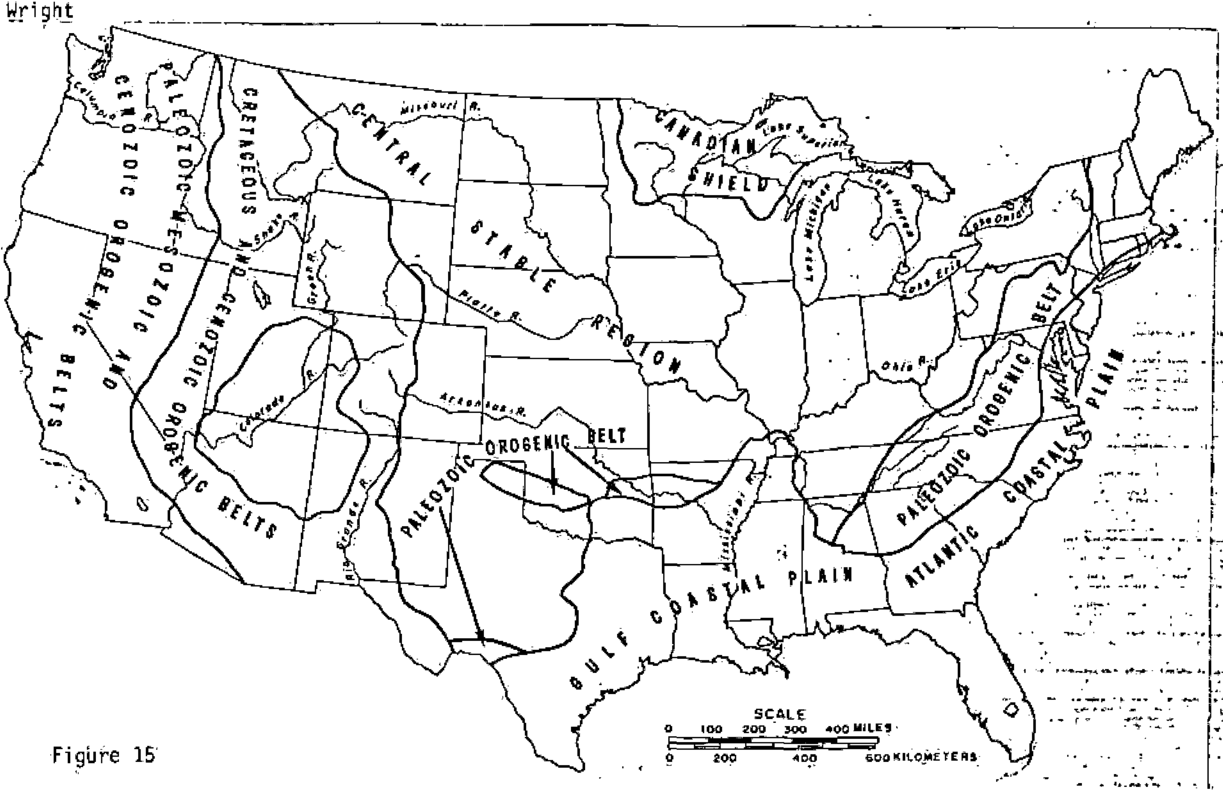


Figure 15

MAJOR TECTONIC DIVISIONS OF USA
(After Eardley, 1951)

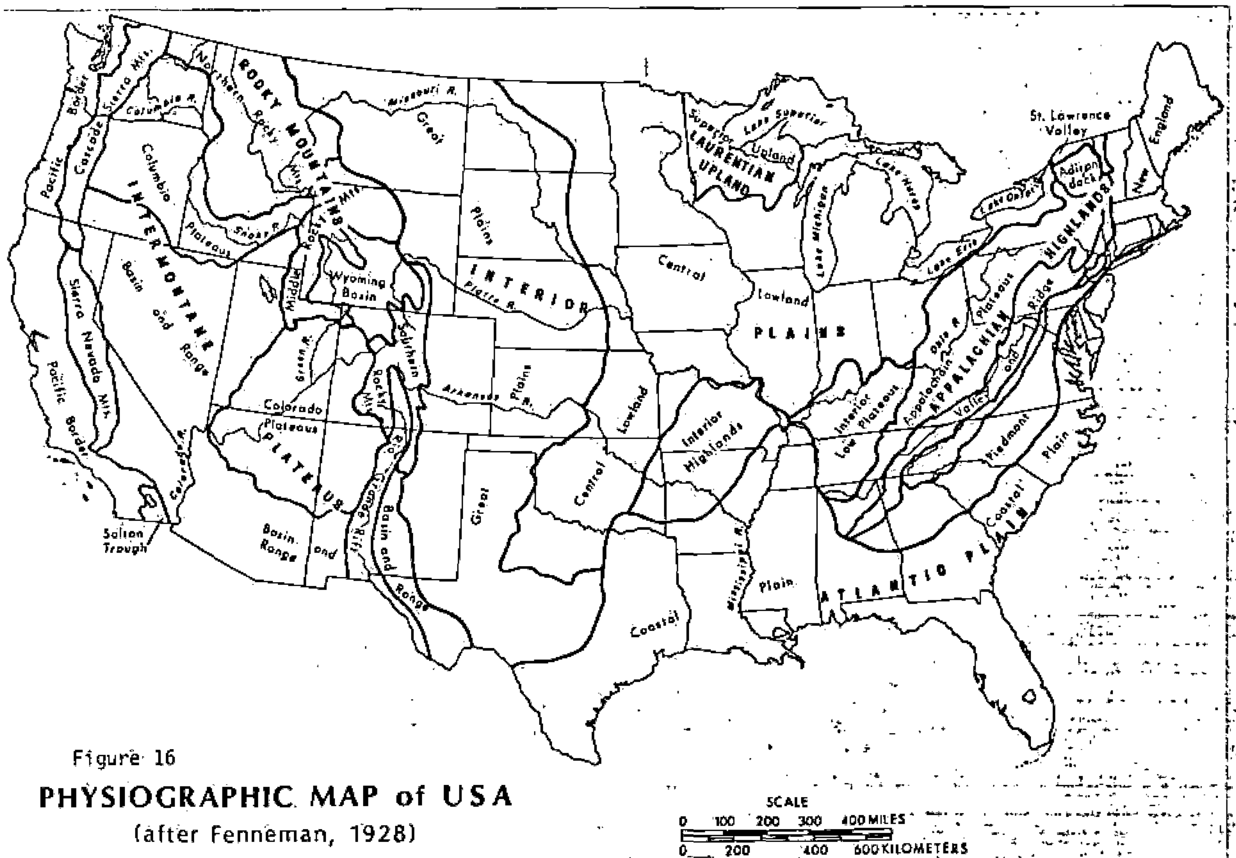


Figure 16

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.

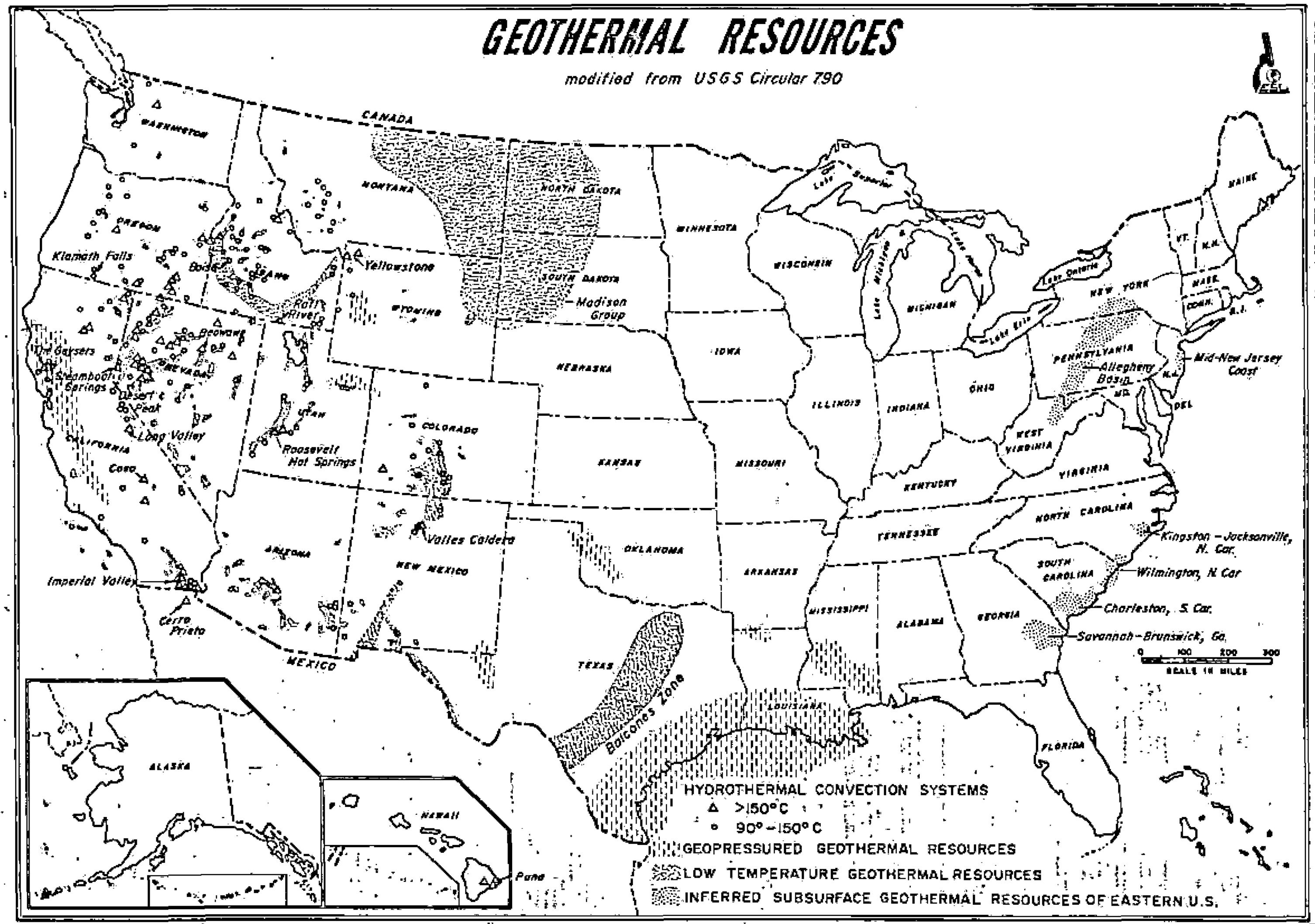
Orogenic Belts of the Rocky Mountains

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



GEOTHERMAL RESOURCES

modified from USGS Circular 790

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.

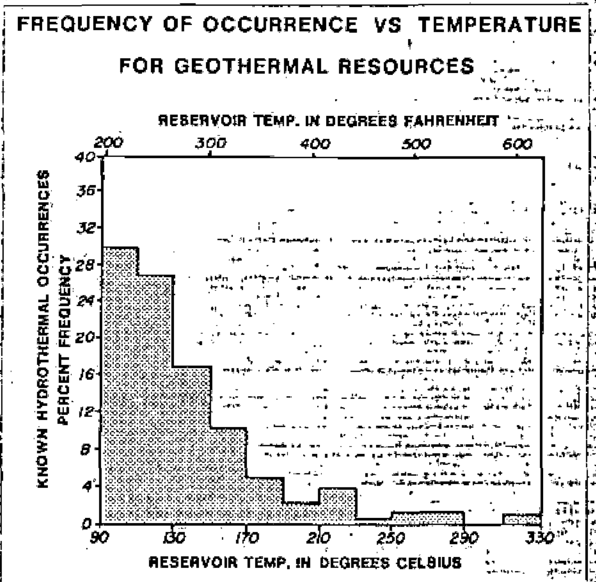


Figure 18

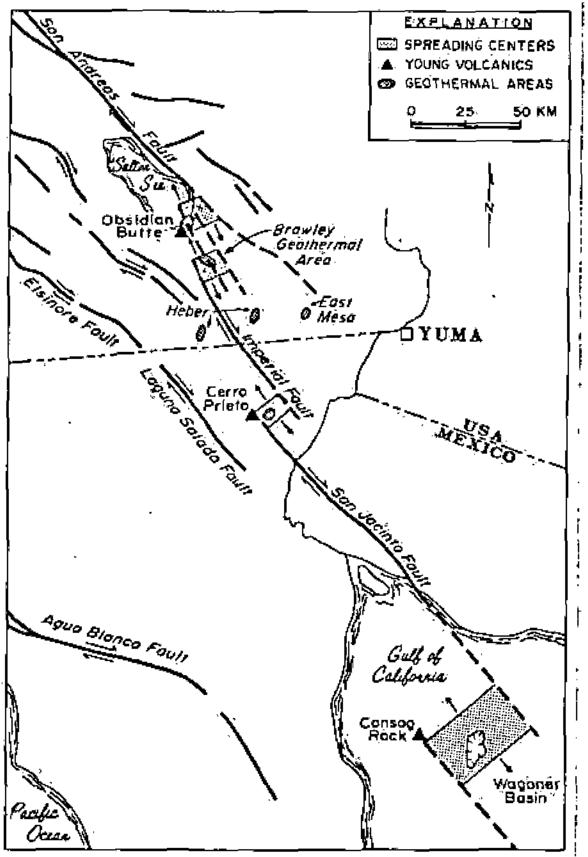
Let us consider the known geothermal occurrences in a bit more detail, beginning in the Western U.S.

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.

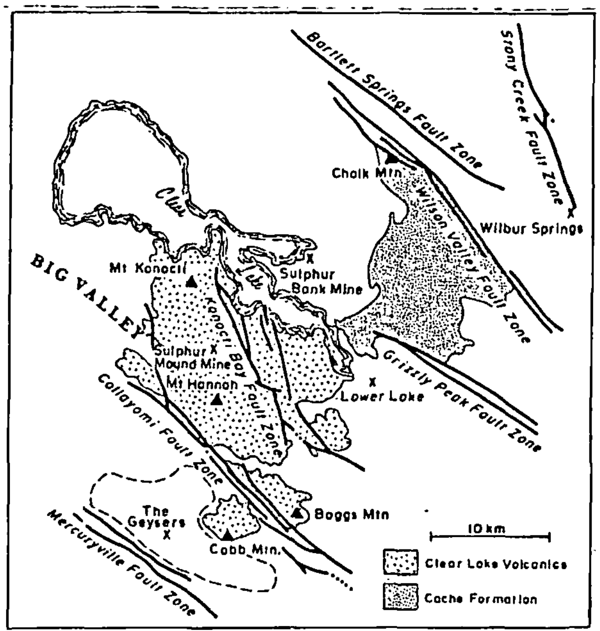
The heat source(s) for the several Salton Trough resources are unknown. Hot, partly molten rock at shallow depth (5-15 km) could underly at least some of the resource areas, or alternatively the active faulting could provide a mechanism where water could circulate to depths great enough to be heated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

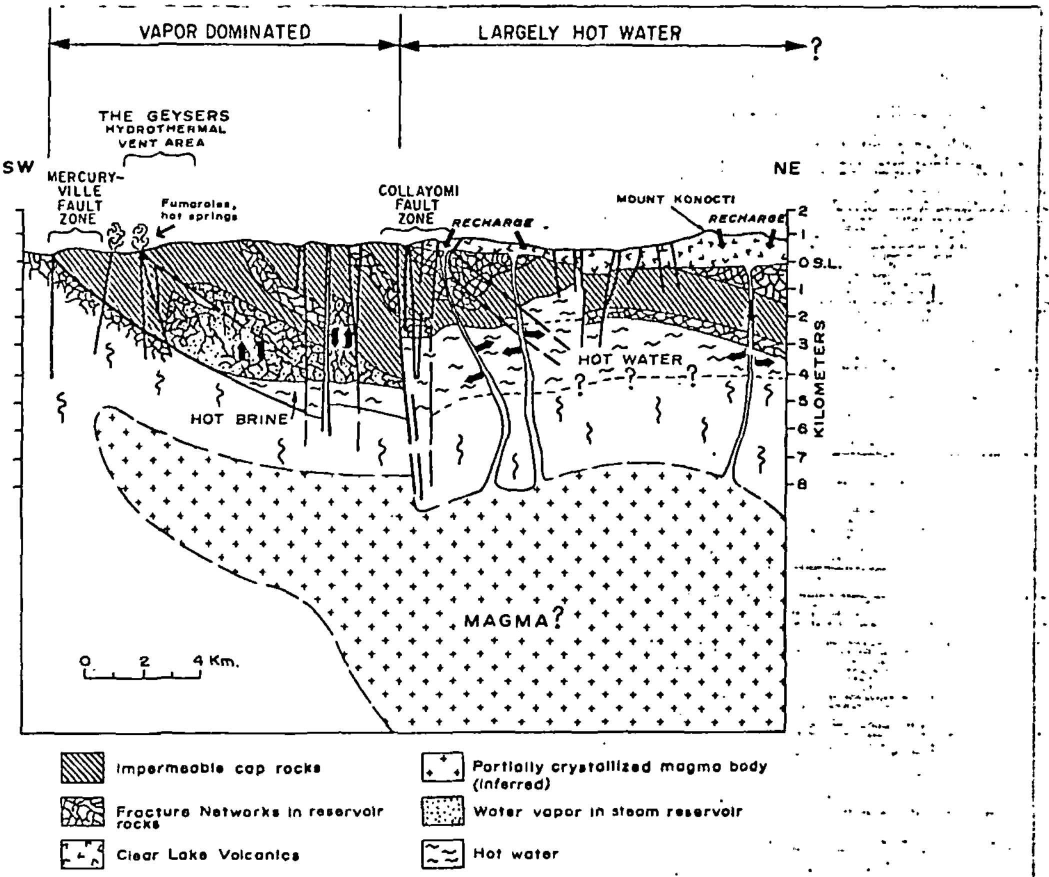
As shown in Figure 20, the presently known steam field is confined between the Mercuryville fault zone on the southwest and the Collayomi Fault zone on the northeast. The northwest and southeast margins are not defintely known. To the east and northeast lies the extensive Clear Lake volcanic field composed 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.

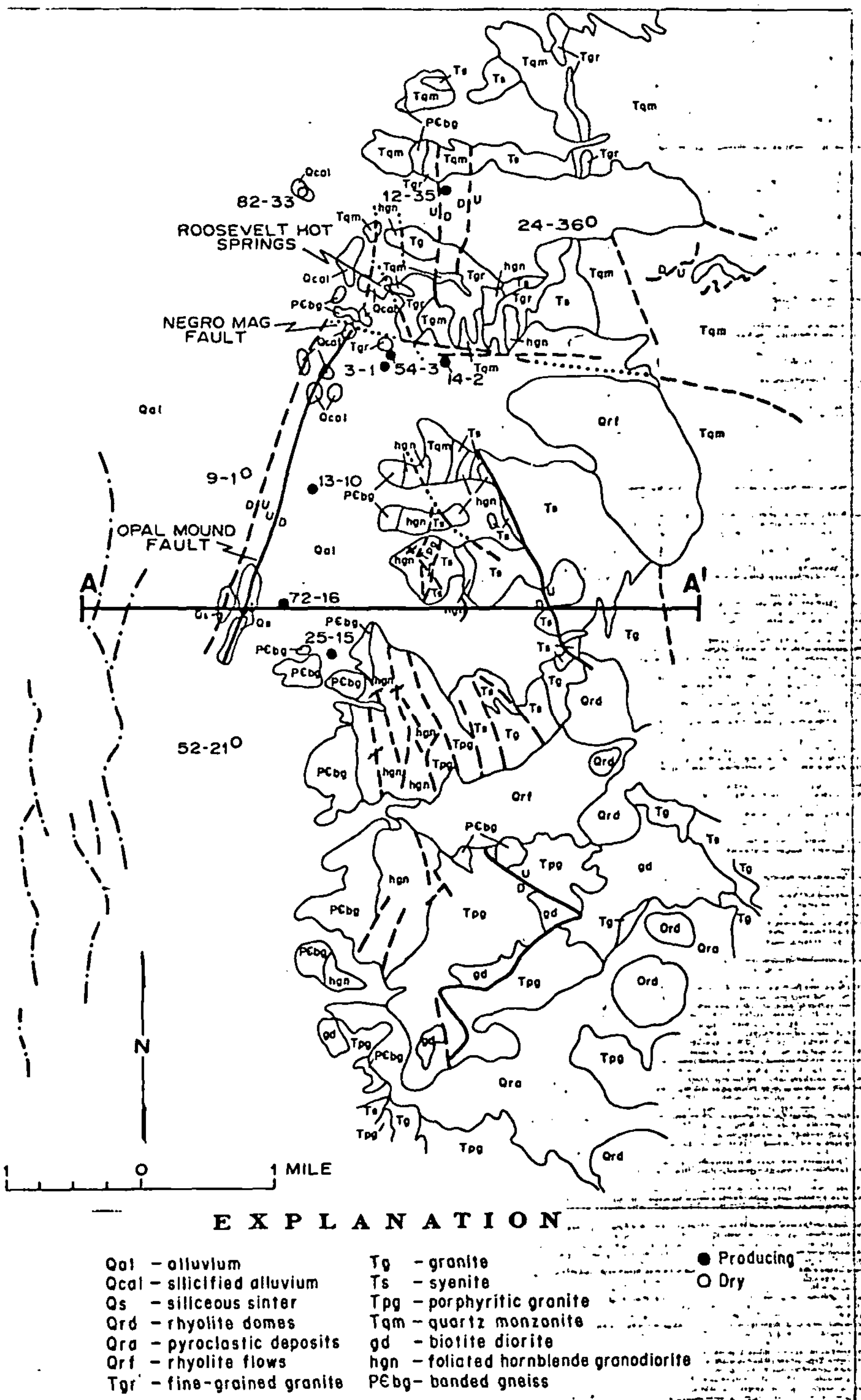
(after McLaughlin, 1977)

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.

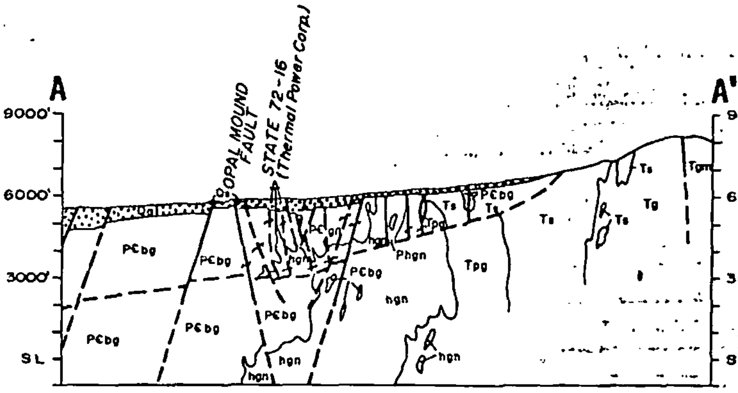
As an example of a Basin and Range hydrothermal system we will discuss Roosevelt Hot Springs, although it should not be supposed to be typical of all high temperature occurrences in this province. This geothermal area has been studied in detail for the past six years (Nielson et al., 1978; Ward et al., 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.



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)

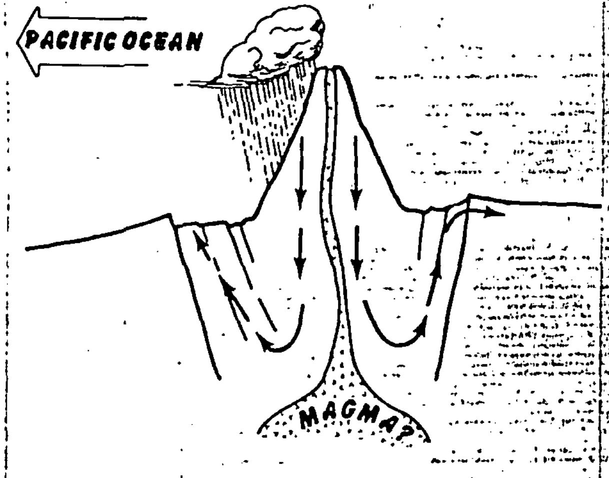
Figure 23

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

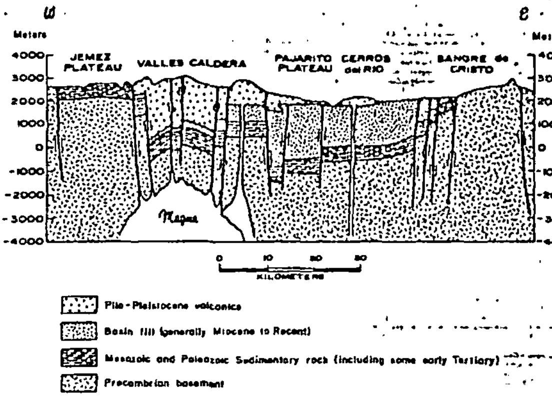
The basalt flows and other volcanic deposits of the Snake River Plain are an extension of the Columbia Plateau eastward across southern Idaho to the border with Wyoming. The plain is divided into a western part and an eastern part. Thermal waters occur in numerous wells and springs in the western portion, 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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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.

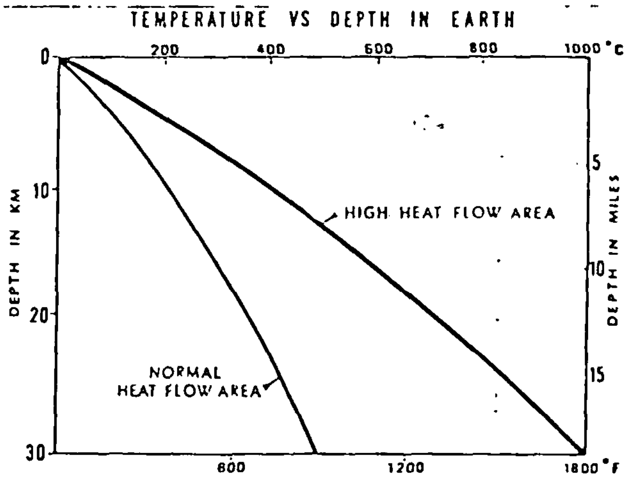


Figure 1

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 60×10^{-3} watts/m^2 (White and Williams, 1975) and since the mean surface area of the earth is about 5.1×10^{14} m^2, the rate of heat loss is about 32×10^{12} watts (32 million megawatts) or about 2.4×10^{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.

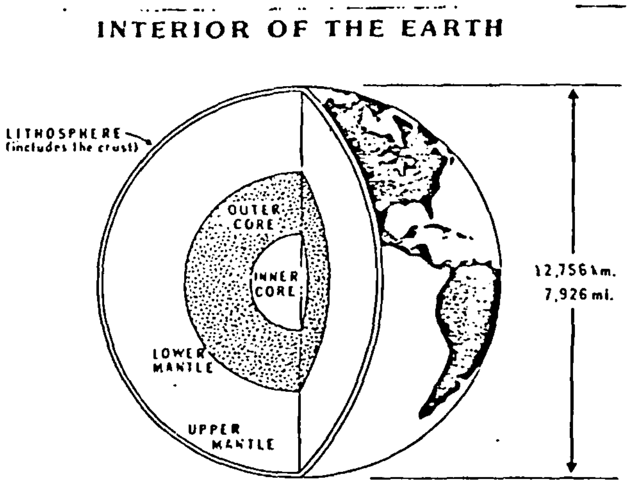


Figure 2_

GEOLOGICAL PROCESSES

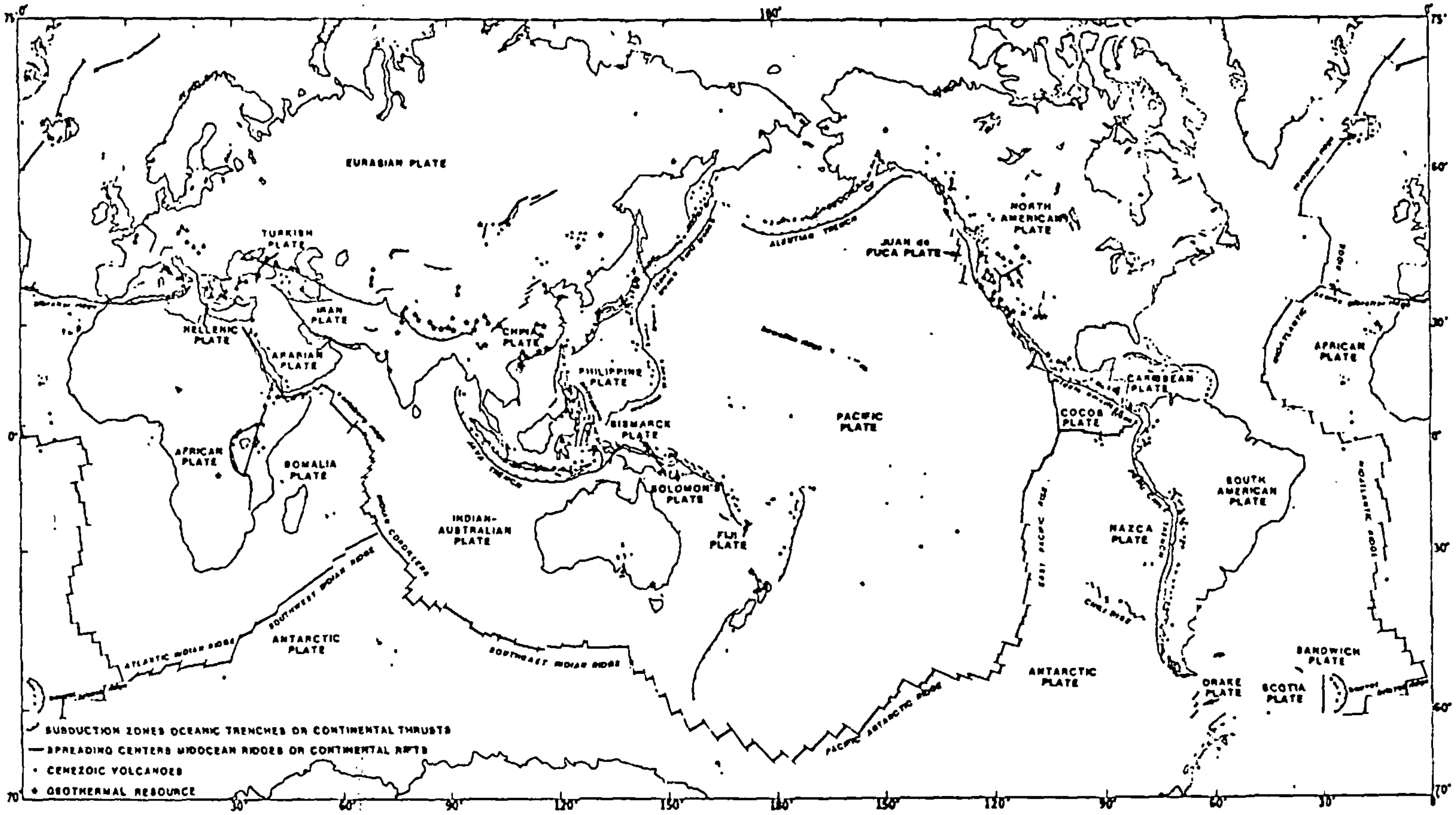
Geothermal resource areas, or geothermal areas for short, are generally those in which higher temperatures are found at shallower depths than is normal. This condition usually results from either 1) intrusion of molten rock to high levels in the earth's crust, 2) higher-than-average flow of heat to the 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

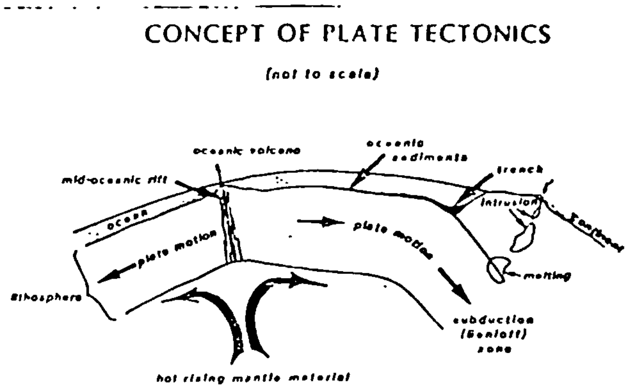


GEOTHERMAL RESOURCES AND PLATE TECTONIC FEATURES

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.


CONCEPT OF PLATE TECTONICS

(not to scale)

Figure 4

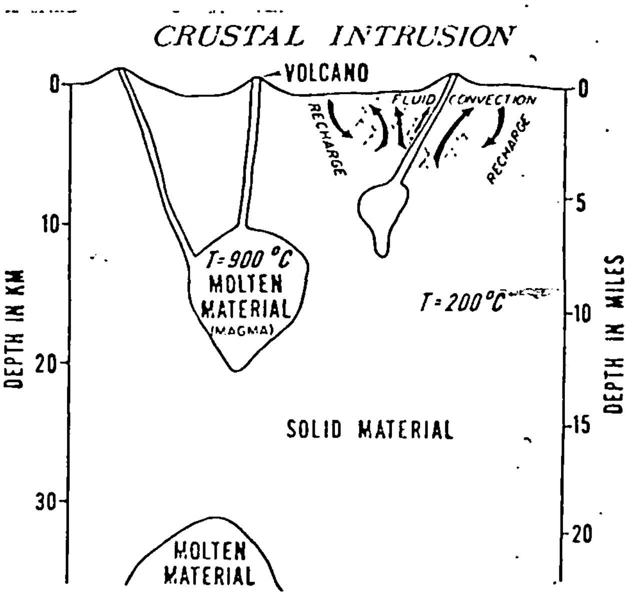

CRUSTAL INTRUSION

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 1 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.

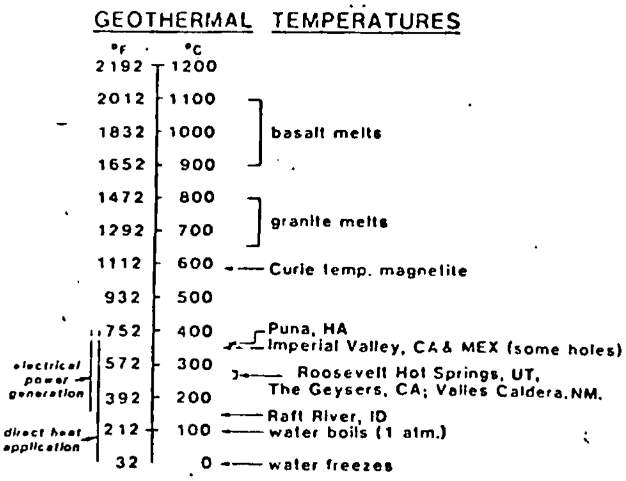


Figure 6

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.

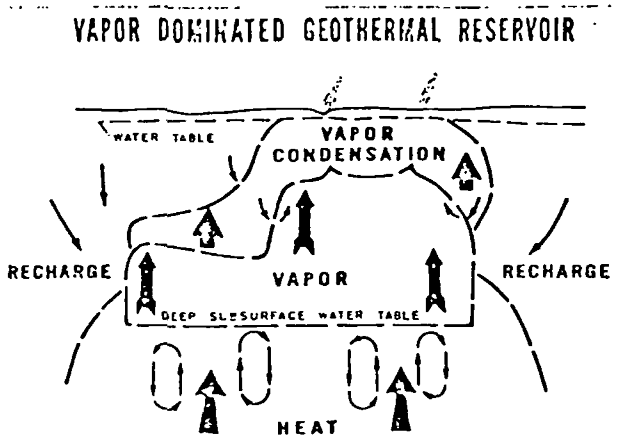


Figure 7

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 (1a 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 (1b(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

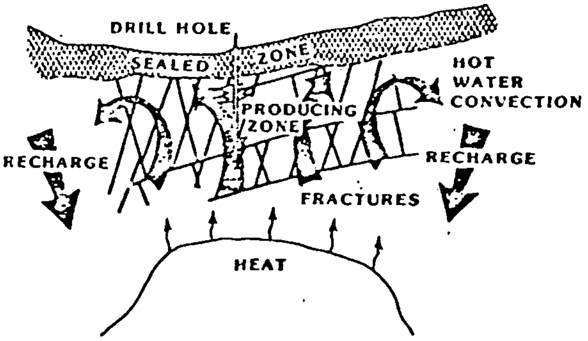


Figure 8

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

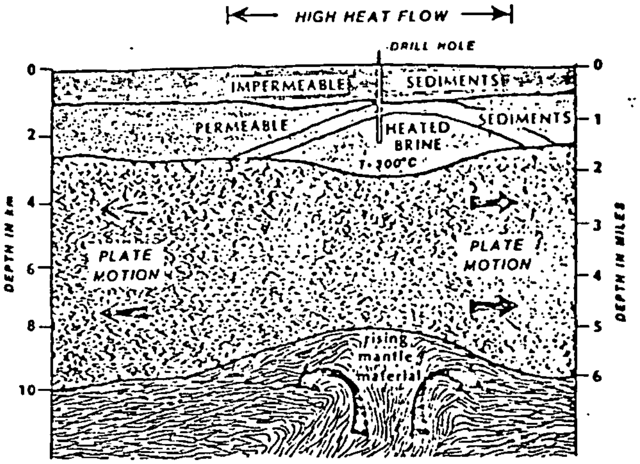
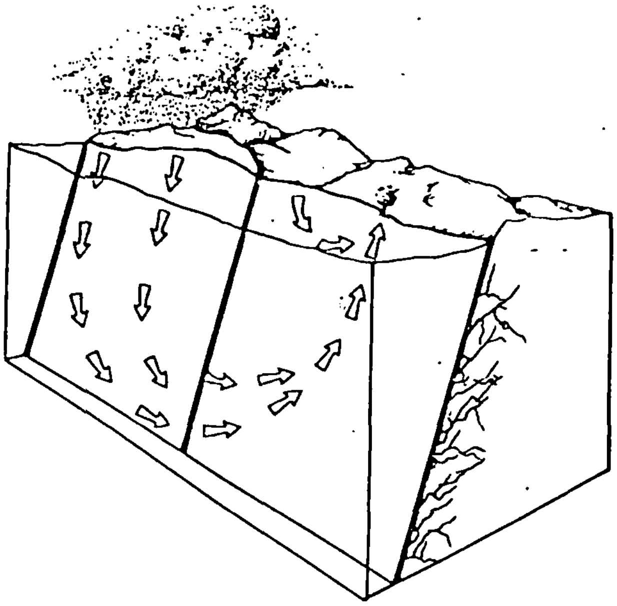


Figure 9

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

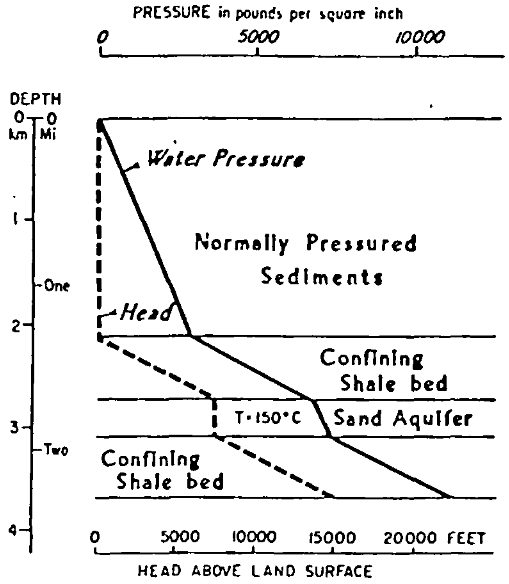


Figure 11

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

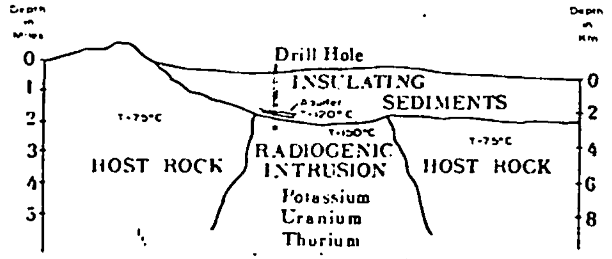
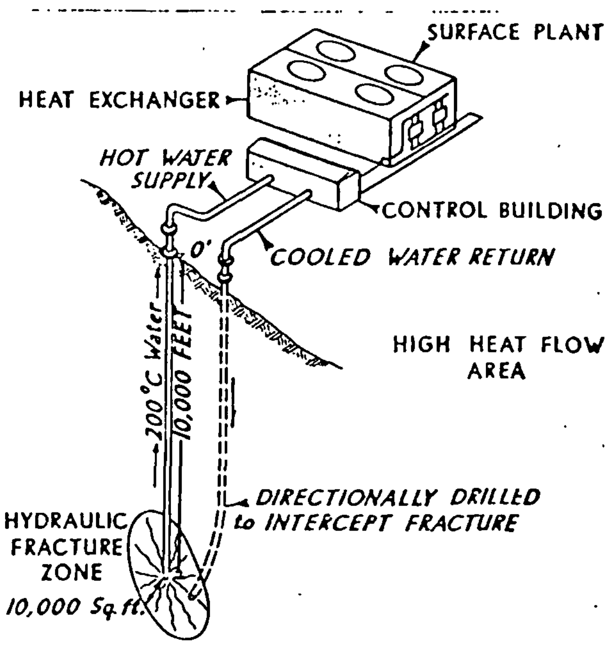


Figure 12

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.

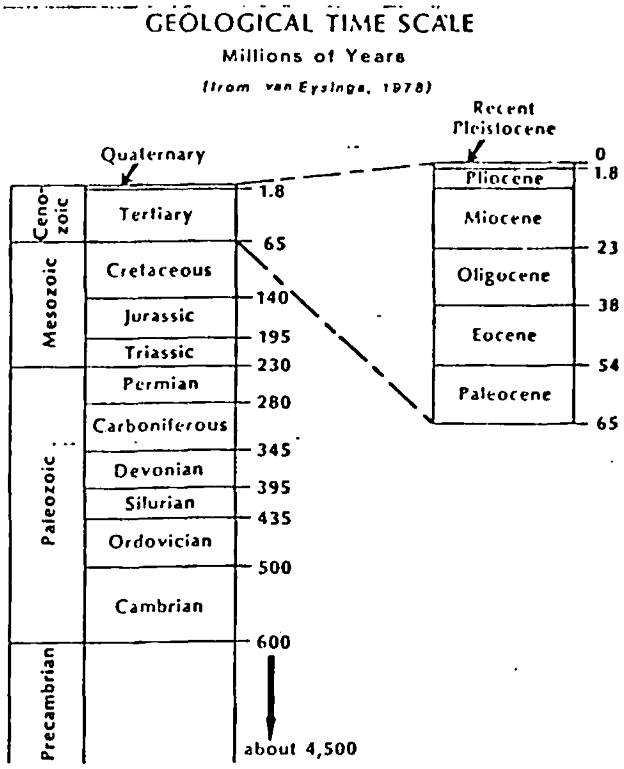


Figure 14

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.

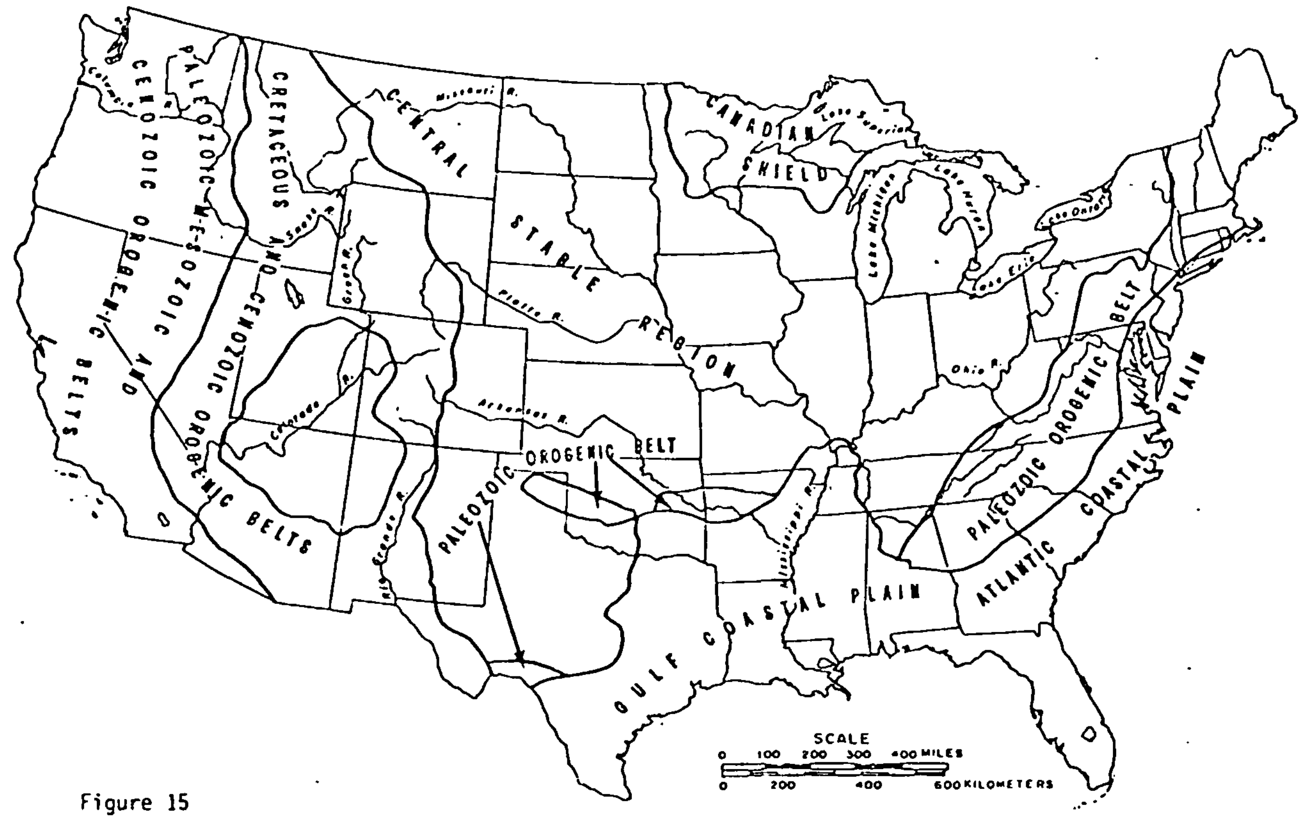


Figure 15

MAJOR TECTONIC DIVISIONS OF USA

(After Eardley, 1951)

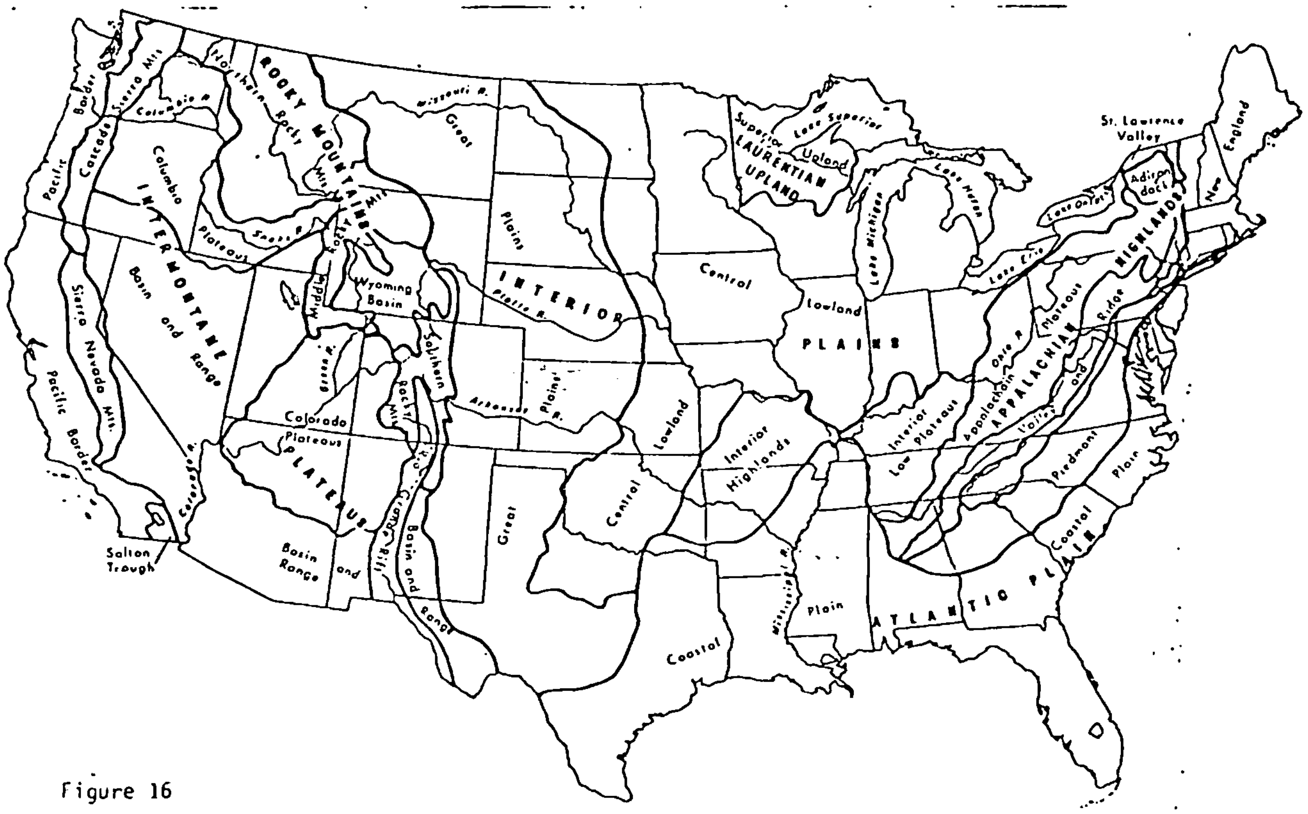


Figure 16

PHYSIOGRAPHIC MAP of USA

(after Fenneman, 1928)

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

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.

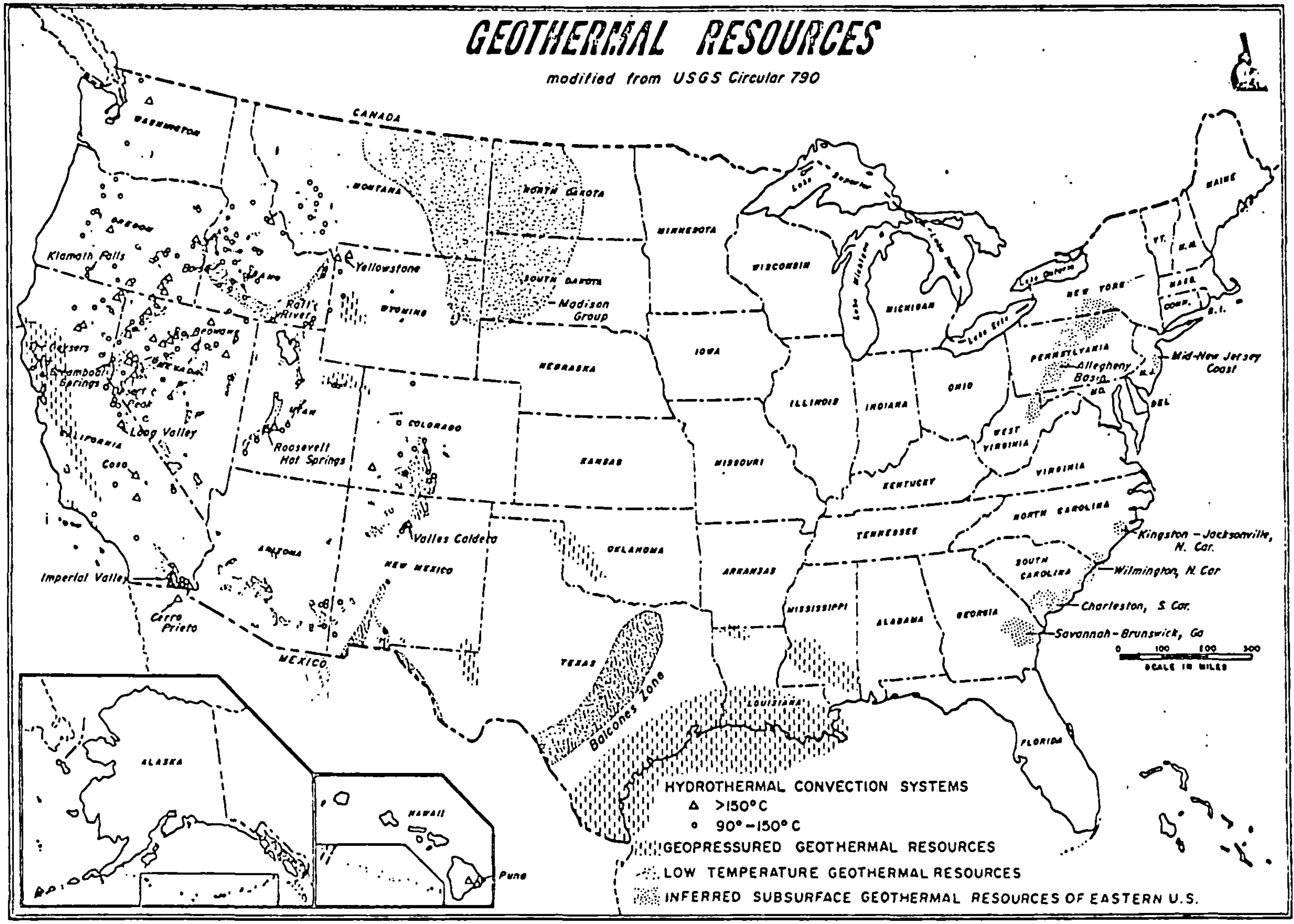
Orogenic Belts of the Rocky Mountains

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


GEOTHERMAL RESOURCES
modified from USGS Circular 790
CANADA
MEXICO
Klamath Falls
Boise
Yellowstone
Raft River
Bruneau
Geysers
Steamboat Springs
Long Valley
Coso
Roosevelt Hot Springs
Valles Caldera
Imperial Valley
Cerro Prieto
Madison Group
Balcones Zone
Allegheny Basin
Mid-New Jersey Coast
Kingston - Jacksonville, N. Car.
Wilmington, N. Car
Charleston, S. Car.
Savannah-Brunswick, Ga
Puna
0 100 200 300
SCALE IN MILES
WASHINGTON
OREGON
IDAHO
MONTANA
WYOMING
NEVADA
CALIFORNIA
UTAH
COLORADO
ARIZONA
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
SOUTH CAROLINA
NORTH CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
NEW YORK
MAINE
VT.
N.H.
MASS.
CONN.
R.I.
N.J.
DEL
MD.
ALASKA
HAWAII
HYDROTHERMAL CONVECTION SYSTEMS
△ >150°C
○ 90°-150°C
GEOPRESSURED GEOTHERMAL RESOURCES
LOW TEMPERATURE GEOTHERMAL RESOURCES
INFERRED SUBSURFACE GEOTHERMAL RESOURCES OF EASTERN U.S.

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

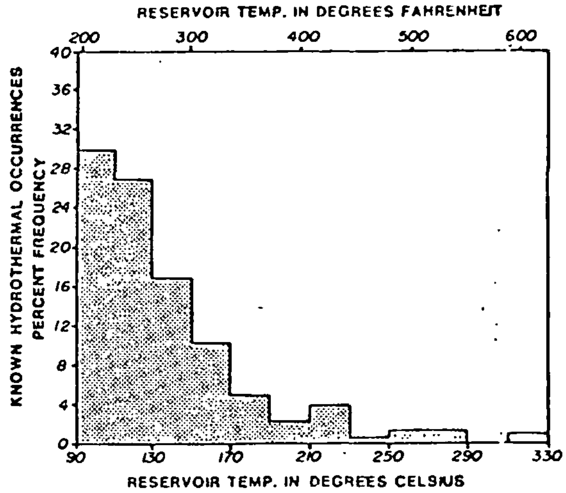


Figure 18

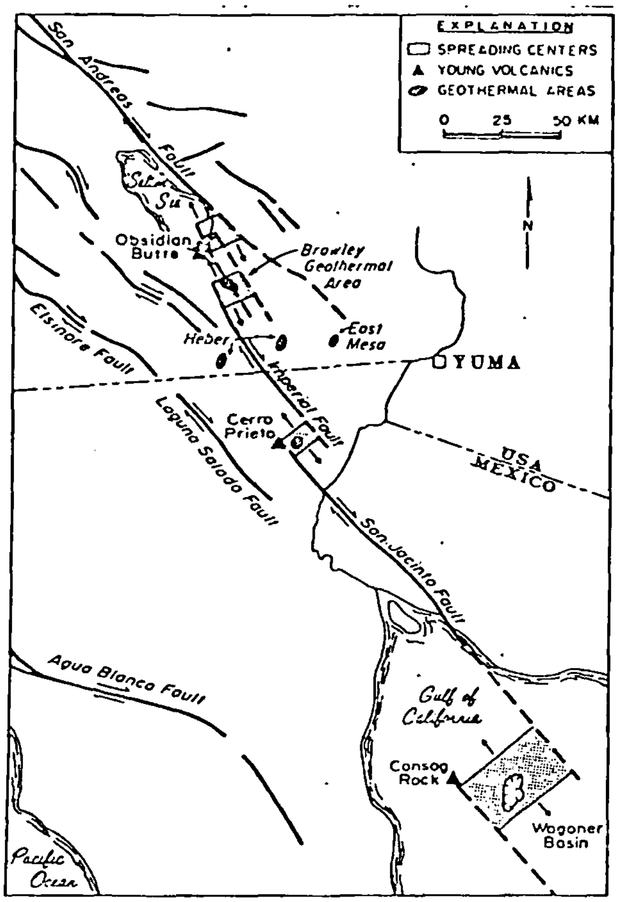
Let us consider the known geothermal occurrences in a bit more detail, beginning in the Western U.S.

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.

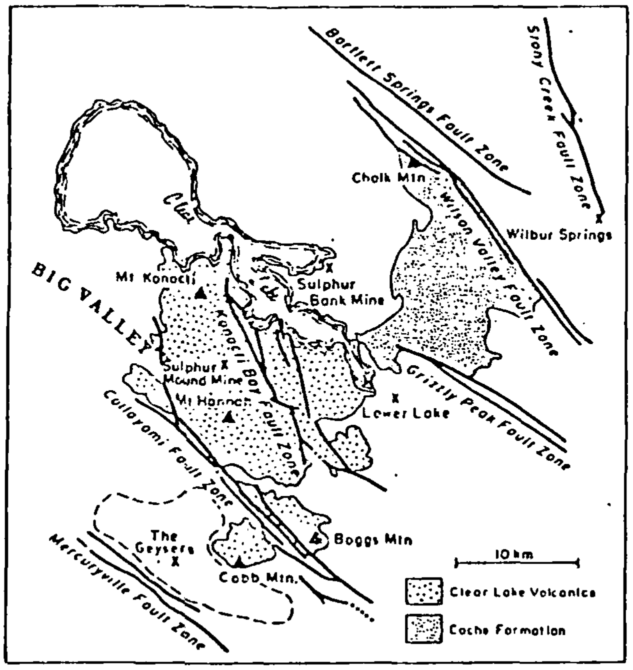
The heat source(s) for the several Salton Trough resources are unknown. Hot, partly molten rock at shallow depth (5-15 km) could underly at least some of the resource areas, or alternatively the active faulting could provide a mechanism where water could circulate to depths great enough to be heated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

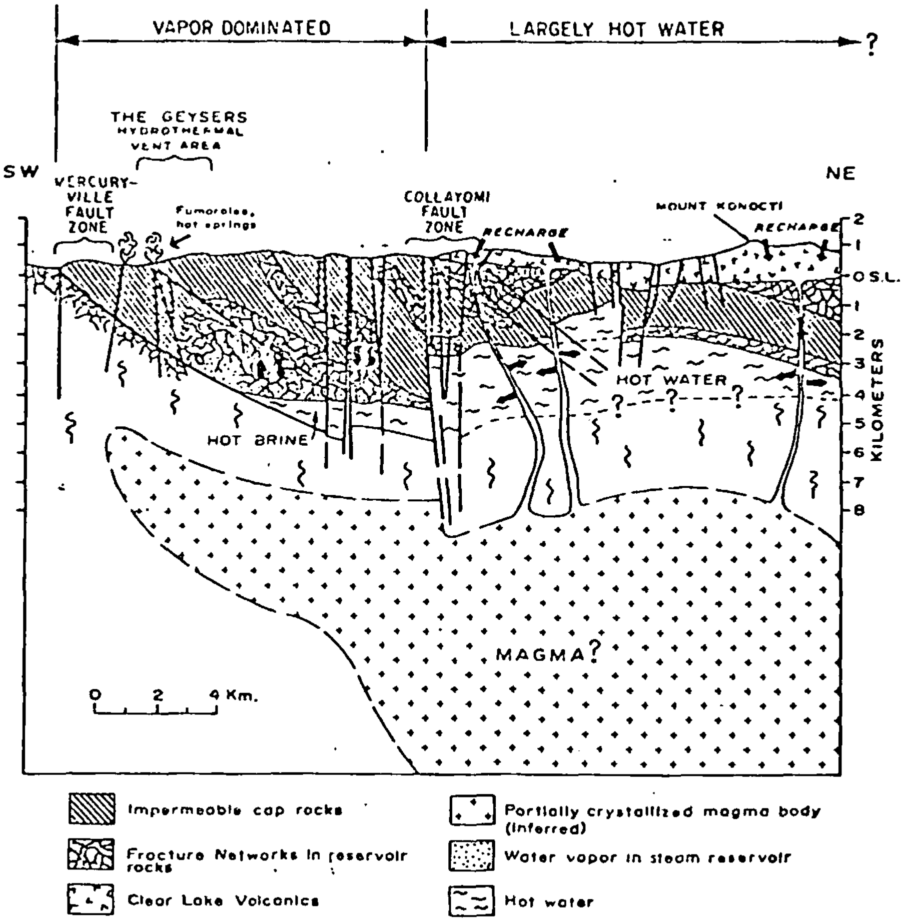
As shown in Figure 20, the presently known steam field is confined between the Mercuryville fault zone on the southwest and the Collayomi Fault zone on the northeast. The northwest and southeast margins are not defintely known. To the east and northeast lies the extensive Clear Lake volcanic field composed 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.

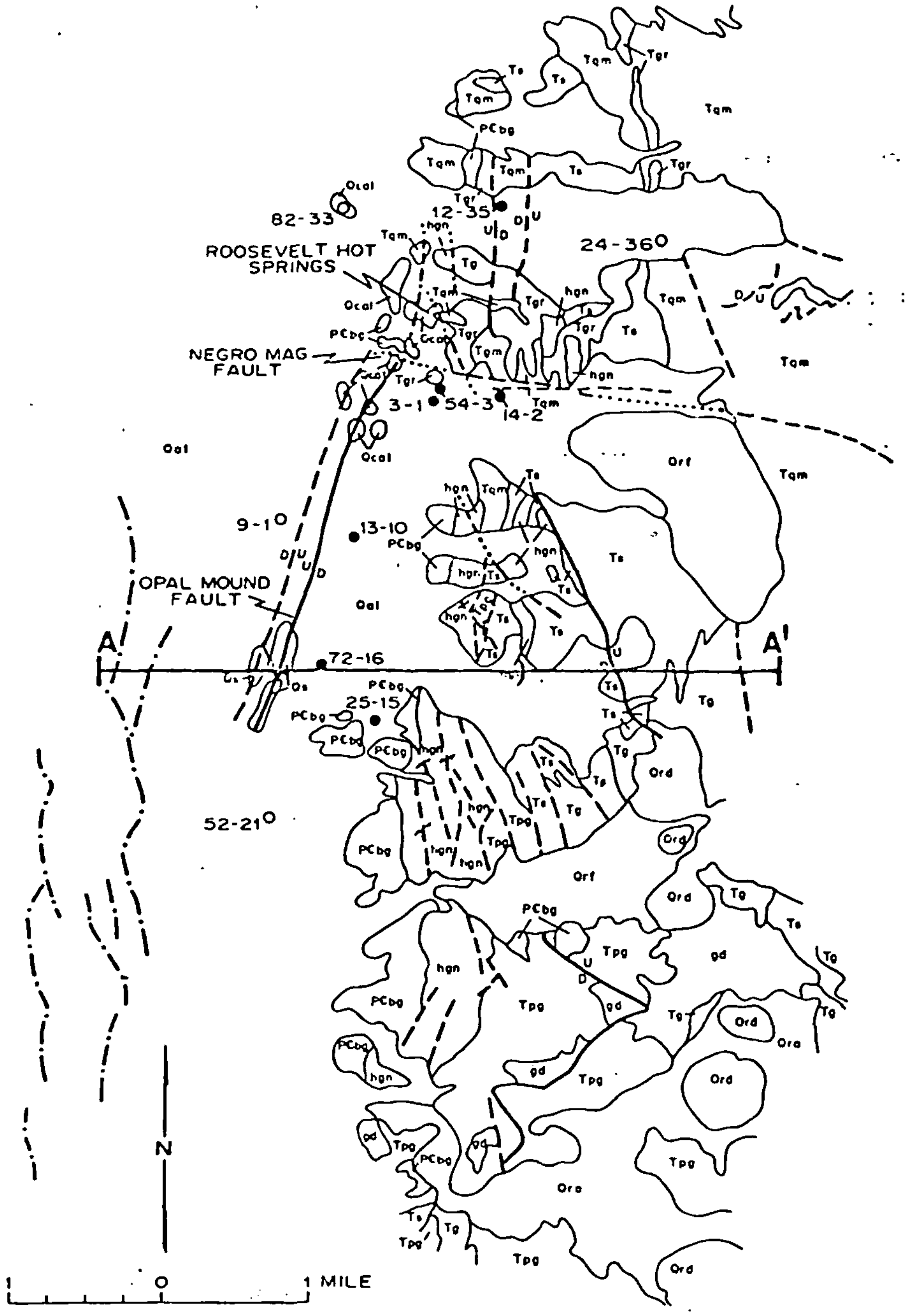
(after McLaughlin, 1977)

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)

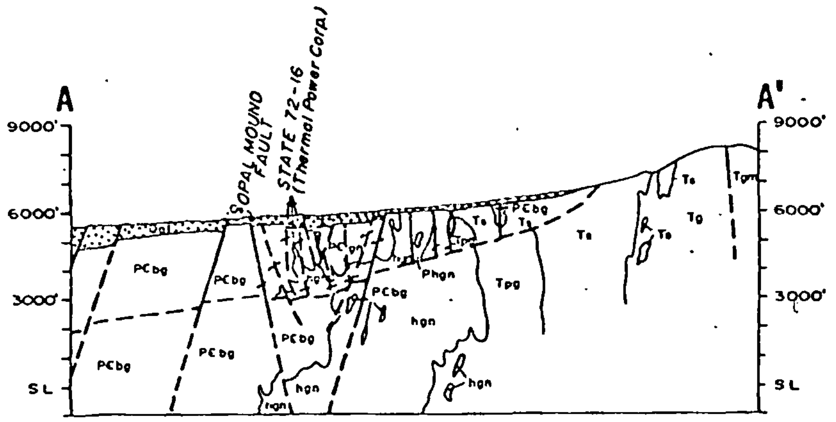


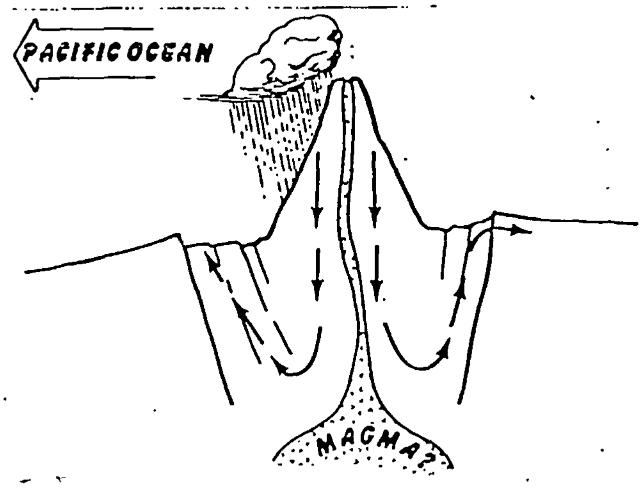
Figure 23

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

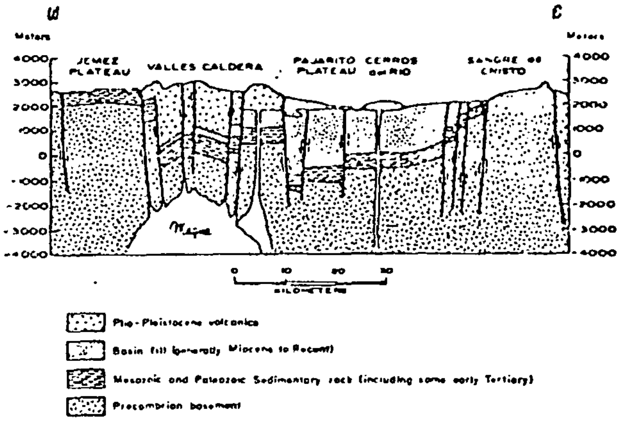
The basalt flows and other volcanic deposits of the Snake River Plain are an extension of the Columbia Plateau eastward across southern Idaho to the border with Wyoming. The plain is divided into a western part and an eastern part. Thermal waters occur in numerous wells and springs in the western portion, 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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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.

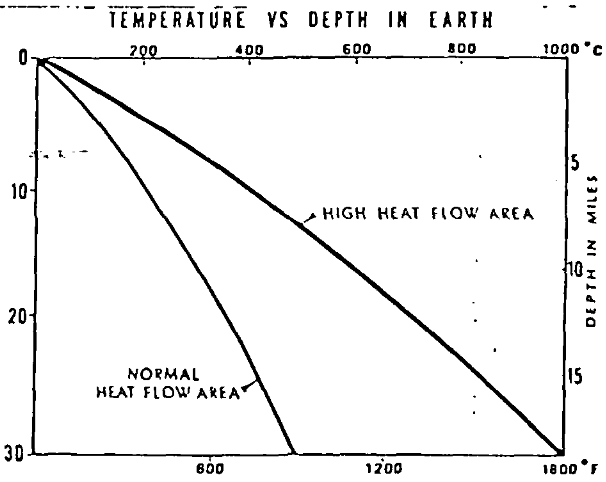

TEMPERATURE VS DEPTH IN EARTH

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 60×10^{-3} watts/m^2 (White and Williams, 1975) and since the mean surface area of the earth is about 5.1×10^{14} m^2, the rate of heat loss is about 32×10^{12} watts (32 million megawatts) or about 2.4×10^{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.

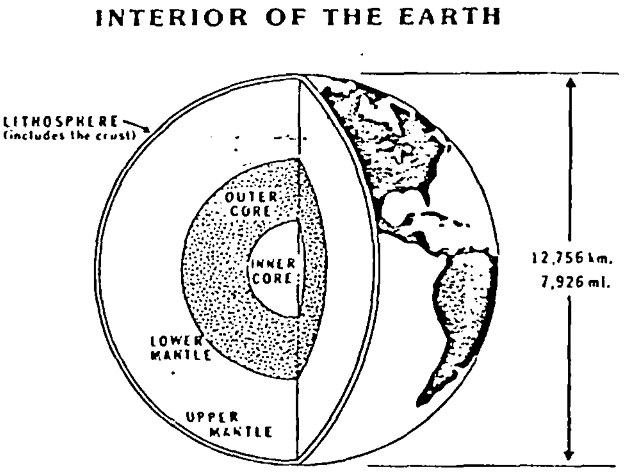


Figure 2

GEOLOGICAL PROCESSES

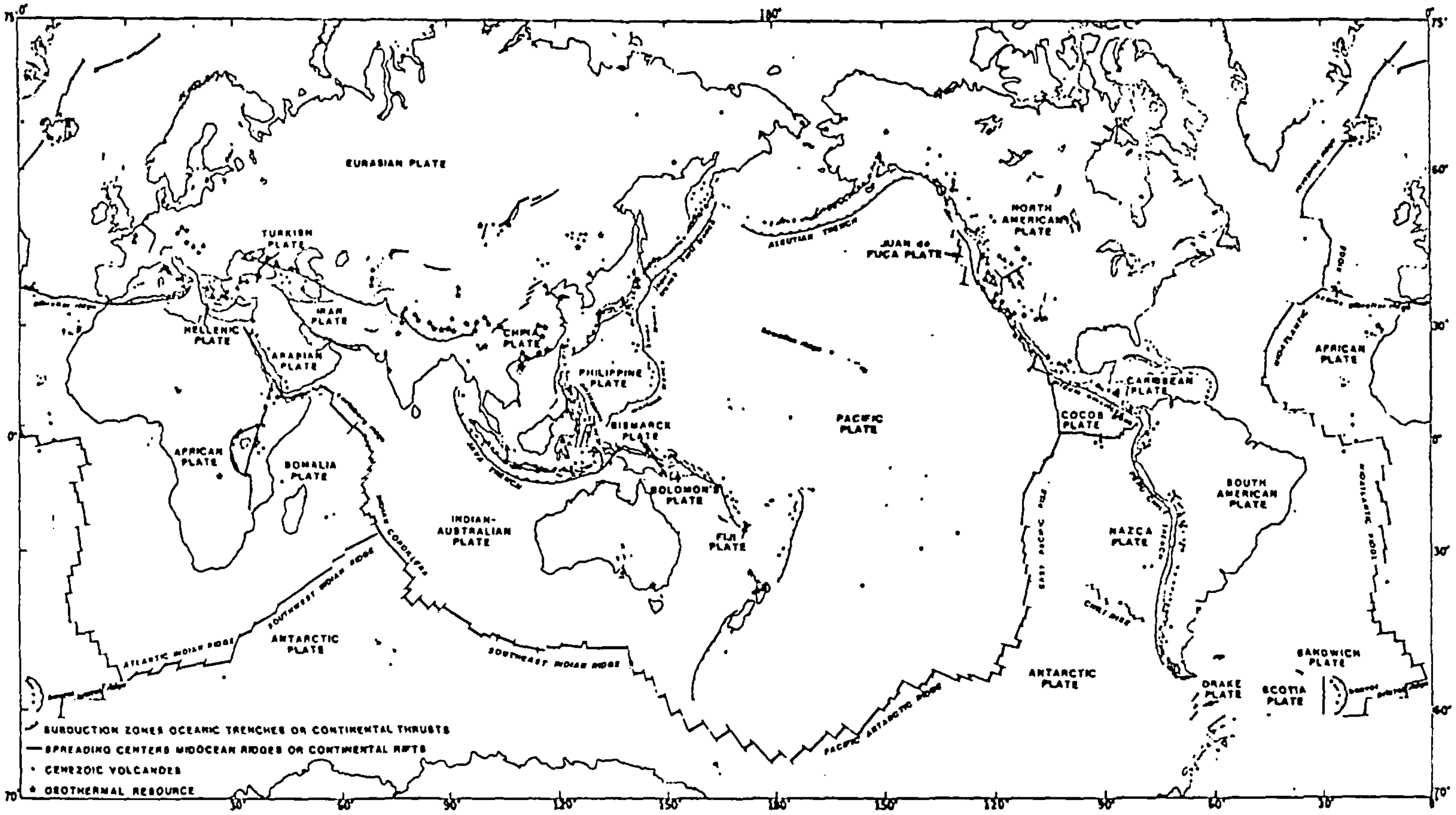
Geothermal resource areas, or geothermal areas for short, are generally those in which higher temperatures are found at shallower depths than is normal. This condition usually results from either 1) intrusion of molten rock to high levels in the earth's crust, 2) higher-than-average flow of heat to the 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.

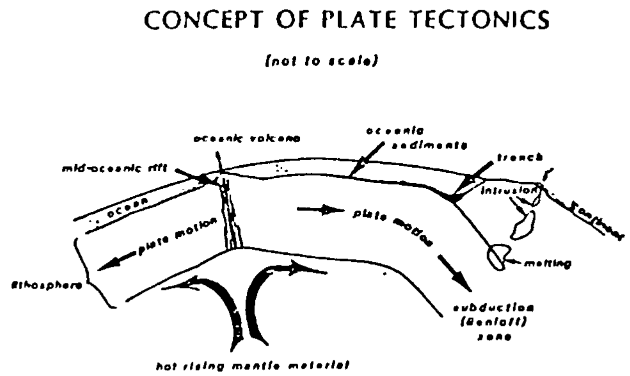


Figure 4

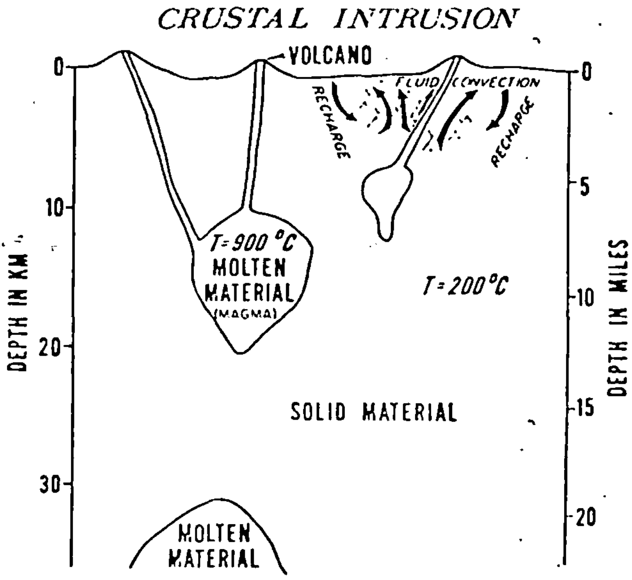


Figure 5

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.

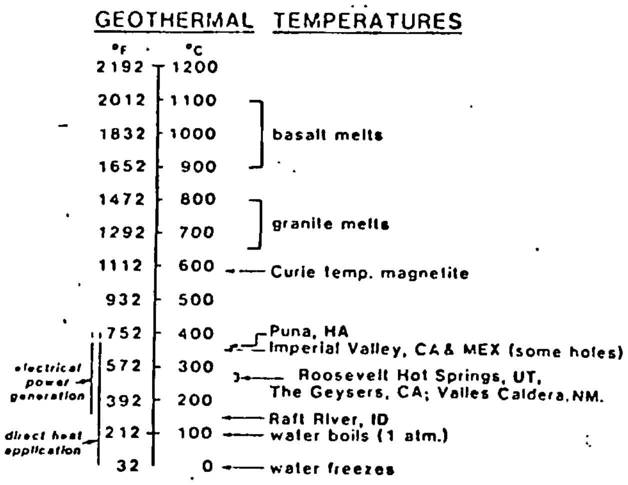

GEOTHERMAL TEMPERATURES

Figure 6

TABLE 1

GEOTHERMAL RESOURCE CLASSIFICATION
(After White and Williams, 1975)

Resource Type	Temperature Characteristics
1. <u>Hydrothermal convection resources</u> (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. <u>Hot rock resources</u> (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. <u>Other resources</u>	
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.

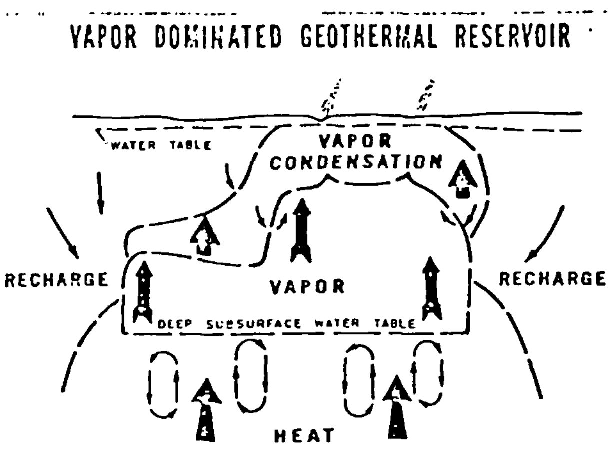


Figure 7

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 (1a 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 (1b(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

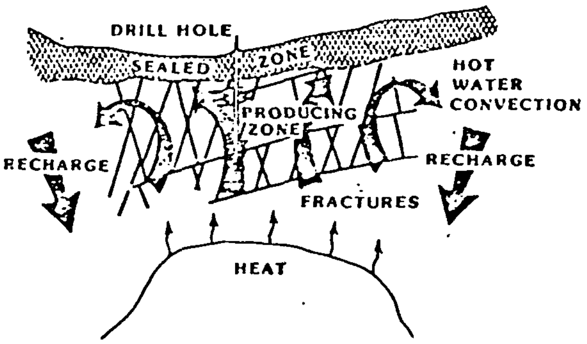


Figure 8

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

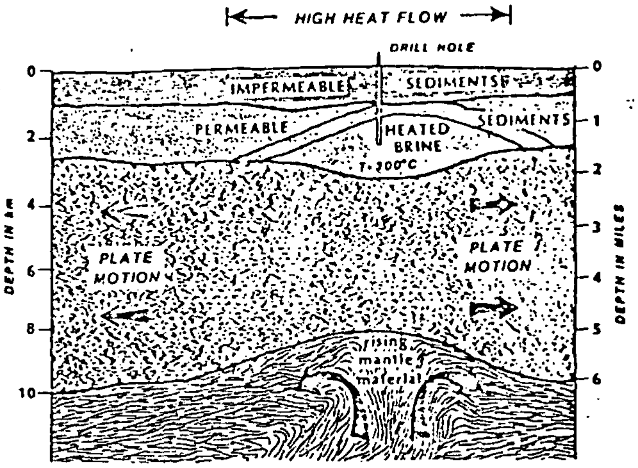
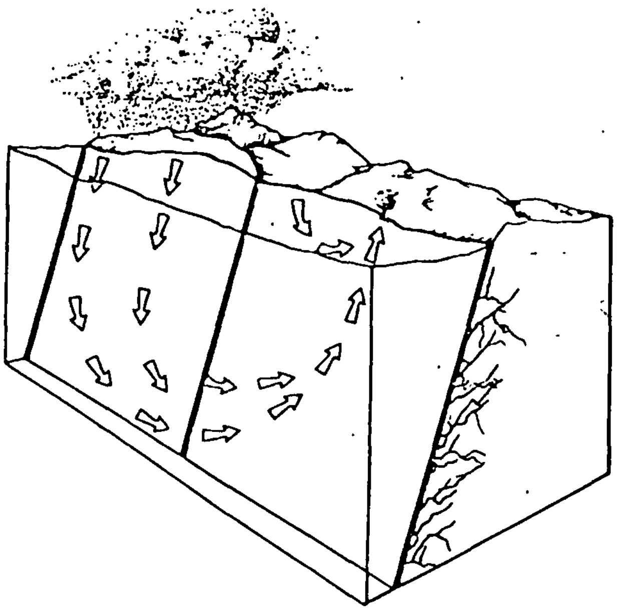


Figure 9

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

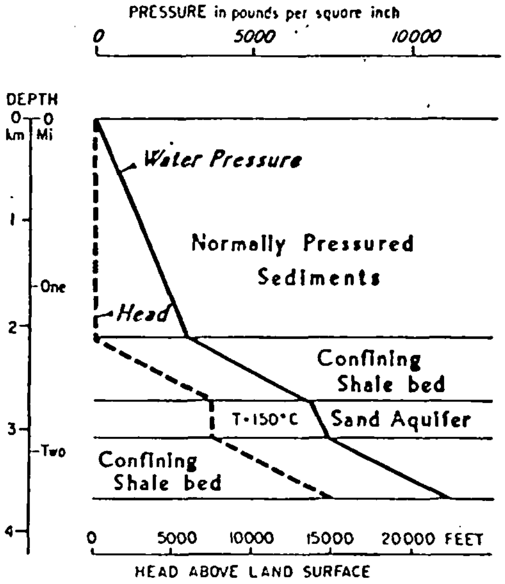


Figure 11

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

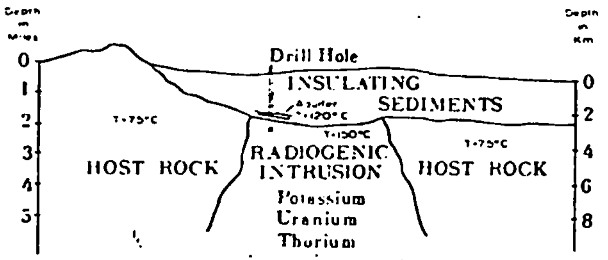
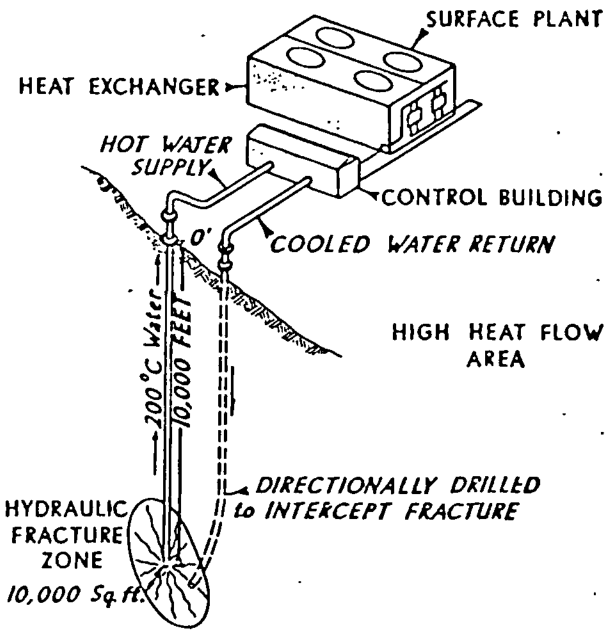


Figure 12

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.

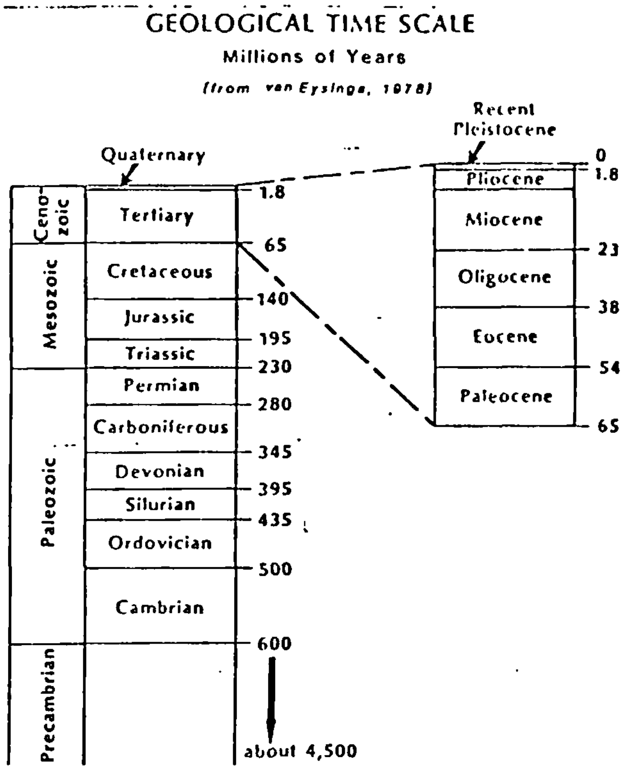


Figure 14

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.

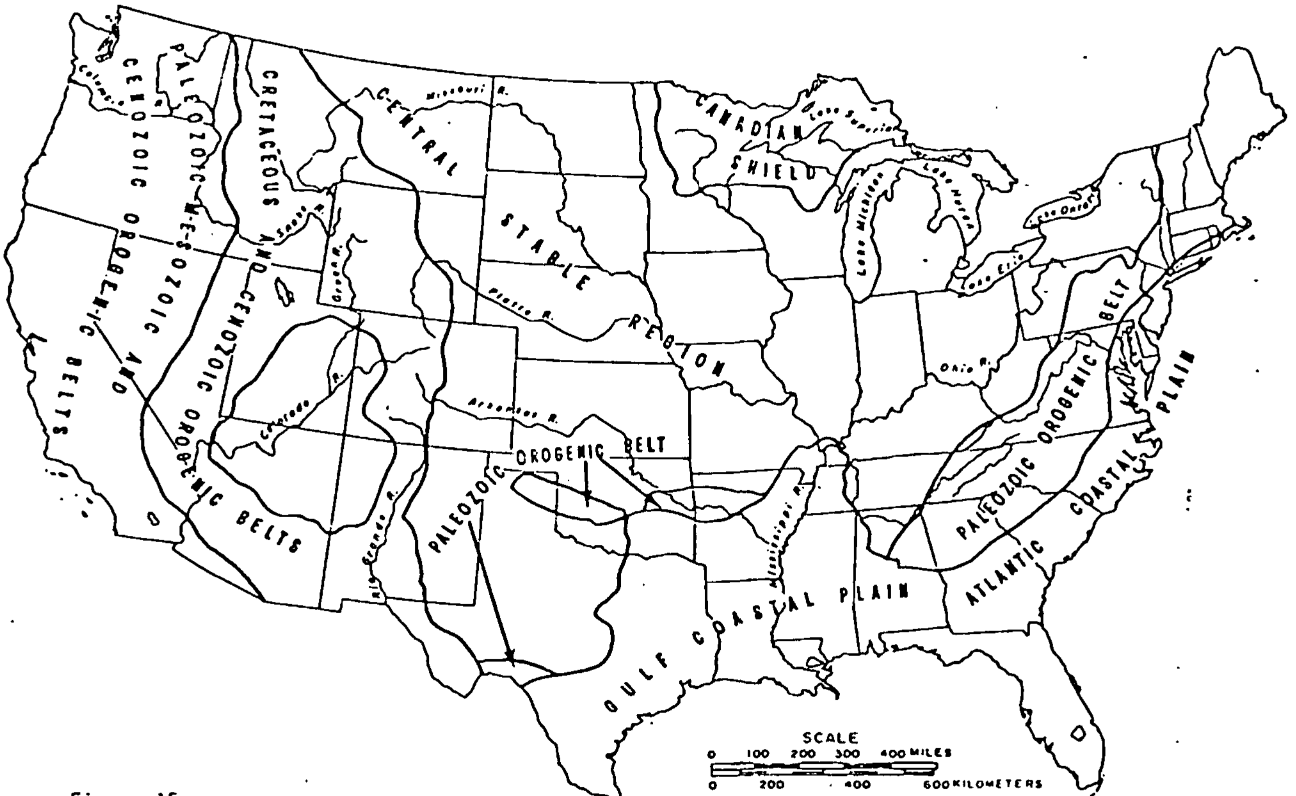


Figure 15

MAJOR TECTONIC DIVISIONS OF USA

(After Eardley, 1951)

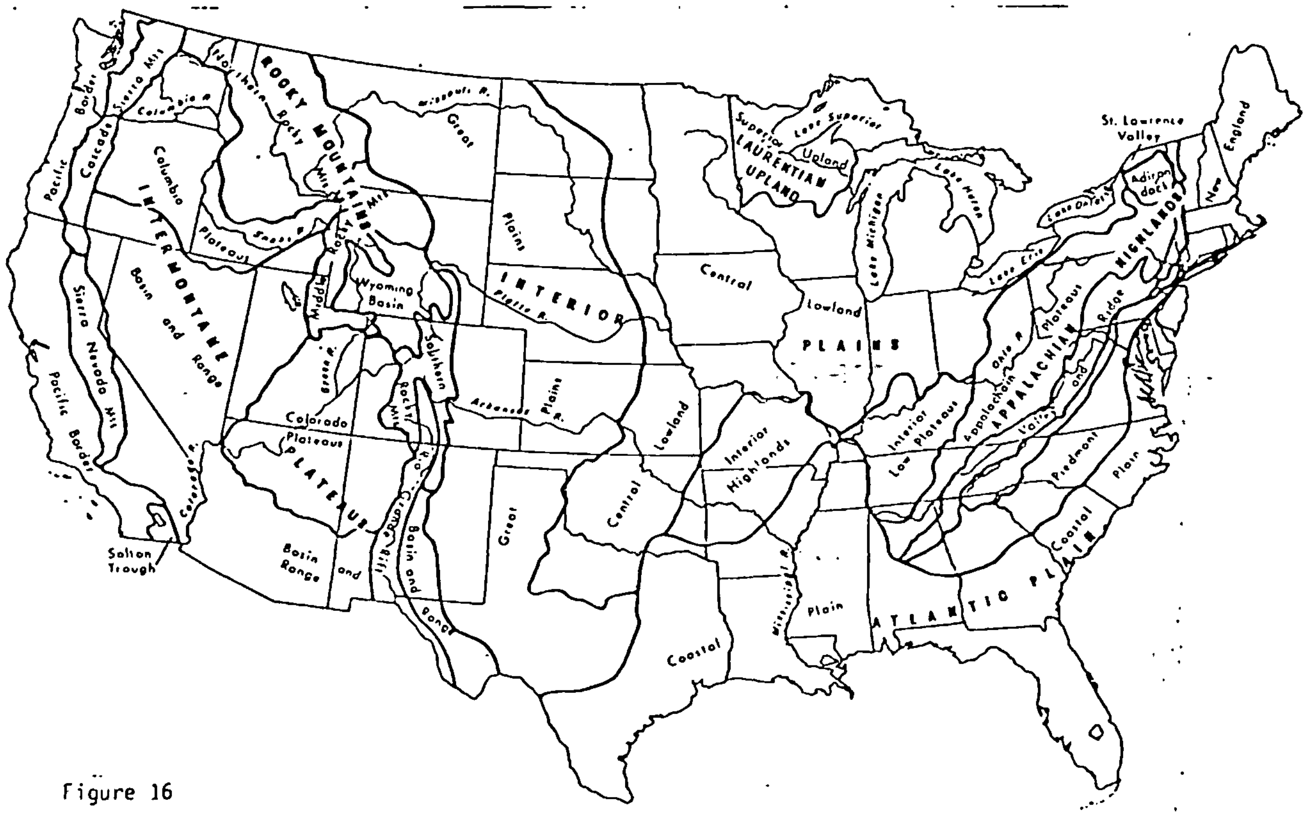


Figure 16

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 Cretaceous 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


GEOTHERMAL RESOURCES
modified from USGS Circular 790
CANADA
MEXICO
WASHINGTON
OREGON
IDAHO
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
NEVADA
CALIFORNIA
UTAH
COLORADO
ARIZONA
NEW MEXICO
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
SOUTH CAROLINA
NORTH CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
NEW YORK
MD.
DEL.
N.J.
CONN.
R.I.
MASS.
VT.
N.H.
MAINE
ALASKA
HAWAII
Puna
Klamath Falls
Boise
Yellowstone
Raft River
Bruneau
Geysers
Steamboat Springs
Long Valley
Coso
Imperial Valley
Cerro Prieto
Roosevelt Hot Springs
Valles Caldera
Madison Group
Balcones Zone
Allegheny Basin
Mid-New Jersey Coast
Kingston – Jacksonville, N. Car.
Wilmington, N. Car.
Charleston, S. Car.
Savannah-Brunswick, Ga
0 100 200 300
SCALE IN MILES
HYDROTHERMAL CONVECTION SYSTEMS
△ >150°C
○ 90°–150°C
GEOPRESSURED GEOTHERMAL RESOURCES
LOW TEMPERATURE GEOTHERMAL RESOURCES
INFERRED SUBSURFACE GEOTHERMAL RESOURCES OF EASTERN U.S.

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.

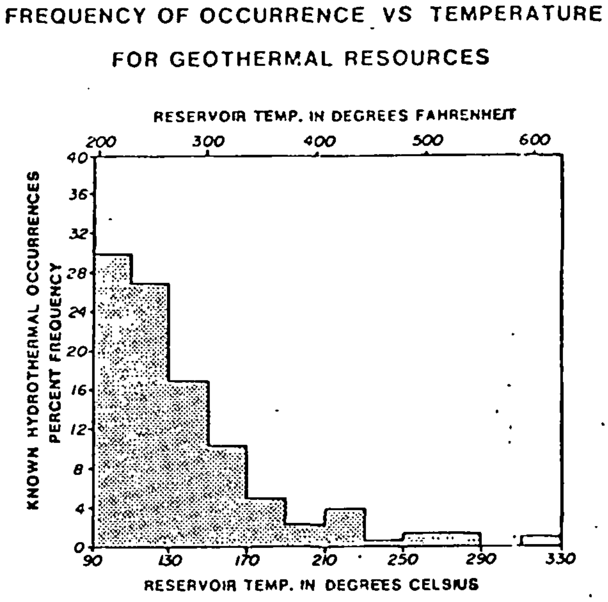


Figure 18

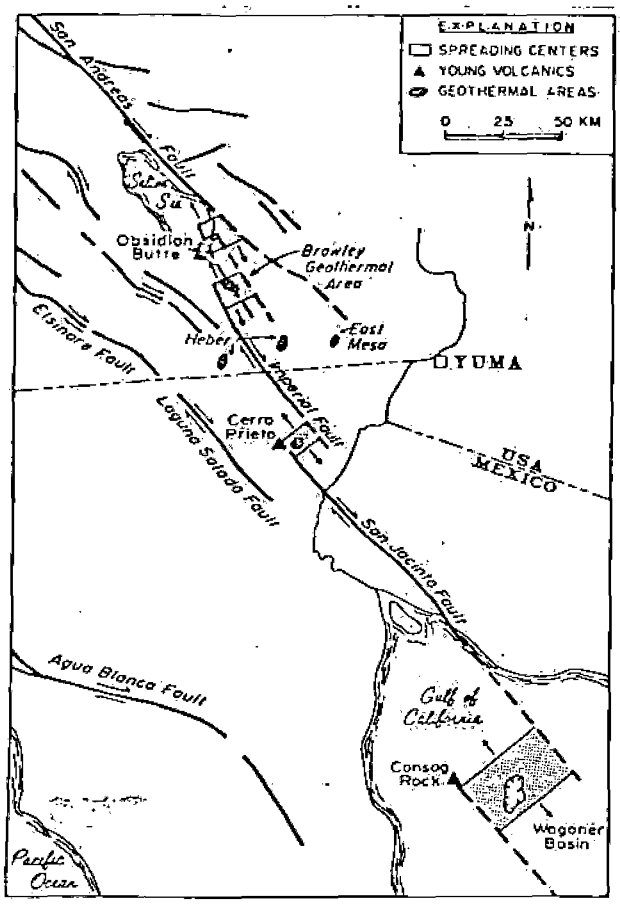
Let us consider the known geothermal occurrences in a bit more detail, beginning in the Western U.S.

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.

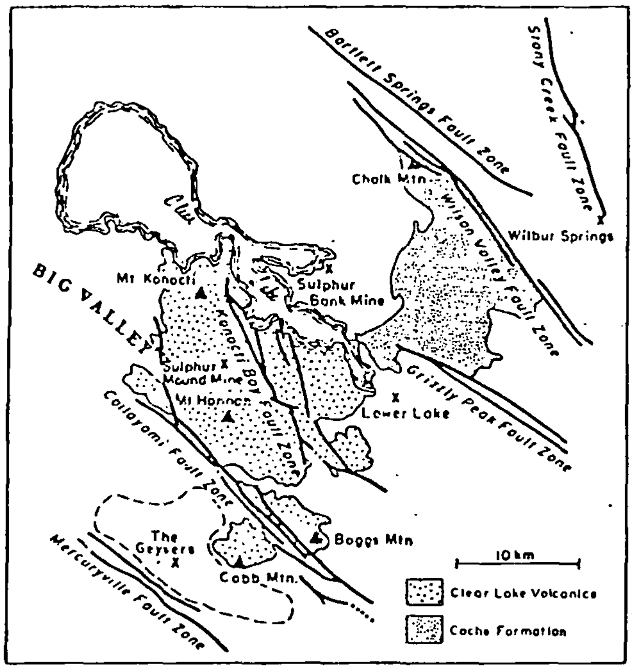
The heat source(s) for the several Salton Trough resources are unknown. Hot, partly molten rock at shallow depth (5-15 km) could underly at least some of the resource areas, or alternatively the active faulting could provide a mechanism where water could circulate to depths great enough to be heated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

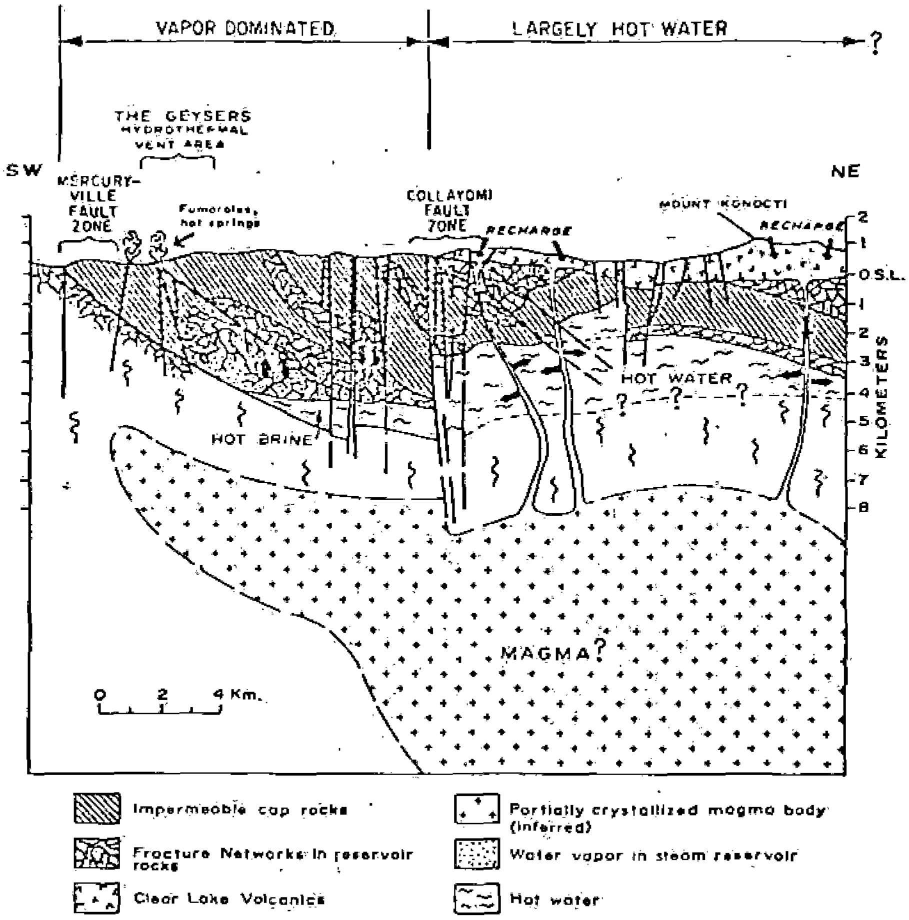
As shown in Figure 20, the presently known steam field is confined between the Mercuryville fault zone on the southwest and the Collayomi Fault zone on the northeast. The northwest and southeast margins are not defintely known. To the east and northeast lies the extensive Clear Lake volcanic field composed 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.

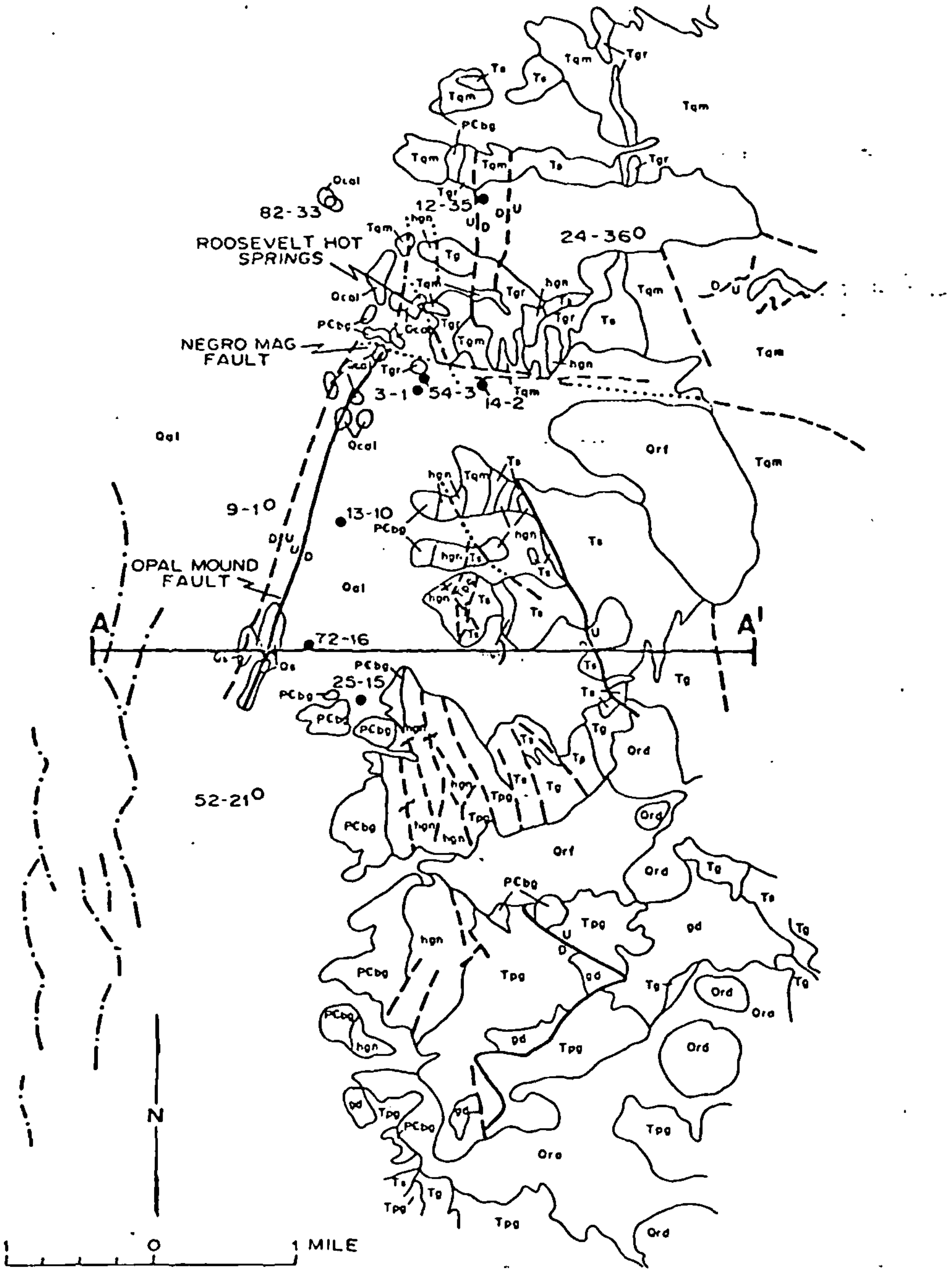
(after McLaughlin, 1977)

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.

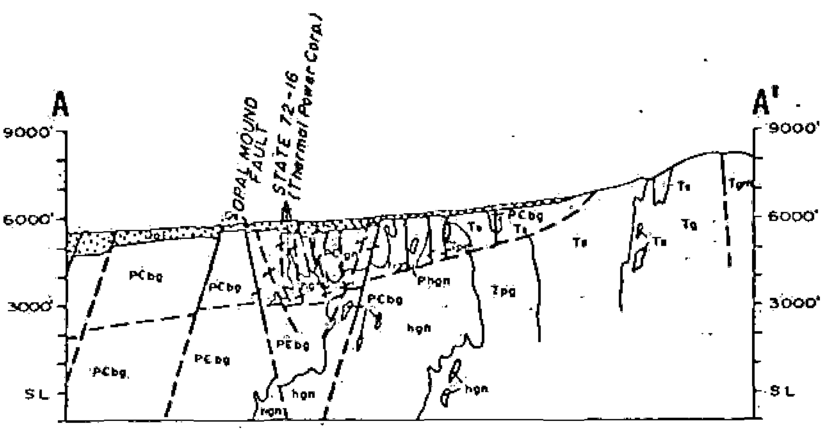


EXPLANATION

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

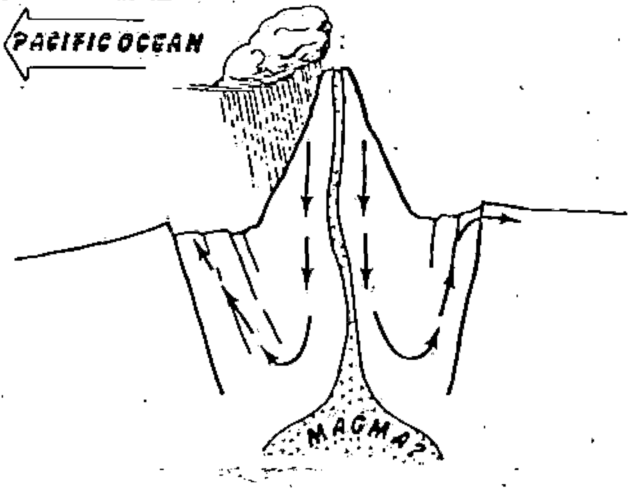
Figure 23

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

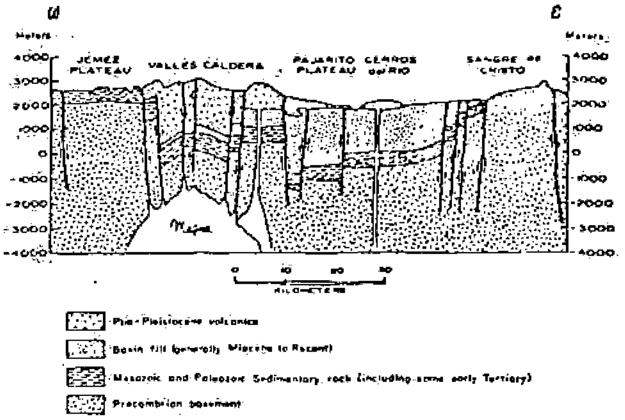
The basalt flows and other volcanic deposits of the Snake River Plain are an extension of the Columbia Plateau eastward across southern Idaho to the border with Wyoming. The plain is divided into a western part and an eastern part. Thermal waters occur in numerous wells and springs in the western portion, 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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NATURE AND OCCURRENCE OF GEOTHERMAL RESOURCES

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INTRODUCTION

Geothermal energy is heat energy which orginates within the earth. Under suitable geologic circumstances, which we will examine in some detail in this paper, 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 geological processes that have helped to shape the earth's surface are powered by transport of internal thermal energy. Such seemingly diverse phenomena as motion of the earth's crustal plates, uplifting of mountain ranges, occurrence of earthquakes, eruption of volcanos and spouting of geysers all owe their origin to the redistribution of the earth's internal heat as it flows from inner regions of higher temperature to outer regions of lower temperature.

Temperature within the earth increases steadily with increasing depth. Figure 1 illustrates this increase of temperature with depth for the first few tens of kilometers in the earth. Plastic or semi-molten rock exists everywhere under the continents at depths ranging from 20 km to 40 km and under the oceans at shallower depths of 10 km. For reference, using present drilling technology, holes can be drilled to depths of about 10 km (6.2 miles) under good drilling conditions. Temperatures at these depths are believed to range between 200°C and 500°C, and to increase substantially with depth so that at the earth's center, nearly 4,000 miles deep, the temperature may be more than 4000°C (Figures 1, 2 and 3). Because the earth is hot inside, heat flows steadily outward to the surface where it is permanently lost by radiation into space at the prodigious rate of 35 million million watts (2.4 x 10^{20} calories/year). At present only a very small portion of this heat can be captured for man's benefit. Two ultimate sources for this heat appear to be most important among a number of contributing alteratives: 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 subsequent mass redistribution when much of the heavier material sank to form the earth's mantle and core (Figure 2).

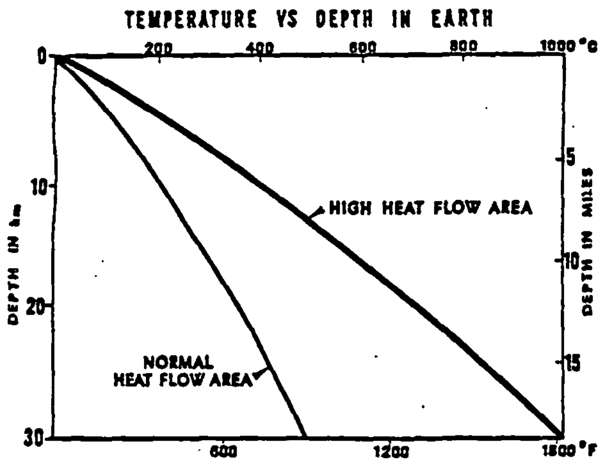


FIGURE 1

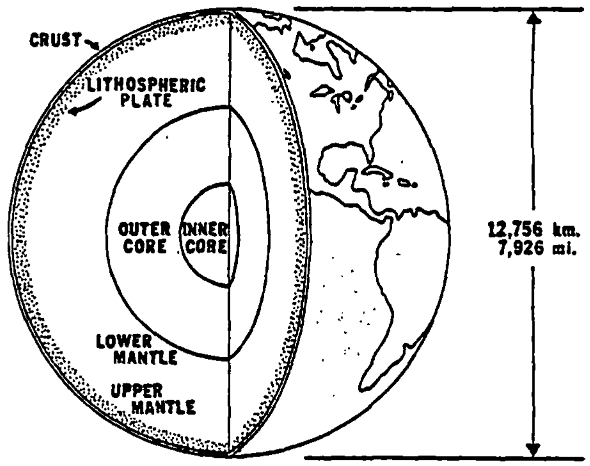


FIGURE 2

Geothermal resource areas, or "geothermal areas" for short, are 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 surface, often in broad areas where the earth's crust is thin, 3) heating of ground water due to deep circulation, or 4) anomalous heating of a shallow rock body by an unusually large content of radioactive elements. We will consider each of these aspects in more detail below. In many geothermal areas heat is brought to the surface or near surface by convective circulation of groundwater. If temperatures are high enough, steam may be produced, and geysers, fumaroles, and hot springs are common surface manifestations of underlying geothermal reservoirs.

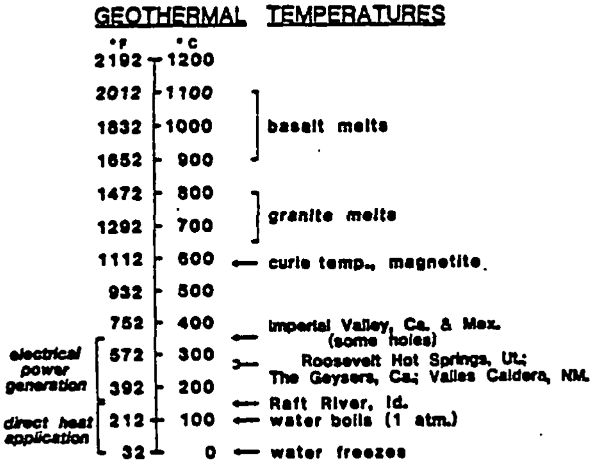


FIGURE 3

GEOLOGIC PROCESSES

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

Figure 4 shows the principal areas of known geothermal occurrences on a world map. Also indicated are areas of young volcanic activity and a number of currently active fundamental geologic structures. It is readily seen that geothermal resource areas correspond to areas that now have or recently have had volcanic and other geological activity. It is interesting to look briefly at some of the reasons why this is true.

Outward flow of heat from the deep interior causes the earth's mantle to form convection cells in which deeper, hotter mantle material rises toward the surface, spreads out parallel to the surface as it cools and, upon cooling, descends again. The crust above these convection cells cracks and spreads apart along linear zones thousands of kilometers long (Figure 5).

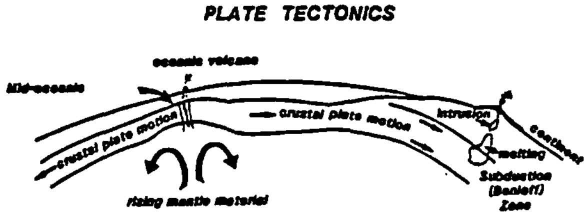


FIGURE 5

The crustal plates on each side of the crack or rift move apart at rates of a few centimeters per year. Molten mantle material rises in the crack and solidifies to form new crust. This process occurs at the mid-oceanic ridges (Figure 4). As the laterally moving oceanic crustal plates collide with certain of the continental land masses, they are thrust beneath the continental plates. At these subduction zones the oceanic plates descend to regions of warmer mantle material. These processes give rise to the diverse phenomenon that geologists call plate tectonics. The cooler, descending plate is warmed both by 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 melting. This gives rise to molten rock bodies (magmas) that ascend buoyantly through the crust (Figure 6). Ascending magmas may reach to within 1.5 to 5 km (5,000 to 15,000 feet) of the surface, and they may give rise to volcanos if part of the molten material escapes to the surface through faults and fractures in the upper crust. Referring to Figures 4 and 5, these processes of subduction and magma generation are currently operating along the west coast of Central and South America, in the Aleutian Islands, Japan and elsewhere. Hachure marks show the linear and

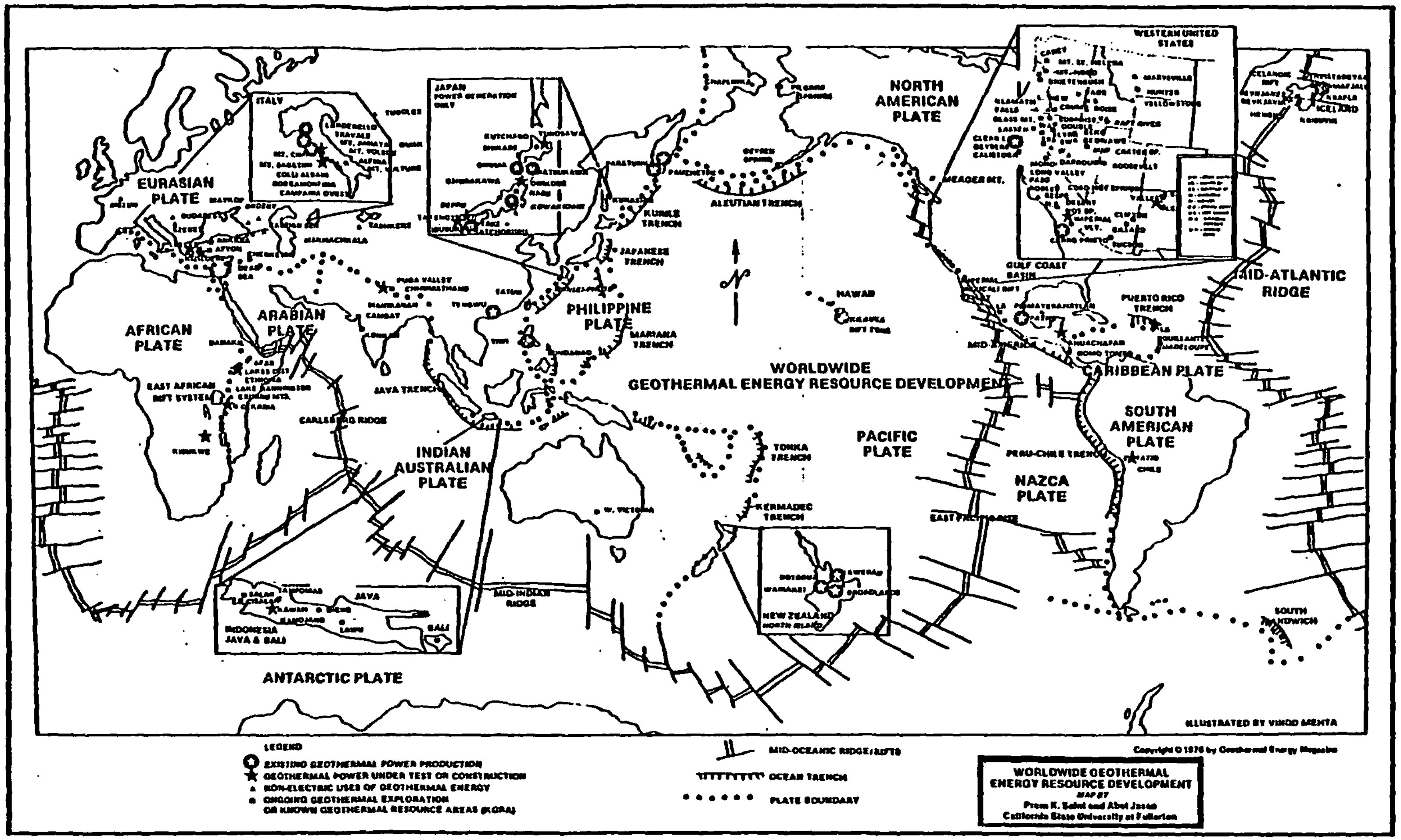


FIGURE 4

Wright, P. M.

arcuate zones, marked by deep ocean trenches, along which subduction of oceanic crust is currently taking place. The above geologic processes, which result in transport of large quantities of heat to shallow depths at mid-ocean ridges and in areas above subduction zones, give rise to some of today's "hot spots" and associated geothermal resources.

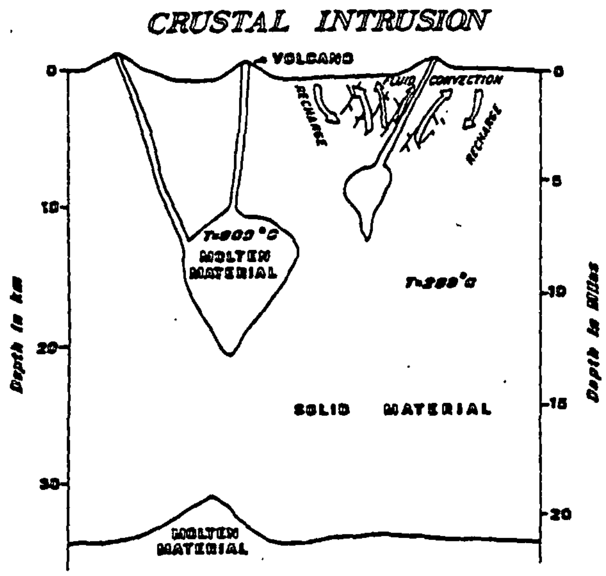


FIGURE 6

A second important geologic process is the "point source" of heat in the mantle (as opposed to the rather large convection cells) which causes surface volcanic eruptions as molten rock is transported to the near surface. As crustal plates move over local mantle hot spots, a linear or arcuate zone of volcanic rocks is seen with young volcanic rocks at one end and older ones at the other end. The Hawaiian Island chain is an excellent example of this process. Geologists speculate that Yellowstone, Wyoming, which is 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 Plain in Idaho are the surface trace of this mantle hot spot in the geologic past.

Geothermal resources are not always due to 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 is such an area of high heat flow. Here geophysical and geologic data indicate that the earth's crust is thinner than normal, and heat therefore flows upward from the mantle correspondingly faster.

Much of the western U. S. is geologically active, as manifested by earthquakes and volcanos. Earthquakes are caused by fracturing and sliding of rocks within the crust. Such processes keep fracture systems open and allow circulation of groundwater to depths of two to four miles. 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 West and elsewhere owe their orgin to such processes.

GEOTHERMAL RESOURCE TYPES

We have seen that the fundamental cause of geothermal resources lies in the transport of hot rock or hot fluids near to the surface through a number of geologic processes. We have also considered what the ultimate source of the heat is. Before considering the more detailed distribution of resources in the United States, let us turn to an examination of the various geothermal resource types.

The classification of geothermal resource types show in Table 1 is modeled after one given by White and Williams (1975) of the U. S. Geological Survey. Each resource type will be described briefly with emphasis on those types that are presently nearest to commercial use.

TABLE 1

GEOTHERMAL RESOURCE CLASSIFICATION
(After White and Williams, 1975)

Resource Type	Temperature Characteristics
1. Hydothermal convection resources (heat carried upward from depth by convection of water or steam)	
a). Vapor dominated	about 240°C(464°F)
b). Hot-water dominated	
i) High Temperature	150° to 350°C+
ii) Intermediate Temperature	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 650°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 resources are geothermal resources in which the earth's heat is carried upward by the convective circulation of hot water or its gaseous phase, steam. Underlying the system is presumably a body of still molten or recently solidified rock that is very hot and that represents a crustal intrusion of molten material (Figure 6). Whether or not steam actually exists in the geothermal reservoir depends critically on temperature and pressure conditions at depth. Figure 7 (after White, et al., 1971) shows a hydrothermal system where steam is present, a so-called vapor-dominated hydrothermal system (1 a. of Table 1). The convection of deep water brings a large amount of heat from depth to a region where boiling takes place at a temperature of about 240°C under the prevailing pressure conditions. Boiling presumably takes place at a deep subsurface water table as well as in pore spaces within the reservoir. Vapor moves upward and is probably superheated further by the hot surrounding rock. A zone of cooler, near-surface rock may induce condensation, 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 fluid convection. Reservoir recharge probably takes place mainly by cool ground water moving downward and into the convection system from the margins. If an open fracture penetrates far enough, steam may vent at the surface. A well drilled into such a reservoir would produce superheated steam.

VAPOR DOMINATED GEOTHERMAL RESERVOIR

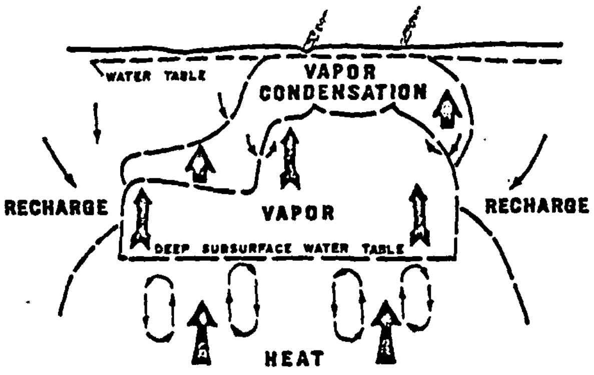


FIGURE 7

The Geysers geothermal area in California (Figure 14) is a vapor-dominated geothermal resource. Steam is produced from depths of 1.5 to 3 km (5,000 to 10,000 feet), and this steam is fed directly to turbine generators that produce electricity. The current generating capacity at The Geysers is 663 MWe (megawatts of electrical power, where 1 megawatt = 1 million watts) and about 860 MWe of additional generating capacity is scheduled to come on line by 1983. Other vapor-dominated resources occur at Lardarello and Monte Amiata, Italy, and at Matsukawa, Japan. Part of the resource at Yellowstone, Wyoming consists of a dry steam field. There are few known vapor-dominated resources because special geologic conditions are required for their formation. However, they are eagerly sought by industry because they are presumably easier and less expensive to develop.

HIGH TEMPERATURE GEOTHERMAL SYSTEM
FLOW CONTROLLED BY FRACTURES

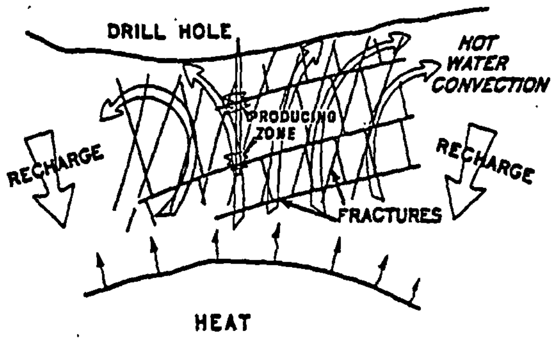


FIGURE 8

Figure 8 schematically illustrates a high temperature hot-water-dominated hydrothermal system (1 b.(i) of Table 1). The source of heat beneath such a system is probably molten rock or rock which has solidified only in the last few tens of thousands of years, lying at a depth of perhaps 3 to 10 km (10,000 to 35,000 feet). 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 seal 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, spring deposits, altered rocks, or alternatively, no surface manifestation at all. If there are no surface manifestations, discovery is much more difficult. 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 surface equipment as pressure is reduced, and the steam is used to drive a turbine generator.

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. A total of 53 such resource areas have been identified (Muffler and others, 1978) in the West, with Nevada having a disproportionately large share.

A second type of hot-water system is shown in Figure 9. Here the reservoir rocks are sedimentary rocks that have intergranular porosity. 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 there is a crustal spreading center, as discussed above, known as that East Pacific Rise. Figure 4 shows that East Pacific Rise goes northward up the Gulf of California. Its location under the continent cannot be traced very far, but 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. The location of specific resource areas appears to be controlled by faults that presumably allow deep fluid circulation to carry the heat upward to reservoir depths. In the Imperial Valley, the geothermal fluids are very saline in places; often dissolved-salt content is more than 30 percent.

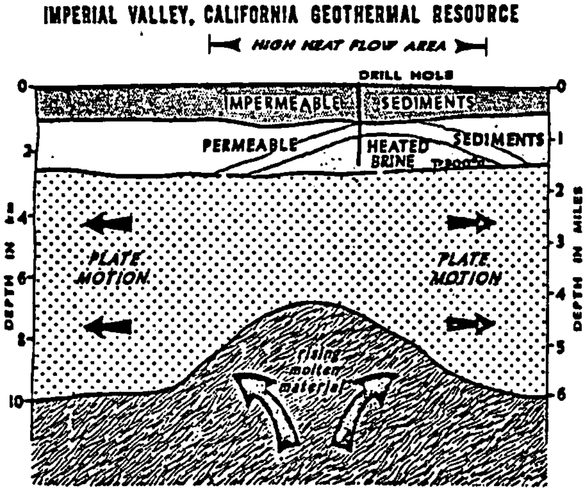


FIGURE 9

Virtually all of industry's geothermal exploration effort is presently directed at locating vapor- or water-dominated hydrothermal systems of the types described above having temperatures above 200°C (392°F). These resources are capable of commercial electrical power generation today. Exploration techniques are generally conceded to be inadequate for discovery of these resources at a fast enough pace to satisfy the reliance the Nation may ultimately put upon them for alternative energy sources. Development of better and more cost-effective exploration is badly needed.

The fringe areas of high-temperature vapor- and water-dominated hydrothermal systems often produce water of low and intermediate temperature (1 b. (ii) and 1 b. (iii) of Table 1). These lower temperature fluids are suitable for direct heat applications but not for electrical power production. In addition, low- and intermediate-temperature waters can 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 two to four miles are warmed in the normal geothermal gradient and they return to the surface or near surface along open fractures because of their buoyancy. 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. (Figure 14).

Sedimentary Basins

Some basins are filled to depths of 10 km (33,000 feet) or more with sedimentary rocks that have intergranular and open-space porosity. In some of these sedimentary units, circulation of ground water can be very deep. Water may be heated in the normal or enhanced geothermal gradient and may then either return to the near-surface environment or remain trapped at depth (3 a. of Table 1). The Madison group carbonate rock sequence of widespread occurrence in the Dakotas, Wyoming and Montana contains warm waters that are currently being tapped by drill holes in a few places for space heating and agricultural purposes (Figure 14). Substantial benefit is being realized in France from use of this resource type for space heating by tapping warm waters contained in the Paris basin. Many other areas of occurrence of this resource type are known worldwide.

Geopressured Resources

Geopressured resources (3 b. of Table 1) consist of deeply buried fluids contained in permeable sedimentary rocks which are warmed in the normal earth's geothermal gradient by their great burial depth. In addition, 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 10 (from Figure 2 of Papadopulos, 1975) gives a few typical parameters for geopressured reservoirs and illustrates the origin of the above-normal fluid pressure. These geopressured waters, found mainly in the Gulf Coast (Figure 14), 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 available methane.

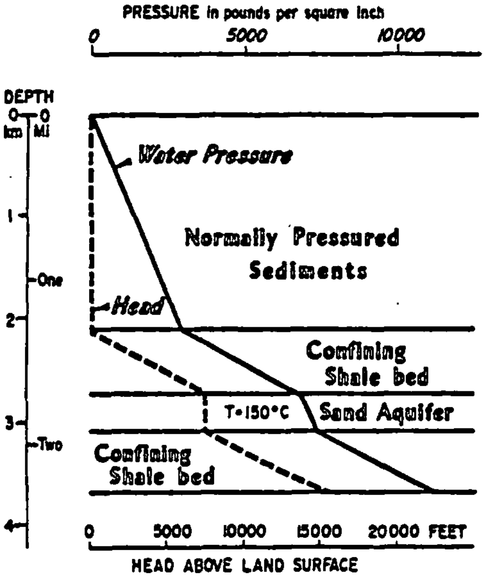


FIGURE 10

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

Radiogenic Resources

Research which could lead to development of radiogenic geothermal resources in the eastern U. S. (3 c. of Table 1) is currently underway following ideas developed at Virginia Polytechnic Institute and State University. The eastern states coastal plains are blanketed in many places by a layer of thermally insulating sediments. In places beneath this thermal blanket, 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 from the molten state. 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 (Figure 11) 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 geologic data indicate that radiogenically heated rock bodies may be reasonably widespread in the East (Figure 14).

RADIOGENIC GEOTHERMAL RESOURCE

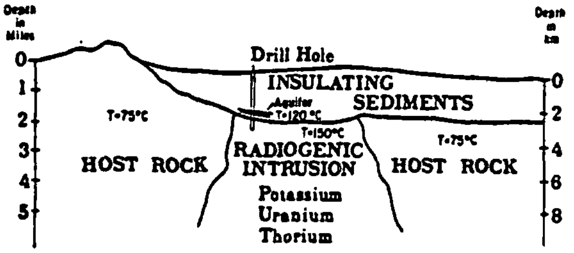
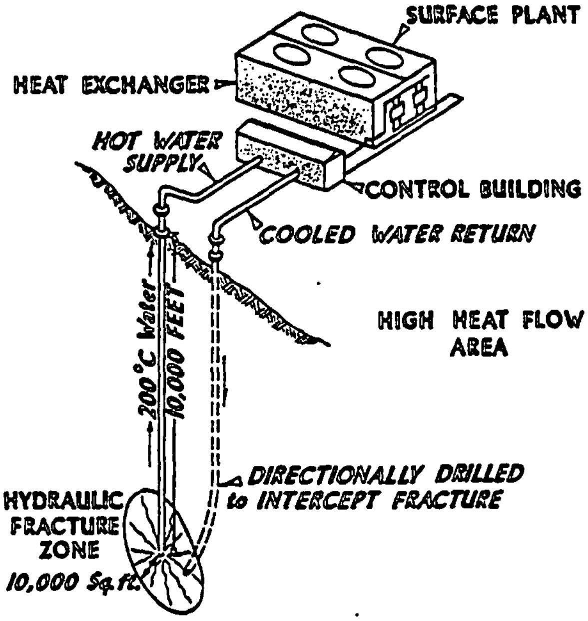


FIGURE 11

Hot Rock Resources

Hot dry rock (2 b. of Table 1) is defined as heat stored in rocks within about 10 km of the surface from which the energy can not be economically extracted by natural hot water or steam. These hot rocks have few pore spaces or fractures, therefore contain little water. The feasibility and economics of extraction of heat for electrical power generation and other uses from hot dry rocks is presently the subject of intensive research at the U. S. Department of Energy's Los Alamos Scientific Laboratory in New Mexico. Their work indicates that it is technologically feasible to induce an artificial fracture system in hot, tight rocks at depths of about 3 km (10,000 feet) 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. Then 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 (Figure 12). 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.

Experiments are underway at the Department of Energy's Sandia Laboratory in Albuquerque, to learn how to extract heat energy directly from molten rock (2 a. 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.



HOT DRY ROCK GEOTHERMAL RESOURCE

FIGURE 12

HYDROTHERMAL FLUIDS

The process causing many of today's high-temperature geothermal resources consists of convection of aqueous solutions around a cooling intrusion. This same process has operated in the past to form many of today's base metal and precious metal ore bodies. The fluids involved in geothermal resources are thus quite complex chemically and often contain elements that cause scaling and corrosion of equipment and 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 large 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 - neither acid nor aklaline. The dissolved solids are usually composed mainly of Na, Ca, SiO_2, Cl, 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 and H_2S, the latter being a safety hazard. Effective means have been and are still being developed to handle the equipment and environmental problems caused by dissolved constituents in geothermal fluids. Some of these methods will be considered in later papers at this conference.

RESOURCES IN THE UNITED STATES

Figure 14 displays the distribution in the United States of the various resource types discussed above. Information for this figure was taken mainly from Muffler and others(1979) where a much more detailed discussion is given. 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 data, so that Figure 14 will rapidly become outdated.

Figure 14 shows that most of the known geothermal resources are in the western half of the U. S. All of the presently known sites that are capable or believed to be capable of geothermal electric power generation from hydrothermal convection systems are in the West. In addition, the preponderance of thermal springs is in the West. Large areas underlain by warm waters in sedimentary rocks exist in Montana, the Dakotas, and Wyoming (the Madison Group of aquifers), but the extent and potential of these resources is poorly undersood. 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 ground water). Resources having temperatures above 150°C are infrequent, but represent important occurrences worth the discovery costs. In U. S. Geological Survey Circular 790, Muffler and others (1979) show a statistical analysis of the temperature distribution of geothermal resources and conclude that the cumulative frequency of occurrence increases exponentially as reservoir temperature decreases (pg. 31), as is the case for many natural resources (Figure 13). For geothermal resources the relationship is based only on the 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. In fact Circular 790 postulates that there are nearly three times more accessible geothermal resources above 90°C in the western U.S. than the amount discovered to date. 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 Circular 790. Table 2 demonstrates our lack of resource knowledge through the ranges and relative amounts of undiscovered resources and through the many missing numbers.

ACKNOWLEDGEMENTS

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Thanks are extended to Geothermal World Corporation for permission to reproduce Figure 4.

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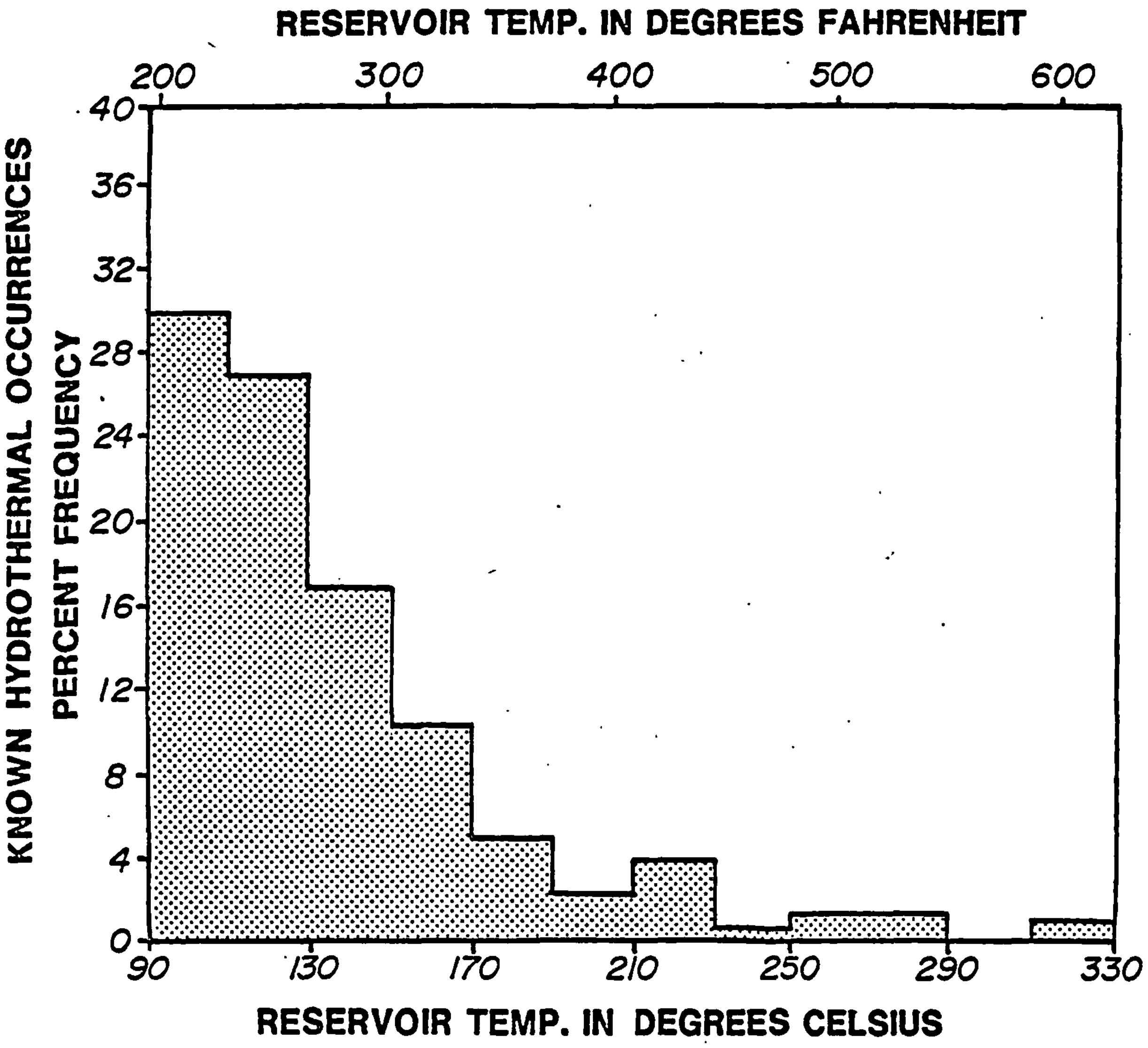
RESERVOIR TEMP. IN DEGREES FAHRENHEIT
200
300
400
500
600
KNOWN HYDROTHERMAL OCCURRENCES
PERCENT FREQUENCY
40
36
32
28
24
20
16
12
8
4
0
90
130
170
210
250
290
330
RESERVOIR TEMP. IN DEGREES CELSIUS

FIGURE 13

TABLE 2

Geothermal Energy of the United States
After Muffler and others (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	?	?	?

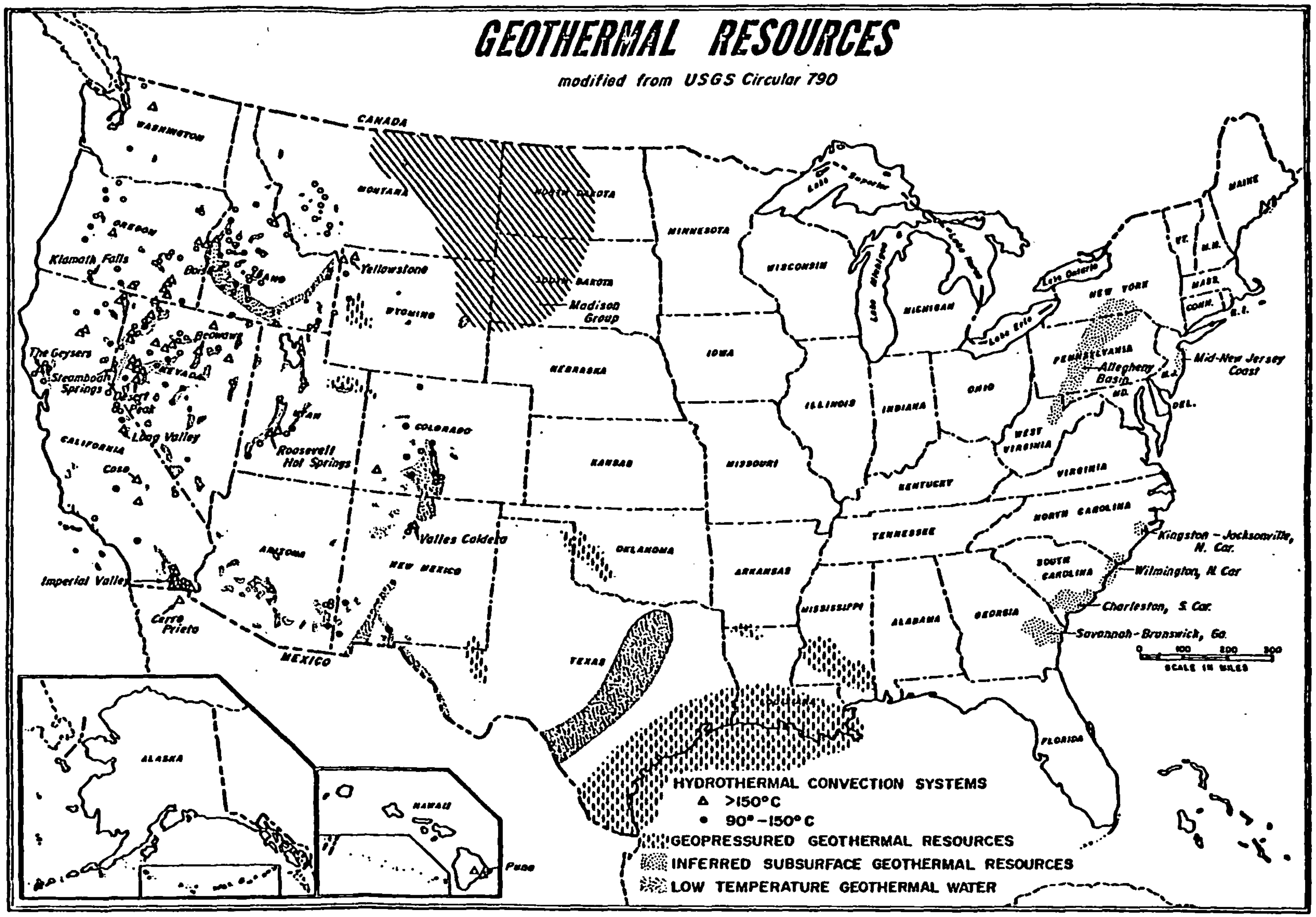
GEOTHERMAL RESOURCES
modified from USGS Circular 790
CANADA
WASHINGTON
OREGON
IDAHO
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
MINNESOTA
WISCONSIN
MICHIGAN
IOWA
NEBRASKA
NEVADA
UTAH
COLORADO
KANSAS
MISSOURI
ILLINOIS
INDIANA
OHIO
KENTUCKY
WEST VIRGINIA
VIRGINIA
PENNSYLVANIA
NEW YORK
MAINE
VT.
N.H.
MASS.
CONN.
R.I.
N.J.
DEL.
MD.
NORTH CAROLINA
SOUTH CAROLINA
TENNESSEE
GEORGIA
ALABAMA
MISSISSIPPI
ARKANSAS
OKLAHOMA
TEXAS
NEW MEXICO
ARIZONA
CALIFORNIA
FLORIDA
MEXICO
ALASKA
HAWAII
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
Klamath Falls
Boise
Yellowstone
Madison Group
The Geysers
Steamboat Springs
Beowawe
Desert Peak
Long Valley
Coso
Roosevelt Hot Springs
Valles Caldera
Imperial Valley
Cerro Prieto
Allegheny Basin
Mid-New Jersey Coast
Kingston - Jacksonville, N. Car.
Wilmington, N. Car
Charleston, S. Car.
Savannah-Brunswick, Ga.
Puna
0 100 200 300
SCALE IN MILES
HYDROTHERMAL CONVECTION SYSTEMS
△ >150°C
● 90°-150°C
GEOPRESSURED GEOTHERMAL RESOURCES
INFERRED SUBSURFACE GEOTHERMAL RESOURCES
LOW TEMPERATURE GEOTHERMAL WATER

FIGURE 14

THE MOST PROMISING GEOTHERMAL FIELDS IN THE WESTERN UNITED STATES (EXCLUDING THE GEYSERS GEOTHERMAL FIELD)

BY
DAVID N. ANDERSON
EXECUTIVE DIRECTOR
GEOTHERMAL RESOURCES COUNCIL

Presented at the
Geothermal Resources Council
Special Short Course No. 9
San Francisco, California
April 8-9, 1980

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ABSTRACT

This paper contains a brief summary of each of the most promising geothermal fields in the Western United States. The summaries contain data on size, ownership, discoveries, number of wells, involved utilities and operators, estimated power production potential, reservoirs, load centers, geology, geothermal phenomena and other important information concerning recent and ongoing activities.

DISCUSSION OF TERMS

Numerous terms have been used on the summary sheets in this report that may not have meaning to a casual acquaintance of geothermal energy. Therefore, a list of the less obvious terms, with a brief explanation of each, follows:

1. KGRA - Known Geothermal Resource Area. This term was originated by the U.S. Geological Survey.
2. AREA - Area is used to define that part of the state in which a specific field is located.
3. SIZE AND LAND OWNERSHIP - Figures are always in acres.
4. DISCOVERY AND TOTAL WELL DATA - Year, refers to year of the discovery; Operator, to who made the discovery; and Deep Wells to the number of wells drilled into the reservoir. Note: Some of the wells in the count may have been abandoned or converted to injection service.
5. UTILITY AND POWER POTENTIAL - Involved Utility, refers to that company which is involved directly in the development of power generation facilities or as otherwise noted. Estimated MWe, means the amount of electrical power in MW's that could be produced for a 30 year period. A MW is equal to 1,000 kilowatts (KW). Note: All power estimates are from U.S.G.S. Circular 790.
6. PRINCIPAL OPERATORS - Names of the most active operators in the field. In some cases not all of the operators in a field have been listed. Wells refers to the number of wells drilled or controlled by the operator that penetrate the reservoir (some of the wells may have been abandoned or converted to injection). Tests refers to the kinds of tests made.
7. FIRST POWER PLANT - Type considered refers to the type of plant design e.g. double flash, single flash, binary, etc. Size refers to the size of the plant in MW's. Status means where the plant development presently sits in time. Scheduled on Line means the date when the plant is expected to start producing power.
8. RESERVOIR DATA - Type refers to what kind of reservoir is present - dry steam (vapor) or hot water (all of the reservoirs covered in this report are hot water types). Temp. refers to the reservoir temperature in degrees Fahrenheit. Depth refers to the distance from the surface to the top of the reservoir. Salinity depicts the amount of dissolved chemicals in parts per million. Max. Flow Rate is the maximum rate of

fluid that a well produced during a flow test. Flows from geothermal wells are usually measured in thousand pounds per hour.

9. RESERVOIR TEMPERATURE - All areas in this report have reservoir temperatures in excess of 300°F (149°C or nominal 150°C) except Raft River, Idaho which has a reservoir temperature of 295°F. Although the Raft River reservoir temperature is below 300°F (the generally agreed threshold for economic power production is 375°F) it has been included because of the construction of two research power plants, a 60 KW and a 5 MW unit.

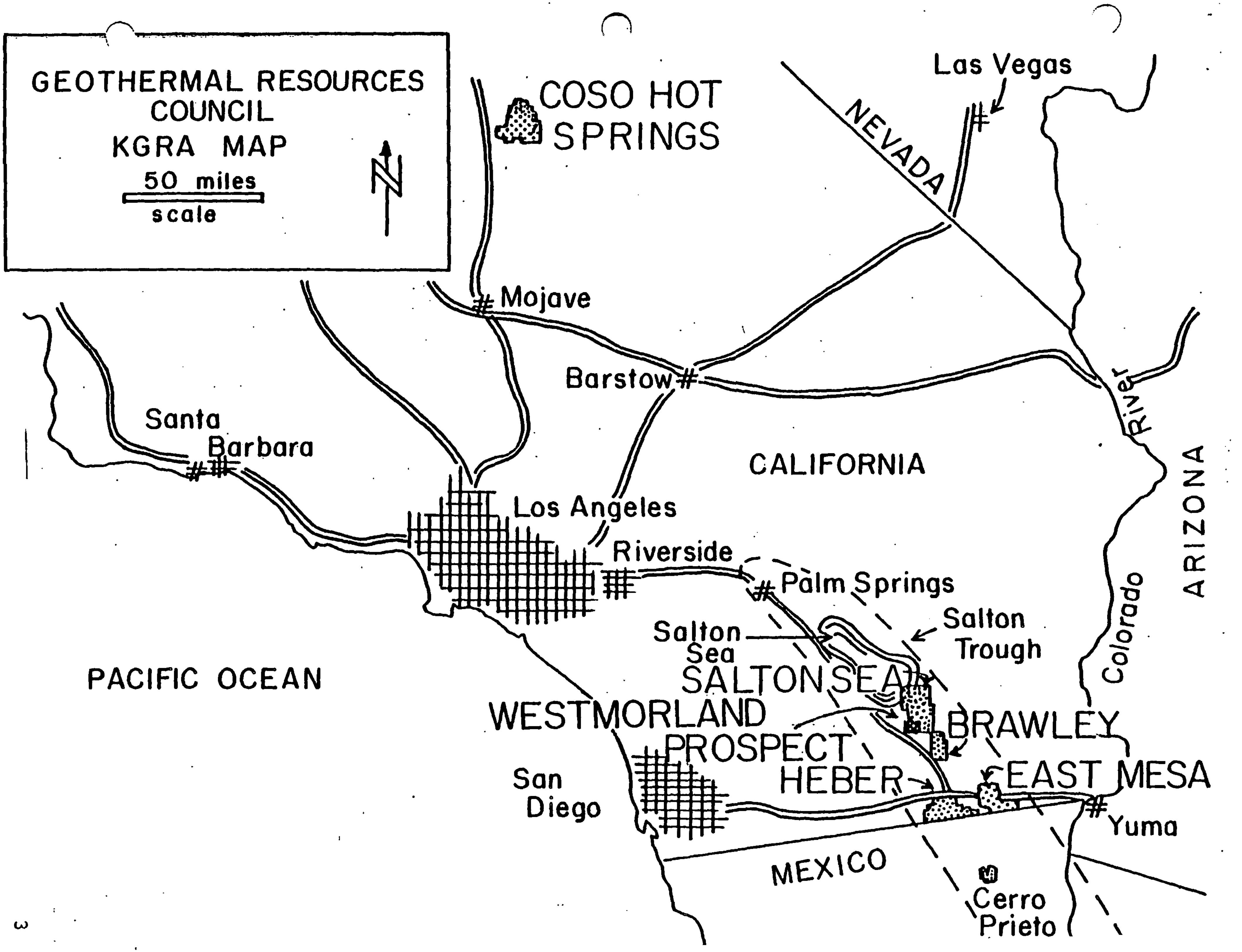
10. LOAD CENTERS - This listing shows the population and the power line distance from the field to the closest city or metropolitan area.

11. GEOLOGY AND GEOTHERMAL PHENOMENA - These terms are self explanatory.

It should be noted that The Geysers geothermal field has been omitted from the following summaries because it is now under production and its details have been widely published. However, this dry steam field is now producing 663 gross MW's of electricity and an additional 600 MW's are now being planned or are under construction.

PRODUCTION RECAP

The total estimated electrical potential of the 13 fields covered in the summaries is 12,684 MWe for 30 years. The estimates are taken from U.S. Geological Survey Circular 790 (1978). It should also be recognized that the fields covered are only a small percentage of the more than 57 Known Geothermal Resource Areas (KGRA's) that have convection systems with temperatures greater than 300°F (150°C) which have been identified by the U.S. Geological Survey.


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
N
COSO HOT SPRINGS
Las Vegas
NEVADA
Mojave
Barstow
Santa Barbara
CALIFORNIA
Los Angeles
Riverside
Palm Springs
River
Colorado
ARIZONA
Salton Sea
Salton Trough
SALTON SEA
WESTMORLAND
BRAWLEY
PROSPECT
HEBER
EAST MESA
San Diego
Yuma
PACIFIC OCEAN
MEXICO
Cerro Prieto

KGRA SALTON SEA   AREA IMPERIAL VALLEY   STATE CALIFORNIA

KGRA

SIZE: 95,824 acres

LAND OWNERSHIP:

Federal: 18,644 acres
State and Private: 77,180 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1958

OPERATOR: Kent Imperial Corp.

DEEP WELLS: 30

INVOLVED UTILITY: Southern California Edison and San Diego Gas & Electric Co.

ESTIMATED POWER POTENTIAL: 3,400 MW

PRINCIPAL OPERATORS

NAME: Magma Power Co.	*NAME:* Union Oil Co.
WELLS: 11	*WELLS:* 6
TESTS: Production and injection	*TESTS:* Production and injection

FIRST POWER PLANT	SCE	Magma/SDG&E
TYPE CONSIDERED:	Flash	Double Flash
SIZE (NOMINAL):	10 MW	49 MW
STATUS:	Under design	Preliminary design
SCHEDULED ON LINE:	1982	--

RESERVOIR DATA

TYPE: Hot water   *TEMPERATURE:* 640°F+   *SALINITY:* 250,000-330,000 ppm

DEPTH (TOP OF RES.): 3,000 ft   *MAXIMUM FLOW RATE:* 500,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area	*CITY:* San Diego area
POPULATION: 9 million	*POPULATION:* 1.5 million
DISTANCE: 185 miles	*DISTANCE:* 130 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales, non marine fluvial and lacustrine sediments and interbedded evaporites; field is traversed by five rhyolite volcanoes trending NE-SW; numerous mud pots and mud volcanoes; minor CO_2 surface vents; major faults strike at high angle to trend of volcanic cones. Area underlain by an active spreading center (the east Pacific rise).

REMARKS

Presence of field known prior to 1925; CO_2 produced from shallow wells during the 1940's; major drilling effort (12 wells) in the early 1960's, which was accompanied by an attempt to reclaim potash from the produced brine; drilling activity renewed in early 1970's; SDG&E and ERDA funded and constructed a 10 MW equivalent (no turbine generator) pilot flash binary power plant in 1975 which is not included under first power plants; high salinity (20 to 30%) will hamper full development due to corrosion and scaling problems. Techniques are being developed to lessen the corrosion problems by a three party association: Union Oil Co., Mono Power Co. (a subsidiary of Southern California Edison), and Southern Pacific Land Company. In addition, Magma Power Co. is also active in corrosion and scaling research.

KGRA WESTMORLAND PROSPECT (Salton Sea) AREA IMPERIAL VALLEY STATE CALIFORN

KGRA

SIZE: approx. 20,000 acres

LAND OWNERSHIP:
Federal: 0
State: 0
Private: 20,000 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1976

OPERATOR: Republic Geothermal, Inc.

DEEP WELLS: 6

INVOLVED UTILITY: Imperial Irrigation District service area

ESTIMATED POWER POTENTIAL: 1710 MW

PRINCIPAL OPERATORS

NAME: Westmorland Geothermal Associates (Republic Geothermal, Inc. and MAPCO)

WELLS: 6

TESTS: Production and injection

FIRST POWER PLANT

TYPE CONSIDERED: Double Flash

SIZE (NOMINAL): 50 MW

STATUS: Under design

SCHEDULED ON LINE: 1983

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 500°F

SALINITY: 20,000-70,000

DEPTH (TOP OF RES.): 4,000 ft

MAXIMUM FLOW RATE: 580,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 185 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 130 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and lacustrine lake bed and deltaic sediments; no surface volcanic expression or geothermal indicators; vertical strike slip faulting controls distinct fault block salinities; distinct gravity and thermal anomalies. Area underlain by an active spreading center (the east Pacific rise).

REMARKS

Area is jointly leased and operated by Westmorland Geothermal Associates (Republic Geothermal, Inc. and MAPCO); a federal loan guarantee for reservoir evaluation and development drilling was obtained in 1979 and work on two additional wells is under way; area lies to the SW of the Salton Sea anomaly.

KGRA BRAWLEY AREA IMPERIAL VALLEY STATE CALIFORNI

KGRA

SIZE: 28,885 ACRES

LAND OWNERSHIP:

Federal: 0
State: 0
Private: 28,885 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1975

OPERATOR: Union Oil Co.

DEEP WELLS: 10

INVOLVED UTILITY: Southern California Edison

ESTIMATED POWER POTENTIAL: 640 MW

PRINCIPAL OPERATORS

NAME: Union Oil Co.

WELLS: 8

TESTS: Production and injection

NAME: Chevron Resources Co.

WELLS: 2

TESTS: Short term production

FIRST POWER PLANT SCE

TYPE CONSIDERED: Single Flash

SIZE (NOMINAL): 10 MW

STATUS: Under construction

SCHEDULED ON LINE: 1980

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 500°F

SALINITY: 100,000 ppm

DEPTH (TOP OF RES.): 3,000 ft

MAXIMUM FLOW RATE: 70,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 200 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 115 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments; no surface volcanic expression or geothermal indicators; field in close proximity to active Brawley fault. Area is underlain by an active spreading center (the east Pacific rise).

REMARKS

Field was identified by University of California at Riverside field studies in late 1960's and early 1970's; high salinity due to close proximity to lowest portions of northern landward extension of Salton Trough (evaporite sink); high salinity will cause problems in the design, construction and operation of power plants; the Union 10 MW power plant is approximately 85% complete.

KGRA HEBER AREA IMPERIAL VALLEY STATE CALIFORNIA

KGRA

SIZE: 58,568 acres

LAND OWNERSHIP:

Federal: 0

Private: 58,568 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1972

OPERATOR: Magma Power Company

DEEP WELLS: 17

INVOLVED UTILITY: Southern California Edison and San Diego Gas & Electric Co.

ESTIMATED POWER POTENTIAL: 650 MW

PRINCIPAL OPERATORS

NAME: Chevron Oil Company

WELLS: 8

TESTS: Extensive production and injection

NAME: Union Oil Company

WELLS: 7

TESTS: Short term, production

FIRST POWER PLANT

	SCE	SDG&E (see remarks)
TYPE CONSIDERED:	Double Flash	Flash Binary
SIZE (NOMINAL):	50 MW	65 MW
STATUS:	In final design	Design complete
SCHEDULED ON LINE:	Late 1982	1984

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 350-375°F

SALINITY: 14,000 ppm

DEPTH (TOP OF RES.): 3,200 ft

MAXIMUM FLOW RATE: 440,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 225 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 100 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments, minor volcanic sills; no surface volcanic expression or geothermal indicators. Area is underlain by an active spreading center (the east Pacific rise).

REMARKS

In 1977-78 the field was considered by U.S. Department of Energy as a possible site for a 50 MW binary power plant (the plant was subsequently awarded to Union Oil Co. at their Baca location in northern New Mexico). In December of 1979 Chevron Resources Company (the major operator) signed a contract with Southern California Edison, who will construct a 50 MW power plant. The completion date is late 1982. San Diego Gas & Electric is contemplating the co-sponsoring of a 50 MW binary type demonstration power plant with the U.S. Department of Energy.

KGRA EAST MESA AREA IMPERIAL VALLEY STATE CALIFORNI

KGRA

SIZE: 38,365 ACRES

LAND OWNERSHIP:

Federal: 32,725
Federal leased: 11,770 acres
State and Private: 4,840 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1972

OPERATOR: U.S. Bureau of Reclamation

DEEP WELLS: 18

INVOLVED UTILITY: San Diego Gas and Electric Co.

ESTIMATED POWER POTENTIAL: 360 MW

PRINCIPAL OPERATORS

NAME: Republic Geothermal, Inc.

WELLS: 8

TESTS: Production and injection

NAME: Imperial Magma

WELLS: 5

TESTS: Production and injection

FIRST POWER PLANT

	Republic	Magma
TYPE CONSIDERED:	Double Flash	Binary
SIZE (NOMINAL):	48 MW (net)	10 MW
STATUS:	Plant designed	Construction completed
SCHEDULED ON LINE:	Late 1982	Spring 1980

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 400°F

SALINITY: 2,500 ppm

DEPTH (TOP OF RES.): 2,450 ft

MAXIMUM FLOW RATE: 740,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 245 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 120 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments; no surface volcanic expression or geothermal indicators; area is slightly westward sloping, sandy mesa with a minimum elevation a few feet above the valley floor; major faults trend NW-SE. Area is underlain by an active spreading center (the east Pacific rise)

REMARKS

In the early 1970's the U.S. Bureau of Reclamation drilled and tested 5 wells and constructed and tested multi-stage flash and vertical tube desalination units; a facility (operated by U.S. DOE) at the site is available for the testing of various prototype energy conversion machines; loan guarantee granted to Republic Geothermal, Inc. for reservoir development; a shallow, slightly brackish aquifer is present over most of the mesa. Magma's 10 MW binary power plant will be the first binary type plant in the United States and the first hot water plant in the United States.

KGRA COSO HOT SPRINGS AREA MOJAVE STATE CALIFORN

KGRA

SIZE: 51,760 acres

LAND OWNERSHIP:
Federal: 43,330 acres
(BLM: 16,690 acres)
(Navy: 26,640 acres)
State and private: 8,430 acres

DEVELOPMENT

Numerous shallow temperature wells have been drilled and a deep reservoir test was completed by U.S. Department of Energy in December 1977.

INVOLVED UTILITY: Mono Power Co. (a subsidiary of Southern California Edison)

ESTIMATED POWER POTENTIAL: 650 MW

PRINCIPAL OPERATORS (see remarks)

NAME:	*NAME:*
WELLS:	*WELLS:*
TESTS:	*TESTS:*

FIRST POWER PLANT

TYPE CONSIDERED: Decision pending confirmation of a reservoir

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 390°F+ *SALINITY:* 6,000 ppm

DEPTH (TOP OF RES.): 2,000 ft *MAXIMUM FLOW RATE:* well was not tested

LOAD CENTERS (see remarks)

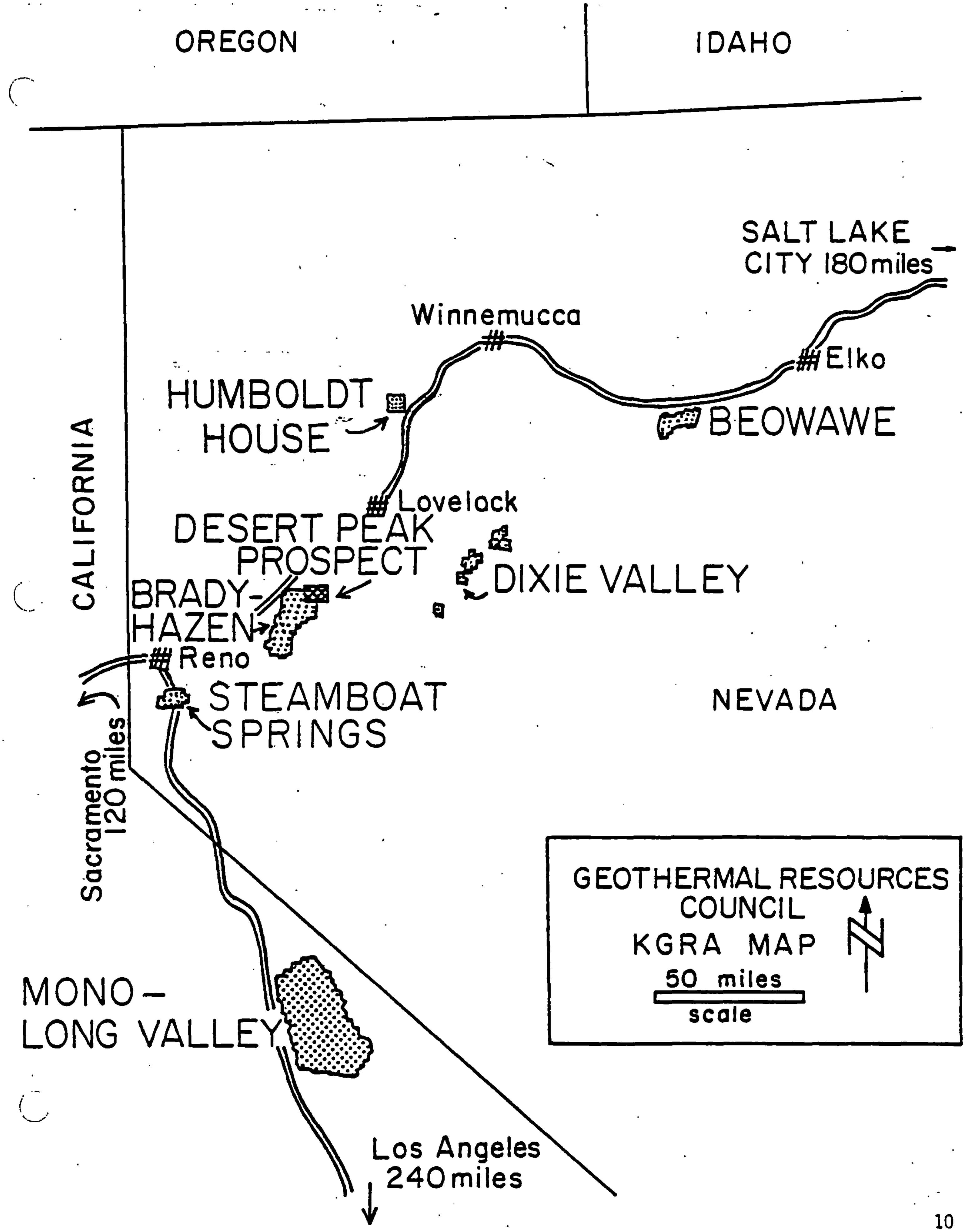
CITY: Los Angeles area	*CITY:* Bakersfield area
POPULATION: 9 million	*POPULATION:* 86,000
DISTANCE: 160 miles	*DISTANCE:* 60 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Granitic, metasedimentary and metavolcanic rocks extruded and overlaid by rhyolites and andesites in the form of cinder cones, pierlitic domes and flows. Volcanic s flows and air falls are interbedded with lacustrine and fanglomerate deposits. Structurally the area appears to have been under tension throughout the late Cenozoic which caused a fault pattern to develop that served as volcanic conduits. Fumaroles and hot springs are common in some parts of the KGRA.

REMARKS

Major portion of KGRA land is controlled by the federal government and is partially overlain by instrumented bombing ranges operated by the U.S. Navy. This aspect, in the past, has caused a general reluctance by the Navy to lease or allow the land to be opened for leasing by the U.S. Bureau of Land Management. Recently the Navy has developed a program to contract directly for the development of several square miles of land owned in fee and to allow the U.S. BLM to commence leasing procedures on other lands. In late 1979 the U.S. Navy and California Energy Company (CEC) signed a contract to develop the Navy fee land. The contract calls for CEC to ultimately develop 75 MW's of electrical power. The power produced on the Navy fee land would go to power Navy


OREGON
IDAHO
SALT LAKE CITY 180 miles
Winnemucca
Elko
HUMBOLDT HOUSE
BEOWAWE
CALIFORNIA
Lovelock
DESERT PEAK PROSPECT
DIXIE VALLEY
BRADY-HAZEN
Reno
STEAMBOAT SPRINGS
NEVADA
Sacramento 120 miles
GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
N
MONO-LONG VALLEY
Los Angeles 240 miles

KGRA STEAMBOAT SPRINGS AREA WESTERN NEVADA STATE NEVADA

KGRA

SIZE: 8,914 acres

LAND OWNERSHIP:

Federal: 4,457 acres
Private: 4,457 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: Unknown

OPERATOR: Unknown

DEEP WELLS: 1

INVOLVED UTILITY:

Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL:

350 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 1 deep, 20+ temp. grad. and four 800-2,000 ft observation wells

TESTS: None

NAME: Gulf Mineral Resources Co. (Gulf has extensive land interests in the area.)

WELLS: None

TESTS: None

FIRST POWER PLANT

(see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 400°F+

SALINITY: 3,000 ppm

DEPTH (TOP OF RES.): 2,000 ft+

MAXIMUM FLOW RATE: --

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 12 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Sierra Nevada granitic rocks, highly fractured; fractures related to the eastern Sierra frontal fault system; hot springs and siliceous sinter terraces common.

REMARKS

Phillips Petroleum Co. drilled a deep test in mid 1979 and the test results looked promising. A follow-up exploration program which includes three 2,000 ft. temperature test holes is in progress.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA DESERT PEAK PROSPECT AREA RENO STATE NEVADA
(Brady-Hazen)

KGRA

SIZE: 98,508 acres
LAND OWNERSHIP:
Federal: 59,358 acres
Federal leased: 26,049 acres
State and private: 39,150 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1976
OPERATOR: Phillips Petroleum Co.
DEEP WELLS: 4

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 750 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.
WELLS: 4
TESTS: Production

NAME:
WELLS:
TESTS:

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:
SIZE (NOMINAL):
STATUS:
SCHEDULED ON LINE: unavailable

RESERVOIR DATA

TYPE: Hot water
TEMPERATURE: 400°F+
SALINITY: 6,000-8,000 ppm
DEPTH (TOP OF RES.): 2,000+ ft
MAXIMUM FLOW RATE: Test program under way

LOAD CENTERS

CITY: Reno
POPULATION: 150,000
DISTANCE: 55 miles

CITY:
POPULATION:
DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Faulted tertiary volcanics (basalts, rhyolites) overlying a metamorphosed basement complex; hot springs, sinter and travertine deposits.

REMARKS

Desert Peak area lies just north of the Brady-Hazen KGRA and will eventually be included. Preliminary meetings have taken place between the operator, utility and an engineering firm concerning the design and construction of a power plant. Additional exploration and development work is under way.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA DIXIE VALLEY AREA CENTRAL NEVADA STATE NEVADA

KGRA

SIZE: 38,989 approx. acres
LAND OWNERSHIP:
Federal: 38,989 approx. acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1978
OPERATOR: Sunoco Energy Devel. Co. (Sunedco)
DEEP WELLS: 4

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: --

PRINCIPAL OPERATORS

NAME: Sunedco	*NAME:* Natomas/Thermal Power Co. / Southland Royalty
WELLS: 4	*WELLS:* 2
TESTS: Production	*TESTS:* Preliminary testing

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:
SIZE (NOMINAL):
STATUS:
SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: -- *TEMPERATURE:* -- *SALINITY:* --
DEPTH (TOP OF RES.): -- *MAXIMUM FLOW RATE:* --

LOAD CENTERS

CITY: Reno	*CITY:*
POPULATION: 150,000	*POPULATION:*
DISTANCE: 110 miles	*DISTANCE:*

GEOLOGY AND GEOTHERMAL PHENOMENA

Jurassic metasedimentary rocks overlain by tertiary sediments, which are overlain by volcanic deposits including basalt and andesitic rocks, rhyolitic flows and ash deposits, and younger alluvial fans. Early structural history consists of complexed folding and thrust faulting. Active structure consists of normal faults bounding a north-northeast trending graben with horst blocks. Numerous hot springs present.

REMARKS

In November 1978, Sunedco completed and production tested the first deep well in the area. Results from the test have been encouraging and have caused the drilling of two additional wells. In addition, a two company association (Natomas/Thermal Power Co. and Southland Royalty) have drilled two additional wells. Although the area was discovered over two years ago, none of the involved operators have made a formal press release concerning the potential.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three men-

FIELD HUMBOLDT HOUSE AREA BATTLE MOUNTAIN STATE NEVADA

FIELD

SIZE: Unknown
LAND OWNERSHIP:

DISCOVERY AND TOTAL WELL DATA

YEAR: 1978
OPERATOR: Phillips Petroleum Co.
DEEP WELLS: 3

INVOLVED UTILITY:

Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL:

47 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.	*NAME:* Union Oil Co.
WELLS: 2	*WELLS:* 1
TESTS: Production tests only	*TESTS:* Preliminary

FIRST POWER PLANT

(see remarks)

TYPE CONSIDERED:
SIZE (NOMINAL):
STATUS:
SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water
TEMPERATURE: 360°F+
SALINITY: 6,000 ppm
DEPTH (TOP OF RES.): 1,800 ft
MAXIMUM FLOW RATE: Unavailable

LOAD CENTERS

CITY: Reno	*CITY:*
POPULATION: 150,000	*POPULATION:*
DISTANCE: 120 miles	*DISTANCE:*

GEOLOGY AND GEOTHERMAL PHENOMENA

Mesozoic metamorphosed volcanic and sedimentary rocks overlain by tertiary lake beds in the valleys; large hydrothermally altered areas, old tuffa mounds and other hot springs deposits; structure is high angle faults bounding basins and mountain ranges.

REMARKS

Phillips Petroleum Co. feels that they have only penetrated a shallow auxiliary reservoir and that the main reservoir exists at depth and will contain water at temperatures of approximately 430°F. The Humboldt House area is not an official KGRA, however, it is near the Rye Patch KGRA.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA BEOWAWE AREA BATTLE MOUNTAIN STATE NEVADA

KGRA

SIZE: 33,225 acres

LAND OWNERSHIP:

Federal: approx. 16,000 acres
State and private: approx. 1,600 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1959

OPERATOR: Magma Power Co.

DEEP WELLS: 8

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 127 MW

PRINCIPAL OPERATORS

NAME: Chevron Oil Co.
WELLS: 4
TESTS: Limited production

NAME: Getty Oil Co.
WELLS: none
TESTS: none

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:
SIZE (NOMINAL):
STATUS:
SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water
TEMPERATURE: 412°F
SALINITY: 1,400 ppm
DEPTH (TOP OF RES.): 700 ft
MAXIMUM FLOW RATE: 1,500,000 lbs/hr ±

LOAD CENTERS

CITY: Reno
POPULATION: 150,000
DISTANCE: 220 miles

CITY: Elko
POPULATION: 10,000
DISTANCE: 40 miles

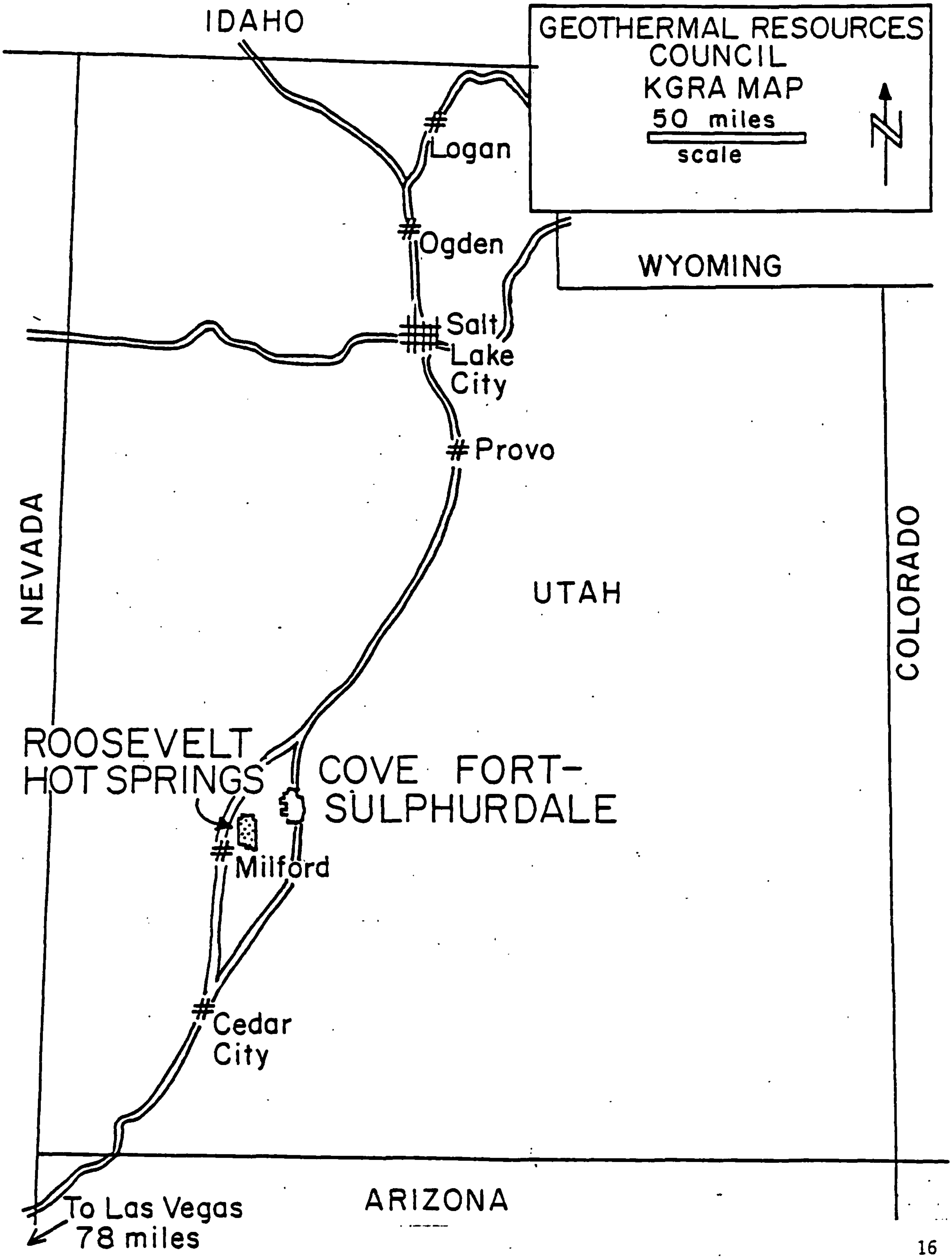
GEOLOGY AND GEOTHERMAL PHENOMENA

Paleozoic sediments overlaid by tertiary volcanics, principally basaltic flows; area centered along a major normal, NE-SW trending fault; numerous hot springs, geysers, fumaroles and sinter deposits.

REMARKS

Chevron Oil Co. has an extensive exploration program under way which includes the drilling of several wells. Getty Oil Co. has started a temperature gradient well program. The field area has been unitized (Chevron and Getty Oil Cos.)

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
IDAHO
Logan
Ogden
WYOMING
Salt Lake City
Provo
NEVADA
UTAH
COLORADO
ROOSEVELT HOT SPRINGS
COVE FORT-SULPHURDALE
Milford
Cedar City
ARIZONA
To Las Vegas
78 miles

KGRA ROOSEVELT HOT SPRINGS AREA MILFORD STATE UTAH

KGRA

SIZE: 29,791 acres

LAND OWNERSHIP:

Federal leased: 24,592 acres
State and private: 5,199 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1975

OPERATOR: Phillips Petroleum Co.

DEEP WELLS: 9

INVOLVED UTILITY: Utah Power and Light service area

ESTIMATED POWER POTENTIAL: 970 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.	*NAME:* Thermal Power Co.
WELLS: 7	*WELLS:* 2
TESTS: Extensive production and injection	*TESTS:* Production

FIRST POWER PLANT

TYPE CONSIDERED: Several power plant proposals are now being considered

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 500°F

SALINITY: 7,800 ppm

DEPTH (TOP OF RES.): 2,700 ft

MAXIMUM FLOW RATE: 1,000,000 lbs/hr

LOAD CENTERS

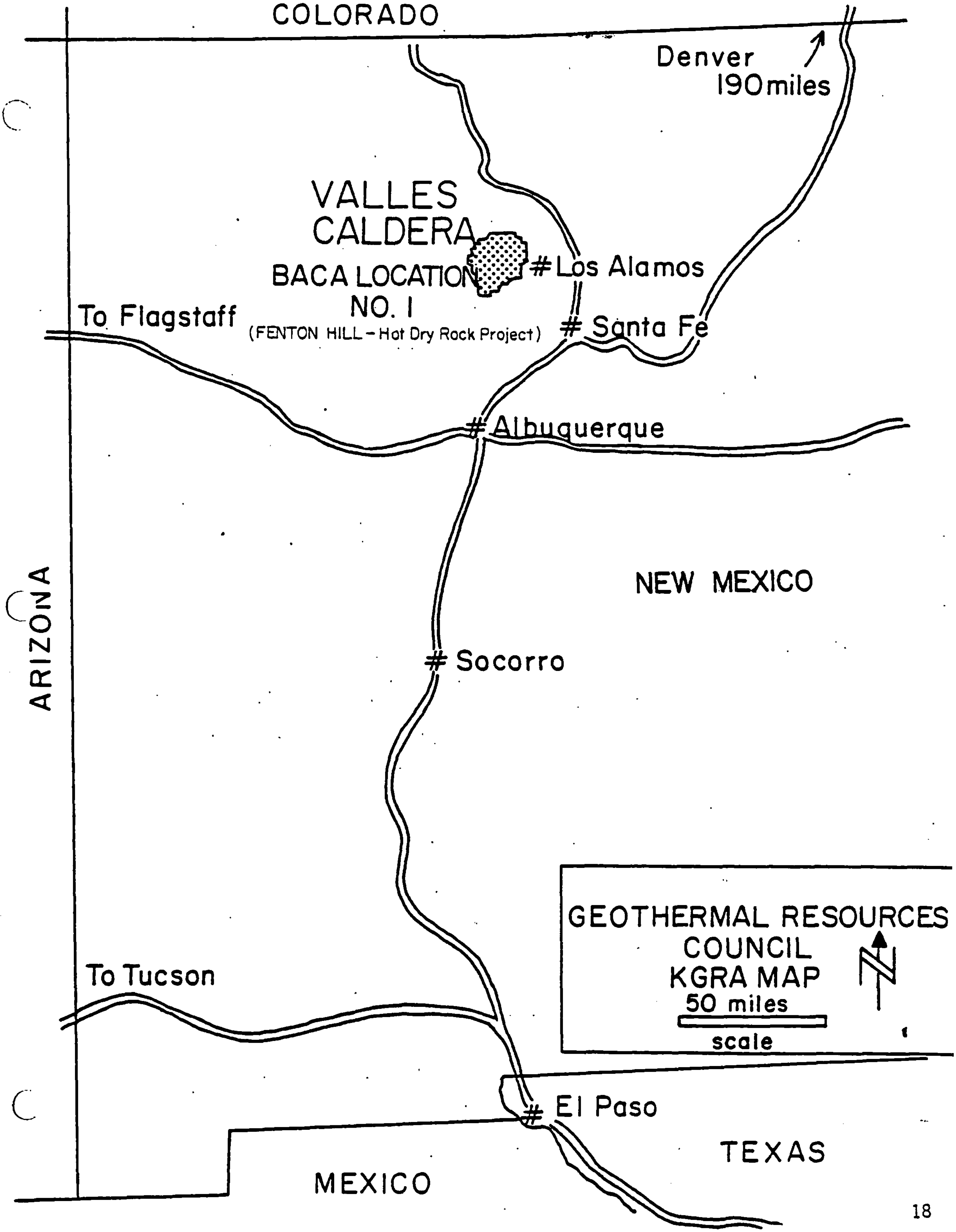
CITY: Salt Lake City area	*CITY:* Las Vegas, Nevada
POPULATION: 820,000	*POPULATION:* 160,000
DISTANCE: 200 miles	*DISTANCE:* 240 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Precambrian (?) metamorphics overlaid by unconsolidated tertiary and quaternary sediments; quaternary volcanics are present on the surface three miles east of the field; sinter deposits in KGRA area.

REMARKS

Large percentage of KGRA has been unitized; cooling water may be difficult to obtain.


COLORADO
Denver
190 miles
VALLES
CALDERA
BACA LOCATION
NO. 1
(FENTON HILL - Hot Dry Rock Project)
Los Alamos
To Flagstaff
Santa Fe
Albuquerque
ARIZONA
NEW MEXICO
Socorro
GEOTHERMAL RESOURCES
COUNCIL
KGRA MAP
50 miles
scale
N
To Tucson
El Paso
TEXAS
MEXICO

KGRA BACA LOCATION NO. 1 AREA -- STATE NEW MEXI
(Valles Caldera)

KGRA

SIZE: 168,761 acres

LAND OWNERSHIP:

Federal: 30,000+ acres
Federal leased: 18,000 acres
State and private: 120,700+ acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1970

OPERATOR: Pat Dunigan

DEEP WELLS: 14

INVOLVED UTILITY: New Mexico Public Service Co.

ESTIMATED POWER POTENTIAL: 2,700 MW

PRINCIPAL OPERATORS

NAME: Union Geothermal Co. of New Mexico (a subsidiary of Union Oil Co.)

WELLS: 14

TESTS: Extensive production and injection

FIRST POWER PLANT

TYPE CONSIDERED: Double Flash

SIZE (NOMINAL): 50 MW

STATUS: Preliminary design under way by Bechtel National Corp.

SCHEDULED ON LINE: 1982

RESERVOIR DATA

TYPE: Hot water
TEMPERATURE: 530°F
SALINITY: 6,000 ppm

DEPTH (TOP OF RES.): 3,200 ft
MAXIMUM FLOW RATE: 50,000 lbs/hr

LOAD CENTERS

CITY: Santa Fe, New Mexico
POPULATION: 50,000
DISTANCE: 65 miles

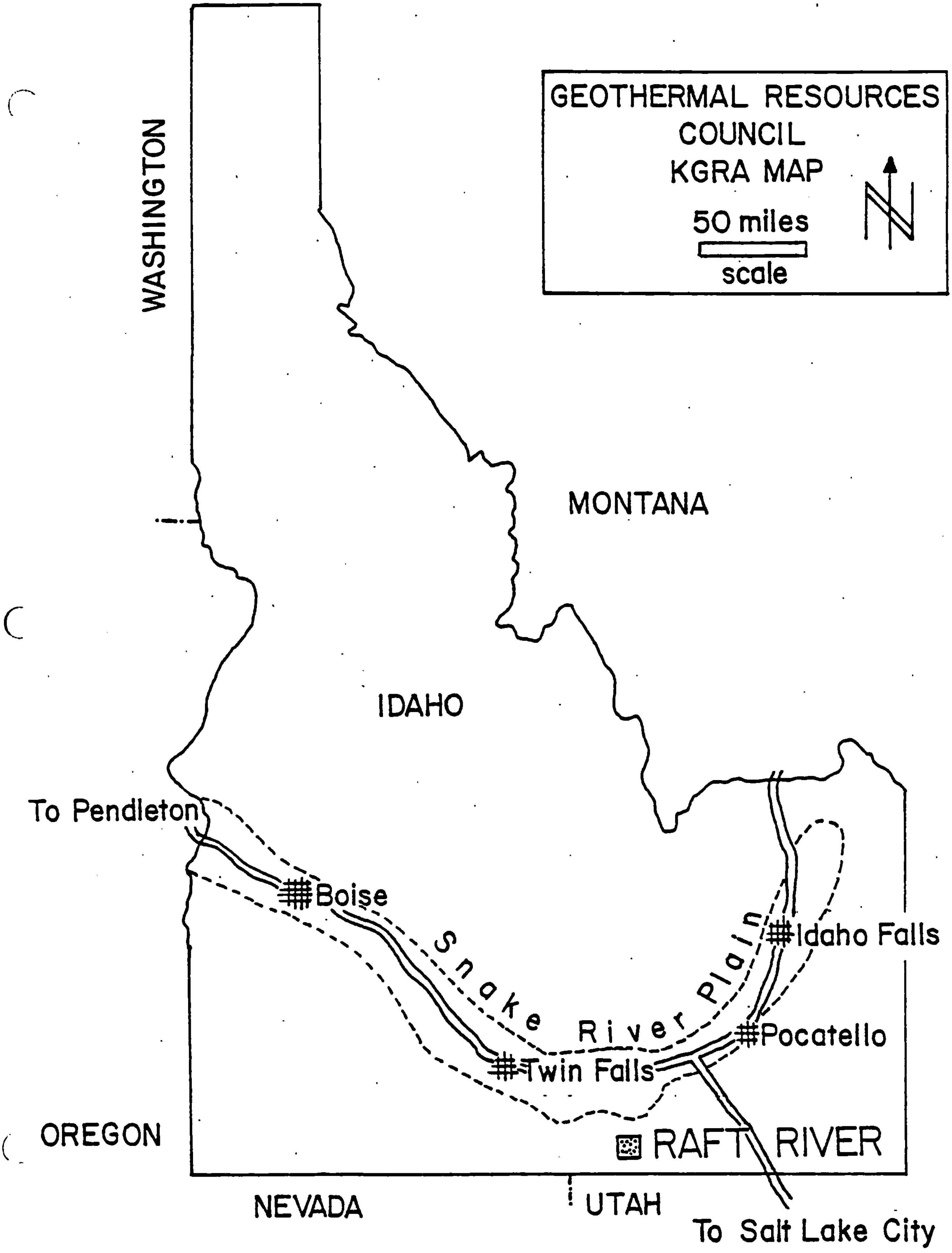
CITY: Albuquerque, New Mexico
POPULATION: 409,000
DISTANCE: 70 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Predominantly quaternary volcanics consisting of rhyolitic ash flows (tuff); subsequent caldera collapse followed by localized volcanic activity; hot springs and travertine deposits.

REMARKS

Union Geothermal Company of New Mexico and New Mexico Public Service Co. have entered into an agreement with the U.S. Department of Energy to construct and operate a 50 MW demonstration plant at the Baca location no. 1; the power plant is now being designed by the Bechtel Corporation; field development drilling will start in mid-1979. Operations are being delayed by environmental problems concerning Native Americans.


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
N
WASHINGTON
MONTANA
IDAHO
To Pendleton
Boise
Snake River Plain
Idaho Falls
Pocatello
Twin Falls
OREGON
RAFT RIVER
NEVADA
UTAH
To Salt Lake City

KGRA RAFT RIVER AREA SOUTHERN IDAHO STATE IDAHO

KGRA

SIZE: 22,529 acres

LAND OWNERSHIP:

Federal: 17,430 acres (No federal land has been leased under the Geothermal Act of 1970. A 5,000 acre federal land withdrawal is pending)

State and private: 5,099 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1974

OPERATOR: EG&G Idaho, Inc.

DEEP WELLS: 7

INVOLVED UTILITY: Raft River Geothermal Cooperative

ESTIMATED POWER POTENTIAL: Unavailable

PRINCIPAL OPERATOR

NAME: U.S. Department of Interior through EG&G Idaho, Inc.

WELLS: 7

TESTS: Extensive production and injection tests

FIRST POWER PLANT (The power plants will probably be operated by a utility group)

TYPE CONSIDERED:	Binary	Binary
SIZE (NOMINAL):	60 KW	5 MW
STATUS:	Constructed	Under construction
SCHEDULED ON LINE:	Compl. 1977	1980

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 295°F

SALINITY: 2,000-5,000 ppm

DEPTH (TOP OF RES.): 4,000-5,000 ft

MAXIMUM FLOW RATE: 1,500 gpm

LOAD CENTERS

The power produced would probably be used within the Raft River Geothermal Cooperative service area for agricultural purposes.

GEOLOGY AND GEOTHERMAL PHENOMENA

The reservoir is basically fractured granitic rock overlain by the tuffaceous sediments of the Salt Lake formation which is also fractured at depth. The main reservoir at depth is leaking into a shallow reservoir that was discovered in the 1930's.

REMARKS

Area has been developed by EG&G Idaho, Inc. under the sponsorship of U.S. Department of Energy as a research site. Experiments have been conducted on aquaculture, agriculture, alcohol, potato waste, multiple direction drilling, injection, reservoir stimulation and power generation. The power generation facilities are research in nature and employ the binary cycle system. Note that the binary system is used because the reservoir temperature is below 390°F.

Selected References

1. Assessment of Geothermal Resources of the United States, U.S. Geological Survey Circular 726, 1975.
2. Assessment of Geothermal Resources of the United States, U.S. Geological Survey Circular 790, 1978.
3. Geothermal Energy Resources of the Western United States, a map. National Geophysical and Solar-Terrestrial Data Center, National Oceanic and Atmospheric Administration, Boulder, Colorado, 1977.
4. Geothermal Handbook, Geothermal Project, Office of Biological Services, U.S. Fish and Wildlife, 1976.
5. Geothermal-Overviews of the Western United States, David N. Anderson and L. Axtell, Geothermal Resources Council, 1972.
6. Site-Specific Analysis of Geothermal Development-Data File of Prospective Sites, F. Williams et al., prepared for Energy Research and Development Administration, Division of Geothermal Energy, by The Mitre Corporation, Oct. 1977.

FINANCING GEOTHERMAL DEVELOPMENT

Paul Rodzianko

Geothermal Energy Corporation

What has always interested me in the geothermal industry is that "Exploration and Development," as in the title of this Short Course, are always linked together. In practice, however, and espeially from the financial aspects of the business, there is a great difference in each of these. In discussing the various options available for the overall geothermal implementation process, I should like to stress the need for parallel development in the financing of both the exploration and the development phases. I must also stress the critical need for involving one's financial personnel and/or out-side financial advisors from the earliest planning stages. In addition, I must point out that the ability to finance a project to completion (through to the beginning of cash flow) is the net result of the successful completion of all of the previous phases of that project. A successful financing is the bottom-line criterion that bespeaks the project's ultimate feasibility. I say this because, in order to finance a project successfully, the prospective investors must understand all of the risks and mitigating measures involved prior to their supplying the required funding. Let me discuss the building blocks upon which our industry is based.

I. INTRODUCTION

The first of these is, of necessity, the exploration phase, the scope of which includes general reconnaissance, leasing, preliminary exploration, deep drilling, testing, and development drilling functions. A resource company must first decide that it is in the geothermal business and it must allocate funding to engage in preliminary reconnaissance activities. Leasing, and the attendant expenditure of funds, then takes place. Further monies are spent in site-specific exploration (geology, geophysics, gradient drilling, etc.) before a decision is made to commit the substantial funds necessary for deep production drilling. Based on a successful completion of the deep well, extensive testing must take place before deciding whether step-out drilling is warranted in order to bring the field to a desired production level.

This brief synopsis tells only half the story, however. Geothermal is a capital-intensive industry. The utilization of the resource requires the construction of a power plant, agribusiness or industrial facility in addition to the investment in drilling. Since these are site-specific utilization investments, the investor in this phase of development must be assured that the resource on which the facility is being built will last as long as it takes to recover his investment. As a result, the investor is sharing the risk of the reservoir's projected performance <u>through time</u>, in some cases as long as thirty years. There are few oil companies that know or care how to own and run a utility or a dehydration plant. The idea of having to invest significant funds or guarantees beyond the normal scope of their ongoing business is hardly appealing either. For example, if a resource company invests $20 million in the development of a resource but then has to spend an additional $50-60 million to develop it to the point of cash flow - that's a lot of dollars to bet on a single reservoir. And only the limited number of the largest of companies could participate in this game. It is clear that the utilization phase also requires the investment of risk capital, but it appears that the sources thereof will most likely be different.

Now that we've defined the different phases of geothermal development process through to cash flow, let us discuss for a moment the types of markets that geothermal resources are active in. Previous speakers have discussed these, so I will summarize the differences between geothermal for electric and for direct-use applications. It is most important to note that the electric market requires generally a higher temperature of geothermal resources (300° F plus) and results in an energy product, electricity, that can be transmitted over long distances. Non-electric or direct-use geothermal applications have generally focused on temperatures below 300 °F (although higher temperatures can be used in industrial and agricultural applications) and the energy has to be consumed within a fairly close proximity to the site (five to ten miles). A further comparison demonstrates that electric projects may require minimum capital investments (resource and plant combined) of approximately $20 million, whereas investments for direct-use projects range from $250,000 to approximately $6 million. In addition, project time scales are very different. For electric projects, from wildcat to busbar may take eight to ten years; for non-electric, two or three years at most. Clearly, based on the capital magnitude differential as well as marketing approaches and time frames, there will be significant differences as to how to proceed with the financing of each type and each type of project.

II. ELECTRIC DEVELOPMENT PROJECTS

A. The Exploration Phase basically has the same dry hole risks in geothermal as exist for oil and gas. Although development techniques differ, the same financing options exist in geothermal as well. They are, among others, as follows:

(1) Resource company financing. Both minerals and oil and gas exploration companies have capital bases which permit the assumption of dry hole risk. The funds available for the exploration and drilling of geothermal production wells presumably would come from the cash flows generated either by high-risk, high-return successful oil and gas or mineral discoveries or high-risk, high-return previous geothermal drilling. In the latter category, only Magma Power, Thermal Power, Thermogenics and Union Oil Company so far share in this distinction in the United States. Phillips Petroleum, AMAX, and Sunedco are representative of the former. In the event a resource company wants to reduce its exposure associated in a given field, it might arrange participations (joint-ventures) with other companies in the well to be drilled. To obtain additional properties or particularly attractive ones, a resource company might farm-in and drill on the above-described basis to earn an interest. There are many varieties to implementing this kind of approach. They originate from the oil patch or minerals sector, but all basically revolve about the investment capabilities of a capital base able to withstand dry hole risk.

(2) Outside investor financing is generally expressed by means of drilling partnerships. The development of an economically attractive prospect might be undertaken by a less-affluent or participation-oriented company or by an operating company interested in acquiring a foothold in a resource which it might not otherwise be capable of developing by itself. Drilling funds have been successfully utilized by Republic Geothermal, Inc., McCulloch Oil Company and some others. This kind of approach to financing should receive added encouragement from the Energy Act of 1978.

(3) User advance payments. In order to secure rights to an energy resource, a utility or a public entity may desire to advance funds towards the development drilling of a given reservoir. It is unlikely, however, that such advances would be available prior to an initial successful discovery well. Apparently, a similar type of arrangement was negotiated at The Geysers between a prospective energy user and a potential developer.

(4) Other. There are numerous varieties to the above approaches, but one particularly interesting option revolves around the utilization of the Geothermal Loan Guarantee Program (GLGP) to fund field exploration and development work in combination with risk capital provided in scenarios 1-3. Other speakers have dealt with the GLGP, so I shall not dwell on this approach further.

B. The Utilization Phase picks up where the exploration phase leaves off. Once the capability to produce resource is demonstrated, the utilization facilities are necessary to provide a marketable product which, in this case, is a power plant. Several questions arise at this point, however. First, what initial size of plant should be the objective of the exploration phase? When should the construction of the power plant be timed for? At what point does the potential financial participant/investor become involved? Clearly, the time value of money being what it is (especially now in these inflationary times), the answer must be that both the exploration and development programs be integrated, at least as to planning, from as early a point as the conception of the project. I shall not dwell on this point in detail herein, but refer you to the article on power plant sizing and refinancing strategy the Geothermal Resources Council is making available in conjunction with this talk. I should like to discuss three general approaches to providing the required equity investment and loan capital sums necessary to implement a power plant financing package.

(1) Venture capital may be defined for the purposes of this paper as tax-oriented risk capital. The ability to accept resource utilization risk as well as the capability to utilize available tax benefits will enable the users of the resource to accelerate the construction of power generation facilities. Combining the use of such capital with portable (1-5 MW), semi-portable (10-20 MW) and fixed (site-specific 55 MW and up) units with bank financing or DOE-guaranteed funding is the most likely source of sizeable funding available for geothermal power plant construction. Both individual as well as corporate investors have the ability to participate under this kind of investment arrangement. Provided the project is structured in the appropriate fashion and that the financing is exempt from utility-type regulation, the vast amounts of "equity" or risk capital required for the expected growth of the geothermal industry can be raised in this manner.

(2) At-risk lending for geothermal power plant construction is a type of financing yet to be made available to the industry. In theory, reservoir evaluation techniques will eventually be judged by financial institutions to be sufficiently reliable to permit the advancing of funds, without recourse, against the risk of the project itself. If the reliability of a given reservoir could be proved to the satisfaction of a prospective lending institution, it would be willing to lend a certain percentage of the total project cost on an at-risk basis.

(3) Intermediary Risk-Assuming Companies (IRAC) represent a financing vehicle combining possibly both of the above mentioned approaches. One can best define an IRAC as a wholesaler of geothermal electric power. The "T formation," as I call it, includes, at left end, the resource company selling geothermal fluid at the well-head to the IRAC. The IRAC itself is the center, purchasing the fluid and converting it to electricity, which it sells to the right end, the utility, by means of a power sales agreement, usually on a take or pay basis. The IRAC produces the electricity by use of the power plant which it leases from the quarterback - the owner/lessor. This concept is spelled out in greater detail in the accompanying article. The basic point of this structure is that the utility accepts a loan planning risk, but avoids the reservoir risk in that it has no investment in the plant on the reservoir. The resource company can sell its product without having to build a power plant, delete its financial strength, and risk regulation as a public utility. As owners/lessors, the power plant owners qualify for full investment tax benefits in exchange for assuming reservoir risk. Used in conjunction with the DOE Loan Guarantee Program, the level of risk is reduced to acceptable levels for the investors in the owner/lessor. The IRAC also accepts the operating risk or farms it out. This overall program of risk and reward allocation places all of the incentives in the right places. This specialized form of project financing has only begun to demonstrate the viability of developing power generation on yet unutilized reservoirs. Current legislation may permit further streamlining of this approach by exempting IRAC's producing less than 30 MWe from regulation in which instance the IRAC would be the power plant owner as well.

C. Summary. Electric commercialization is most efficiently achieved when both the exploration and development phase are integrated financially and a construction program appropriate to the resource in question is developed. The financing of such projects can be streamlined and the net result, the cost of electricity, be achieved on the most cost-effective basis possible.

III. DIRECT-USE DEVELOPMENT PROJECTS

A. The Exploration Phase has similar risk characteristics as drilling for electric with one important difference. The depth of the resource, and therefore the cost of reaching it, is significantly smaller. This results in a lot of differences in the direct-use field as compared with the electric. Many more and smaller companies can be and are involved in direct-use projects, often for their own utilization. The variety of companies is much greater because BTU production can be used for any industry requiring process heat, be it agriculture, dehydration, space heating, etc. Many more non-electric prospects appear to have been identified, and once development is planned, a much shorter turn-around time to cash flow can be expected. This appears to be the result of the minimal environmental impacts of such projects as well as of the significantly smaller capital investment (and lead time) necessary to start-up the project. Shallower and less expensive production wells can be drilled more quickly. Depending on depth, temperature, and flow rates desired, completed non-electric production well cost could run from as low as a few thousand to as much as $250,000. In contrast, an average electric production or injection well to 7,000 feet could run from a million dollars to two million or more. Sources of funds for non-electric production well drilling are essentially the same as outlined in Section IIA, with one further addition. Given the significantly lower cost threshold of entry, an end-user such as a food processor or agricompany might be willing to invest in shallow production drilling themselves if the cost savings or back-up system potential appeared favorable enough.

B. The Utilization Phase for direct uses involves the same types of risks and has available to it all the same sources of funding as described in Section IIB above. A detailed paper will be coming out soon describing sources and types of funds available to direct-use projects. This information is contained in Section Seven on "Financing" of the Workshop on Direct Utilization of Geothermal Energy conducted by the GRC/OIT in Klamath Falls, Oregon in February 1979. I shall basically restrict my comments on this topic to the fact it is generally easier to finance a small project with a quick turn-around to cash flow as opposed to a large project with a long lead time to cash flow where delay and environmental hazards are inherently much greater. Since geothermal can furnish the energy for a wide variety of different businesses, evaluation and analysis of each of these different businesses should not concentrate primarily on the geothermal aspect alone. Overall management capability, economic viability, process and technological risks, marketing, and business structure - all have to be exhaustively reviewed. In this context, geothermal energy is but one component in a processed product and is but one additional variable - that of the fuel supply - to be assessed in a business with many variables. In non-electric, if the resource fails, the option may exist to retrofit to a conventional fuel source, in electric development, if the resource fails, the project fails.

In summary, based on the availability of recently enacted tax benefits, and based on the environmentally and economically desirable aspects of lower temperature geothermal resources, it appears that these projects offer desirable investment opportunities, although on a smaller scale. In fact, at-risk loan capital should become much more rapidly available to the commercialization of such direct-use quality geothermal resources than for electric, because options do exist for the use of the facilities on a commercial basis even with failure of the resource.

IV. CONCLUSIONS

In both the electric and direct-use sections of this paper, I have maintained a parallel structure in discussing the kinds of capital available to the exploration and development phases. Because the successful commercialization of a previously unutilized geothermal resource depends on obtaining different kinds of investment capital for each of the phases, I strongly recommend that one not be undertaken without planning for the other. Integration will save both time and significant amounts of money, thereby enhancing the project's potential for profitable implementation.

ECONOMIC RISK OF GEOTHERMAL PROJECTS

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Management methods for evaluating business opportunities involving uncertainties have included the concept of risk analysis. Risk analysis can be a powerful tool to compare the economic attractiveness of the various investments available to the business community. Natural resource development groups utilize this technique to select their exploration targets and to appraise the anomalies found. Additional funds can be allocated to those providing the opportunity for greatest return per dollar risked.

What is the risk factor used in economic analysis? When the probability of occurrence of any given event has been established, the risk factor will be known. The mathematical concept of risk factor can be considered as: The probability that an event will occur in one of several ways is the sum of the probabilities of the occurrence of all the possible ways that event can occur.

For example, a review of exploration work on geothermal prospects determines that in basin fill areas containing water saturated rocks four electrical resistivity anomalies are due to low resistivity sediments and one is due to an unusual amount of heated pore water.

The chances for being successful in a temperature confirmation drilling program on these resistivity anomalies will be 1:5. The probability of being successful is not the same as risk. In this example, in five attempts at success in a series when the risk is 1:5, the probability of success is approximately 68 percent.

The summation of risks involved in geothermal development evolves to essentially the question: Can the energy compete with other sources of energy available to the customer and still provide a reasonable rate of return on the necessary investment? The competitive fuel in the area of major geothermal steam occurrences is fuel oil. Coal is a strong competitor for hot water flash systems. Coal prices will probably follow oil prices in the next two decades. At this time hot water systems at temperatures below 400° F. cannot produce the energy for electricity generation inexpensive as coal fueled generating plants.

A look at the oil supply situation will provide a background for assessing the risk of oil prices increasing more rapidly than cost associated with geothermal development.

Saudi Arabia oil production is around 8.7 to 9 million barrels per day. Two years ago that country produced 10.2 million barrels a day. Present capacity is believed to be 11 million barrels per day. ARAMCO has added about three million barrels per day capacity during the past two years. The capability for producing much more exists. The willingness to produce in increased amount is another thing that poses a risk to the assumption they will. The Saudis are determined to maintain OPEC as an effective organization and will continue their production at around 8 to 9 million barrels per day. World oil demand should continue to increase 2 to 3 percent per year until the end of 1980.

OPEC production in 1978 was approximately 29 million barrels per day. This has gradually moved back to the 1977 high of 30 million barrels per day.

All free world net growth in oil demand (now 48 million barrels per day) during the next three years will be satisfied by non-OPEC sources: Mexico, North Slope and the North Sea.

Until 1985 world oil prices will be increasing, about the average rate of inflation. From 1985 on, world oil prices will be increasing at accelerating rates as OPEC countries maximize their return on a diminishing number of barrels.

Natural sources of heat above 450° F. in the western United States can produce electricity at prices competitive with low sulfur coals shipped from the Powder River Basin of Wyoming to the electricity generating centers supplying western Nevada and California. Water within the low energy 150° F. temperature range can provide processing heat, if the source is in a location where the energy can be used in the United States. It is expected that sulfur limits for fuel oil will be set similar to coal. To meet such standards, additional investment and costs will be required to prepare acceptable fuel. With such increases in cost, additional new uses for geothermal heat (energy) will become practical. As that happens, more people become interested in joining the exploration search to find and develop new deposits of heat for production of energy.

The development of a geothermal reservoir is capital-intensive, requires expert planning, and long times from initial expenditure until positive income is achieved. The utilization of a geothermal reserve requires extensive engineering, approximately two years in negotiation and planning with governmental agencies, and significant capital. (35 to 50 million dollars per 50 mw.)

The costs of maintaining and operating producing fields is about four to five times greater than the capital investment. An important portion of this cost is associated with the injection system that collects the cooled water and returns it to the sub-surface reservoirs after the heat is removed. Reducing these costs is an essential objective if geothermal energy is to remain competitive with other fuels.

Countries with high fuel costs and geothermal sites are now developing a wide variety of geothermal plants. Japan appears to be building the most efficient flash systems for use in hydrothermal areas with reservoir temperatures above 350° F.

Useful geothermal reserve assessment requires professional engineering analysis. The goal is to determine how much heat can be produced at a useful rate and temperature for at least 20 years from one area. This demands a thorough understanding of the manner in which heat is transported to areas of accumulation, how it accumulates, the methods and costs to find, produce and convert to a useable form of energy. With those studies in hand, a person can then determine what part of this resource can be sold in competition with other fuels and thereby establish the size of the reserve.

The supply of geothermal energy has been related to: all the heat present above an arbitrary temperature datum; the amount of heat between certain temperature levels, that heat contained in producing water, and; that heat contained in the rock framework transferred to the moving body of water.

The amount that could be produced in the United States if the government would provide incentives equal to other energy sources is now thought to be between 12,000 and 15,000 megowatts.

These incentives have included tax credits, deductions in tax calculations, investment tax credits, rapid depreciation, and depletion allowances. Other incentives include aid in exploration, aid in developing, engineering of generating plants, financing of generating plants, and reservoir engineering studies. Very little has been prepared showing the increased benefit to governmental programs, including tax revenue by demonstrating the increased flow of dollars from projects that would become profitable with this aid compared to project tax revenues that would be commercial without this aid. Dr. Robert Rex has calculated that for a 48 net mw plant paying 25 mils/KWH for the energy the government income would be more than 213 million dollars during the 30 year productive life. If this were on private land the government income would be 178 million dollars.

The actual potential of geothermal energy is affected by how the resource and reserves are calculated. These calculations must consider availability and application of governmental incentives, the price of other energy sources, versus the market price of geothermal energy, and the reliability of the production forecast. The size of required investment, the expected profit generated by those investments, plus the availability of lands to explore will be the motivating forces in developing the true potential of geothermal energy in the United States.

The most important factor in converting any resource into a reserve is how the individuals that are actively dedicated to discovery and development attack the problem. The key to successful reserve development is the quality of the people assigned to the task.

The critical economic factors affecting the risk of a geothermal project being successful can be considered in two categories. The first is that associated with the production of the geothermal energy. The second is in the conversion of the energy into a useful form for the production of electricity.

The energy producer, after finding the geothermal anomaly, must consider his risk of resource development concentrated into four major items. These are the reservoir life, the sales price for the energy, the plant design, and the pricing structure. Other opportunites for investment will affect the amount of money he may dedicate to the program.

The number of years of reservoir production at useful temperatures and volume of fluid that can be expected is of utmost importance. The reservoir economic life is affected by the rate of decline in temperature and production as this affects the drilling and equipment investment and the operating costs.

The risk the project succeeds depends upon the price of energy produced. The sales price defines the cash flow available for development and operating expense. This price establishes the limits of investment that can be made and the potential rate of return on this investment. The competitive stature of the resource will be prescribed by the price of the delivered energy. The final size of the economic reserve is thus determined by these factors. That size then determines the amount of risk the energy producer can assume at various stages of exploration and development.

The plant design affects the cost of designing the production mode as the delivered product must conform to the requirements of the plant. Single-phase fluid delivery (for other than dry steam) requires greater investment to maintain that phase from the reservoir into the plant than does a two-phase system. Injection disposal facilities are dependent upon the plant requirements. The rate of production from the reservoir is also dependent upon the plant design. The limits of fluid temperature useful in running the plant are established by the plant's design. The life of the producing facility is seriously affected by this factor.

The pricing structure can encourage efficiency in developing new reservoirs or negate the advantage of searching for deeper, though hotter, horizons. Provisions for reservoir failure can allow the taking of a greater risk in developing the reservoir to its maximum size. If the reservoir performance must be guaranteed by the producer, he can then only develop the amount of energy that has very little risk. Thus, the fuel producer and the utility have little chance for maximizing their return on the use of this impressive source of energy unless pricing structures recognize this effect.

Electricity producers are not prepared to undertake projects that have a risk of complete failure in the early stages. They are not oriented to taking risks of the magnitude considered acceptable by natural resource developers. For instance, developers know the risk of finding one million barrels of oil with a wildcat is about one in forty times being successful. So their organization has the ability to provide for the unsuccessful exploration ventures effect on their marketable supply of energy. The ability to evaluate and predict the reservoirs' capability for producing certain quantities of fluid is highly developed in oil companies because the few successful finds must be developed to their full capacity.

Utilities historically expect a certain amount of fuel to be delivered on schedule throughout the plant's lifetime. The utility organization has not developed the capability of being comfortable with reservoir engineering analysis. Geothermal energy does not provide the risk abatement feature of having another source of supply that can be brought in to augment a premature declining geothermal energy supply. This is the major risk the utility management recognizes in the economic viability of building a geothermal plant. The risk of having a favorable cost at the Busbar for the electricity produced can be determined after the design of the generating plant has established the production requirements for delivery of the geothermal energy. These requirements are strong factors in the producer of the energy identifying his costs of production and therefore a likely energy sales price.

The fixed costs affect the final price of produced electricity. Dry steam plants can be constructed for a lower investment than single-flash plants. The single-flash plants require a lower investment than the double-flash design.

The lower efficiency of the single-flash plant requires a much higher volume of fluid to be produced and handled to produce the same number of kilowatt hours. This effect of these design segments on the producer of energy and producer of electricity create the risk that each will have selected the optimum design for their components.

Knowing the size of the available fuel supply lowers the risk of underfinancing a development project. For rocks to be considered a reservoir, there must be sufficient horizontal and vertical permeability to allow the fluid to move easily. A 6,000-foot to 8,000-foot well must sustain flow rates of more than 100,000 pounds of steam per hour, or 500,000 pounds of water (at no less than 325 degrees Fahrenheit) per hour for 20 to 25 years to be considered commercial for electricity generation. Direct use of heat for industrial or space heating and cooling does not require such high heat output. The lower temperatures for such uses can be found in a greater number of anomalies. However, their usefulness is dependent upon low cost being achieved in development and production.

The geologic model that is generally accepted by geothermal explorers and developers has three basic requirements:

1. A heat source (presumed to be an intrusive body) that is about 2000° F. and within 40,000 feet of the surface.

2. Meteoric waters circulating to depths of 10,000 feet where heat is transferred from the conducting impermeable rocks above the heat source.

3. Vertical permeability above the heat source connecting the conducting rocks with a porous permeable reservoir that has a low conductivity impermeable heat retaining member at its top.

Geological investigation is the necessary ingredient that makes all exploration techniques useful. Broad reconnaissance of the surface data integrated into subsurface data is used to find an area of general interest. The ingenuity of the prospect finder in using data available to all workers determines whether an exploration program moves into advanced stages of using the proper combinations of the acceptable methods.

Geologic interpretation of the data acquired may justify the money required for exploratory drilling. The results of the drilling must be integrated into the geologic investigation to determine if a promising prospect is present.

The investigation must establish that:

1. High heat flow or strong temperature gradients are present at depth.
2. The geology provides reasonable expectation that a reservoir sequence of rocks is present at moderate depths from 2000 to 6000 feet.
3. The sequence of rocks offers easy drilling with minimal hole problems.
4. A high base temperature and low salinity waters as indicated by geo-chemistry of water sources should be present. The surface alteration and occurrence of high heat flow should cover an area large enough to offer the chance for a field capacity of more than 200 megawatts.

Table I (adjusted for 1980 costs) from C. Heinzelman's presentation of October 15, 1977 illustrates exploration techniques and associated costs. The overall amount of money (per succesful prospect) required is 3 million to 4.75 million 1977 dollars. This provides for limited failure and followup costs, but does not include the other exploration failures and land costs.

Table I

Exploration Techniques and Approximate Costs

Objective	Technique	Approximate Cost ($)
Heat Source & Plumbing	Geology	$ 20,000
	Microseismicity	15,000
Temperature Regime	Gravity	20,000
	Resistivity	25,000
	Tellurics and magneto-tellurics	50,000
	Magnetics	15,000
	Geochemistry (hydrology)	12,000
	Land analysis and permitting	25,000
	Temperature gradient - 20 holes(500' or less)	100,000
	Stratigraphic holes -4	160,000 - 240,00
Reservoir Characteristics	Exploratory and confirmation tests -3-	1,800,000 - 4,000,00
	Reservoir testing	250.000

To establish a discovery approximately $2,500,000 - $5,000,000 will be required.

This is probably the minimum expenditure needed to change a portion of the resource base into an area of reserve with production potential.

Upon deciding that a significant geothermal anomaly exists, the rate of engineering expenditures must increase rapidly to determine whether the development can proceed into a commercial venture. Essentially, there are no set figures for what it costs to develop a geothermal field. The basic reason for this is that each depends upon engineering the development to be compatible with the geology of the accumulation, and the requirements of the electricity generating system. The electricity generating system must be designed within the constraints of available temperature, rate of production, and ambient conditions of the field site. The key variables affecting risk are:

1. Temperature of the fluids produced.
2. Composition of the reservoir fluids.
3. Composition of surface or near surface fluids.
4. Geology of the reservoir framework.
5. Flow rates that can be sustained by the reservoir.
6. Cost of drilling in the prospect area.
7. Well spacing and geometry of the producing and injection sites.
8. Turbine system to be used.
9. General operating costs in the area.

Test Wells - Thermal evaluation requires the drilling of test holes. Heat flow and temperature gradient evaluation requires drilling to intermediate depths. Confirmation drilling requires holes drilled to the actual reservoir for diagnostic evaluation.

Heat flow and temperature gradients measured in the upper 100 to 500 feet of depth are useful in describing the area where the heat transfer is most intense. These do give a qualitative analysis as to the location and shape of the hottest near surface heat accumulation. Linear projection of temperatures obtained near the surface cannot be used to predict the temperatures that will be encountered 2000 to 3000 feet below the surface, even if the section below has a uniform lithology and the geothermal gradient is a straight slope. The temperature for a fluid-saturated system cannot be projected to a maximum above that for boiling water at the pressure calculated for the depth of projection. At some point along the boiling point curve, the temperature of the system may become isothermal and the rocks and fluids will have the same temperature for many hundreds of feet deeper. The rock temperature may decrease as a hole is drilled deeper if the hole is on the descending edge of a plume of hot water or merely below the spreading top of a plume. Heat flows from a hot body to a cooler body. This is not a function of being above or below a reference point of depth.

To lower the risk that the performance of the geothermal cell can be predicted, deep tests must be drilled. These holes must be of sufficient size to adequately determine the ability of the reservoir to produce fluids above 365° F. at rates approaching 100,000 pounds of steam per hour, or 500,000 pounds of liquid per hour.

To determine if a commercial development is possible, three or four wells must test the reservoir to obtain the basic reservoir engineering data. Reservoir pressure drawdown and buildup analysis must be conducted to determine reservoir permeability and extent. Fluid characteristics and analysis of non-condensible gas present require extensive flow testing. Injectivity testing is required to develop plans for disposal and pressure maintenance systems. Rocks may produce fluids easily, but may not accept them on return to the reservoir. This must be established in the laboratory and confirmed in the field for a developer to consider risking the investment needed to develop a field. The utility customer needs the same assurance.

A summary of estimated development costs after exploration expenses for the field supply, power plant, and ancillary equipment for a 50-megawatt hot water flash unit is as follows:

Table II

Development wells - 12	$ 14,400,000
Injection wells - 6	6,000,000
Pipelines	2,800,000
Miscellaneous field expense (includes interest and working capital)	9,000,000
Power plant	35,000,000
	$ 67,200,000

Economic Considerations

To obtain an economic comparison of geothermal fuels with the more widely used fuels is quite difficult, because each geothermal area requires a plant design specifically useful for that local area. The California Geyser's steam price of 17.5 mills per kilowatt hour is as inexpensive as geothermal energy can be produced in the United States today. This is a dry steam fuel, and the operators have more than a decade of experience in drilling, completion, and production operations. Optimum techniques have been developed so that maximum steam production per dollar invested can be maintained. The high energy content of this fluid provides a competitive heat rate, easy to construct collection systems, and the most simple of plant and reinjection facilities. The actual cost of the wells is frequently as high as $1,500,000, but the operation and the high utility of the steam allows a minimal price for the energy.

The wide variation of estimates of fuel costs and electricity generating costs derives from treatment of fuel processing and storage expense, income taxes, ad valorem taxes, insurance, interest during construction, return on investment required, and specific requirements for plants in the area of operation for the estimating companies.

The utility usually expects to earn a minimum of 25 percent return on investment on its equity portion of the investment. The exploration and producing investors have learned that a minimum acceptable rate of return on investment for their portion of the projects is 25 percent return on investment. The average conventional energy venture (non-geothermal) usually obtains about twice this rate of return to compensate for the risks involved. The prime rate has risen so high today that low risk venture returns will provide a ROI that is nearly as attractive.

The return on investment for the developer is most sensitive to the price received for the energy. Next to reliability of supply, the utilities' desires to use geothermal energy in electricity generating systems is dependent upon its price being low enough to make its use worthwhile. Much like coal and uranium, geothermal fuel prices will be a negotiated price between the supplier and the user. Each field will have significant differences in design so a uniform price cannot be expected for construction of the production facilities, or construction of the utilities conversion plant.

The nature of the reservoir geometry and the ability of the reservoir to respond to changes in production, rates, and temperatures, will determine the final costs for producing electricity from each geothermal project.

The basic structure of price must provide an attractive rate of return to the prospector. To achieve this, the prospector's risk capital investment and time at risk before income must be minimized. Most important, the revenue should reflect the actual value of the energy sold.

Cost Comparisons

The cost comparisons between the various sources of energy that will be available and useable for electricity generation during the next decade will affect the rate of geothermal energy's growth. The economic desirability of the production or use of a fuel is sensitive to its price. Regulatory requirements have direct effect upon production and construction costs. The tax treatment for each fuel system is a dynamic one. This makes it very difficult to assess the resulting economics.

The amount of money needed to construct and operate plants to use each fuel is a strong component of how much the electricity producing customer will pay per unit of fuel. The average coal and oil burning plant uses 8,500 to 10,500/Btu/kwh. A nuclear plant uses about 14,000 Btu/kwh. Geothermal plants use between 21,000 to 33,000 Btu/kwh.

Oil

Electricity produced from oil fired plants is directly related to the cost of low sulfur fuel oil. An oil fired turbine generator plant costs between $400 - 500 per kilowatt. A combined cycle plant is about $360 per kilowatt. The difference in heat factor, operating cost, and available capital for these plants establish which will be used for meeting the increased demand and plant replacement schedule within a utilities service area. The estimated cost developed by Stanford Research Institute of fuel oil in mills per kilowatt hour is approximately 23 mills per kilowatt hour. Strong competition between suppliers results in a stabilizing effect upon the overall price of oil. Utility planners have estimated the range of price of oil to be 20.5 to 21 mills per kilowatt hour. These cost ranges combined with the new plant costs will produce electricity between 33 and 44 mills per kilowatt hour. This figure must be adjusted for the strong energy price increase during the last twelve months.

Coal

Coal prices are related to specific sources of supply and dedication of specific sources of coal to certain plants. Coal does not presently have the wide range of usefulness that oil enjoys today. This limits the substitution of one coal for another.

The price of steam coal and plant construction costs to meet environmental requirements result in an estimated price of 35 mills for electricity generated in new coal plants. Fuel suppliers currently estimate coal can be delivered within a 1,000-mile radius for 10 to 15 mills per kilowatt hour if surface mining methods are used.

Nuclear

Nuclear fuel plants appear to offer the least expensive electricity for a non-indigenous source of energy.

The utility industry estimates they will be paying 6 to 6.5 mills per kilowatt hour for nuclear fuels and plant costs in 1977 dollars will be $800 to $1,000 per kilowatt. The estimated cost of electricity from such plants will be between 32 to 34 mills per kilowatt hour.

Geothermal

Comparison of conventional electricity prices with geothermal steam prices are a matter of public record. This is the least expensive of all thermal systems employed in the United States. To obtain a comparison of hot water flash steam plants, it is necessary to use developments outside the United States for performance factors. Economics of hot water flash to steam projects continue to be impressive. Cerro Prieto's development is very encouraging as exploratory work confirms this development can exceed 500 mw. The improvement in heat recovery with double flash units would reduce the cost of electricity and increase the size of reserves significantly. Seventy-five megawatts have now been developed and work is underway on the next 75 megawatts. The first unit of 75 megawatts was developed for $264/kw and produced electricity for approximately $.008, tax free. Today, costs would be about twice that amount. The cost includes the well field operation as this is an integrated operation. It is estimated the second 75 megawatt plant will produce electricity for about 16 mills, tax free.

It is possible to use the development work at Momotombo Nicaragua to evaluate the costs of developing a hot water flash field today. DeGolyer McNaughton, the international consulting firm, and Herman Dykstra, a reservoir engineering consultant, have completed examination of all the field test data from Momotombo. Tests using bottom hole pressure devices in selected wells were combined with field flowing tests. The firm concluded that double flash turbines could produce 96 megawatts for more than 30 years using the portion of the reservoir developed. Subsequent completion tests have demonstrated more than 100 megawatt capacity.

Turbine specifications prepared provide for a plant turbine with 80 psig first stage and 20 psig second stage. The power plant for this 225° C. field may have two 35 megawatt units in operation by mid-1980. The estimated cost for the electricity generating plant installed will be $460 per kilowatt. A savings of $26 million in foreign exchange would result from this development.

Steam

Geyser's steam price is about as inexpensive as geothermal energy can be produced today. The 1979 price of 17.5 mills per kilowatt hour is well below the competitive value of this energy. Twenty-five mills per kilowatt hour would be a price more nearly reflecting its actual value in an area using oil or coal for electricity generation.

PG&E's plant #15 is expected to cost $320 per kilowatt with provisions for H_2S treatment. This is an increase of 250 percent over the average of the 1961-1974 period. In the same period, the cost of electricity generated averaged about 5.6 mills per net kilowatt hour. 1979 operating costs will have increased the busbar price to 25 to 30 mills per kilowatt hour.

Summarizing the preceding discussion on comparison of costs and resultant prices of electricity, we can tabulate oil, coal, nuclear versus geothermal as follows:

	Oil	Coal	Nuclear
Fuel mills per kilowatt hour	20-23	9-11	6-7
Plant $/kw	400-500	780-1000	1000-1200
Electricity Busbar mills/kwh	33-34	38-40	38-40

	Geothermal		
	Steam	Flash 450°F.	Binary
Fuel mills per kilowatt hour	17.5	18-22	26-30
Plant $/kw	320	450-475	500-1000
Electricity Busbar mills/kwh	25-30	27-32	40-48

Reserve Esitmates

With these competitive conditions and an idea of the required investments in plant and fields, we can estimate the potential reserves identified in relation to the proven reserve.

The proven reserves of the Geysers is now 1507 megawatts. The potential reserves are another 1200 megawatts. To infer that the hot water area surrounding the dry steam reservoir will produce waters that will be used in flash steam plants is reasonable. Inferred hot water flash reserve should be approximately 1,000 megawatts.

The proven reserves in the Imperial Valley are 400 megawatts. Potential reserves of Brawley, East Mesa, Heber, Niland, and Westmoreland total 1600 megawatts. Reserves have been inferred with anothe 1,000 megawatts in these and similar anamolies within the province. Considerable work must be done on conversion systems, and deep drilling in the California portion of the Imperial Valley if another 5,000 megawatts are to be moved from the resource category into the reserve category in the next 20 years.

In the western Utah area Roosevelt is the only area with proven reserves. It appears that sufficient testing and plant design work has been completed to assign 80 megawatts to that classification. 120 megawatt potential and 300 megawatt inferred reserves can be assigned to Roosevelt on information now available. The remainder of that general area including Cove Fort - Sulfurdale, Thermal-Black Mountain, should have 1,000 megawatts potential reserves and 500 megawatt inferred.

Dixie Valley should have 100 mw potential if continuity of productive zones can be established. Another 400 mw may be inferred on similar anomalies within the Valley. South Nevada from Tonopah to Ely should contain 500 mw of potential and inferred reserves. Testing of potential areas in Nevada has not progressed to the stage where proven reserves can be assigned. The potential reserves of Phillips' three areas, and Chevron's two areas in the norhtern half of the state, indicates 400 megawatt reserve. An additional 600 megawatt can be inferred on the basis of drilling data being extrapolated with geophysical surveys. With continued confirmation success in the Carson sink area, an additional 500 megawatts could be moved from resource to inferred reserves. New Mexico's Valles Caldera is considered as having 100 megawatt potential reserve. From the size of the anomaly and the temperature indicated by surface springs, an inferred reserve of another 300 megawatts should be assigned. This area has a total reserve of 400 megawatts.

Summary

Electricity Generation Reserves

	Proven (Measured) MW	Potential (Indicated) MW	Inferred (Geol-Geoph) MW
Geysers	1520	1240	1000
Imperial Valley	400	1600	1000
Coso-Lassen		0	700
Long Valley			
Mammoth			
Randsburg			
Dixie Valley		100	400
Roosevelt	80	120	300
Cove Fort			
Sulfurdale			
Black Mountain-Thermal		300	400

	Proven (Measured)	Potential (Indicated)	Inferred (Geol-Geoph)
N. Nevada - Fallon to Winnemucca		400	600
S.Nevada Tonopah to Ely		200	300
New Mexico		100	300
Alvord Area		100	100
Alvord to Vale			300
Subtotal	2050	4160	5400
Total	11,600 megawatts		

The direct use of geothermal heat in the United States is on a local project basis except in Klamath Falls, Oregon and Boise, Idaho. Local greenhouse operations, individual processing plants in industrial and agricultural projects, are found throughout the western United States, Alaska, Texas and the southeast Appalachians. It is estimated these present direct uses represent proven reserves of 35 megawatts. It is easy to estimate the direct use potential is two to three times the 11,600 mw indicated as electricity generation reserves. The geographic distribution of direct use reserves is the major constraint to such development.

Reserves cannot be assigned to geopressure-geothermal projects. It is hoped the government research work in progress can develop sufficient data to provide inferred reserves in 20 years. The resource is large but definition criteria are not established.

An oil accumulation to provide 164,000,000 barrels per year for 30 years, would require 4.9 billion barrels to be available for production. Consider that less than 0.2 of 1 percent of all wildcats drilled in the United States during the last four years discovered producible reserves over the life of the field greater than 1 million barrels of oil.

To assess the impact of the development of this reserve now identified plus the stimulus such development will give to exploration requires an assumption that the governmental agencies believe indigenous sources of energy are necessary to the economy of the U.S.A.

Stanford Research Institute, The University of California, Riverside, and Science Application Ind. have each provided thoughtful studies on the effect of tax incentives for the development of geothermal resources. The effect of such tax treatment has been focused on the resulting price of electricity or upon how much income this would "shelter" for the producer. This focus should be changed. The size of increased resources resulting from incentives should be emphasized.

Each study has sidestepped critical questions of: How large a capacity can be economically developed from recognized prospects with the subject incentives? How many would be developed lacking such economic stimuli? What is the flow back to the government agencies in tax revenues if certain incentives are initiated? This demands careful analysis of the possibility of reduced tax flow from projects that are certain to be developed without the incentives versus the increased tax revenue from those projects that would not have been developed without the incentives.

Consideration of the dynamic effect of taxation regulations on an incipient industry will show a tremendous benefit to government agencies in increased tax revenues. Robert Rex prepared the following illustration demonstrates the flow of monies to federal, state and county agencies for a single 48 net megawatt project on federal lands.

ESTIMATED GOVERNMENT REVENUES FROM FIELD DEVELOPMENT PROGRAM

EAST MESA 48 MW PROJECT

10 percent federal royalty payments	$ 70,200,000
federal income taxes	67,110,000
state income taxes	16,590,000
ad valorem taxes	59,700,000
	$213,600,000

ASSUMES 25 MILS/KWH - 30-YEAR PROJECT LIFE - 6 PERCENT ANNUAL INFLATION RATE

If the reserves now known on federal lands are developed, additional ones will be added in the process of development and by the increased exploration attracted to the area of successful development. Five thousand megawatts production on federal lands and two thousand megawatts on non-federal lands should return to the government $903 million in revenues each year over the first 30 years of the projects' lives. $7.02 billion would flow to the federal government as royalty, $9.4 billion as income tax. $2.3 billion would be allocated to the various states' income tax revenues and more than $8.4 billion to local county governments as ad valorem taxes.

Summary

In 1973 the geothermal reserves in the United States were 500 megawatts. reserves identified since 1970 total about 11,100 megawatts. This is enough energy to supply the total electrical needs for 11,000,000 people. To generate the same electricity using fuel oil, 164 million barrels per year would be needed. Five billion barrels of oil would need to be discovered to supply the equivalent energy for 30 years.

Geothermal energy can compete with the other types of energy now being used in the United States. To do so, the energy must be available from its reservoir at a temperature above 400° F. Below this temperature, operating costs rise significantly as the number of wells to produce and reinject the fluid increases.

Tax incentives must be provided to encourage significant investment in the mid-temperature hot water resources if this type energy is to be developed.

The cost of the plants rise rapidly as the temperature of the reservoir decreases. The volume of fluid required to move through the system increases rapidly to supply the required heat. There are economic limits established by temperataure that must be recognized. If the Btu content of a ton of coal drops, there is a point where it is not useable for power production. The same is true for oil and gas fluids as their associated water or inert gas ratio increases. Geothermal fluids quality and usefulness is also dependent upon its Btu content per unit volume produced. The building of power plants for mid-temperature projects is critical to the utilization of this large resource.

For this reason, it is difficult to present a specific cost of electricity produced by broad types of resource. The probable range of prices for electricity generated from steam and hot water reservoirs today is:

Steam 450 degrees F and above	24-30	mills/kwh
Hot water flash - below 400° F	36-50	
above " "	27-32	
Binary	40-48	

Research must continue on how to make fluids with temperatures below 400°F. useful. The technology is now mature. There are vast quantities of heat in this resource awaiting the solution to the economic problems of using this low grade heat.

Risk capital must be readily available in units of 10 to 15 million dollars at the beginning of exploration. Development to 400 megawatts may require up to $100 million investment before payout of the first 50 megawatt unit is obtained. The investors with sufficient money to carry out a successful program will compare the return of invested capital offered by similar projects (utilizing similar technology and business know-how). The projects offering the best rate of return for similar risk and investment will usually be the ones selected for funding.

The biggest problem in obtaining risk capital is the uncertainity of the business. This includes the discrimination in tax treatment of hot water versus steam. This precludes being able to market the energy at competitive prices and obtain as favorable rate of return as other industries offer. Prospective investors should have assurance that government rules and regulations will encourage the discovery and use of this energy.

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TAXATION OF GEOTHERMAL ENERGY

Sharon Wagner

INTRODUCTION

Whenever the issues of taxes, tax credits, tax incentives, depletion allowances, and/or intangible deductions are raised, it must be remembered that there are 51 tax systems in this country: one federal and 50 state. State corporate and personal income tax structures may or may not parallel the federal corporate and personal income tax structure. Generally the states have followed the federal government's lead in constructing their own tax systems. However, in the post-Proposition 13 mood of the electorate, it is not clear that states will adopt tax incentives for geothermal resources. Moreover, since the geothermal tax incentives adopted as part of the 1978 Energy Tax Act are so new, there will be some uncertainty as to their application until the IRS promulgates its Treasury Regulations for these new internal Revenue Code (IRC) sections. Until that time, it is safe to assume that the IRS will follow (with certain exceptions) the Treasury Regulations and court cases that are applied to the oil and gas industry. Most of the Treasury Regulations cited in the footnotes in the text below were written for the oil and gas industry but they are generally applicable to geothermal.

THE FEDERAL TAX SYSTEM

Prior to the passage of the Energy Tax Act of 1978,[1] the federal tax treatment of geothermal resources was based mainly on judicial decisions; not statutory authority. In 1969 the 9th Circuit Court of Appeals[2] held that the federal intangible drilling deduction[3] and the percentage depletion allowance[4] applied to the geothermal drilling at The Geysers. To reach this result the Court held that geothermal steam was "gas" within the meaning of §263(c) and §613(b) (1) of the IRC.

In 1975 the Code was revised to provide a 22% percentage depletion allowance for any geothermal deposit in the U.S., or a U.S. possession that was determined to be gas.[5] But the IRS refused to follow either the Court decisions or the new Code provision and contested both the intangible drilling deduction and depletion allowance on activities and income from The Geysers. Furthermore, because of the IRS intransigence the tax treatment of drilling a geothermal deposit that was hot water instead of the steam was even less clear.[6]

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[1] P.L. 95-618, §403(b), amending IRC, §613A(b).

[2] Arthur E. Reich, 52 T.C. 700 (1969), aff'd, 454 F. 2d 1157 (9th Cir. 1972) and George D. Rowan, 28 T.C.M. 797 (1969).

[3] IRC §263(c).

[4] IRC §613.

[5] P.L. 94-455.

[6] In Miller v. United States, 78-1 U.S.T.C. P9127 (D.C.C.D. Cal. 1977) the federal district court denied the intangible drilling deduction to investors who drilled geothermal wells in Nevada in an area of hot water, not steam, reservoirs.

The Energy Tax Act of 1978 has eliminated most of the uncertainties of tax treatment of geothermal exploration and development. The new tax provisions can be used to promote capital investment and to generate for the investor certain tax savings which reduce the risk of investment. Furthermore, the definition of geothermal deposits[7] is broad enough to include all the various forms of geothermal energy including dry steam, hot water or dry hot rocks. The act covers three basic subjects: intangible drilling costs, depletion allowance, and tax credits.

I. INTANGIBLE DRILLING COSTS

A. Option to Deduct Intangible Drilling Costs

§402 of the Energy Tax Act amends §263(c) of the IRC to allow a taxpayer the option to deduct as expenses intangible drilling costs (called "intangibles" or IDCs) [8] The costs of drilling and completing a geothermal well are divided for tax purposes into two classes: intangible drilling costs and equipment costs. The equipment costs must be capitalized and "recovered" through depreciation or depletion. Intangible drilling costs may be treated in two ways.[9]

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[7] "A geothermal reservoir consisting of natural heat which is stored in rocks or in an aqueous liquid or vapor (whether or not under pressure)."

[8] Intangible drilling costs are defined by Part 5A, Temporary Income Tax Regulations for the Energy Tax Act, 45 Fed. Reg. 6779 (1980) (to be codified in 26 CRF Part 1) as any cost incurred which in itself has no salvage value and which is "incident to and necessary for the drilling of wells and the preparation of wells for the production of geothermal steam or hot water." Such expenditures expressly include "labor, fuel, repairs, hauling, supplies etc." that are used (1) in the drilling, shooting and cleaning of wells; (2) in such clearing of ground, road making, surveying, and geological works as are necessary in preparation for the drilling of wells; and (3) in the construction of such derricks, tanks, pipelines, and other physical structures as are necessary for the drilling of wells and the preparation of wells for the production of geothermal steam or hot water.

[9] Since the geothermal provision for the option to expense intangibles is separate from oil and gas activities, a taxpayer may make one kind of election for his geothermal deposits and a different one for his oil and gas wells. For example, he could decide to expense intangibles for both geothermal and oil and gas properties or he could capitalize oil and gas and expense geothermal intangibles.

They may be deducted as expenses (in tax terminology they may be expensed) in the year in which they are incurred or they may be capitalized and deducted over a certain period of time as depreciation or depletion.[10] Allowing a taxpayer to expense (deduct) all the intangibles in the year in which they were incurred gives the taxpayer a kind of "accelerated depreciation."

The taxpayer must make his election to expense or to capitalize intangibles in his first taxable year in which he incurs such costs.[11] Once the election is made, the taxpayer must treat such expenditures on all geothermal properties in the same manner for all future years.[12] For example, if Taxpayer (T)[13] has spent $50,000 of intangible costs, T may claim as a deduction on his income tax return the $50,000 of intangible costs. But if T decides to capitalize intangible drilling costs T will not take $50,000 for 1978, but instead will deduct this amount over a given period of time as depreciation or depletion. However, if the taxpayer elects to capitalize his intangibles, he is granted a second election for dry or productive wells.[14]

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[10] Part 5A, Temp. Reg. supra note 8, states that intangibles, if capitalized, are to be separated and recovered as depreciation or depletion. Intangibles not represented by physical property (clearing ground, draining, road making, surveying geological work, excavating, grading, and the drilling, shooting, and cleaning of wells) are to be recovered through depletion. But intangible expenditures represented by physical properties (wages, fuel, repairs, hauling, supplies, etc.) are to be recovered through depreciation.

[11] A taxpayer must make a clear election either to expense or to capitalize. If he does not, the IRS will hold that he elected to capitalize intangibles. It is best that if a taxpayer desires to expense intangibles, he include with his income tax return an express statement of election to expense in accordance with the option.

[12] U.S. Treasury Regulation §1.611-4(e)

[14] But this second election need not have to be exercised until the first year in which a dry hole is drilled.

[13] The owner of the operating rights in a property who has the responsibility to develop the property is granted the option of expensing intangibles. But each taxpayer, regardless of his relationship to another taxpayer, is entitled to a separate election. Thus each partner in a partnership is entitled to a separate election. Trusts as separate taxpayers are entitled to an election regardless of the kind of election made by the beneficiaries.

The costs incurred in drilling a nonproductive well may be deducted by the taxpayer as an ordinary loss provided a proper election is made. But the taxpayer must make a clear statement of election to deduct as ordinary losses intangible drilling and development costs of nonproductive wells. If a clear statement is not made, such costs can be recovered only through depreciation and depletion.

But a noncorporate taxpayer, a Subchapter S corporation or a personal holding company that decides to expense intangibles instead of capitalizing them, may be subject to one of the following: the minimum tax (see "B"); a limitation on deductions to the amount "at risk" (see "C"); recapture of intangible deductions if the property is sold at a profit (see "D").

B. Preference Income-Minimum Tax

Some types of income are given preferential treatment by special provisions of the tax law. A minimum tax applies to a number of items that are considered to be of a tax preference nature. These types of income include capital gains, stock options, and income offset by depletion, amortization, and intangible drilling costs. The tax is computed by totaling all the items of tax preference, then reducing this amount by the greater of $10,000 or one-half a taxpayer's regular income tax after reduction by credits. A flat 15% rate is then applied against the balance.[15]

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[15] A taxpayer may be able to claim the unused part of certain credits against his minimum tax. Also if a taxpayer has a net operating loss that remains to be carried forward to a succeeding tax year, the minimum tax otherwise due may be deferred in an amount of up to 15% of the net operating loss to be carried forward to subsequent tax years when the loss is absorbed. In the years when the loss is absorbed, the taxpayer will be liable for the minimum tax deferred in an amount equal to 15% of the net operating loss absorbed in each year. See IRC §57(a)(11).

If taxpayer has "excess intangible drilling costs" that exceed net geothermal income, he will have preference income subject to the minimum tax. Intangible drilling costs are considered to be excessive when the intangible drilling and development costs of a geothermal well allowable for the tax year are greater than the sum of (1) the amount allowable if the costs had been capitalized and straight-line recovery of the intangibles had been used and (2) the net income for the tax year from the geothermal property.

Straight-line recovery means the rateable amortization of such intangibles over the 120 month period beginning with the month in which production from the well begins (or, if elected, any method which would be permitted for purposes of determining cost depletion). Net income from all such property reduced by any deductions allocable to the properties, except intangible drilling and development costs in excess of straight recovery.

This preference does not apply to taxpayers who elect to capitalize by straight-line recovery their intangibles. Nor does it apply to nonproductive wells.[16]

Special rules apply to corporations in computing their minimum tax[17]. And the IRS will publish rules under which items of tax preference of both individuals and corporations are to be properly adjusted where the tax treatment that gave rise to the preference does not result in a reduction of the taxpayer's income tax for any tax year.

In effect what this provision does is to lessen the benefit of the option to expense intangible drilling costs. Few taxpayers now have geothermal income and if they chose to expense intangibles, they will have preference income (that is, the amount they deduct by expensing intangibles will definitely be greater than the sum of intangibles capitalized and net geothermal income).

C. Losses Limited to Amount at Risk. [18]

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[16] Nonproductive wells are those which are plugged and abandoned without having produced steam or hot water in commercial quantities for any substantial period of time.

[17] See IRS Publication 542, Corporations and the Federal Income Tax.

[18] See IRC §465(c).

The 1976 Tax Reform Act limited the tax benefits available to persons engaging in oil and gas operations. These same limitations with some changes were extended to geothermal operations by the 1978 Energy Tax Act.

Before passage of the 1976 Act a taxpayer could take deductions up to the amount of this cost (or "basis") in a business or investment venture. But the basis of a taxpayer often included expenditures financed by nonrecourse loans for which the taxpayer had no personal liability (i.e., he had nothing "at risk" because of the way the loan was made to him or to an investment group). Such leveraged nonrecourse loans were often employed by investors to finance drilling and development costs of oil and gas activities. Since a taxpayer could elect to expense intangible drilling costs, he could take deductions far in excess of his own actual investment. This kind of investment was desirable for a high bracket taxpayer because the large deductions for intangibles could be used to offset income earned from other sources.

The 1976 law added §465 to the IRC and limited the amount of losses[19] deductible by a taxpayer engaged in exploring for and exploiting oil and gas. The taxpayer's deduction cannot exceed the total amount the taxpayer has at risk in the venture. Deductions taken for intangibles are considered losses for purposes of this section.

The Revenue Act of 1978 changed the "at risk" rules for years beginning after December 31, 1978. The most significant change is that previously allowed losses must be recaptured when the taxpayer's "at risk" amount is reduced below zero. But only the excess of the losses previously allowed in a particular "at risk" activity over any amounts previously recaptured will be recaptured under this provision. However, such recaptured losses may be deductible in a later year if at the "at risk" is later increased.

The practical effect of these "at risk" provisions is to eliminate the use of nonrecourse financing to increase available deductions.

D. Recapture of Intangible Costs Expenses As Ordinary Income on Disposition of Geothermal Property.

Probably the most far-reaching change of the 1976 Tax Reform Act affecting corporate and noncorporate taxpayers is the requirement that upon the disposition of oil and gas property taxpayers are required to recapture all or some part of the intangible costs incurred as ordinary income if the property is disposed of at a gain (a profit). These recapture provisions were extended by the Energy Tax Act of 1978 to intangible drilling costs incurred in connection with geothermal deposits.[20]

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[19] A loss is the excess of allowable deductions allocable to a particular activity over the income derived from the activity during the taxable year.

[20] P.L. 95-618, §402(c), amending IRC §1254(a).

This recapture provision applies only to intangibles which the taxpayer elects to expense in the year in which they were incurred and does not apply to intangibles which were capitalized. The amount of intangibles recaptured as ordinary income (instead of as capital gains) is the lesser of (1) the intangible costs incurred (reduced by an amount which would have been allowed as cost depletion had such intangibles been capitalized) or (2) the gain realized on the disposition. Or, in other words, the amount recaptured and taxed as ordinary income is the amount that the intangibles deducted exceed that which would have been allowed had the intangibles been capitalized and amortized on a straight-line basis (120 months) from the time the property went into production.[21]

II. PERCENTAGE DEPLETION

The IRC provides two methods of computing a depletion allowance: cost depletion and percentage depletion. Cost depletion provides for a deduction for the taxpayer's basis (cost) in the property in relation to the production and sale of minerals from the property. On the other hand, percentage depletion is a statutory concept that provides for a deduction of specified percentages of the gross income from the property. The deduction, however, cannot exceed 50% of the net income from the property. A taxpayer is required to compute depletion both ways and to claim the larger of the two amounts.

A depletion allowance reduces the taxpayer's basis in a property but the total amount taken as a depletion allowance is not restricted to the taxpayer's basis. Even though cost depletion will be zero after the taxpayer's initial basis has been recovered (for example, T deducts $5,000 per year for five years for a total of $25,000 - the amount of his original investment), the taxpayer may continue to claim a percentage depletion based on income from the property.[22]

§403 of the 1978 Energy Tax Act grants percentage depletion on income from geothermal deposits. The rate through 1980 is 22%. It decreases by 2% yearly until 1983 and thereafter the rate is 15%.

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[21] It should be noted that there are questions as to the proper method of calculating the reduction of recapturable intangibles under this section.

[22] A depletion allowance on the income derived from production and sale of the minerals from a property is available only to the owner of an economic interest in that property. An owner of an economic interest can be an owner of mineral interests, royalties, working interests, overriding royalties, net profits interests or certain kinds of production payments.

This percentage depletion allowance is much more favorable than the one allowed oil and gas. It is not limited in any way to a specified amount of production. It has no 65% of taxable income limitation nor is it restricted to independent producers. However, the percentage depletion cannot exceet 50% of the taxable income from the property and is subject to the minimum tax-preference income rules.[23]

There is some question about the availability of depletion on minerals which are consumed by the producer of such minerals. Many manufacturers are now exploring and developing their own sources of energy supplies, particularly natural gas reserves and in some areas geothermal. But the depletion allowance is dependent upon the sale of a mineral. Some courts have held that no depletion is allowable for minerals consumed in the operation of the producing energy property. It is not clear, however, if a depletion allowance is precluded with respect to gas used in manufacturing operations. For example, the IRS ruled in 1968 that the value of dry gas manufactured from wet, gas and used as fuel for gasoline absorption plant is includible in determining "gross income from the property" for percentage depletion purposes, but the value of dry gas reinjected into the geological formation is not includible. One way for the corporate taxpayer to avoid the problem is to conduct its exploration and development activities through a wholly-owned subsidiary. The subsidiary could sell the gas to the parent at an arm's length price and create depletable gross income.

III. TAX CREDITS

A. Residential Energy Credit

§101 of the 1978 Energy Tax Act provides for a nonrefundable tax credit for certain expenditures incurred for equipment which uses geothermal energy in a taxpayer's principal residence in the United States. The equpment must be new and must meet certain performance and quality standards; it must reasonably be expected to remain in production for five years. The credit is as follows: (a) 30% of the expenditure up to $2000, (b) 20% of the expenditure from $2000 to $10,000. The maximum credit is is $2200. The credit may be carried over to future years for equipment purchased after April 20, 1977 and before January 1, 1986.

B. Additional Investment Tax Credit for Alternative Energy Property

A 10% investment tax credit in addition to the existing investment tax credit is available for geothermal equipment which qualifies as either "alternative energy property" or "specially defined energy property." Public utilities cannot benefit to the extent of "alternative energy property" but can use the credit for "specially defined energy property."

The business energy credit is limited to 100% of tax liability, except for solar or wind energy property on which the credit is refundable. Until the IRS issues its regulations on this new section it will not be completely clear what kind of equipment qualifies.

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[23] The excess of the depletion deduction over the adjusted basis of the property at the end of the year (determined without regard to the depletion deduction for the year) is what would be preference income.

STATE TAX SYSTEMS[24]

Of the fifteen states with known geothermal resources Nevada, Texas, Washington and Wyoming have no state personal or corporate income tax. Alaska, Colorado, Hawaii, Idaho, Montana, and New Mexico apply their income tax levies to adjusted gross income as calculated for federal income tax. But five states have an independently determined income tax: Arizona, California, Louisiana, Oregon and Utah. Their differences from the federal law are largly due to the state provisions concerning percentage depletion for resources extraction industries.

Two states, California and Arizona, provide two examples of how complex the state tax picture can be. California has a franchise tax and a corporate income tax. The franchise is for the privilege of exercising a corporate franchise within the state. The tax rate is 9.6% for calendar or fiscal years ending in 1980. For subsequent years the rate is dependent on bank and corporation tax revenues. The following chart gives these rates.

1981

Revenues Collected in 1979-80	Corporation Tax Rate for 1981
Less than $2,950,000,000	9.6%
$2,950,000,000--$3,025,000,000	9.5%
$3,025,000,000--$3,100,000,000	9.45%
Greater than $3,100,000,000	9.40%

1982

Sum of Revenues Collected in 1979-80 and 1980-81	Corporation Tax Rate for 1982
Less than $6,000,000,000	9.6%
$6,000,000,000--$6,075,000,000	9.50%
$6,075,000,000--$6,150,000,000	9.45%
$6,150,000,000--$6,225,000,000	9.40%
Greater than $6,225,000,000	9.35%

1983

Sum of Revenues Collected in 1979-81, 1980-81 and 1981-82	Corporation Tax Rate for 1983
Less than $9,450,000,000	9.6%
$9,450,000,000--$9,525,000,000	9.50%
$9,525,000,000--$9,600,000,000	9.45%
$9,600,000,000--$9,675,000,000	9.40%
$9,675,000,000--$9,750,000,000	9.35%
Greater than $9,750,000,000	9.30%

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[24] For an extensive analysis of state tax systems see State Taxation of Geothermal Resources Compared with State Taxation of Other Energy Minerals, Sharon C. Wagner, published by the Geothermal Resources Council, Davis, CA.

Insofar as the franchise tax overlaps the corporate income tax, the amount due under the franchise tax is offset against the amount due under the income tax. The computation of income for both the franchise tax and the income tax follows generally the pattern of the federal income tax and interpretations of the federal law by the Treasury Department, with the exception of depletion provisions.

Prior to 1975 California provisions for depletion allowance for oil and gas and other minerals conformed basically to federal law. However, California did not follow the Federal Tax Reduction Act of 1975 which eliminated percentage depletion for oil and gas wells (with a few exceptions). California merely placed a limit on the total amount deductible by each individual taxpayer. These limitations apply only after the total accumulated depletion allowed or allowable exceeds the adjusted cost of the property.

A deduction of 22% of gross income, less rentals and royalties, for the taxable year is allowed for oil and gas properties. This deduction may not exceed 50% of taxable income computed without allowance for depletion. In addition, where the deduction exceeds $1.5 million and is greater than the adjusted cost of the taxpayer's interest in the property, the deduction is reduced. The reduction equals 125% of the amount in excess of $1.5 million.[25]

For example, suppose that the 22% depletion is $3.5 million and that this amount exceeds the cost of the taxpayer's interest in the property. The deduction in this case is reduced by 125% of $2 million ($3.5 million minus $1.5 million), which equals $2.5 million. The allowed deduction in this case is $3.5 million minus $2.5 million which equals $1 million. If, instead, the 22% depletion amounts to $7.5 million, then the reduction is 125% of $6 million, which is equivalent to the depletion allowance itself, and no deduction is allowed.[26]

In September 1979, Governor Brown signed a bill[27] that conforms selective provisions of the Bank and Corporation Tax Law and the Personal Income Tax Law to the 1978 federal Energy Tax Act. The major changes that affect geothermal development are:

1) The at risk loss restriction provision of present law, which applies to four specified activities (farming, oil and gas, motion pictures, and equipment leasing) is extended to apply to all activities except real estate carried on by individuals and partnerships. This applies to geothermal properties. See discussion of federal "at risk rules" above.

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[25] CAL. REV. & TAX CODE §17686.

[26] Bock, <u>1978 Guidebook to California Taxes</u>, p. 123.

[27] Chapter 1168, Laws 1979, effective January 1, 1979.

2) Under §24832 and §17686 both individuals and corporations are given a 22 percent depletion allowance for geothermal wells. The 22 percent is computed on the gross income from the property during the taxable year, excluding from such gross income the amount equal to any rents or royalties paid or incurred by the taxpayer in respect of the property. The allowance cannot exceed 50 percent of the taxable income of the taxpayer (computed without allowance for depletion) from the property. See discussion above under oil and gas deduction rules.

3) Excess intangible drilling costs are an item of tax preference for personal income tax only.

4) Owners of geothermal wells are specifically permitted to treat drilling costs as a current expense rather than being required to capitalize these costs. But "excess intangible drilling costs" are subject to recapture. See discussion above under the federal law.

Arizona has raised its corporate tax rates several times in recent years and another change for corporate and individual income tax rates was pending before the Legislature in December, 1979. The current rates are as follows:

1st	$1,000.	2.5%
2nd	1,000.	4
3rd	1,000.	5
4th	1,000.	6.5
5th	1,000.	8
6th	1,000.	9
Over	6,000.	10.5

In 1977 Arizona was the first state specifically to provide for a depletion allowance and depreciation deduction for geothermal wells in computing new income. The depletion allowance is 27 1/2% of gross income, excluding an amount equal to any rents or royalties paid in respect of the property. The allowance cannot exceed 50% of the taxable income of the taxpayer from the property, computed without subtraction for depletion. Also expenditures paid or incurred during the income tax year for the development of a geothermal resource well, if paid or incurred after 12/31/53, may be deducted from gross income or charged to the capital account. Amounts up to $75,000 paid or incurred for the purpose of ascertaining the existence, location, extent or quality of any deposit of geothermal resources are allowed as a deduction.

APPLICATIONS OF MODERATE-TEMPERATURE GEOTHERMAL RESOURCES

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ABSTRACT

Moderate-temperature hydrothermal resources will, in time, be the "bread and butter" of the hydrothermal industry. Estimates indicate that thirty-seven states in the U.S. have geothermal resources that may be presently economically exploitable. The medium- and low-temperature (50 to 150°C) hydrothermal resource contains about five times as much recoverable energy as the high-temperature (above 150°C) resource. Direct use of the energy from the resource, in process and space heating, is viable today. Economic electrical production using fluids in the 150°C range is possible in the near-term future.

INTRODUCTION

The upper 10 kilometers of the earth's crust may contain more than 8 x 10^{24} calories of heat; however, the majority of this heat is too diffuse to be economically exploitable as an energy source. Estimates indicate that thirty-seven states in the U.S. have geothermal resources that may be presently economically exploitable. The medium- to low-temperature (50 to 150°C) hydrothermal resource contains about five times as much recoverable energy as the high-temperature (above 150°C) resource when extraction practices are limited to current or near-term technology (Figure 1). The direct application of geothermal energy is a viable technology that already is in worldwide use. Commercial and government cooperative projects are now underway which will expand the use of direct applications in the United States.

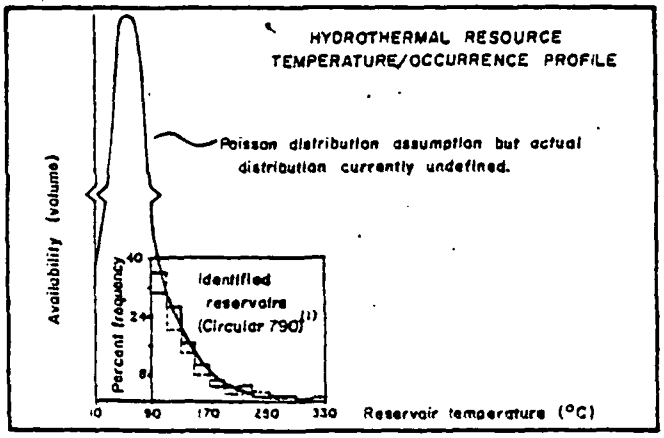


Figure 1

DIRECT APPLICATIONS

The practices employed in the direct use of geothermal energy encompass a wide spectrum. At one end is the age-old balneological use, while at the other is the use of geothermal energy for refrigeration. Applications range from melting snow to providing the thermal energy requirements for a modern food dehydration plant.

It is startling to realize that the commercial use of geothermal energy is older than the commercial use of natural gas. District space heating by the Artesian Hot and Cold Water Company of Boise, Idaho, was initiated in 1893. This system at one time serviced a peak of 400 customers. Currently, the space heating requirements of approximately 200 homes are met by the system. The largest known, and probably the most economical, district heating system is in Reykjavik, Iceland. It supplies a total population of about 90,000 with space and domestic water heating. The present capacity for the system is 350 MW (th). The average cost of heating is about 30% below oil heating costs.(2)

The earliest utilization of geothermal energy in modern industrial processing is not well documented, but appears to have been initiated in the early 1950's. The Italians used steam at Larderello in the early 1800's for evaporator heating. A compilation of the types of industrial processes and the country in which they are currently utilized is presented in Table 1.

Hydrothermal resources are now being employed for industrial processing in the United States. The first of these operations was the Medo-Bel Creamery in Klamath Falls, Oregon. Medo-Bel has been using this energy source since 1973 for milk pasteurization. Geothermal Food Processors have recently initiated onion and celery drying operations at Brady Hot Springs, Nevada. In addition, the DOE field demonstration (PON) program has stimulated industrial developments in potato processing, grain drying, aquaculture, agribusiness, and sugar processing.

Table 1
CURRENT INDUSTRIAL PROCESSES USING GEOTHERMAL ENERGY(3)

Application	Country	Description of Application
Wood & Paper Industry		
Pulp & Paper	New Zealand	Processing and a small amount of electrical power generation. Kraft process used.
Timber Drying	New Zealand	Kiln operation.
Washing & Drying of Wood	Iceland	Steam drying.
Mining		
Diatomaceous Earth Plant	Iceland	Production of dried diatomaceous earth recovered by wet-mining techniques.
Chemicals		
Salt Plant	Japan, Philippines	Production of salt from sea water.
Sulphur Mining	Japan	Sulfur extraction from the gases issuing from a volcano.
Boric Acid, Ammonium Bicarbonate, Ammonium Sulphate, Sulphur	Italy	Includes recovery of substances from the volatile components which accompany the geothermal steam.
Miscellaneous		
Confectionary Industry	Japan	
Grain Drying	Philippines	Geothermal steam heats rotary kiln dryer.
Brewing & Distillation	Japan	
Stock Fish Drying	Iceland	Fish drying in shelf dryers.
Curing Cement Building Slabs	Iceland	Curing of light aggregate cement building slabs.
Seaweed	Iceland	Drying seaweed for export.
Onion Drying	United States	Dehydration of onions.
Milk Pasteurization	United States	Milk processing using low-temperature resource.

Industrial use represents 40% of our national energy consumption, the single largest share, with residential space conditioning and water heating using 20%, commercial space conditioning and water heating using 15%, and transportation accounting for the remaining 25%.

The energy used by industry can be broken into the following categories:

Process Steam	40.6%
Electric Drive	19.2%
Electrolitic Process	2.8%
Direct Process Heat	27.8%
Feedstocks & Chemicals	8.8%
Other	0.8%

Process steam and direct process heat account for 68.4% of the total industrial use of energy, much of which can potentially be supplied by hydrothermal energy. Today, high-temperature processing is being practiced in many cases only because those are the temperatures naturally achieved when fossil fuel is consumed. A study by Intertechnology Corporation(4) reviewed in excess of 75 processes and defined the associated heat requirements. Typical processes which can be operated in the low to moderate range, together with the percentage of the process energy needs as a function of maximum temperature required, are given in Table II. It should be noted that the methodology of the study considered the process temperature required, not the temperature supplied. However, in many processes, time and temperature can be traded-off to permit the use of lower temperature energy sources. Thus, there are potentially many additional processes which can be adapted to low-temperature energy sources.

Although a national market analysis has not been completed, an analysis of ten Rocky Mountain states shows that space conditioning and industrial processing are prime market sectors for the direct applications of hydrothermal energy. Currently, greater than 75% of the energy requirements of these market sectors is met by fossil fuel consumption, with electricity claiming the majority of the remaining sales. Energy competition projections for the referenced states indicate a future higher dependence upon coal, which may encounter environmental or other growth constraints.

Table II

TYPICAL INDUSTRIAL PROCESS HEAT REQUIREMENTS

	40°C-60°C	60°C-80°C	80°C-100°C	100°C-120°C	120°C-140°C	140°C-160°C	160°C-180°C	180°C-200°C	200°C
Dehydrated Fruits & Vegetables	0	100%	——→						
Concrete Block - Low-Pressure	0	100%	——→						
Autoclave	0	0	0	0	0	0	0	100%	
Frozen Fruit & Vegetables	0	0	39%	100%	——→				
Poultry Dressing	100%	——→							
Meat Packing	0	99%	100%	——→					
Prepared Feeds - Pellets	0	0	100%	——→					
Alfalfa Drying	0	0	0	0	0	0	0	0	100%
Plastic Materials	0	0	0	0	0	0	0	0	100%
Dairy Industry - Cheese	23%	100%	——→						
Condensed Milk	0	63%	63%	93%	100%	——→			
Dried Milk	0	0	42%	66%	71%	71%	71%	100%	——→
Fluid Milk	0	0	100%	——→					
Soft Drinks	61%	100%	——→						
Soap	0	0	0	1%	——→				100%
Detergents	0	0	0	52%	——→				100%

A cross matching of the hydrothermal resources, as known today and projected for the future, on a county-by-county basis with the potential user sectors, has defined the prime commercial sectors that could most effectively convert to hydrothermal energy. This analysis reveals that all ten states under study have significant resources which correlate with potential energy market areas, and that the majority of the industrial and population centers are co-located with hydrothermal resources. The current energy use, considering all potential uses of direct heat, is 362 x 10^{12} Btu/yr, with a growth potential, by the year 2020, of 3980 x 10^{12} Btu/yr.

The largest single user segment is space conditioning and water heating. The current energy use for this is 288 x 10^{12} Btu/yr, and this could grow to 2504 x 10^{12} Btu/yr by 2020.

Many of the major industrial energy consumers in the states studied can use low to moderate heat sources to meet a portion, if not all, of their energy needs. These industries include food and kindred products processing, wood and lumber products, mining and minerals, chemical processing, and the concrete industry. Table III lists the top prospect industries that are matched by counties with hydrothermal resources.

The energy requirements of the industrial sector are somewhat smaller than the energy needs for residential/commercial space conditioning, but the ten-state area growth potential is excellent. In addition, it appears that the market can be more readily penetrated in the industrial sector since industrial applications are energy intensive (therefore decreasing the delivered cost per Btu), require less public acceptance, and have favorable tax benefits for investors. Current industrial energy use in the low to moderate heat processing sector which can be served by hydrothermal energy is 74 x 10^{12} Btu/yr, with a growth potential to 1476 x 10^{12} Btu/yr by the year 2020.

Table III

TOP 20 INDUSTRIAL PROCESS HEAT APPLICATIONS DIRECTLY MATCHED(a) FOR GEOTHERMAL ENERGY REPLACEMENT IN THE RMB&R REGION

($\times 10^{12}$ BTU/HR)

Industry	Matched 1975 Energy Use(b)
Dehydrated Fruits & Vegetables	11.80
Concrete Block	7.10
Frozen Fruits & Vegetables	5.24
Poultry Dressing	4.82
Meat Packing	4.45
Prepared Feeds	3.65
Plastic Materials	3.63
Dairy Industry	3.24
Soft Drinks	2.91
Soaps	1.24
Inorganic Chemicals	1.06
Ready-Mix Concrete	.98
Gypsum	.97
Canned Fruits & Vegetables	.97
Beet Sugar	.82
Treated Minerals	.69
Cotton Seed Oil Mills	.34
Prepared Meats	.34
Pharmaceuticals	.25
Furniture	.21

(a) Industries matched by co-location with resources and compatible process temperatures in those counties having hydrothermal resources.

(b) Regional consumption of direct heat energy in 1975 replaceable by hydrothermal energy from co-located and temperature-matched resources.

Market growth projections for hydrothermal energy in the ten-state area analyzed present an attractive profile. From the data illustrated in Figure 2, it is evident that a substantial portion of the region's energy needs can be satisfied by hydrothermal energy. Competition from conventional energy sources, as well as other alternative energy types (solar, biomass, etc.) result in the choice of conservative market penetration rates, as shown by the estimated penetration (bottom) curve.

ENERGY CONSUMPTION PROJECTIONS

FOR THE RMB & R REGION

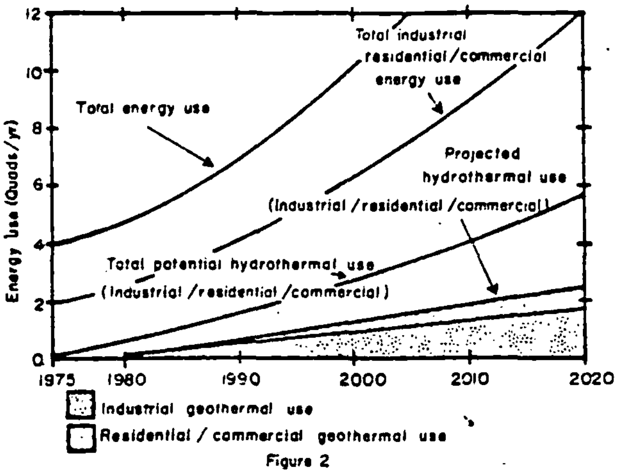


Figure 2

In the U.S., direct applications of hydrothermal energy are minimal, a result of our former abundant, inexpensive fossil fuel supply. However, with reduced fossil fuel supplies and increasing energy requirements, the nation can no longer delay implementing the significant contributions that the direct utilization of geothermal resources can make to meeting energy demands. Reducing resource uncertainties, assisting industry in developing confidence in the applications of hydrothermal fluid, removing unnecessary barriers, solving environmental issues, demonstrating uses, and providing incentives are necessary activities if the objective of widespread utilization of geothermal resources is to be attained. Many applications of geothermal heat are considered straightforward applications of existing technology, but there are applications, such as industrial drying with low- to medium-temperature geothermal fluids, where technical issues remain to be resolved by experiment, demonstration, or analysis. Small-scale and pilot testing are important incentives to demonstration and full-scale applications of industrial processes.

At the Raft River Geothermal Test Site in southcentral Idaho, a highly successful aquaculture experiment has demonstrated the desirability of raising aquatic species directly in geothermal fluids, a fluidized-bed geothermal dryer has converted potato wastes into high protein fish food, and an agriculture/irrigation experiment has explored the benefits and detriments of raising field crops with spent geothermal fluids. In addition, the first U.S. geothermal-powered air conditioner cools a Raft River office building; on-line building space heating is being examined, and new heat exchanger designs are being evaluated for highly corrosive and scaling water applications.

To further promote the develoopment and early commercialization of direct applications, the Department of Energy has issued two Program Oppartunity Notices for field experiments. Currently, eight projects are in progress and an additional fourteen are in the contract negotiation stage. The projects are listed in Table IV.

Table IV

GEOTHERMAL DIRECT USE FIELD EXPERIMENTS

Project	Location	Application
Utah Roses, Inc.	Salt Lake City, UT	greenhouse space heating
Utah Energy Office	Salt Lake City, UT	space & water heating
Montana Energy & MHD Research & Development Institute, Inc.	Butte, MT	space heating
Madison County Energy Commission	Rexburg, ID	district heating & industrial food processing
Chilton Engineering	Elko, NV	space & water heating
Town of Pagosa Springs	Pagosa Springs, CO	district heating
City of Boise	Boise, ID	district heating
Haakon School	Philip, SD	space & water heating
South Dakota School of Mines	Diamond Ring Ranch, SD	space heating & agribusiness
St. Mary's Hospital	Pierre, SD	space heating
Ore-Ida Foods, Inc.	Boise, ID	space heating & industrial food processing
Monroe City	Monroe, UT	district heating
City of Klamath Falls	Klamath Falls, OR	district heating
Torbett-Hutchings-Smith Memorial Hospital	Marlin, TX	space & water heating
Klamath County YMCA	Klamath Falls, OR	space & water heating
City of El Centro	El Centro, CA	space heating & cooling
TRW, Inc.	Redondo Beach, CA	industrial food processing
Navarro College	Corsicana, TX	space & water heating
City of Susanville	Susanville, CA	district heating
Geothermal Power Corp.	Novato, CA	space heating & agribusiness
Hydrothermal Energy Corp.	Reno, NV	space & water heating
Aquafarms International, Inc.	Mecca, CA	aquaculture

Each project, with minor variations, is organized to include the following major phases:

a) Environmental Report Preparation
b) Resource Assessment
c) Well Drilling
d) Well Evaluation
e) Corrosion Evaluation
f) Water Disposal Method Decision
g) System Design
h) System Construction
i) System Monitoring

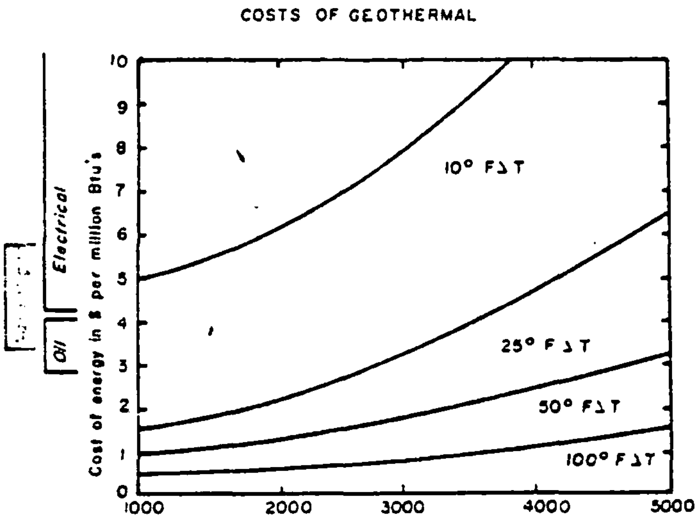
The type and complexity of the current projects vary from space heating and grain drying (Diamond Ring Ranch) to food processing (Ore-Ida Foods, Inc.). While only existing technology is being employed to carry out the projects, they will provide an excellent baseline for future commercial development.

Valuable environmental, technical, operational and economic information will be generated as a result of these projects. In addition, institutional barriers will be tested, private firms and organizations will gain experience, and public awareness of hydrothermal energy will be increased.

Since it is difficult to discuss direct application economics except in a generic manner, these projects are especially important to the development of the hydrothermal market. Economics are extremely site and application dependent. Major factors which determine the economics are:

a) Depth of Resource
b) Geophysical Surveys Required
c) Utilization Factor
d) ΔT Available
e) Pumping Costs
f) Disposal Method Required
g) Fluid Transmission Distance
h) Water Quality
i) Heat Exchanger Surface Area Required
j) Cost of Investment Capital
k) Taxation Position of Developer/User

Figure 3 illustrates the importance of using as much of the energy as possible. If only a 10°F ΔT is available for use, the resource must be shallow and near its utilization point, whereas the project economics are greatly improved if ΔT's of 50 to 100°F can be obtained. Estimates from the field experiments program and actual cost data from several private developments yield energy cost rates from $.46/MBtu to $5.83/MBtu.



Plot assumes 500 gpm production and one mile of main distribution pipe

Figure 3

ELECTRIC APPLICATIONS

The lower temperature limit for economic electric power generation approaches 170 to 180°C. Since many of the presentations at this symposium will discuss power cycles, power economics, resource definition and reservoir engineering for electric power production, only a brief description of the research being performed to include the moderate-temperature resources into the "economic" power production range is discussed herein.

As one of the initial steps in the application of moderate-temperature hydrothermal resources to electrical power production, a prototype power plant, rated at 60 kW, was constructed in Idaho's Raft River Valley. This was the first time a binary cycle generated electricity from medium-temperature geothermal fluid and supplied power to a commercial grid. Isobutane is being used as the working fluid in this system. The primary function of this facility is to test advanced components and systems, and to gain actual operating experience.

Attempts to find less expensive devices to transfer heat are also continuing. Both fluidized-bed and direct-contact heat exchangers have been developed. Models of fluidized-bed exchangers, which use a bed of floating sand to scrub the scale from heat-exchanger tubing, were tested to analyze their flow-distribution characteristics. It now appears, however, that component development will center on direct-contact exchangers in which the secondary fluid mixes with the hot geothermal fluid.

A second prototype system, a 500 kW direct contact heat exchanger pilot plant, is being designed by Barber Nichols Company for the Lawrence Berkeley Laboratory. This system will be tested at Raft River in the fall of 1979. It will be the first test of a binary geothermal system with heat exchangers large enough to eliminate size effects.

As an outgrowth of this research and development work, a 5 MW(e) binary cycle pilot plant is being built at Raft River, Idaho. This plant will utilize state-of-the-art components, but will employ a dual boiling power cycle using isobutane as a working fluid. It is designed to take maximum advantage of the valley's low seasonal temperatures which are typical of the intermountain west. Design work was completed in January of 1978, and construction initiated in August, 1978. The facility should begin operation by mid-1980.

The 5 MW(e) plant will require about 2250 gallons per minute of 143°C geothermal fluid. The Raft River well field has four deep production wells. These wells will produce a flow of approximately 2850 gallons per minute, which is sufficient to operate both the power plant and auxiliary experiments. The production wells range in depth from 5000 to 6500 feet, and draw geothermal water from a zone of fractures 3750 to 6000 feet deep.

To protect the shallow groundwaters, and to prevent subsidence or ground settling, the expended hydrothermal fluid will be injected back into the ground. The Raft River well field contains three medium-depth injection wells. Tests are presently being conducted to determine their ability to accept long-term injection.

This research and development work, coupled with industry participation, will be instrumental in determining the economic and technical feasibility of the use of moderate-temperature resources for electric power production.

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