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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).

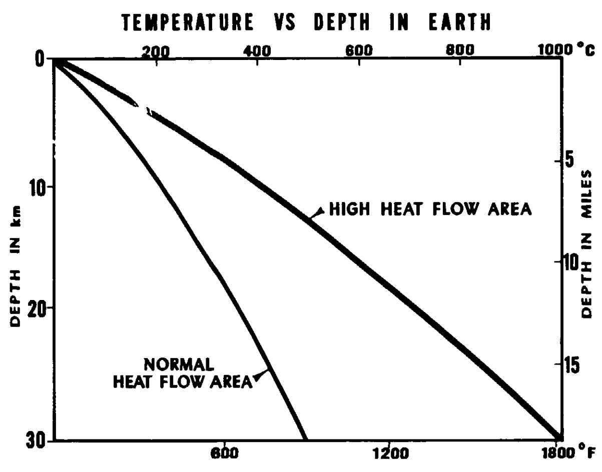


FIGURE 1

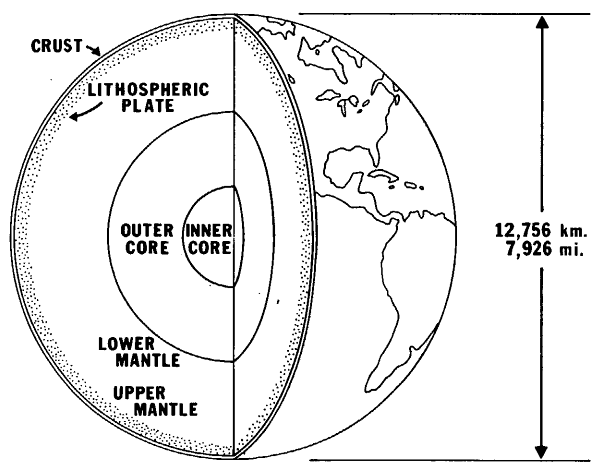


FIGURE 2

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.

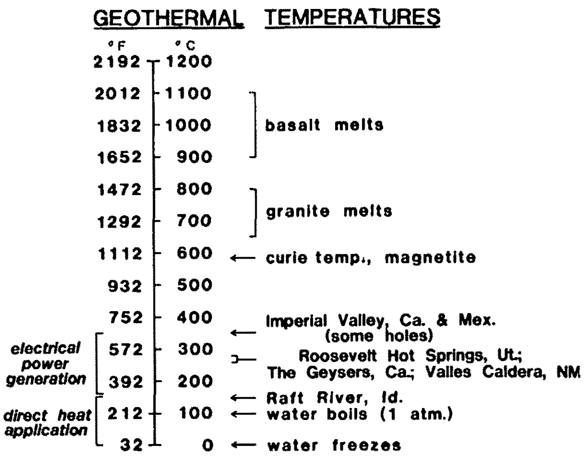


FIGURE 3

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).

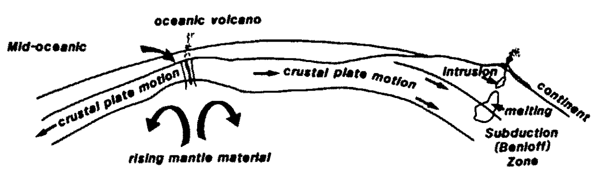
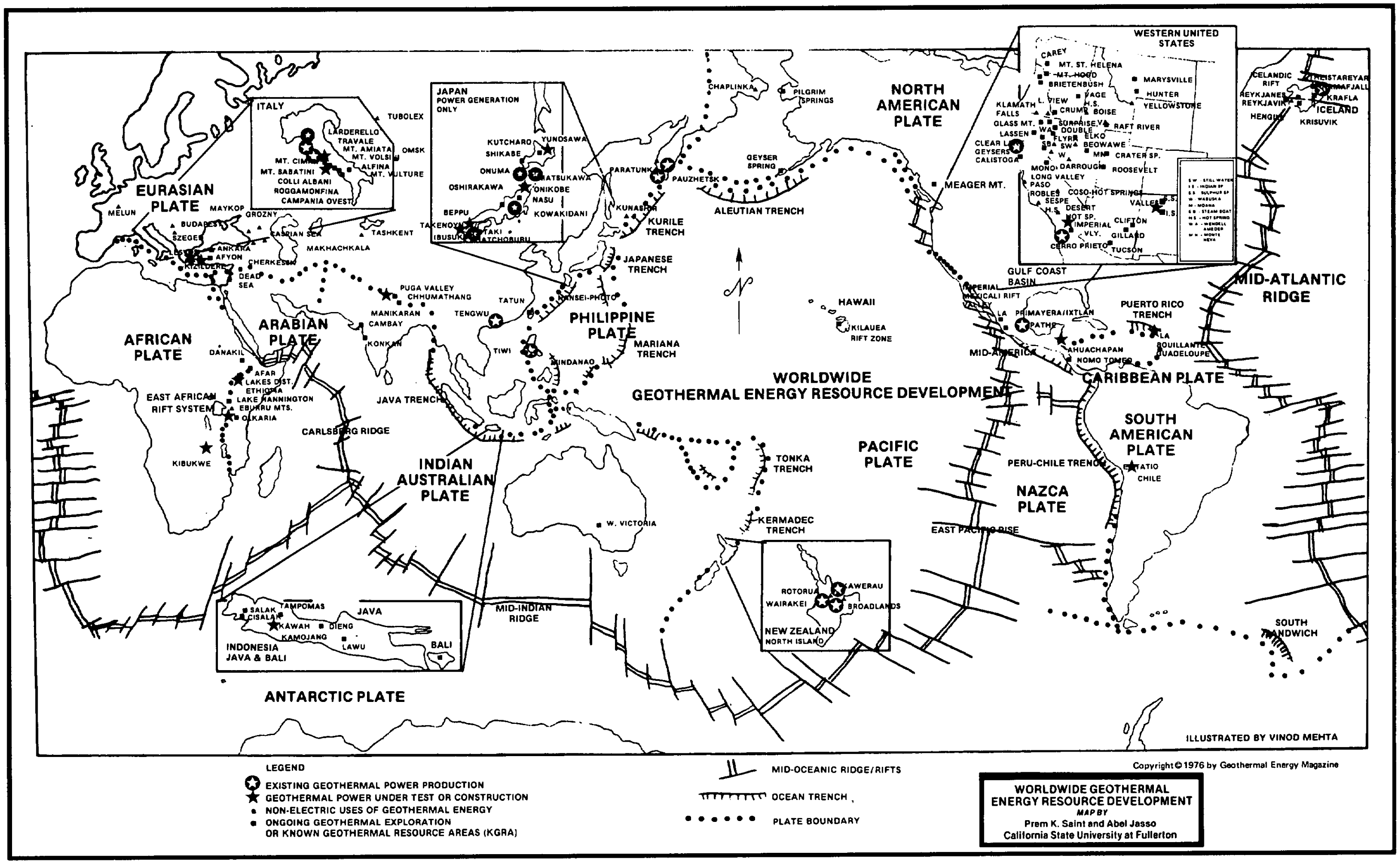


FIGURE 5

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


WORLDWIDE GEOTHERMAL ENERGY RESOURCE DEVELOPMENT
EURASIAN PLATE
AFRICAN PLATE
ARABIAN PLATE
INDIAN AUSTRALIAN PLATE
PHILIPPINE PLATE
PACIFIC PLATE
NORTH AMERICAN PLATE
SOUTH AMERICAN PLATE
NAZCA PLATE
CARIBBEAN PLATE
ANTARCTIC PLATE
MID-ATLANTIC RIDGE
MID-INDIAN RIDGE
CARLSBERG RIDGE
EAST AFRICAN RIFT SYSTEM
JAVA TRENCH
JAPANESE TRENCH
KURILE TRENCH
ALEUTIAN TRENCH
MARIANA TRENCH
TONKA TRENCH
KERMADEC TRENCH
PERU-CHILE TRENCH
PUERTO RICO TRENCH
ITALY
JAPAN POWER GENERATION ONLY
WESTERN UNITED STATES
INDONESIA JAVA & BALI
NEW ZEALAND NORTH ISLAND
ICELAND
HAWAII
KILAUEA RIFT ZONE
ILLUSTRATED BY VINOD MEHTA
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LEGEND
EXISTING GEOTHERMAL POWER PRODUCTION
GEOTHERMAL POWER UNDER TEST OR CONSTRUCTION
NON-ELECTRIC USES OF GEOTHERMAL ENERGY
ONGOING GEOTHERMAL EXPLORATION OR KNOWN GEOTHERMAL RESOURCE AREAS (KGRA)
MID-OCEANIC RIDGE/RIFTS
OCEAN TRENCH
PLATE BOUNDARY
WORLDWIDE GEOTHERMAL ENERGY RESOURCE DEVELOPMENT
MAP BY
Prem K. Saint and Abel Jasso
California State University at Fullerton

FIGURE 4

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.

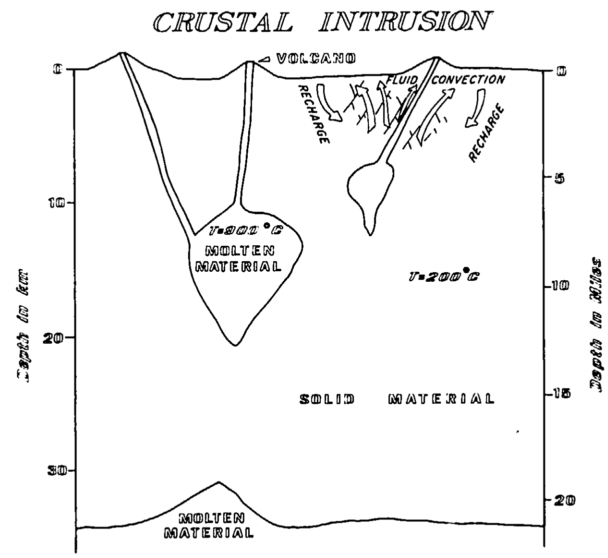


FIGURE 6

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

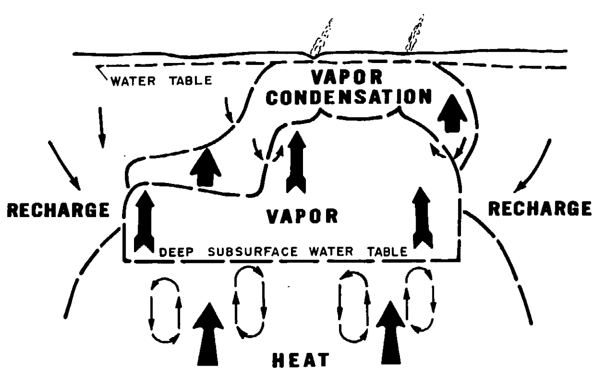


FIGURE 7

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

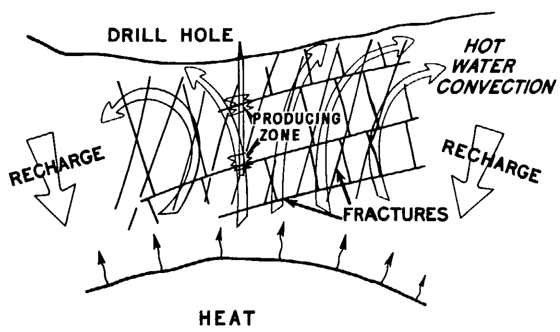


FIGURE 8

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.

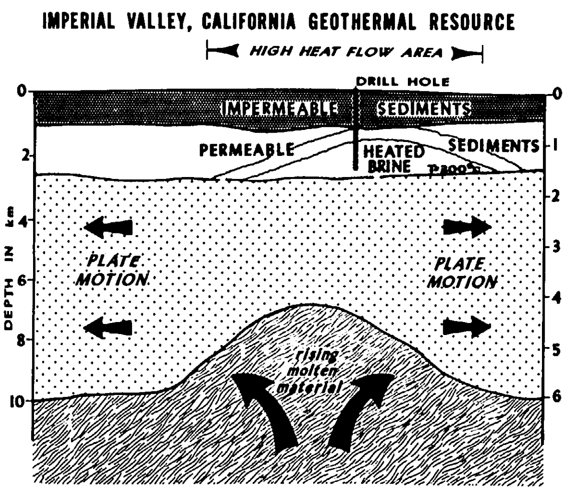


FIGURE 9

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.

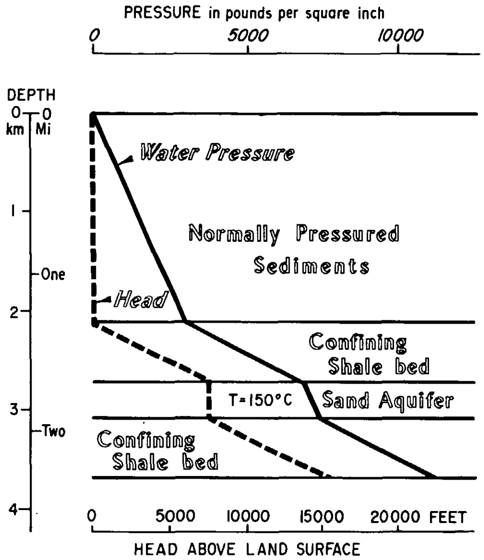


FIGURE 10

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

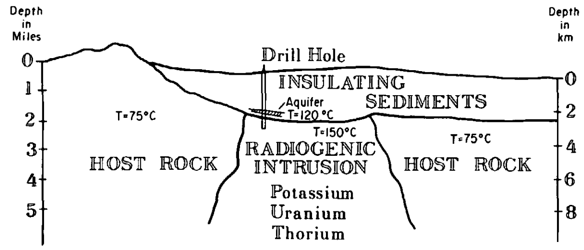
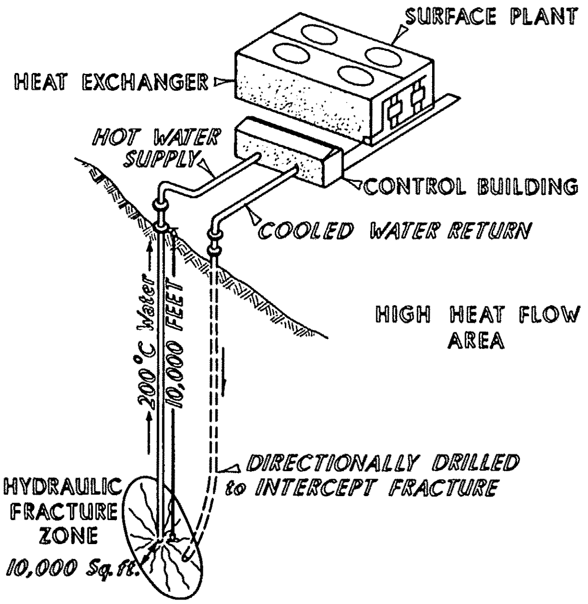


FIGURE 11

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 alkaline. 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

Preparation of this paper resulted from work funded under Contract DE-AC07-78ET-28392 from the Department of Energy to the University of Utah. Typing was done by Cindy Schouten and the figures were drafted by Doris D. Cullen.

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

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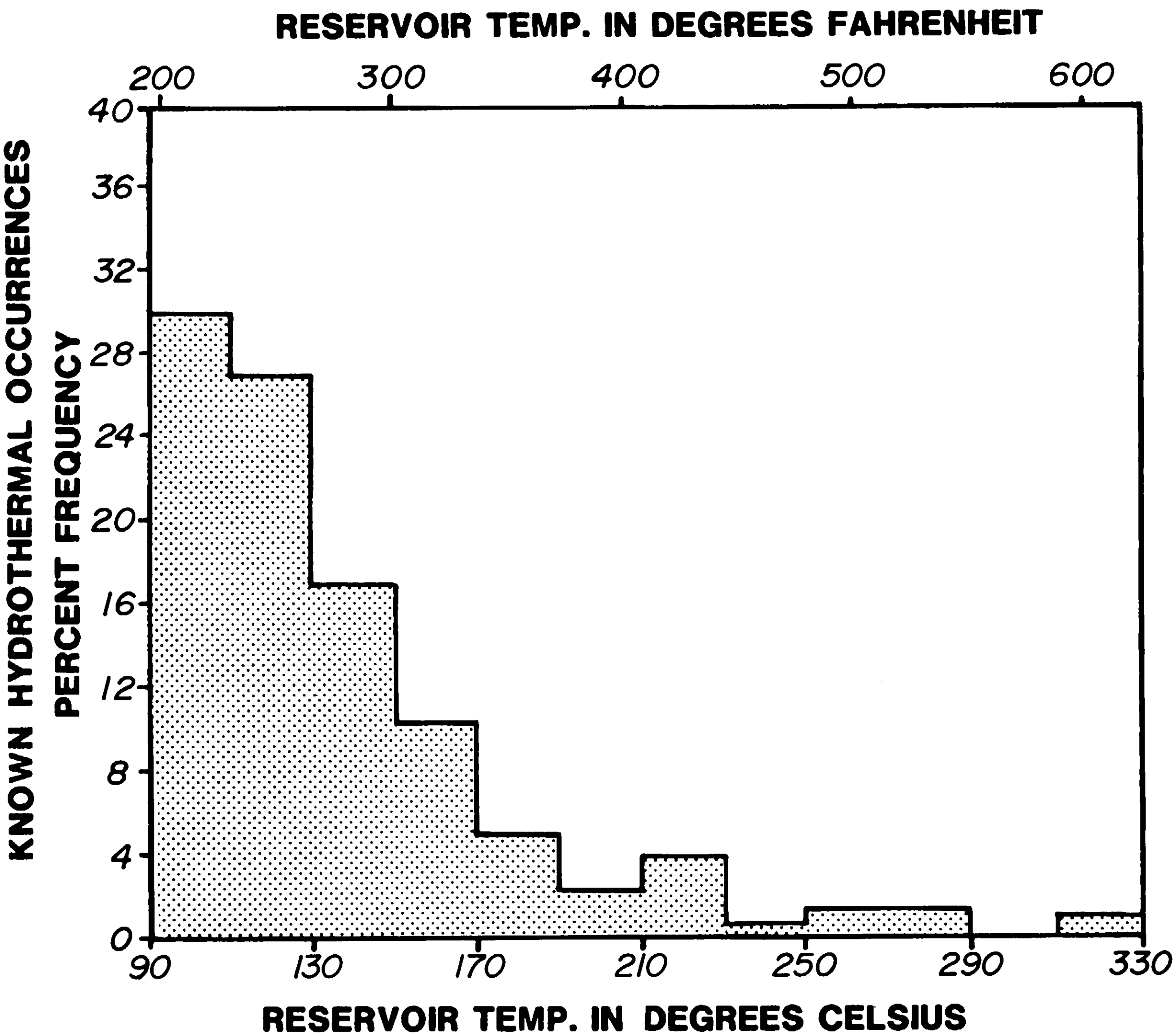
RESERVOIR TEMP. IN DEGREES FAHRENHEIT
200
300
400
500
600
KNOWN HYDROTHERMAL OCCURRENCES
PERCENT FREQUENCY
40
36
32
28
24
20
16
12
8
4
0
90
130
170
210
250
290
330
RESERVOIR TEMP. IN DEGREES CELSIUS

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	?	?	?

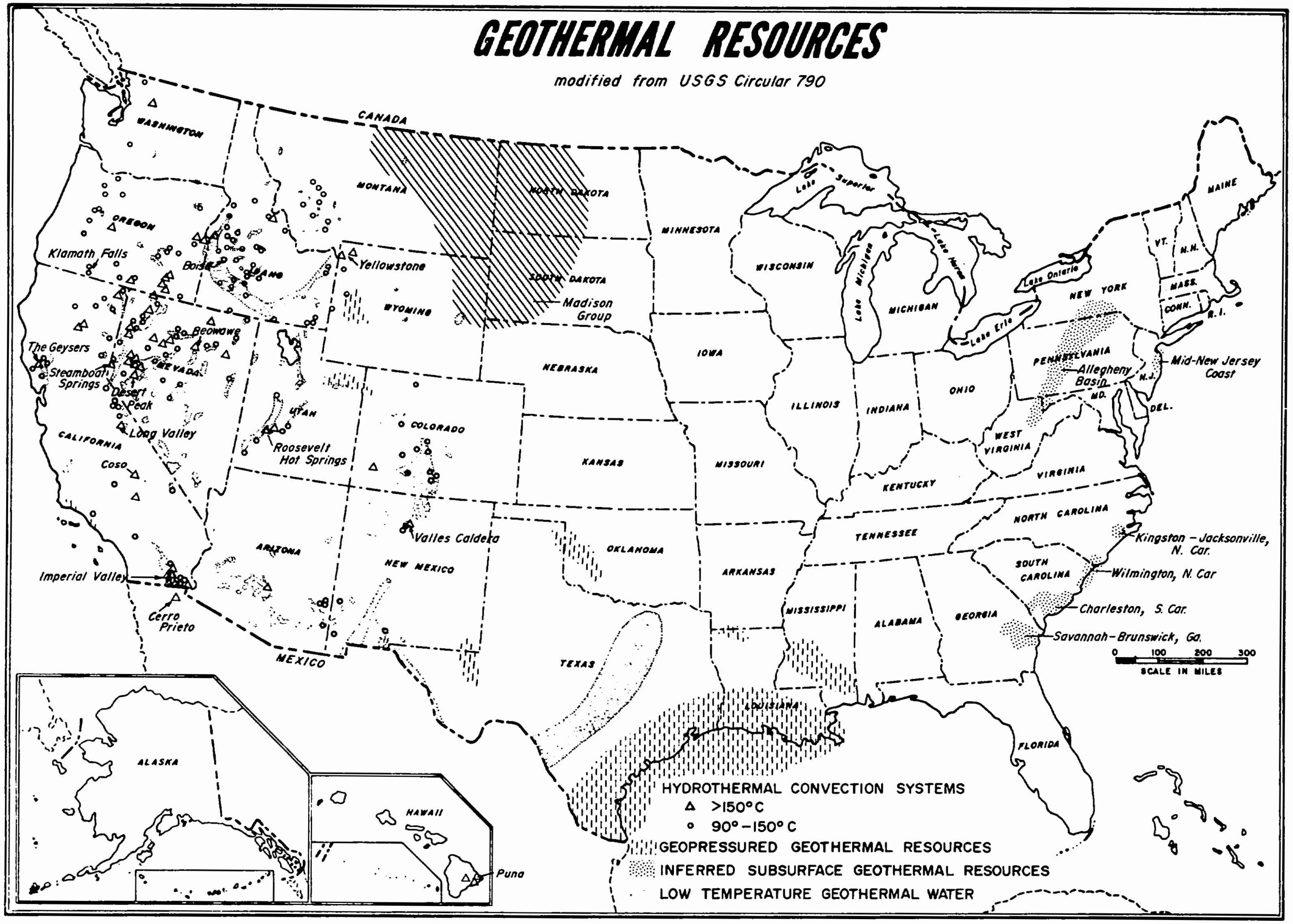
GEOTHERMAL RESOURCES
modified from USGS Circular 790
CANADA
MEXICO
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
OHIO
KENTUCKY
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
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