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).

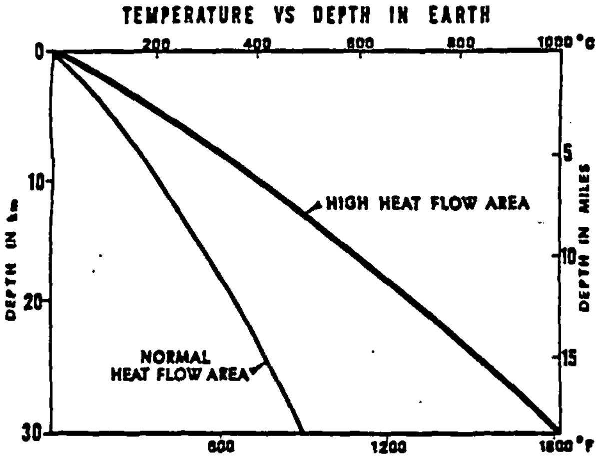


FIGURE 1

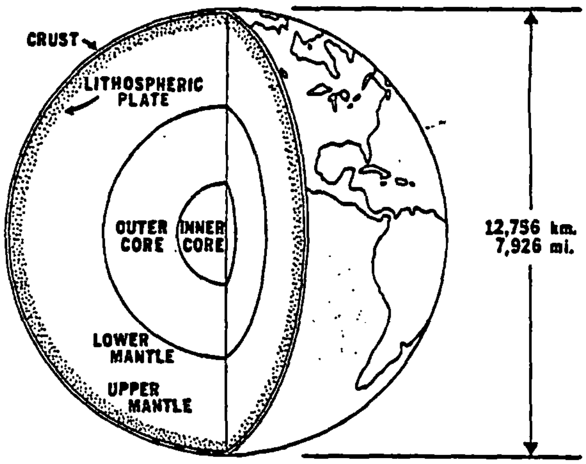


FIGURE 2

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.

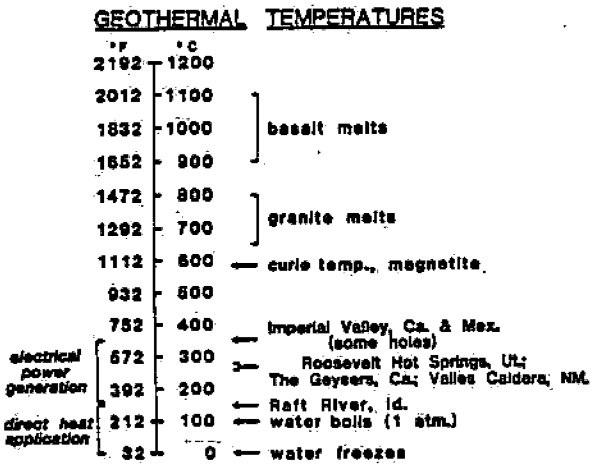


FIGURE 3

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).

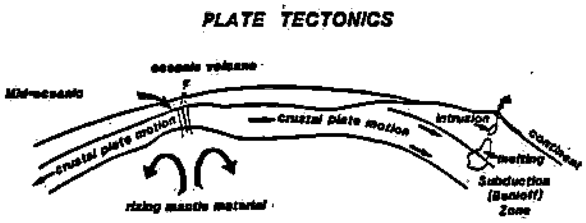


FIGURE 5

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

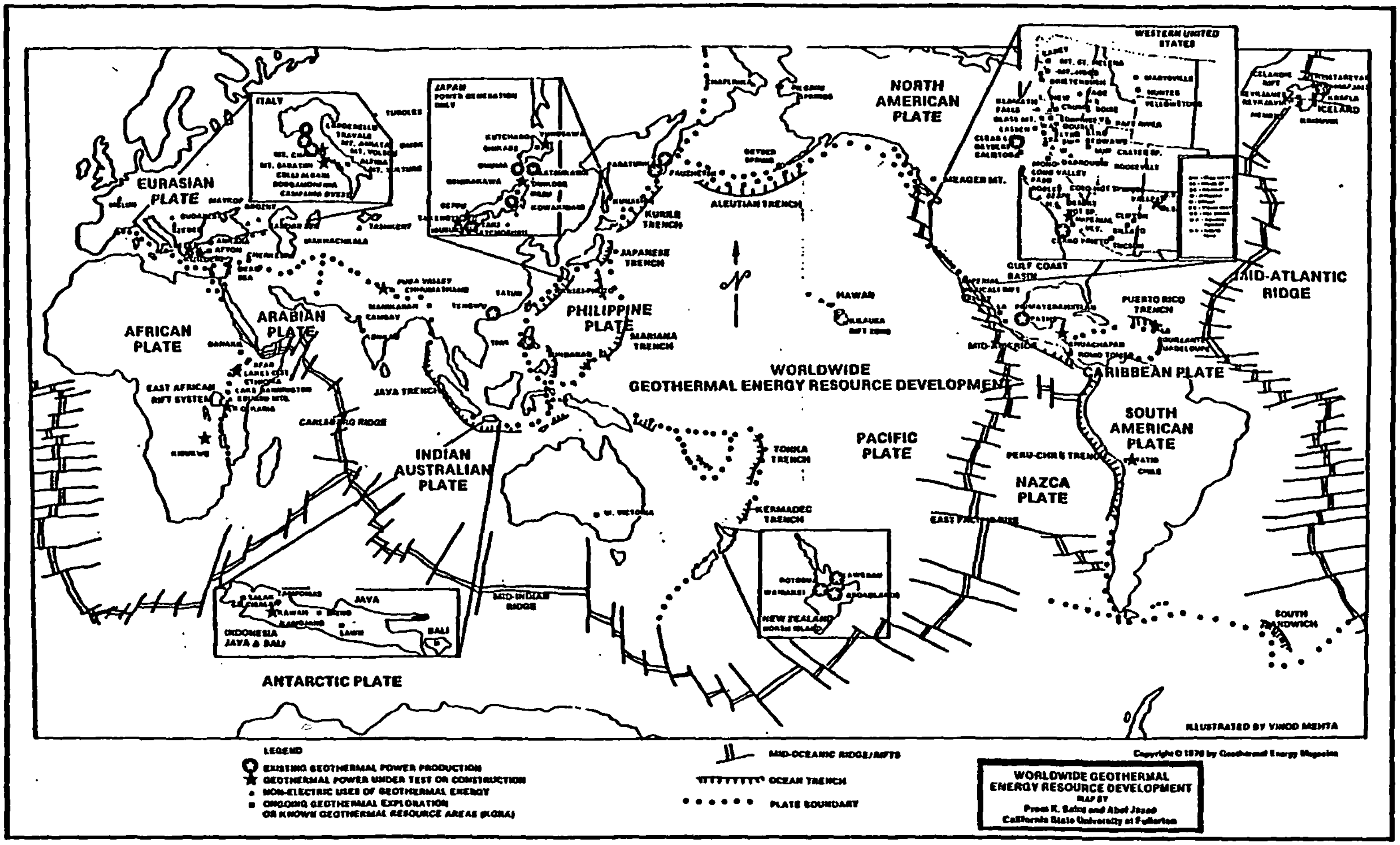


FIGURE 4

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.

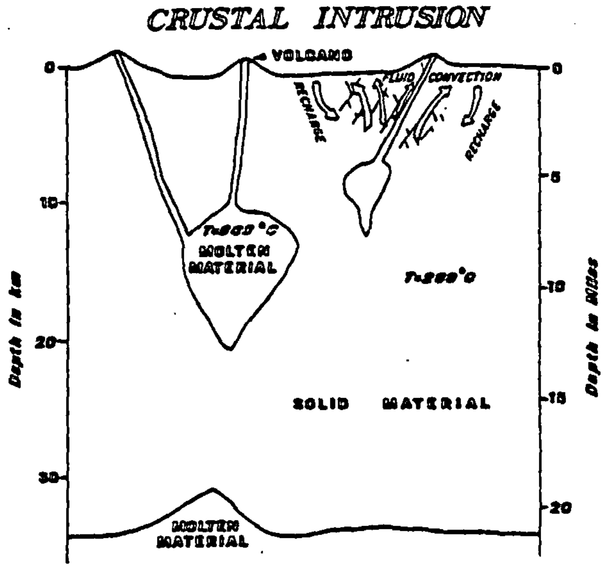


FIGURE 6

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

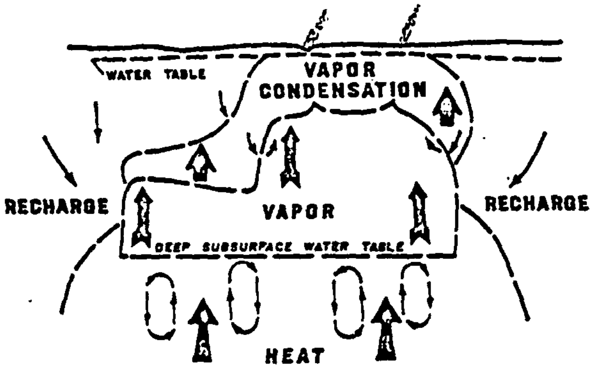


FIGURE 7

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

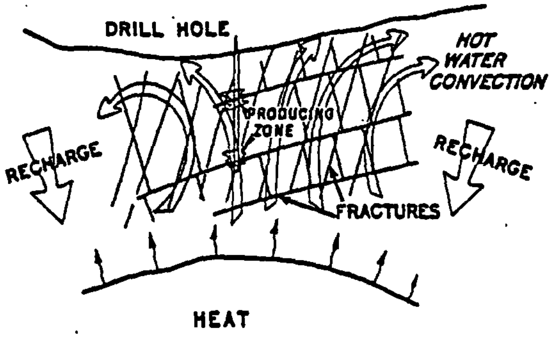


FIGURE 8

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.

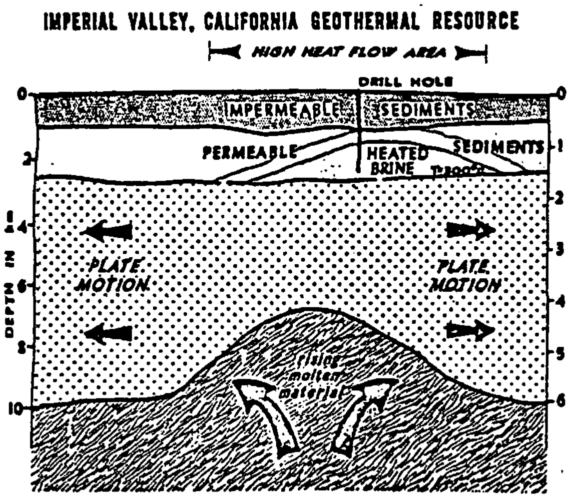


FIGURE 9

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.

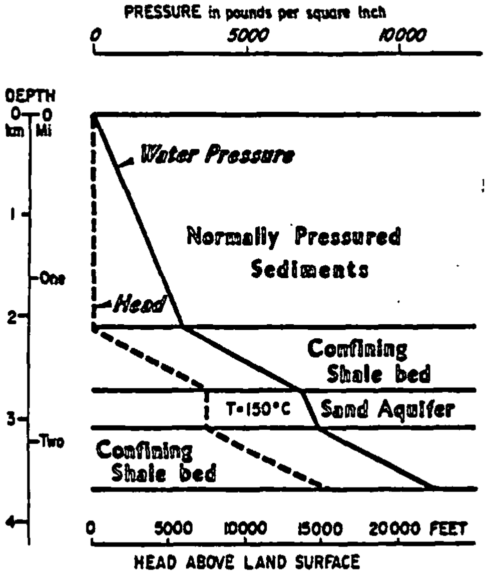


FIGURE 10

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

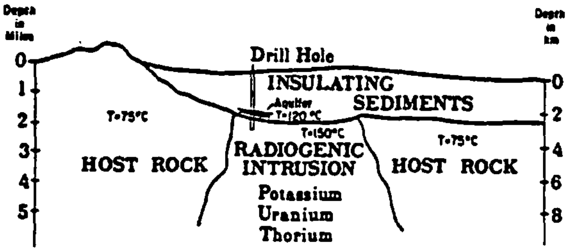
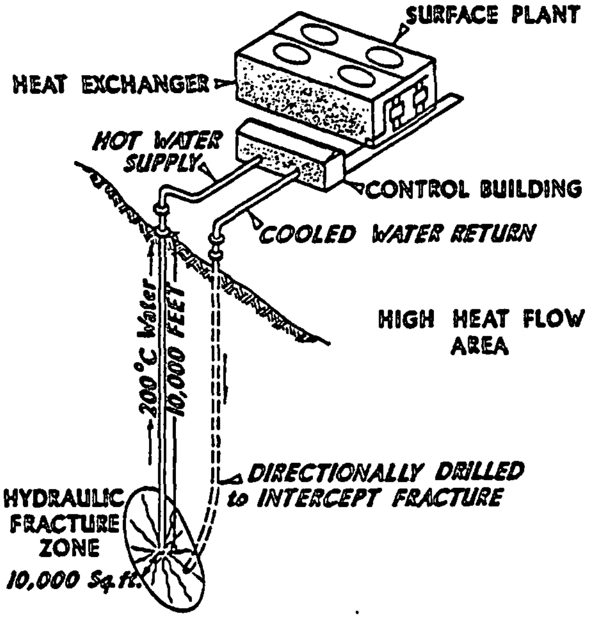


FIGURE 11

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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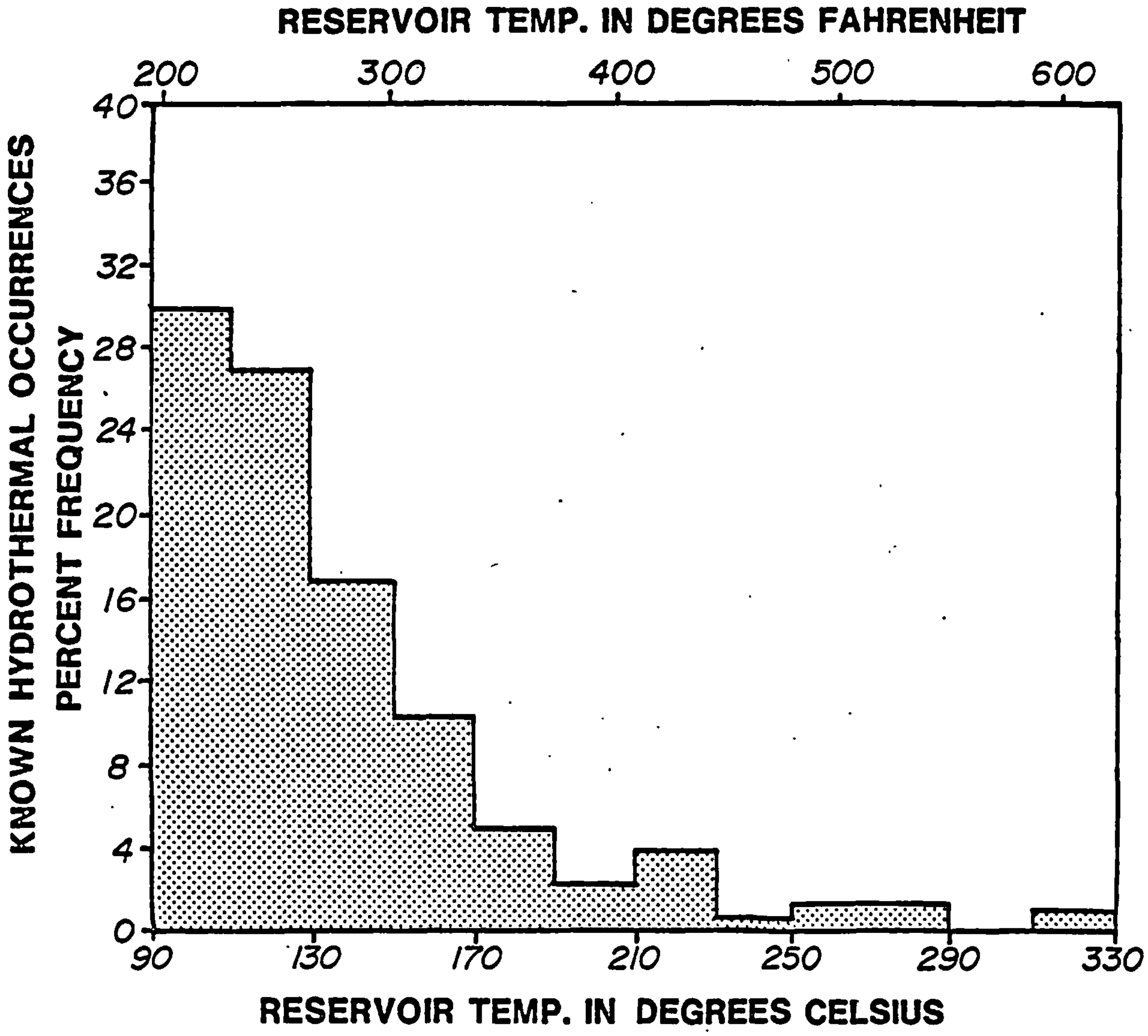
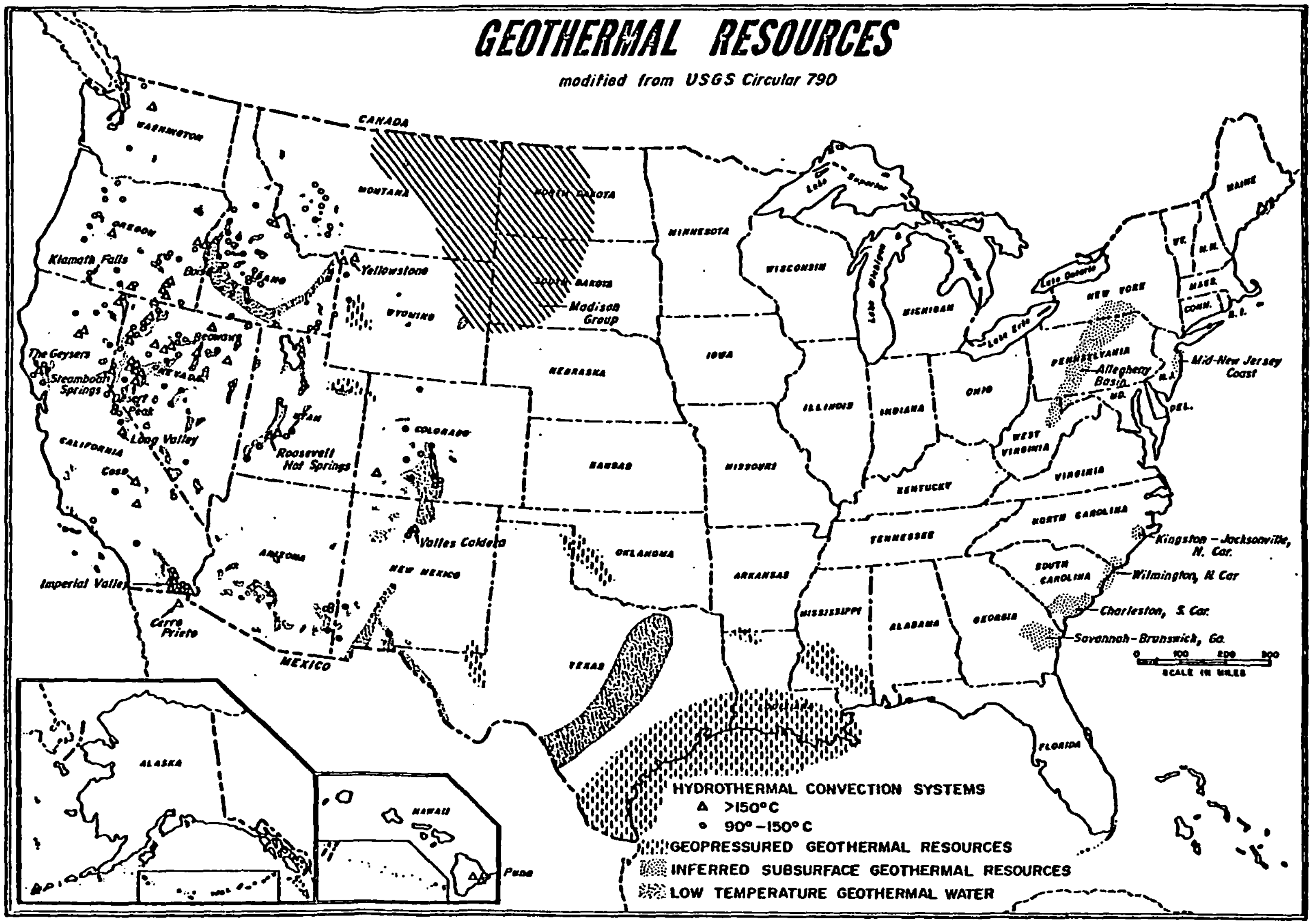

RESERVOIR TEMP. IN DEGREES FAHRENHEIT
200
300
400
500
600
KNOWN HYDROTHERMAL OCCURRENCES
PERCENT FREQUENCY
40
36
32
28
24
20
16
12
8
4
0
90
130
170
210
250
290
330
RESERVOIR TEMP. IN DEGREES CELSIUS

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

FIGURE 14

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NATURE AND OCCURRENCE OF GEOTHERMAL RESOURCES IN THE UNITED STATES

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INTRODUCTION

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

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

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

THE EARTH'S INTERNAL HEAT

Although the distribution with depth in the earth of density, pressure and other related physical parameters is well known, the temperature distribution is extremely uncertain. We do know that temperature within the earth increases with increasing depth (Fig. 1) at least for the first few tens of kilometers, and we hypothesize a steadily increasing temperature to the earth's center. Plastic or partially molten rock at estimated temperatures between 700°C and 1200°C is postulated to exist everywhere beneath the earth's surface at depths of 100 km, and the temperature at the earth's center, nearly 6400 km deep, may be more than 4000°C. Using present technology and under good conditions, holes can be drilled to depths of about 10 km, where temperatures range upward from about 150°C in areas underlain by cooler rocks to perhaps 600°C in exceptional areas.

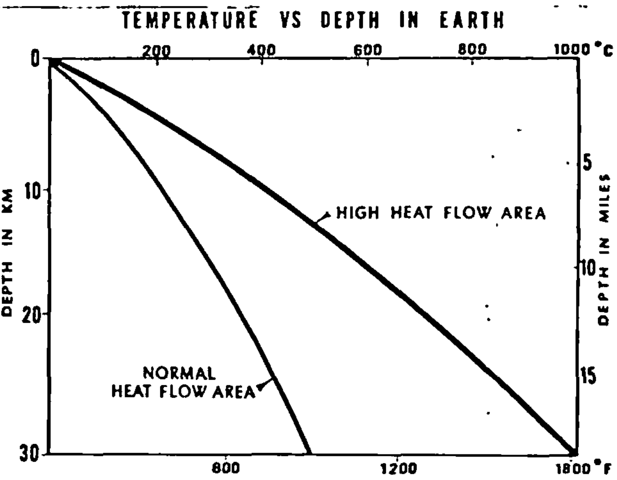


Figure 1

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

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

INTERIOR OF THE EARTH

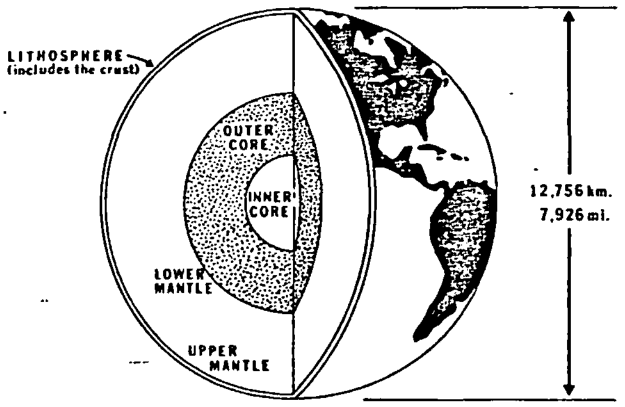


Figure 2

GEOLOGICAL PROCESSES

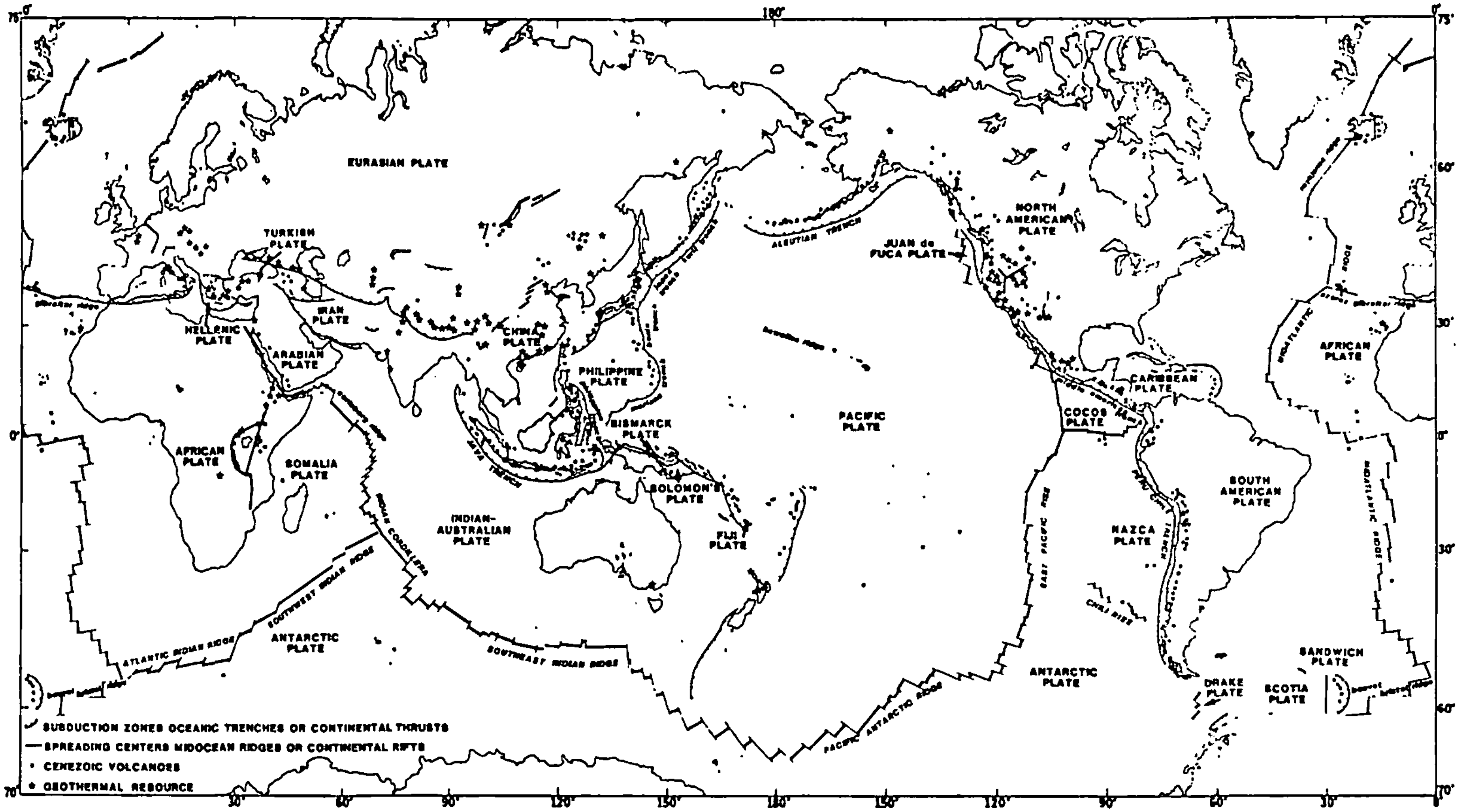
Geothermal resource areas, or geothermal areas for short, are generally those in which higher temperatures are found at shallower depths than is normal. This condition usually results from either 1) intrusion of molten rock to high levels in the earth's crust, 2) higher-than-average flow of heat to the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

Wright

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

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

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

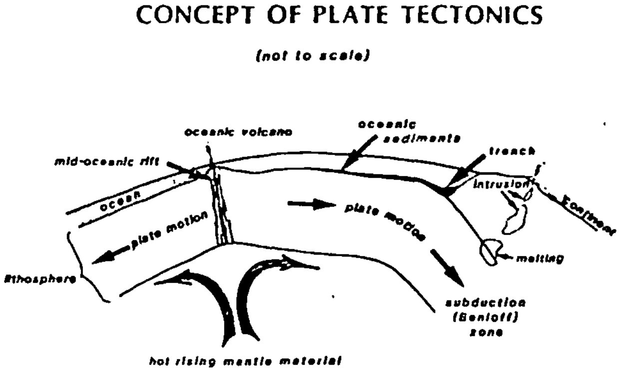


Figure 4

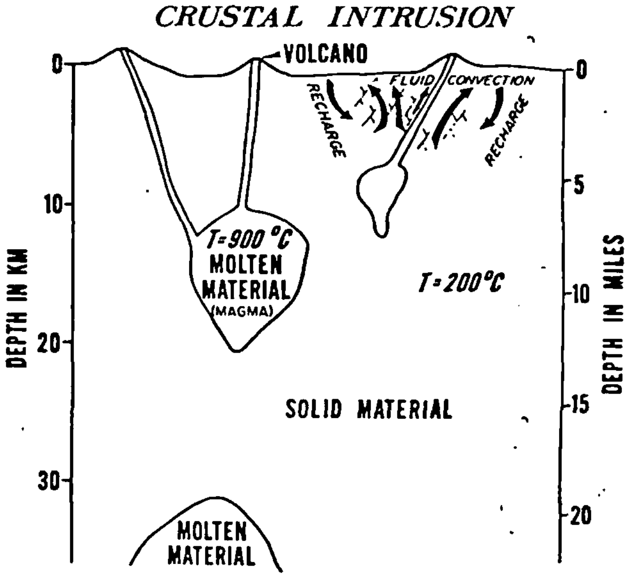


Figure 5

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

Volcanic rocks that have been extruded at the surface and crystalline rocks that have cooled at depth are known collectively as igneous rocks. They vary over a range of chemical and mineral composition. At one end of the range are rocks that are relatively poor in silica (SiO_2 about 50%) and relatively rich in iron (Fe_2O_3 + FeO about 8%) and magnesium (MgO about 7%). The volcanic variety of this rock is basalt and an example is the black rocks of the Hawaiian Islands. The crystalline, plutonic variety of this rock that has consolidated at depth is known as gabbro. At the other end of the range are rocks that are relatively rich in silica (SiO_2 about 64%) and poor in iron (Fe_2O_3 + FeO about 5%) and magnesium (MgO about 2%). The volcanic variety of this rock, rhyolite, is usually lighter in color than the black basalt and it occurs mainly on land. The plutonic variety of this rock is granite, although the term "granitic" is sometimes used for any crystalline igneous rock. Magmas that result in basalt or gabbro are termed "basic" whereas magmas that result in rhyolite or granite are termed "acidic"; however these terms are misleading because they have nothing to do with the pH of the magma.

The upper portions of the mantle are believed to be basaltic in composition. The great outpourings of basalt seen in places like the Hawaiian Islands and on the volcanic plateaus of the Columbia and Snake rivers (Fig. 16) seem to indicate a more or less direct pipeline from the upper mantle to the surface in places. The origin of granites is a subject of some controversy. It can be shown that granitic magmas could be derived by differential segregation from basaltic magmas. However, the chemical composition of granites is much like the average composition of the continental crust, and some granites probably result from melting of crustal rocks by upwelling basaltic magmas whereas others probably result from differentiation from a basaltic magma. In any case, basaltic magmas are molten at a higher temperature than are granitic magmas (see Fig. 6) and more importantly for our discussion basaltic magmas are less viscous (more fluid) than are granitic magmas. Occurrence of rhyolitic volcanic rocks of very young age (less than 1 million years and preferably less than 50,000 years) is generally taken as a sign of good geothermal potential in an area because presumably a large body of viscous magma may be indicated at depth to provide a geothermal heat source. On the other hand, occurrence of young basaltic magma is not as encouraging because the basalt, being fairly fluid, could simply ascend along narrow conduits from the mantle directly to the surface without need for a shallow magma chamber that would provide a geothermal heat source. In many areas both basaltic and rhyolitic volcanic rocks are present and often the younger eruptions are more rhyolitic, possibly indicating progressive differentiation of an underlying basaltic magma in a chamber like those illustrated in Figure 5.

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

Not all geothermal resources are caused by near-surface intrusion of molten rock bodies. Certain areas have a higher than average rate of increase in temperature with depth (high geothermal gradient) without shallow magma being present. Much of the western United States contains areas that have an anomalously high mean heat flow (100 mwatt/m^2) and an anomalously high geothermal gradient (50°C/km). Geophysical and geological data indicate that the earth's crust is thinner than normal and that the isotherms are upwarped beneath this area. Much of the western U.S. is geologically active, as manifested by earthquakes and active or recently active volcanoes. Faulting and fracturing during earthquakes help to keep fracture systems open, and this allows circulation of ground water to depths of 2 km to perhaps 5 km. Here the water is heated and rises buoyantly along other fractures to form geothermal resources near surface. Many of the hot springs and wells in the western United States and elsewhere owe their origin to such processes.

GEOTHERMAL RESOURCE TYPES

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

All geothermal resources have three common components:

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

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

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

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

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

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

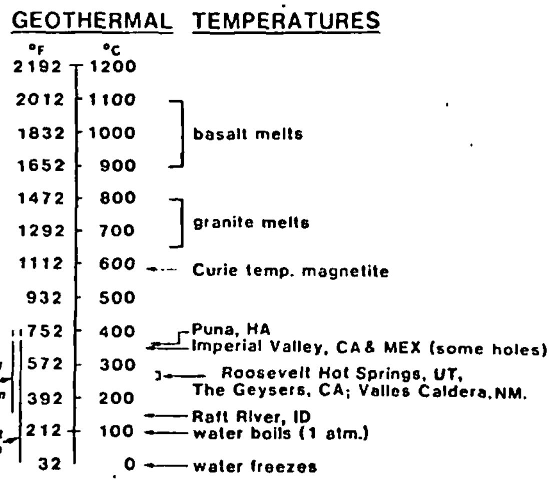


Figure 6

TABLE 1

GEOTHERMAL RESOURCE CLASSIFICATION
(After White and Williams, 1975)

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

Hydrothermal Resources

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

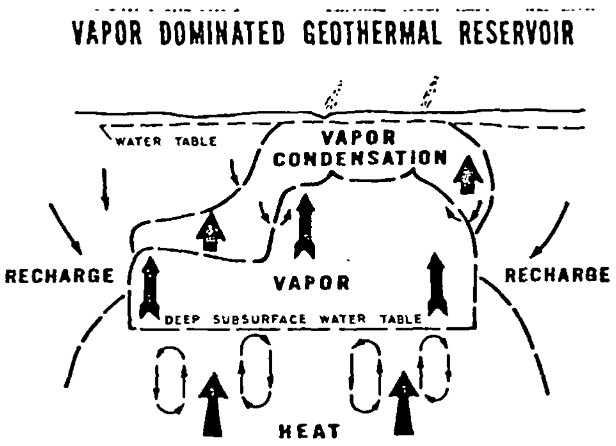


Figure 7

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

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

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

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

Figure 8 schematically illustrates a high-temperature, hot-water-dominated hydrothermal system (Ib(i) of Table I). The source of heat beneath many such systems is probably molten rock or rock that has solidified only in the last few tens of thousands of years, lying at a depth of perhaps 3 to 10 km. Normal ground water circulates in open fractures and removes heat from these deep, hot rocks by convection. Fluid temperatures are uniform over large volumes of the reservoir because convection is rapid. Recharge of cooler ground water takes place at the margins of the system through circulation down fractures. Escape of hot fluids at the surface is often minimized by a near-surface sealed zone or cap-rock formed by precipitation from the geothermal fluids of minerals in fractures and pore spaces. Surface manifestations of such a geothermal system might include hot springs, fumaroles, geysers, thermal spring deposits, chemically altered rocks, or alternatively, no surface manifestation may occur at all. If there are no surface manifestations, discovery is much more difficult and requires sophisticated geology, geophysics, geochemistry and hydrology. A well drilled into a water-dominated geothermal system would likely encounter tight, hot rocks with hot water inflow from the rock into the well bore mainly along open fractures. Areas where different fracture sets intersect may be especially favorable for production of large volumes of hot water. For generation of electrical power a portion of the hot water produced from the well is allowed to flash to steam within the well bore or within surface equipment as pressure is reduced, and the steam is used to drive a turbine generator.

WATER DOMINATED GEOTHERMAL SYSTEM

FLOW CONTROLLED BY FRACTURES

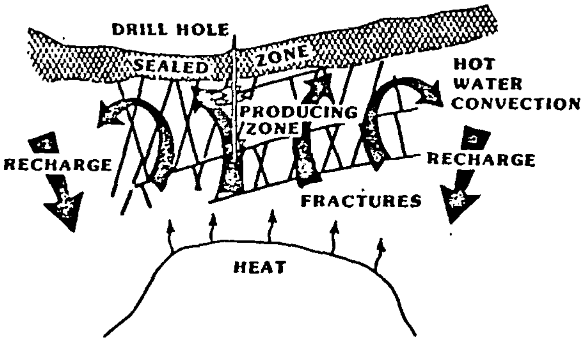


Figure 8

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

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

IMPERIAL VALLEY, CALIFORNIA GEOTHERMAL RESOURCE

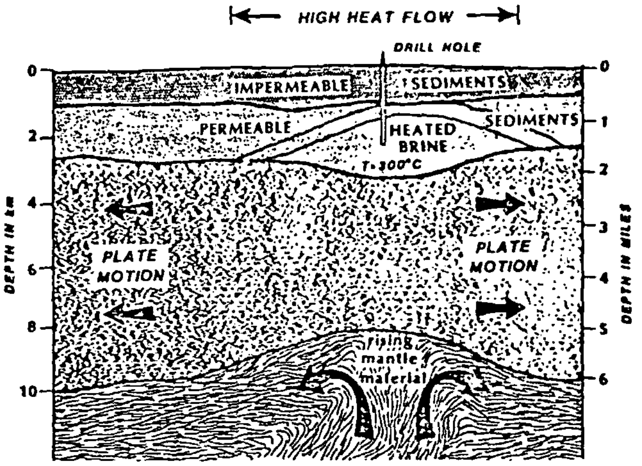
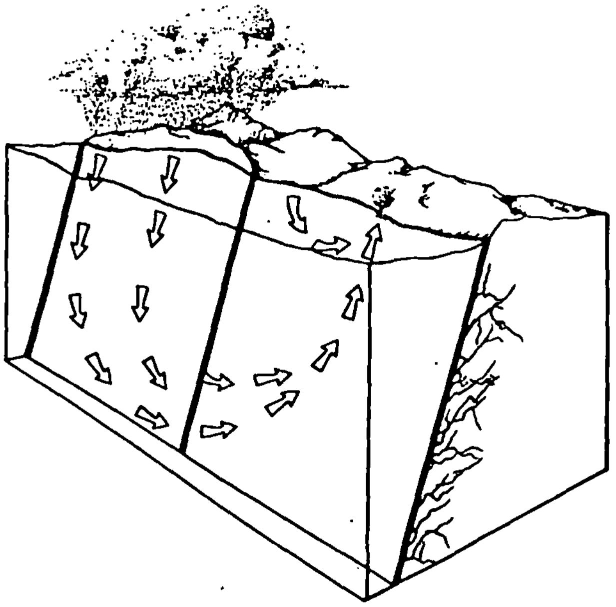


Figure 9

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

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



MODEL OF DEEP CIRCULATION HYDROTHERMAL RESOURCE

Figure 10

Sedimentary Basins

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

Geopressured Resources

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

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

GEOPRESSURED GEOTHERMAL RESOURCE

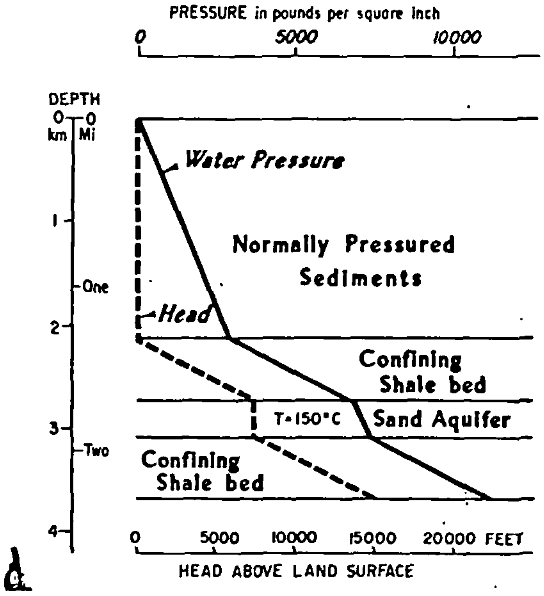


Figure 11

Radiogenic Resources

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

RADIOGENIC GEOTHERMAL RESOURCE

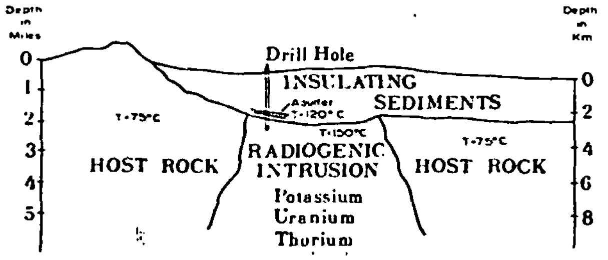
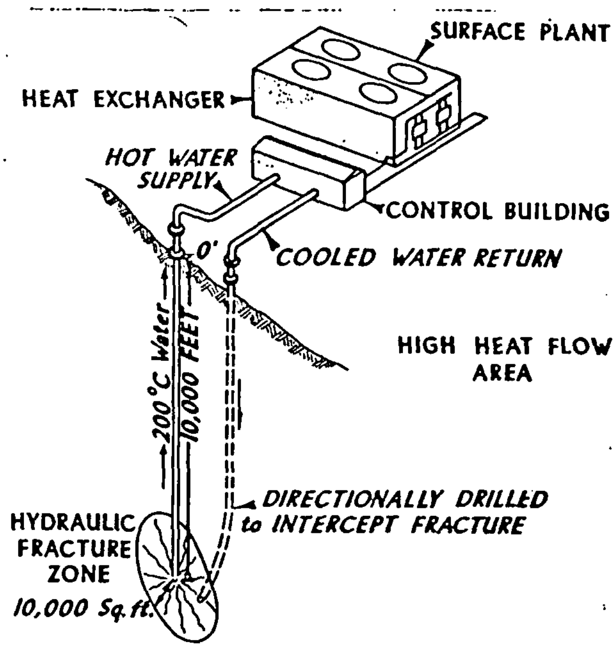


Figure 12

Hot Dry Rock Resources

Hot dry rock resources (2b of Table 1) are defined as heat stored in rocks within about 10 km of the surface from which the energy cannot be economically extracted by natural hot water or steam. These hot rocks have few pore spaces or fractures, and therefore contain little water. The feasibility and economics of extraction of heat for electrical power generation and direct uses from hot dry rocks is presently the subject of intensive research at the U.S. Department of Energy's Los Alamos National Laboratory in New Mexico (Smith et al., 1975; Tester and Albright, 1979). Their work indicates that it is technologically feasible to induce an artificial fracture system in hot, tight crystalline rocks at depths of about 3 km through hydraulic fracturing from a deep well. Water is pumped into a borehole under high pressure and is allowed access to the surrounding rock through a packed-off interval near the bottom. When the water pressure is raised sufficiently, the rock cracks to form a fracture system that usually consists of one or more vertical, planar fractures. After the fracture system is formed, its orientation and extent are mapped using geophysical techniques. A second borehole is sited and drilled in such a way that it intersects the fracture system. Water can then be circulated down the deeper hole, through the fracture system where it is heated, and up the shallower hole (Fig. 13). Fluids at temperatures of 150°C to 200°C have been produced in this way from boreholes at the Fenton Hill experimental site near the Valles Caldera, New Mexico. Much technology development remains to be done before this technique will be economically feasible.



HOT DRY ROCK GEOTHERMAL RESOURCE

Figure 13

Molten Rock

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

HYDROTHERMAL FLUIDS

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

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

GEOLOGY OF THE CONTINENTAL UNITED STATES

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

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

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

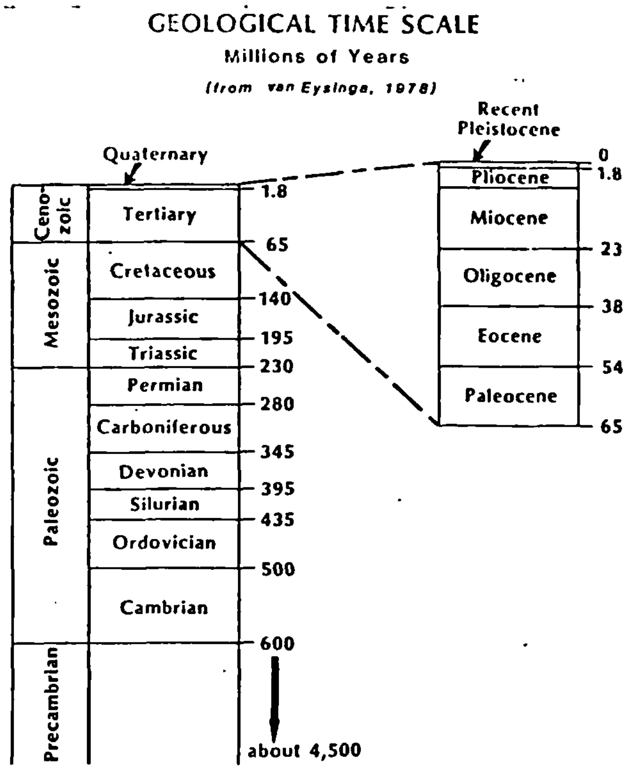

GEOLOGICAL TIME SCALE
Millions of Years
(from van Eysinga, 1978)

Figure 14

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

Canadian Shield

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

Central Stable Region

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

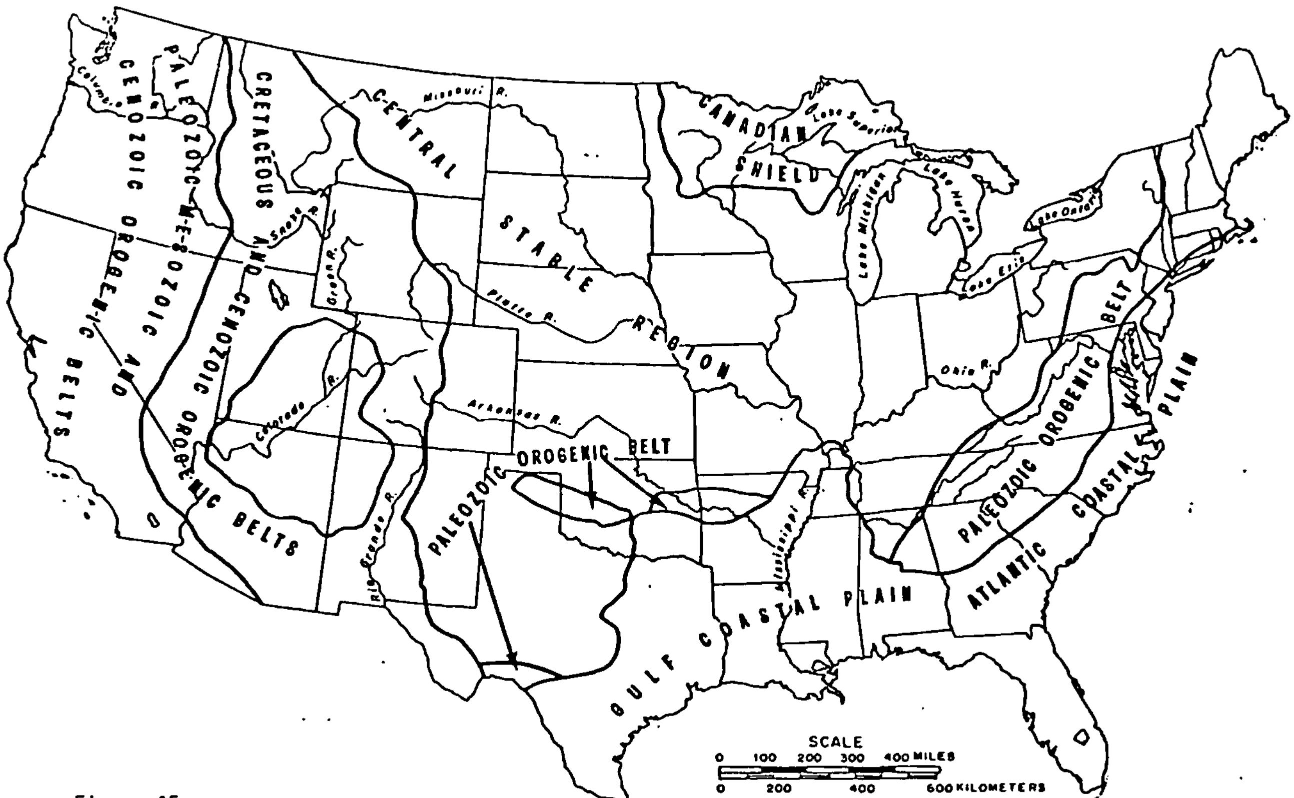


Figure 15

MAJOR TECTONIC DIVISIONS OF USA
(After Eardley, 1951)

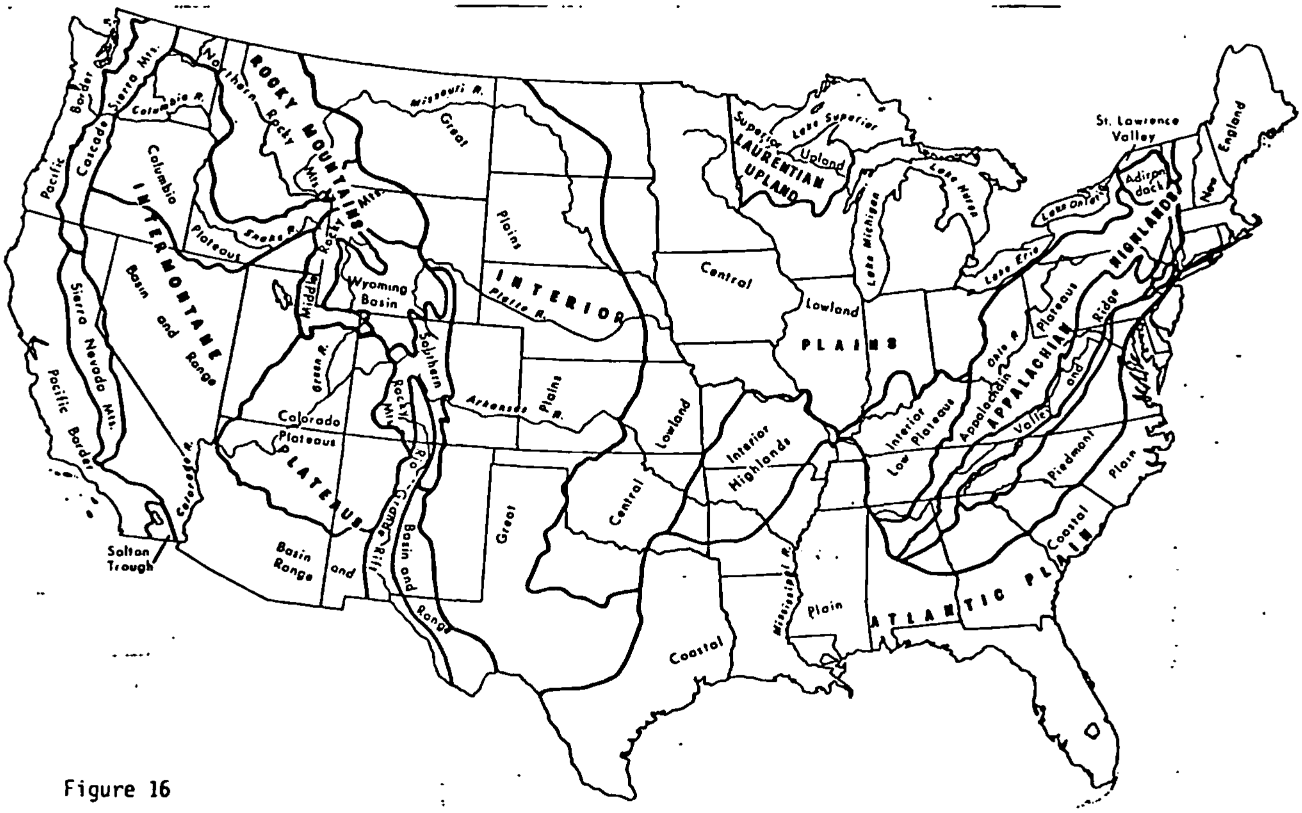


Figure 16

PHYSIOGRAPHIC MAP of USA
(after Fenneman, 1928)

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.

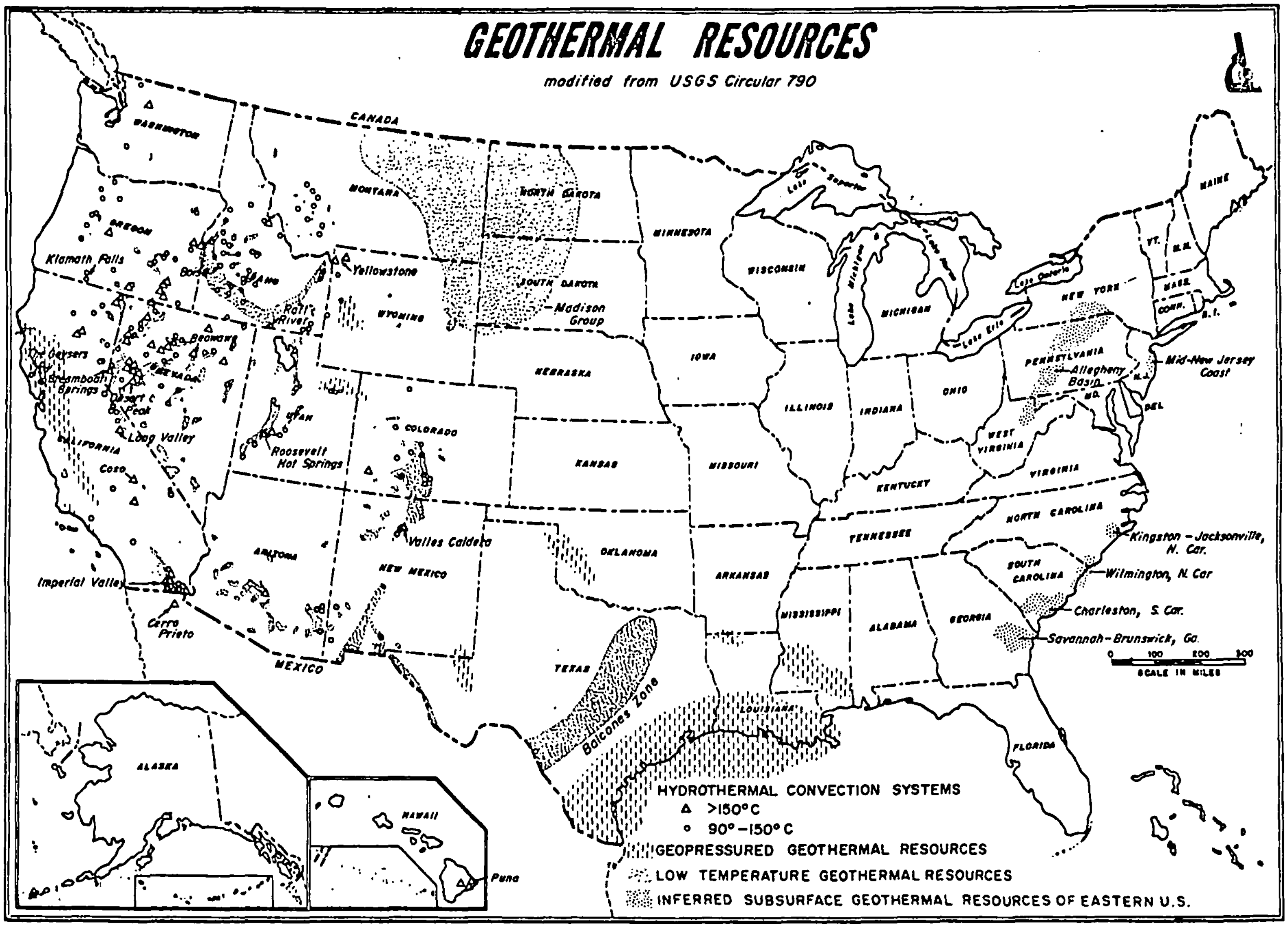
Orogenic Belts of the Rocky Mountains

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
WASHINGTON
OREGON
IDAHO
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
NEVADA
UTAH
COLORADO
CALIFORNIA
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
MAINE
VT.
N.H.
MASS.
CONN.
R.I.
N.J.
DEL.
MD.
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
Klamath Falls
Boise
Raft River
Yellowstone
Madison Group
Geysers
Steamboat Springs
Desert Peak
Beowawe
Long Valley
Coso
Roosevelt Hot Springs
Valles Caldera
Imperial Valley
Cerro Prieto
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
ALASKA
HAWAII
Puna
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

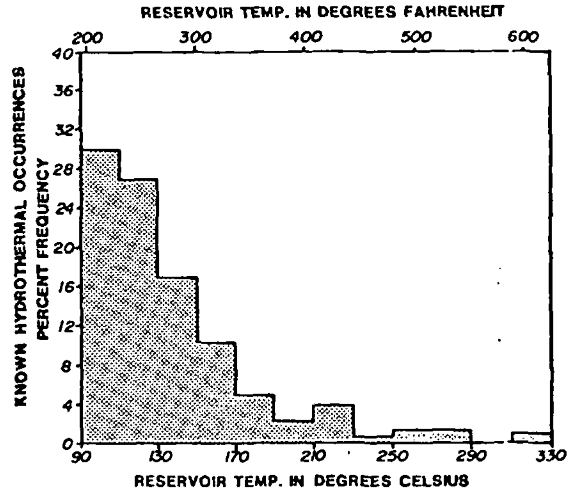


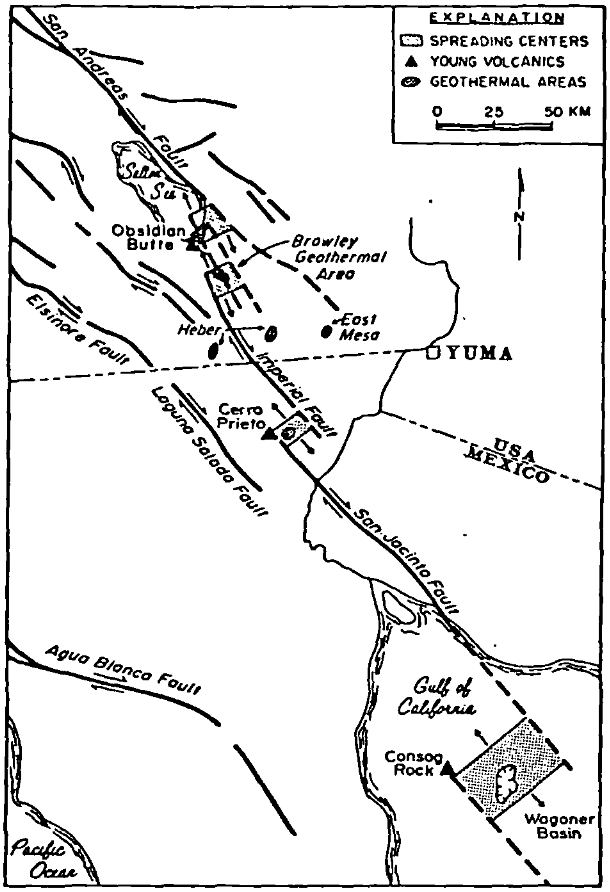
Figure 18

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).

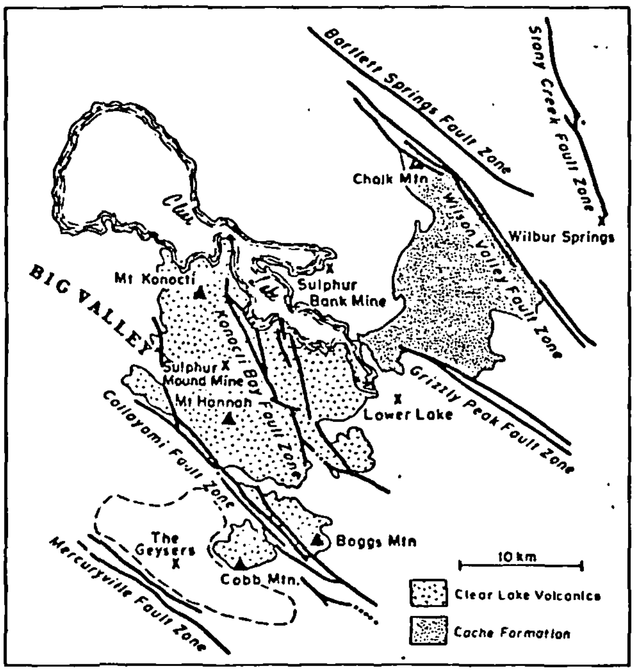
The geothermal fluid from Cerro Prieto, after steam separation, contains about 25,000 ppm total dissolved solids. This figure is much lower than some of the other resources in the Salton Trough. For example, the Salton Sea area contains 20 to 30 percent by weight by solids (Palmer, 1975). Primarily because 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

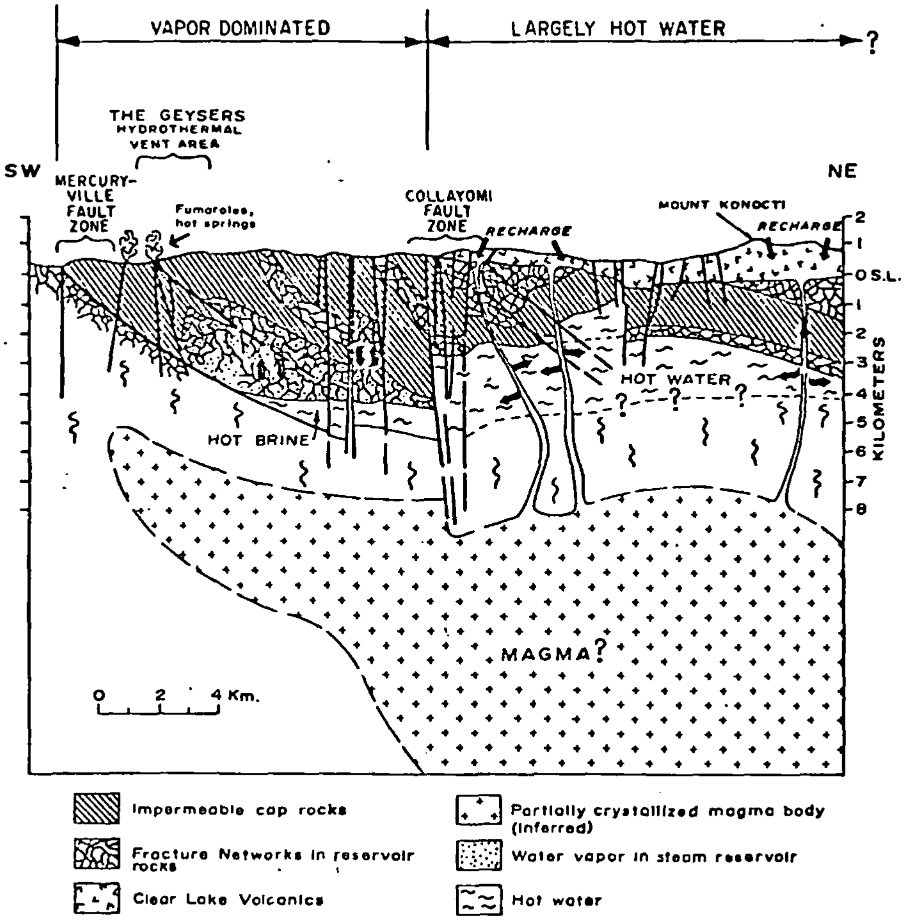
As shown in Figure 20, the presently known steam field is confined between the Mercuryville fault zone on the southwest and the Collayomi Fault zone on the northeast. The northwest and southeast margins are not defintely known. To the east and northeast lies the extensive Clear Lake volcanic field composed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

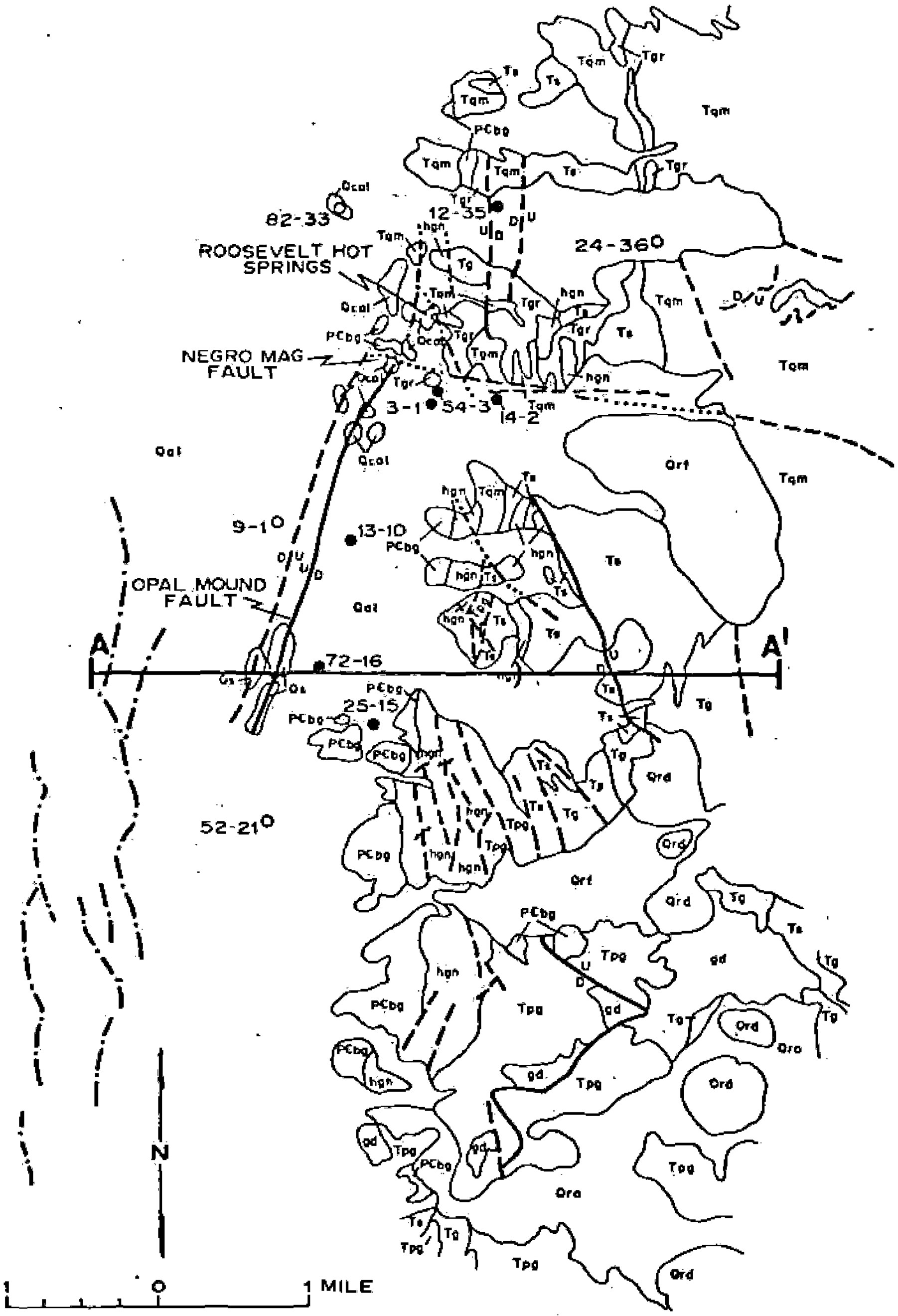
(after McLaughlin, 1977)

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.



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
P€bg - 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)

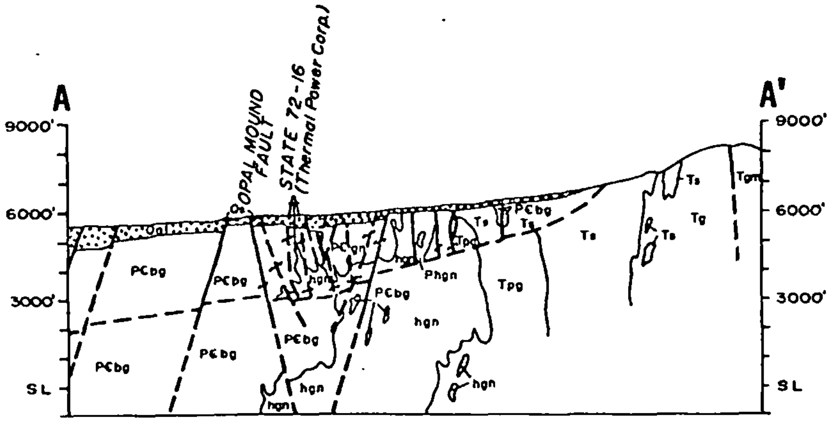


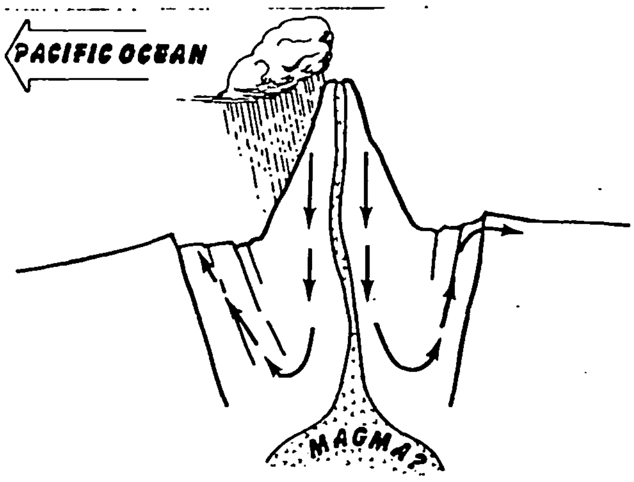
Figure 23

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

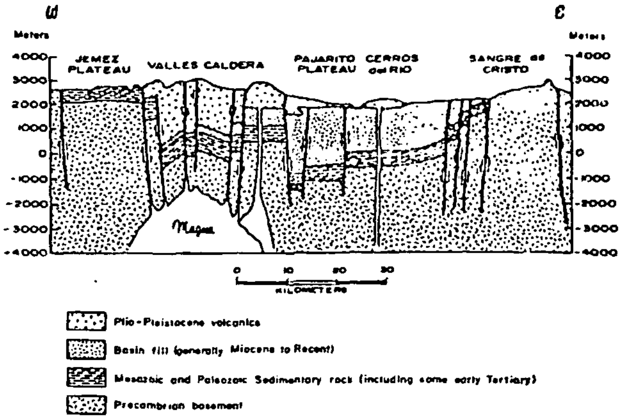
The basalt flows and other volcanic deposits of the Snake River Plain are an extension of the Columbia Plateau eastward across southern Idaho to the border with Wyoming. The plain is divided into a western part and an eastern part. Thermal waters occur in numerous wells and springs in the western portion,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

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Abstract—Analyses of waters from many New Zealand hydrothermal areas (both volcanic and non-volcanic) are presented for discussion. The natural hot-water compositions are compared with those resulting from the experimental interaction of water at 150–350°C with volcanic rocks and a greywacke from the central part of the North Island of New Zealand. Appreciable quantities of the minor components Cl, B, F, As and NH_3 were liberated into solution from the rocks along with silica and alkalis. The ease of solution of the former group of elements, the kinetics of solution, and the slight degree of rock alteration, showed that they existed to a large extent on surfaces in the rocks (particularly for crystalline rocks) rather than in silicate structures.

It appears that volcanic thermal water compositions could be approached in nature by the reaction of high-temperature water with rock, without requiring a contribution from a "magmatic" fluid rich in the typical hydrothermal phase elements. It would be difficult to define the so-called "magmatic" solutions supposedly involved in the genesis of volcanic hydrothermal systems, as key elements such as lithium, caesium, chloride and boron would at equilibrium be concentrated into a hot-water phase interacting with either crystalline silicates or a rock melt. Preliminary experimental work at 500–600°C adds support to this suggestion.

The composition of solutions obtained from the interaction of greywacke and water was of similar type to that of warm springs occurring in this rock.

INTRODUCTION

HOT-SPRING areas occur in many regions of the world and several have been described in detail, e.g. Yellowstone Park U.S.A. by ALLEN and DAY (1935), Iceland by BARTH (1950), Kamchatka U.S.S.R. by PIIP (1937), and the North Island of New Zealand by WILSON (1961). WHITE (1957a, b) presented a general discussion on thermal waters and of the mechanisms that could lead to their formation. He reviewed the range of chemical compositions of thermal waters found in various parts of the world, and suggested tentative chemical criteria that could be used to distinguish waters of volcanic, metamorphic or connate origin.

Both the temperature and composition of thermal waters vary widely. The temperature of surface springs ranges from a few degrees above mean atmospheric temperatures up to the boiling point of water for the local atmospheric pressure. Drill-holes in many volcanic thermal regions reveal temperatures higher than are found in the surface springs, and the maximum temperature found to date was over 300°C in a hole drilled to 5230 ft in Imperial Valley, California. In the hot waters, the concentration of dissolved material ranges from a few hundred parts per million, up to the concentrated 30% brine obtained from the Imperial Valley drill-hole (WHITE, ANDERSON and GRUBBS, 1963).

The source of the waters, the origin of the heat, the mechanism of heat transfer to the water and the source of the dissolved chemicals have been the objects of discussion in many papers over the last 100 years. Agreement has been reached on many points, particularly on the predominance of local meteoric water in volcanic hydrothermal systems. A major point of controversy is the amount, if any, of water from a "magmatic" source present in these systems, and whether the dissolved material in the thermal waters and some of their heat content is derived from such a source. Early viewpoints of workers such as Suess (1903), that volcanic spring waters were almost entirely magmatic fluids are untenable when evidence from deuterium and O^{18} determinations (Craig, Boato and White, 1956) are taken into consideration. These investigators showed that the volcanic thermal waters in general had isotopic compositions similar to the local surface waters. The possibility that 5–10 per cent of another type of water was present could not however be disregarded.

For high-temperature volcanic hydrothermal systems, difficulties are experienced in proposing simple convective models in which all the heat is derived by conduction from hot rock. It is difficult to maintain sufficient heat transfer over the life of a hydrothermal system because of the low thermal conductivity of rock. To overcome this difficulty, additional postulates must be made, such as a short period of flow following the heating of a stored body of water or convection within a molten magma and heat transfer to water across a thin solidified rock zone. The addition of "magmatic" water is often suggested as an extra supply of heat, which would at the same time explain the chemical composition of the hot waters. The concept that meteoric waters are heated by both conduction and magmatic steam from a molten rock intrusion to produce thermal waters (often at 200–300°C) has been used by several recent authors including White (1957a), Bodvarsson (1961) and one of the present writers (Ellis and Wilson, 1960).

The relatively low-temperature (about 100°C) hydrothermal systems in the Tertiary Basalts of Iceland have been explained satisfactorily by conductive heating alone, and the low concentrations of dissolved chemicals in the waters were assumed to have been derived by solution from the country rock (Einarsson, 1942).

In this paper, attention is focused on the composition of waters found in hydrothermal systems of recent volcanic areas, such as the Taupo Volcanic Zone of the North Island of New Zealand. Three main types of thermal water compositions are found in these areas. The waters described are all from New Zealand, but the types are common to other volcanic zones of the world.

A. Neutral chloride waters with a predominance of sodium and potassium chlorides, close to saturation for their temperature with calcite and silica, and containing also arsenic, boric acid, fluoride, bromide, sulphate, bicarbonate, ammonia, lithium, rubidium and caesium. The chloride/sulphate ratio is high. These waters are found in extensive reservoir systems which extend to deep levels of at least a mile. In the underground systems the hot waters (often 200–300°) contain dissolved gases (mainly carbon dioxide and hydrogen sulphide), the total gas to water proportion being in the range 0·01–0·1 mole per cent. The pH of the deep hot underground water is about neutral compared with that for pure water at the same temperature (pH 5·7 at 260°C), but when the waters reach the surface and lose steam and carbon

dioxide they become slightly alkaline due to the buffering action of the bicarbonate, silicate and borate ions.

B. Acid–sulphate–chloride waters which contain comparable concentrations of chloride and sulphate and are acid (pH 2–5), can originate in two ways.

(1) In a variation of Type-A waters, a high proportion of the associated sulphide has been oxidized at depth to bisulphate ions. Because of the change in acid dissociation constant of the bisulphate ion with temperature, the waters change from hot neutral pH waters underground to cooler acid waters at the surface (Ellis and Wilson, 1962).

(2) In active volcanic areas, high-temperature, low-pressure steam rises from hot rock at a shallow level to condense in surface waters. The thermal waters often contain high fluoride concentrations derived from the hydrogen fluoride in volcanic steam. With a decrease in steam temperature the fluoride, chloride and sulphur gases, in order, decrease in abundance, so that acid–sulphate–chloride–fluoride waters merge into acid–sulphate–chloride waters, then into acid–sulphate waters of class C(2). Many of the constituents in the waters are derived by surface leaching of rocks by the acid solutions containing hydrochloric acid and sulphuric acid from sulphide and sulphur dioxide oxidation.

C. Acid sulphate waters. These are waters low in chloride content, formed, and made acid by the condensation of a low temperature (up to about 250–300°) steam phase in surface waters, and the oxidation of the hydrogen sulphide contained in the steam. They may be found *either* in (1) solfatara areas where steam rises from underlying hot water of Type A or B(1), *or* in (2) areas of surface volcanic activity where in the cooler stages, gases containing mainly carbon dioxide and hydrogen sulphide remain in the vapour phase.

Mixtures of the principal types of water sometimes occur. For example, some acid–sulphate–chloride waters are formed by mixing of Types A- and C(1)-waters in areas where chloride water springs exist close to the outcrop of the water table at the surface and perched acid–sulphate pools occur at higher levels (e.g. in the Waiora Valley near Wairakei). These "mixed" waters are not to be confused with the Type-B waters formed by a different mechanism.

Opinion as to the origin of the chemicals present in the higher-temperature hydrothermal systems (particularly Types A and B(1) which are of greatest importance because of their extent and volume) has alternated between derivation from a magmatic fluid, and from country rock. As elements such as boron, fluorine, lithium, potassium, rubidium and caesium are present in unusually high concentrations in volcanic thermal waters and are known to be concentrated in the residual fluid of a crystallizing rock melt, the theory of a magmatic origin has been supported by most writers since the time of the major researches of Allen and Day (1935) at Yellowstone Park. Little was known of the concentration of many of the elements of interest in the volcanic and associated rocks of the various thermal regions, so that the alternative view of derivation by interaction of hot water with country rock has been largely neglected. The concentration in waters of major rock constituents such as sodium, potassium, calcium and silica have been recognized as being influenced by rock/water interaction (e.g. Fenner, 1936), but elements in minor concentration in average igneous rocks such as chlorine, fluorine, boron and nitrogen have been referred to a deep magmatic fluid without first testing adequately whether they could be derived by simple rock/water interaction at shallow levels. Hague (1911) in early studies at Yellowstone Park presented some analyses to show that constituents in the spring waters were derived from local rocks at shallow levels, but the results were too limited in scope. In this work Hague followed the earlier writings of Bunsen (1847) on investigations of Iceland springs, but these waters are not really comparable to Yellowstone waters because of their lower temperatures and mineral contents. Allen and Day (1935) later wrote that the concentration of elements such as chlorine, fluorine, sulphur and arsenic from rocks into the spring waters was "unthinkable".

It was decided to test by experiment the quantities of various elements which were liberated from rocks typical of the Taupo Volcanic Zone of New Zealand when they were exposed to hot water. Accordingly, eight rocks from this area were reacted with water at temperatures ranging from 150 to 350° and at a pressure of about 500 bar. (A few preliminary runs have also been made at 500–600° and 1000–1500 bar pressure.) The resulting solutions were analysed at intervals of time to see the rate at which the various elements were liberated from the rocks, and to see for each element whether an equilibrium between water and solid was set up, or whether continuous leaching from the rock occurred. The composition of the experimental solutions is compared with that of hot waters of New Zealand hydrothermal areas. Typical analyses of waters from both high-temperature hydrothermal systems and from warm springs are now given for this purpose.

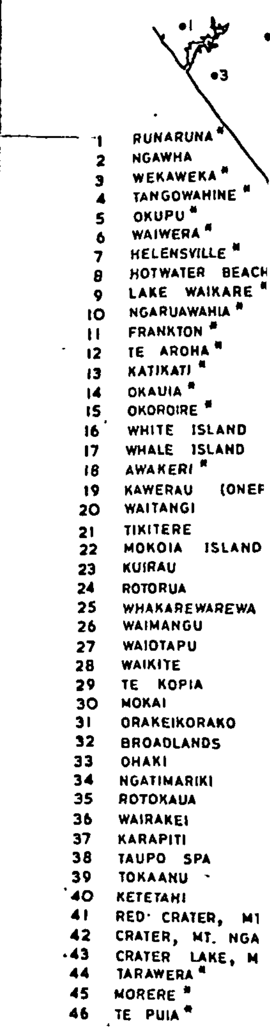
COMPOSITION OF NEW ZEALAND THERMAL WATERS

Areas of active and recent volcanism

Table 1 gives some representative analyses of thermal waters from the Taupo Volcanic Zone of the North Island of New Zealand. Deep drill-holes of 1500–4000 ft depth exist at Wairakei, Waiotapu and Kawerau; Rotorua has shallow holes down to about 800 ft; the remaining representative areas have no existing holes. Figure 1 is a map showing the hydrothermal areas of New Zealand.

(*a*) *Active volcanic areas.* The sample from the 1933 Crater on White Island is an example of a water from an active andesite volcanic crater. It is acid, high in mineral content and contains many constituents leached from the rocks. Steam temperatures up to 570°C have been measured in fumaroles on White Island (unpublished report, Dominion Physical Laboratory, N.Z., D.S.I.R., 1956), and the steam has a high content of sulphur gases (H_2S, SO_2, SO_3) and hydrogen chloride, together with ammonia, hydrogen fluoride and boric acid. Wilson (1959) discussed in detail the chemistry of the fumaroles and pools on the Island. Fumarole condensates up to molar in hydrochloric acid were collected. The low value for the ratio Cl/F, and high ratios of Cl/B and Cl/As are notable features of the waters, although recent analyses show that Cl/B ratios for pools in the 1933 Crater range from 50 to 70 at similar chloride concentrations.

(*b*) *Recent volcanic areas.* The remaining analyses in Table 1 are of neutral sodium chloride waters, except for Rotokaua which is given as an example of a water from a deep-seated acid–chloride–sulphate area. All these occur in a volcanic



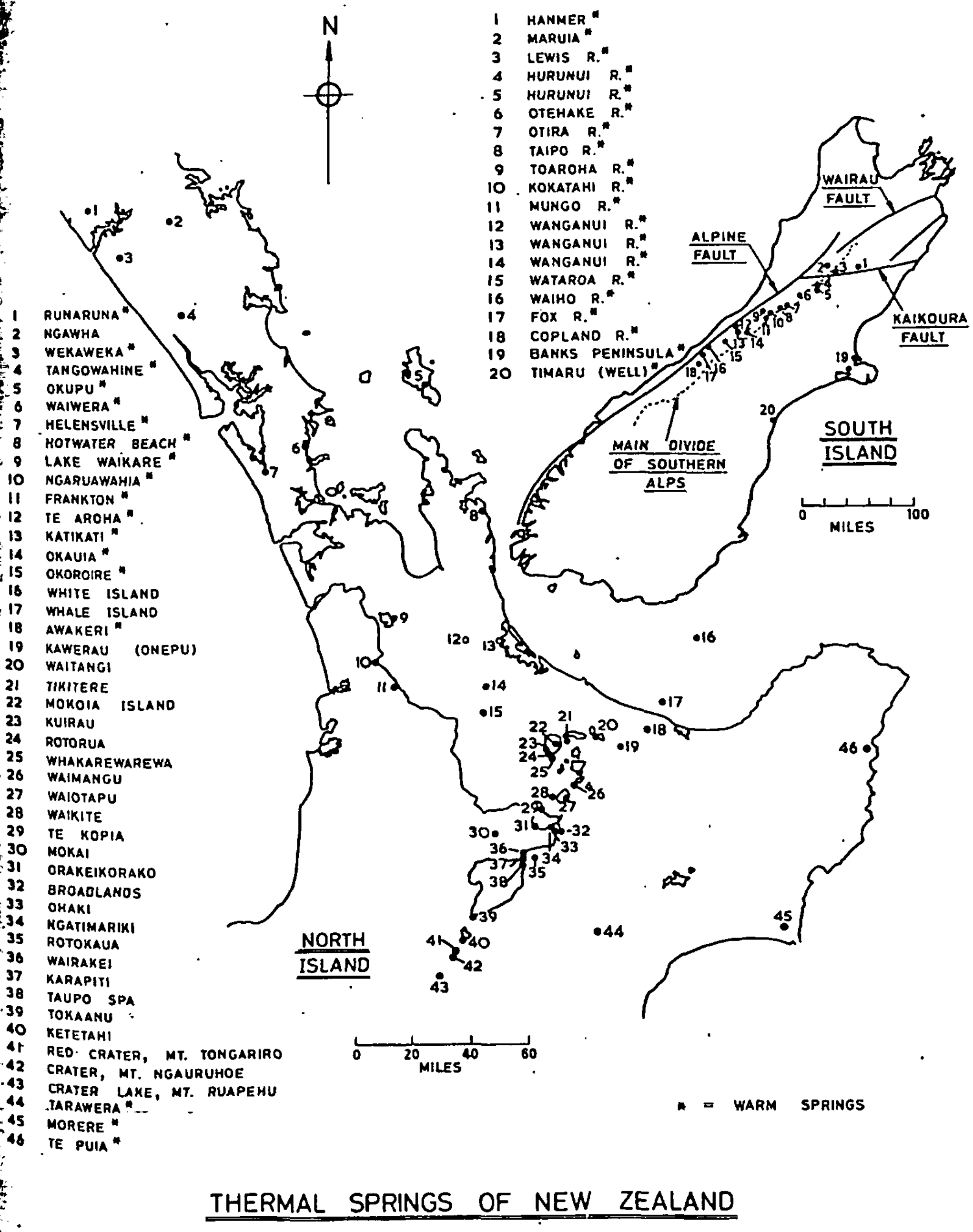


Fig. 1. Thermal spring areas of New Zealand.

Table 1. New Zealand volcanic thermal waters

Thermal area	pH	Concentrations in waters in ppm												
		Li	Na	K	Rb	Cs	Ca	Mg	F	Cl	Br	I	SO_4	As
Hole 4/1 Wairakei	7·9	12·6	1300	192	2·9	2·2	23	0·02	6·9	2140	5·7	<0·2	33	4·3
Hole 20 Wairakei	8·4	13·8	1300	220	3·1	2·6	18	0·04	8·2	2215	5·5	0·4	35	4·7
Hole 44 Wairakei	8·6	14·2	1320	225	2·8	2·5	17	0·03	8·3	2260	6·0	0·3	36	4·8
Spring 97 Wairakei	6·8	6·8	665	68	0·7	1·7	45	4·2	4·4	1110	2·5	0·4	72	1·8
Spring 190 Wairakei	7·5	10·0	950	62	n.d.	n.d.	20	0·05	5·8	1596	n.d.	n.d.	56	2·8
Hole 6 Waiotapu	8·9	6·6	860	155	2·4	0·8	10	0·06	7·5	1450	4·7	0·2	52	3·1
Hole 7 Waiotapu	8·8	6·4	790	90	0·7	0·9	10	n.d.	5·3	1310	3·7	1·0	86	n.d.
Spring 64 Waiotapu	5·7	9·0	1220	160	2·3	1·7	35	n.d.	5·5	2000	7·2	0·4	145	4·9
Spring 20 Waiotapu	8·6	4·0	450	22	0·3	0·6	9	n.d.	5·2	688	2·0	0·8	93	1·1
Hole 7a Kawerau	6·9	7·6	915	152	0·85	0·85	3·5	0·16	1·2	1473	n.d.	n.d.	60	n.d.
Hole 8 Kawerau	7·5	7·1	833	149	0·70	0·50	1·0	n.d.	1·4	1314	n.d.	n.d.	60	1·9
Spring 2 Onepu/ Kawerau	6·2	2·7	330	49	n.d.	n.d.	13	n.d.	1·4	445	n.d.	n.d.	158	n.d.
Spring 4 Onepu/ Kawerau	7·6	3·3	398	53	0·27	0·25	13	n.d.	1·9	544	1·6	0·8	96	n.d.
Hole 219 Rotorua	9·4	2·5	375	35	0·27	0·23	<1	0·06	n.d.	355	0·1	0·2	12	0·08
Hole 137 Rotorua	9·4	1·4	565	31	0·26	0·31	<1	0·22	4·0	632	2·1	0·7	30	0·30
Spring 98 Orakeikorako	8·3	4·0	280	42	0·15	0·22	2·5	0·5	8·5	284	0·6	0·2	220	0·30
Spring 14 Tokaanu	7·2	14·8	1170	116	1·5	2·6	25	n.d.	1·5	1956	5·5	0·6	42	5·5
Spring 6 Rotokaua	2·5	7·8	990	102	1·7	2·0	12	10	<1	1433	4·0	0·5	520	—
Taupo, Terraces Hotel	7·4	4·6	405	47	0·23	0·13	11	2·3	1·1	537	n.d.	n.d.	101	0·4
White Island*	Acid	n.d.	7670	1000	n.d.	n.d.	2560	7310	870	61840	40	6	10500	6

Concentrations in waters open to atmospheric pressure.

n.d. = not determined.

* Total CO_2, H_2S, etc, includes both the molecular form and the derived ions.

Hole and spring numbers as recognized by N.Z. Department of Scientific and Industrial Research.

Table 1 *cont.*

Thermal area	pH	Concentrations in waters in ppm					Atomic ratios						
		Total SiO_2	Total HBO_2	Total NH_3	Total CO_2	Total H_2S	Cl/B	Cl/F	Cl/Br	Cl/As	Na/K	Na/Li	Na/Ca

n.d. = not determined.

Total CO_2, H_2S, etc, includes both the molecular form and the derived ions.

Hole and spring numbers as recognized by N.Z. Department of Scientific and Industrial Research.

Table 1 cont.

	Concentrations in waters in ppm						Atomic ratios						
Thermal area	pH	Total SiO_2	Total HBO_2	Total NH_3	Total CO_2	Total H_2S	Cl/B	Cl/F	Cl/Br	Cl/As	Na/K	Na/Li	Na/Ca
Hole 4/1 Wairakei	7·9	590	112	0·25	25	—	23·6	165	850	1050	11·5	31	100
Hole 20 Wairakei	8·4	590	110	0·20	17	—	24·9	145	910	1000	10·0	28	125
Hole 44 Wairakei	8·6	640	117	0·15	19	—	23·9	145	850	990	10·0	28	135
Spring 97 Wairakei	6·8	235	57	0·22	88	1·9	24·1	135	1000	1300	16·6	30	26
Spring 190 Wairakei	7·5	245	82	0·37	38	2·0	24·0	145	—	1200	26	29	83
Hole 6 Waiotapu	8·9	470	56	0·9	65	—	32	105	690	990	9·4	39	150
Hole 7 Waiotapu	8·8	n.d.	63	n.d.	90	—	25·7	130	800	—	14·9	37	140
Spring 64 Waiotapu	5·7	490	117	11·5	235	6	21·1	195	620	860	13·0	41	60
Spring 20 Waiotapu	8·6	380	27	0·4	58	5	31	71	770	1300	35	34	87
Hole 7a Kawerau	6·9	760	273	n.d.	115	—	6·7	660	—	—	10·2	36	450
Hole 8 Kawerau	7·5	770	255	1·5	135	—	6·4	500	—	1450	9·5	35	1500
Spring 2 Onepu/ Kawerau	6·2	245	85	4	85	n.d.	6·5	170	—	—	11·5	37	44
Spring 4 Onepu/ Kawerau	7·6	240	102	4	110	n.d.	6·6	150	750	—	12·8	36	53
Hole 219 Rotorua	9·4	405	25·4	<0·05	206	36	17·2	—	8000	9000	18·2	45	> 700
Hole 137 Rotorua	9·4	314	32·3	<0·05	143	74	24·2	85	680	4500	31	120	> 1000
Spring 98 Orakeikorako	8·3	280	13·6	0·55	190	1·3	25·8	17·9	1100	2000	11·3	21	190
Spring 14 Tokaanu	7·2	220	246	2·6	170	0·05	9·8	700	800	750	17·2	24	81
Spring 6 Rotokaua	2·5	340	183	1·6	144	0·2	9·7	> 800	810	—	16·5	38	140
Taupo, Terraces Hotel	7·4	235	38	0·1	180	0·4	17·5	260	—	3000	14·7	27	64
White Island*	Acid	180	26	17	n.d.	30	2900	38	3500	22000	13	n.d.	5·2

* From WILSON (1959); water from the centre of 1933 Crater, which also contained Al^{3+}, 2030 ppm; Fe^{3+}, 140 ppm; Fe^{2+}, 11340 ppm; Mn^{3+} 260 ppm; Sr^{2+}, 10 ppm; $S_4O_6^{2-}$, 170 ppm; and H^+, 196 ppm.

zone of predominantly rhyolitic rocks (pumice, rhyolite and ignimbrite flows), and the waters reach the surface at boiling point. With the exception of Rotokaua, the waters from this recent volcanic area have rather similar chemical characteristics. The pH values range from about 6 to 9, rarely being higher or lower.

There is about a ten-fold variation in the total ion concentrations of the various spring waters, those from Orakeikorako being the lowest, and from Tokaanu the highest. The concentrations in the underground reservoir systems feeding the springs, and tapped by drill-holes are not the same as in the surface discharges. For example, at Wairakei the underground reservoir temperature is about 260°, and in allowing this water to separate steam in flashing to atmospheric pressure, a concentration factor of about 1·46 is introduced. The factor is rather higher at Waiotapu and Kawerau, where underground temperatures of up to 295 and 285° respectively have been measured by N.Z. Ministry of Works engineers. In the areas tested by deep drilling, the concentrations of chloride in the underground waters range from about 800–1600 ppm.

All the waters contain several parts per million of lithium (Na/Li atomic ratios range from 20–40 with one exception). Rubidium and caesium are also present at the level of 0·01–0·001 of the potassium molar concentration (Ellis and Wilson, 1960; Golding and Speer, 1961).

Calcium contents do not exceed 50 ppm, and are lowest in waters from Kawerau drill-holes where underground temperatures are highest. This suggests that the ion is limited in concentration by a temperature-dependent solubility equilibrium. The increase in the calcium content of waters at Wairakei as they travel through the field and cool has been used as a means of indicating water movement (Ellis and Wilson, 1960). The magnesium concentrations are so low that in the past they have not been determined satisfactorily by titration in the presence of calcium. By atomic absorption flame photometry, concentrations in the deep underground waters at 250–280° prove to be of the order of 0·01–0·1 ppm, and are probably dependent on a solubility equilibrium involving magnesium carbonate or magnesium hydroxide. At the surface, at lower temperatures, magnesium concentrations in the waters increase to several parts per million, and are still higher in acid pools.

As discussed by Mahon (1963) the fluoride contents are dependent on underground temperatures and solution compositions, but the usual concentrations of this ion are in the range 1–12 ppm. Spring waters in an area often have lower Cl/F ratios than water tapped from the deep reservoir, due to leaching of fluoride from the country rock by the water on its upward journey.

With one exception, a Rotorua drill-hole, the chloride-to-bromide atomic ratios are in the range 600–1100 and are rather higher than the value of 660 for sea water (Ellis and Anderson, 1961). The atomic ratios of chloride to arsenic are usually about 1000, being slightly higher for the more dilute waters. They are particularly high at Rotorua (Ritchie, 1961).

The sulphate contents are erratic, but it is of interest that the minimum value of 12 ppm SO_4^{2-} corresponds to about the content that would be formed by quantitative oxidation of sulphide by oxygen dissolved in water at 15°. Higher contents presumably come from oxidation underground by ferric iron, or from hydrolysis of old buried sulphur deposits ($4S + 4H_2O \rightleftharpoons 3H_2S + H_2SO_4$). The springs selected

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The regular analysis of the discharges from about 70 drill-holes at Wairakei shows that silica contents of the waters correspond closely to the solubility of quartz at the measured underground temperatures. As water cools from 260° in rising through the country, the silica in the waters decreases by depositing quartz in the rock. However, below about 150–200° the quartz/solution equilibria is too slow to maintain equilibrium silica concentrations and further deposition in the rock takes place only when the solubility of amorphous silica is exceeded, close to, or at the surface (ELLIS, 1961). The solubility of amorphous silica at 100° is about 400 ppm according to KENNEDY (1950), and the experiments below show that silica solubilities of similar magnitude can be expected from glassy volcanic rocks.

With respect to boron, there are two groups of water systems; those with atomic ratios of Cl/B of about 20–30, and the other group with Cl/B ratios of 6–10. Kawerau, the highest temperature area is in the latter group, as is Tokaanu and Rotokaua, but the deep underground temperatures in the latter two areas are not known. The tendency for the group with the low Cl/B ratios to also have low fluoride concentrations hints at high-temperature water reservoirs. As noted, the low pH of the Rotokaua waters is only a surface phenomenon.

Other minor constituents have been determined on the neutral chloride type waters. As typical examples the concentrations of various elements in the Wairakei drill-hole waters are as follows; Sr, 0·1 ppm; Ba, 0·01 ppm; Sb, 0·1 ppm; P, 0·05 ppm; Se, 0·01 ppm; Mo, 0·02 ppm; Pb, 0·002 ppm; Ni, 0·001 ppm.

As discussed by WILSON (1961), the general concept of a deep and major water storage system beneath each hydrothermal area is supported by the constancy of ratios of elements within each area (e.g. Wairakei and Kawerau). Rotorua and Waiotapu appear to be areas where more than one reservoir system exists in the top few thousand feet.

The concentration of gaseous constituents (CO_2, H_2S, NH_3) is really only of significance when given as contents in solution in the underground hot water before steam separation. In springs and drill-hole discharges, the concentration of gases in the waters depends on the way in which the waters pass from the underground storage to the surface, i.e. the amount of steam and gas separation and loss before a water is sampled. The content of total CO_2, H_2S and NH_3 appearing in the water analyses in Table 1 is the summation of the molecular and ion forms of the compounds, expressed as the molecule, found by analysis. They are not the concentrations in the underground waters, as steam separation and temperature changes influence many interacting acid/base equilibria involving silicic, hydrofluoric, boric and carbonic acids, hydrogen sulphide, the bisulphate ion and ammonia.

For Wairakei drill-hole discharges it is possible to add together the separate gas contents of the steam and water phases collected at a particular pressure from a discharge to obtain an adequate idea of the gas contents of the underground 260° water. At Kawerau and Waiotapu this knowledge of underground conditions is not so certain, as the drill-holes often tap at their bases a water/steam mixture derived from the parent liquid phase. Average compositions of gases from the three areas of deep drilling are given in Table 2, together with approximate gas contents

Table 2

Area	Approx. average drilling depth (ft)	Average gas content of total discharge (moles/100 moles H_2O)	% gas composition				
			CO_2	H_2S	HCS	H_2	N_2
Wairakei	2000	0·020	92·8	4·2	0·9	1·8	0·3
Waiotapu	3000	0·10	88·0	10·3	0·2	1·0	0·5
Kawerau	3000	0·25	94·0	2·6	2·1	0·3	1·0

HCS = total hydrocarbons, mainly methane (compositions, as volume percentages).

in the parent hot water systems. Carbon dioxide and hydrogen sulphide are the predominant gases.

Warm spring areas (*Table 3*)

(*a*) *Springs in non-volcanic areas.* In the South Island of New Zealand at Hanmer, Maruia and the Wanganui River, hydrothermal systems rise in Mesozoic or Paleozoic greywacke and pass through Recent sands and gravels. Major faulting and uparching of the old rocks has occurred in the zone about the flanks of the Southern Alps, and the hot waters are thought to be associated with these rock movements and a high geothermal gradient (HEALY, 1948). Springs at Tarawera and Awakeri in the North Island also rise in greywacke close to the margin of rhyolitic volcanic rocks of the Taupo Volcanic Zone.

On the East Coast of the North Island at Morere and Te Puia, springs occur in quite a different environment in an area of Tertiary sediments. There are no signs of volcanic activity that could be considered as a heat source, and the origin of the heat is unknown.

The spring waters from both greywacke and sediments are characterized by high Na/K, Na/Li, Na/Rb, Na/Cs ratios and low silica concentrations. The springs associated with greywacke (except Wanganui River) have low Cl/B ratios, but in Morere and Te Puia waters, although the boric acid concentrations are considerable, the Cl/B ratios are high because of high sodium chloride concentrations which approach the level found in sea water. The fluoride concentrations are similar to those for springs of volcanic origin. Calcium and magnesium concentrations are high only at Morere and Te Puia. These ions are not accompanied by an equivalent concentration of bicarbonate, but correspond with low fluoride contents in the waters. Morere and Te Puia springs also have particularly high bromide and iodide concentrations, as might be expected from their sedimentary environment (ELLIS and ANDERSON, 1961), but their ammonia contents are low.

Iodide is relatively high in concentration in the Tarawera spring compared with that in South Island greywacke springs, and in volcanic spring waters. All the waters are low in sulphate, and have negligible amounts of arsenic.

(*b*) *Springs in old volcanic areas.* Te Aroha springs are situated along a fault scarp in an area of Tertiary and Pleistocene andesites. The country has extensive sulphide mineralization and a high thermal gradient. Helensville and Waiwera

Table 3. Warm spring waters

Area	Temp (°C)	pH	Concentrations in waters in ppm Li^+	Na^+	K^+	Rb^+	Cs^+	Ca^{2+}	Mg^{2+}	F^-	Cl^-	Br^-
North Island												
Ngawha: Jubilee Bath	42–83*	6·4	8·0	830	63	0·3	0·55	7·8	2·5	0·3	1250	2·6
Waiwera: Hotel Baths	40	7·2	1·7	720	8	<0·2	0·2	38	2·2	1·6	1110	3·2
Helensville: Hotel Supply	65	6·5	2·3	600	22	<0·1	<0·1	63	3·0	2·2	1030	n.d.
Te Aroha: CO_2 Geyser	85	7·5	2·0	3500	108	<0·1	<0·1	8·2	3·9	0·3	518	1·8
Awakeri: Pukaahu Spring	54	8·6	0·24	120	8	<0·02	<0·02	1·9	0·3	3·9	42	<0·2
Spring, Tarawera, Napier-Taupo Rd.	49	8·4	1·9	500	9	<0·1	<0·1	12	0·1	11·5	660	1·9
Morere: Baths 1 and 2	62	6·7	5·4	6100	100	<0·1	<0·1	3900	137	0·4	16000	8.
Te Puia: Bath	65	6·8	n.d.	4550	22	n.d.	n.d.	815	8	1·5	8300	n.d.
South Island												
Hanmer: Bath	54	8·0	1·7	360	7	<0·1	<0·1	6·5	0·2	4·4	451	1·3
Maruia: Pool	58	7·0	1·6	130	5	<0·02	<0·02	6·5	0·3	2·5	99	0·7
Wanganui River Spring	39	6·2	0·9	170	14	0·08	0·05	15	1·5	2·0	188	n.d.
Lyttelton Tunnel Spring	21·5	7·1	n.d.	174	18	<0·02	<0·02	152	163	0·7	513	1·9

* Temperatures at surface and base of pool.

Table 3 *cont.*

Area	Concentration in waters in ppm I^-	SO_4^{2-}	As	Total CO_2	Total SiO_2	Total HBO_2	Total NH_3	Atomic ratios Cl/B	Cl/F	Cl/Br	Na/K	Na/Li	Na/Ca
North Island													
Ngawha: Jubilee Bath	1·0	347	0·2	490	178	3690	140	0·42	2200	1100	22	31	185
Waiwera: Hotel Baths	1·2	1	<0·02	77	40	39	1·9	35	370	780	150	130	33
Helensville: Hotel Supply	n.d.	1	0·06	87	72	54	0·05	23·5	250	—	46	78	16·5
Te Aroha: CO_2 Geyser	0·6	321	0·4	8050	120	651	3·4	0·98	920	730	55	530	740
Awakeri: Pukaahu Spring	0·5	29	n.d.	106	70	15	<0·1	3·5	5·8	>500	25	150	110
Spring, Tarawera, Napier-Tapuo Rd.	2·5	82	n.d.	111	42	322	2·4	2·5	31	780	94	80	73
Morere: Baths 1 and 2	25	21	n.d.	25	28	198	1·5	100	20000	450	104	340	2·7
Te Puia: Bath	18	110	<0·01	60	52	290	2·1	35	2900	—	350	—	9·7
South Island													
Hanmer: Bath	0·7	43	n.d.	140	46	216	3·4	2·6	55	780	87	64	96
Maruia: Pool	0·1	25	n.d.	—	70	12·5	1·7	9·8	21	320	44	24	35
Wanganui River Spring	n.d.	7	n.d.	298	70	6·9	0·13	34	50	—	21	57	20
Lyttelton Tunnel Spring	<0·2	110	<0·01	—	93	4·7	0·01	135	400	610	16	—	2·0

thermal systems are in an area of basalts and andesites of similar age, and the hot waters emerge through Miocene sandstone (HEALY, 1948). Ngawha in North Auckland occurs in an area of deep Cretaceous shales and sandstones, and in which there have been extensive Quaternary basaltic eruptions. The heat is assumed to be derived from a basaltic intrusion within or beneath the sediments, but isolated rhyolite intrusions are also known in North Auckland. As drilling has revealed temperatures over 100° within a few hundred feet of the surface, its classification as a warm spring area is arbitrary, as is its assessment as an old volcanic area. In the South Island, the Lyttelton thermal springs are probably related to the basaltic volcanic activity of late Tertiary age about Banks Peninsula. Water temperatures are low and range from 21–27°C.

Notable features of the Ngawha waters are the very high boric acid, bicarbonate and ammonia concentrations. Boric acid is also high at Te Aroha, as are the bicarbonate ion concentrations. The silica contents for these two areas are the highest of the warm springs.

All the waters are of neutral pH, and have chloride concentrations of about 500–1000 ppm. The ratios of sodium to rare alkalis are similar to those for non-volcanic springs in greywacke country, but calcium and magnesium contents are in general higher, particularly for the Lyttelton tunnel water.

Sulphate and ammonia contents are extremely variable and arsenic concentrations uniformly low. The ratios of chloride to bromide are similar to those for springs in recent volcanic areas.

PREVIOUS WORK ON ROCK LEACHING

BASHARINA (1958) extracted many water-soluble constituents from a pyroxene andesite ash from Bezymiany volcano. The following amounts, expressed on an air-dried rock basis, were extracted into distilled water at room temperature: chloride, 760–5300 ppm; fluoride, 30–67 ppm; bromide traces to 21 ppm; sulphate, 2370–4690 ppm; bicarbonate, 120–1040 ppm; sodium, 100–1240 ppm; potassium, 24–345 ppm; calcium, 840–4890 ppm; magnesium, 173–388 ppm; silica, 25–200 ppm; boric acid, 16–42 ppm. The pH values of the solutions were 3·2–6·8. Rather similar results were reported by TOVAROVA (1958), but in addition several tens of ppm of ammonia were extracted. These ashes probably contained hydrogen chloride and sulphur gases etc., adsorbed during the eruption, and their very acid characteristics would only be temporary.

The interaction of acid sulphate and chloride solutions at 100°C with finely ground Kamchatka basalts, andesites and dacites was examined by NABOKO and SILNICHENKO (1960). The concentrations of major rock constituents leached into, and held in solution, depended on the pH rather than on the rock compositions. The experiments provided a reasonable model for explaining the compositions of the acid surface waters of active volcanic areas, which may contain high concentrations of iron, aluminium, calcium and magnesium.

KHITAROV (1957) studied the interaction of water with feldspars, micas and granite at higher temperatures and much higher pressures than in the present work, but his interests were in the concentrations of the major rock constituents passing into solution.

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(a) *Procedure*

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(a) *Rock petrology*

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for some fifty rocks

EXPERIMENTAL

The following technique and apparatus was used in the laboratory investigation of solution compositions resulting from the interactions of various rock types with water.

(a) *Procedure*

Grains (1–5 mm) of the rock under investigation were packed into 105 cm^3 stainless-steel pressure vessels and after sealing, the vessels were heated dry in 3-ft electric tube furnaces to the required temperatures. The pressure vessels were connected at their bases, by capillary stainless-steel tubing, to a Sprague air-driven liquid pump unit, capable of delivering and maintaining water pressures up to 30,000 lb/in^2. After the vessels reached thermal equilibrium, water was pumped in until the pressure was 5000 lb/in^2, giving a rock-to-water weight ratio of about unity for the rhyolite pumice experiments, and about two for the other rocks. The water pressure was sufficient to maintain a single liquid–water phase in the vessels for all the runs. Temperatures at the top and bottom of the vessels were measured by chromel–alumel thermocouples.

At intervals during the runs, samples of water were taken from the top of the vessel through a capillary line and a valve, the pump maintaining the pressure, and replacing the water sampled with distilled water. Sampling times depended on the reactivity of the rock and the temperature at which the experiment was being conducted. For example, with rhyolitic pumice, a reactive rock, samples were taken after intervals of a few hours but for most other rocks the time intervals were increased to at least 24 hr. By taking samples of 10 cm^3, the resultant dilution of the reaction solutions by fresh water was approximately 15 per cent. It was confirmed that mixing did occur in the times between sampling. At the completion of each experiment the rock was removed from the vessel, air dried and stored for subsequent examination.

(b) *Methods of analysis*

In the reaction solutions, ten to thirteen constituents were determined on 10 cm^3 of reaction solution by micro-analytical techniques. Sodium, potassium, lithium, rubidium and caesium were determined by flame photometry. Calcium and magnesium were determined by both emission flame photometry and atomic absorption flame photometry (DAVID, 1960).

Chloride was determined by differential potentiometry using silver/silver chloride electrodes (BLAEDEL *et al.*, 1952). For fluoride, a distillation from perchloric acid and silica was followed by a thorium nitrate–chromazurol titration (MILTON *et al.*, 1947). Silica was determined photometrically after the formation of silicomolybdic acid. The water samples were first heated with alkali to get the silica into the monomeric reactive form.

Sulphate was reacted with barium chromate to form insoluble barium sulphate and the chromate ions liberated in the reaction were determined photometrically (IWASAKI *et al.*, 1958). Boron was determined photometrically after reaction with carminic acid in concentrated sulphuric acid (SMITH *et al.*, 1955). The estimation of ammonia consisted of a micro-distillation, followed by the reaction of the distillate with Nessler's reagent. Arsenic was determined by the Gutzeit method. The pH values of a number of samples were determined by mixing with indicator solutions on spot plates and comparing with standard pH buffer solutions.

Minor rock constituents were determined as follows: chloride by the procedure of KURODA and SANDELL (1950), fluoride according to CHU and SCHAFER (1955), ammonia by WLOTZKA's (1961) method and boron by a spectrographic technique developed in this laboratory (SEWELL, 1963).

RESULTS

(a) *Rock petrology and compositions*

The eight rocks investigated cover the range of compositions and types typical of the Taupo Volcanic Zone of the North Island of New Zealand. Four of the eight were of rhyolitic composition, and this reflects the preponderance of silica-rich volcanics in this region. Typical major-constituent analyses made in this laboratory for some fifty rocks from the central volcanic zone were brought together by STEINER

(1958a), while Reed (1957) reviewed the compositions of many New Zealand greywackes. Brief petrological descriptions of the rocks used in the present experiments were provided by Dr. A. Ewart of the N.Z. Geological Survey, who also assisted in choosing the specimens from surface outcrops or quarrys so that only fresh and unaltered material was used. They were selected from areas away from natural hydrothermal activity. After the reaction with water a further examination of the rocks was made in thin section by Dr. Ewart to check on hydrothermal alteration. The numbers following the rock types are New Zealand grid references of the localities from which the rocks are taken.

Pumice (*N*33–5528). This was a rhyolitic pumice; 98 % glass together with andesine plagioclase, minor hypersthene and magnetite phenocrysts.

Obsidian (*N*94/462490). This rock was of rhyolitic composition and consisted of practically 100 % fresh glass.

Ignimbrite (*N*53/274923). This rhyolitic ignimbrite consisted of 60 % glass which was fresh and unaltered. Crystalline material included plagioclase, quartz, minor biotite, hornblende and magnetite. Some pumice inclusions were present.

Rhyolite (*N*94/605462). This was a flow rhyolite showing a well-developed spherulitic structure. Between the spherulites, patches of glass showed crystallization to a microcrystalline mosaic, probably of feldspar and tridymite. About 5 % plagioclase phenocrysts and minor magnetite and hypersthene constituted the remainder of the rock.

Dacite (*N*94/635376). A matrix consisting of andesine plagioclase, glass and cristobalite, constituted 78 per cent of this rock. Also present were plagioclase and quartz phenocrysts together with hypersthene, hornblende, augite and magnetite.

Andesite (*N*111/970870). This rock consisted of a largely devitrified glass matrix (65 per cent), together with plagioclase phenocrysts (25 per cent), hypersthene (10 per cent) and minor augite and magnetite.

Basalt (*N*84/418745). Fresh crystals of plagioclase feldspar, pigeonite and a matrix largely consisting of oxidized interstitial glass made up the bulk of this rock.

Greywacke (*N*33–0013). The rock consisted of poorly sorted angular fragments of quartz, sodic plagioclase, potash feldspar, some rhyolitic volcanic fragments, together with biotite, rare chlorite, laumontite and muscovite.

(*b*) *Minor constituents of rocks*

Surveys of the chloride, boron, fluoride and ammonia contents of New Zealand volcanic rocks are at present being made, and will be reported elsewhere. The concentrations of the elements shown in Table 4 for the eight rocks used in the present work are typical for the rock types.

The nitrate nitrogen of the rocks was also determined by the method of Wlotzka (1961), but the contents were all under 5 ppm and are of little significance.

Table 4

Constituent rock	Cl	F	HBO_2	NH_3
Pumice	990	440	70	31
Obsidian	900	400	100	—
Ignimbrite	690	410	200	—
Rhyolite	600	300	80	19
Dacite	120	290	45	30
Andesite	190	190	90	50
Basalt	360	180	30	20
Greywacke	12	280	140	280

(c) *Compositions of solutions from rock/water interaction*

Table 5 gives the compositions of the solutions after contact with various rocks for periods up to 300 hr, at temperatures in the range 150–350°. Samples were taken in each run at 24, 48, either 72 or 120, and 300 hr. In runs with obsidian and greywacke, samples were also taken at 480 hr. All the solutions were analysed, but little of importance is lost by reporting only the analyses for 24 and 300 hr, or in the case of 300° runs at 24, 120 and 300 hours. Trends which are more complicated than a simple increase or decrease in concentration-with-time are discussed in greater detail later.

In many analyses it will be apparent that the equivalent concentrations of anions and cations reported do not balance. The concentration of bicarbonate was not determined, and it is likely that this common ion makes up the apparent deficiency of anions in solution compositions.

For the ignimbrite and rhyolite, single runs were made at 350°, the results appearing in Table 6. The sampling schedule was as for the other rocks.

Pumice was very reactive, and solution compositions were obtained at short intervals of time. Figure 2 shows the change in concentration with time for the constituents in solution at 180°, while Fig. 3 gives this information for the 270° experiment. Figure 4 summarizes the concentrations of constituents found in six runs with pumice at various temperatures at the longest common time of 72 hr allowed for reaction. Lithium was determined only on the 72 hr, 310° experiment solution, the concentration being 0·5 ppm.

On a small number of solution samples estimations of arsenic, rubidium, caesium and magnesium were made. The results are summarized in Table 7. In the discussion rubidium and caesium determinations on solutions from some higher temperature reactions are given.

(d) *Hydrothermal alteration of rocks*

Following the reactions, a selection of the rocks were re-examined in thin section under the microscope, and by X-ray diffraction. Determinations were also made of water contents. This work was concentrated on the highest temperature experiments where the maximum alteration could be expected.

With the exception of the pumice and obsidian, the rocks showed little change, even after reaction with water at 350°C. No alteration was apparent for basalt and dacite in the 350° experiments, and for greywacke only slight oxidation of matrix occurred. With andesite there was a slight devitrification of the margins of the groundmass glass. The ignimbrite under these conditions showed intense oxidation and the earliest stage of devitrification in its glassy matrix. After reaction with water at 350°, the obsidian grains showed three zones of alteration. On the outside there was a micro-crystalline zone, followed by an opaque zone of cryptocrystalline material (possibly cristobalite and feldspar) and an inner zone of hydrated glass. The pumice from the 310° experiment showed strong strain polarization, presumably due to the increased hydration of the glass during the run. No definite devitrification could be identified under the microscope.

Each rock was examined by X-ray diffraction before and after reaction with water at 350° (pumice at 310°). No changes were noted in the X-ray patterns, except

Table 5. Constituent concentrations (ppm) in reaction solutions

Rock:		Obsidian	Dacite	Andesite	Basalt	Greywacke
Temperature (°C)	Time of reaction (hr)					
(a) *Chloride and* (*fluoride*)						
150	24	4·4(<1)	12(4·4)	8(1·5)	21(<1)	15(<1)
	300	3(<1)	10(4·4)	12(5·0)	28(3·5)	4(<1)
200	24	7(<2)	16(4·5)	17(4·0)	58(6·5)	9(<1)
	300	4(<2)	12(11)	20(5·0)	61(9·0)	4(<1)
250	24	5(9·5)	22(16)	23(10)	71(17)	8(<2)
	300	9(9·5)	40(15)	52(10)	250(6)	3(<2)
300	24	9(5)	28(20)	40(10)	140(17)	12(<2)
	300	54(43)	28(18)	48(20)	250(3·0)	3(2)
350	24	39(21)	60(23)	115(11)	460(7·5)	10(<2)
	120	45(20)	37(16)	150(10)	n.d.(n.d.)	6(2)
	300	320(8·5)	37(12)	270(7·5)	390(3·0)	5(2)
(b) *Boric acid as* HBO_2 *and* (*ammonia*)						
150	24	n.d.(1·1)	0·3(0·9)	n.d.(1·8)	2·0(3·4)	4·9(1·2)
	300	0·8(0·6)	0·6(0·4)	1·3(1·8)	2·0(n.d.)	4·9(0·7)
200	24	n.d.(2·1)	1·7(0·8)	1·5(4·2)	2·8(1·3)	12(1·2)
	300	n.d.(1·9)	2·6(1·9)	3·5(6·1)	2·6(n.d.)	3·3(2·2)
250	24	1·2(1·7)	3·0 n.d.	5·7(7·0)	3·0(3·1)	12(4·2)
	300	1·5(1·3)	7·5(3·3)	10(3·2)	5·4(3·7)	7·0(n.d.)
300	24	0·6(1·9)	5·3(4·6)	4·7(3·2)	18(4·0)	17(4·4)
	300	0·7(0·1)	3·1(2·2)	5·8(3·9)	17(5·6)	7(9·0)
350	24	0·1(1·0)	12(15)	10(12)	n.d.(12)	36(34)
	120	1·0(0·6)	3·8(7·6)	18(7·0)	n.d.(n.d.)	11(18)
	300	35(0·6)	3·5(4·3)	33(6·7)	10(4·2)	8·0(18)
(c) *Silica and* (*sulphate*)						
150	24	150(n.d.)	160(n.d.)	235(n.d.)	230(n.d.)	200(n.d.)
	300	155(15)	390(32)	240(36)	235(45)	220(75)
200	24	290(n.d.)	790(n.d.)	560(n.d.)	830(n.d.)	520(n.d.)
	300	460(30)	890(24)	400(32)	750(39)	415(135)
250	24	770(n.d.)	1320(n.d.)	890(n.d.)	720(n.d.)	760(n.d.)
	300	860(14)	990(42)	1150(n.d.)	1170(35)	550(135)
300	24	910(n.d.)	1540(n.d.)	1060(n.d.)	1540(n.d.)	700(n.d.)
	300	800(4)	1360(28)	1240(24)	1360(28)	530(145)
350	24	1150(n.d.)	1600(n.d.)	1800(n.d.)	950(n.d.)	1060(n.d.)
	120	1000(n.d.)	1340(n.d.)	1760(n.d.)	n.d.(n.d.)	910(n.d.)
	300	900(10)	1400(10)	1800(n.d.)	2600(10)	890(40)

Rock:	
Temper-ature (°C)	Time reacti (hr
(d) *Sodium and* (*pot*	
150	24
	300
200	24
	300
250	24
	300
300	24
	300
350	24
	120
	300
(e) *Lithium and* (*cal*	
150	24
	300
200	24
	300
250	24
	300
300	24
	300
350	24
	120
	300

n.d. = not deter

Constituent (ppm)	Rea Ti (h
Ignimbrite	2 12
Rhyolite	2 12

Table 5 *cont.*

Rock:		Obsidian	Dacite	Andesite	Basalt	Greywacke
Temperature (°C)	Time of reaction (hr)					
(*d*) *Sodium and* (*potassium*)						
150	24	30(3)	36(10)	55(21)	70(22)	65(25)
	300	30(2)	42(9)	75(24)	85(24)	60(11)
200	24	55(5)	55(12)	60(21)	100(31)	80(11)
	300	65(5)	55(11)	85(27)	95(29)	70(5)
250	24	80(7)	58(13)	55(15)	125(31)	55(6)
	300	90(9)	65(10)	65(18)	150(47)	70(4)
300	24	75(9)	65(14)	70(23)	125(46)	40(4)
	300	110(21)	70(7)	70(22)	340(150)	50(5)
350	24	70(12)	52(10)	68(27)	230(130)	25(5)
	120	70(13)	36(6)	92(30)	n.d.(n.d.)	25(5)
	300	440(110)	38(6)	160(33)	175(87)	25(4)
(*e*) *Lithium and* (*calcium*)						
150	24	0·15(20)	0·10(4)	0·05(7)	n.d.(9)	0·1(13)
	300	0·10(7)	0·10(4)	0·10(3)	n.d.(5)	0·1(4)
200	24	0·25(6)	0·20(5)	0·05(<2)	0·5(n.d.)	0·35(5)
	300	0·25(1)	0·20(2)	0·10(3)	n.d.(4)	0·25(3)
250	24	0·35(0·4)	0·35(6)	0·1(4)	0·4(5)	0·7(4)
	300	0·45(0·3)	0·65(9)	0·5(4)	0·3(3)	0·5(5)
300	24	0·35(1)	0·5(7)	0·35(18)	0·1(4)	0·5(2)
	300	0·5(1)	0·6(0)	0·6(n.d.)	1·5(5)	0·9(5)
350	24	0·2(1)	0·4(3)	0·7(12)	0·4(5)	0·6(3)
	120	0·2(n.d.)	0·4(5)	0·9(6)	n.d.(n.d.)	0·8(n.d.)
	300	1·3(1)	0·4(0)	1·5(12)	0·5(3)	0·6(4)

n.d. = not determined.

Table 6. Solution compositions at 350°

Constituent (ppm)	Reaction Time (hr)	Cl	F	HBO_2	NH_3	SiO_2	SO_4	Na	K	Li	Ca
Ignimbrite	24	530	8·5	21	3·3	870	n.d.	280	136	0·9	5
	120	420	5·0	30	3·2	840	17	205	98	0·7	2
Rhyolite	24	160	16	5·0	4·1	825	n.d.	95	22	1·3	4
	120	110	19	1·5	3·9	850	8	75	14	1·2	4

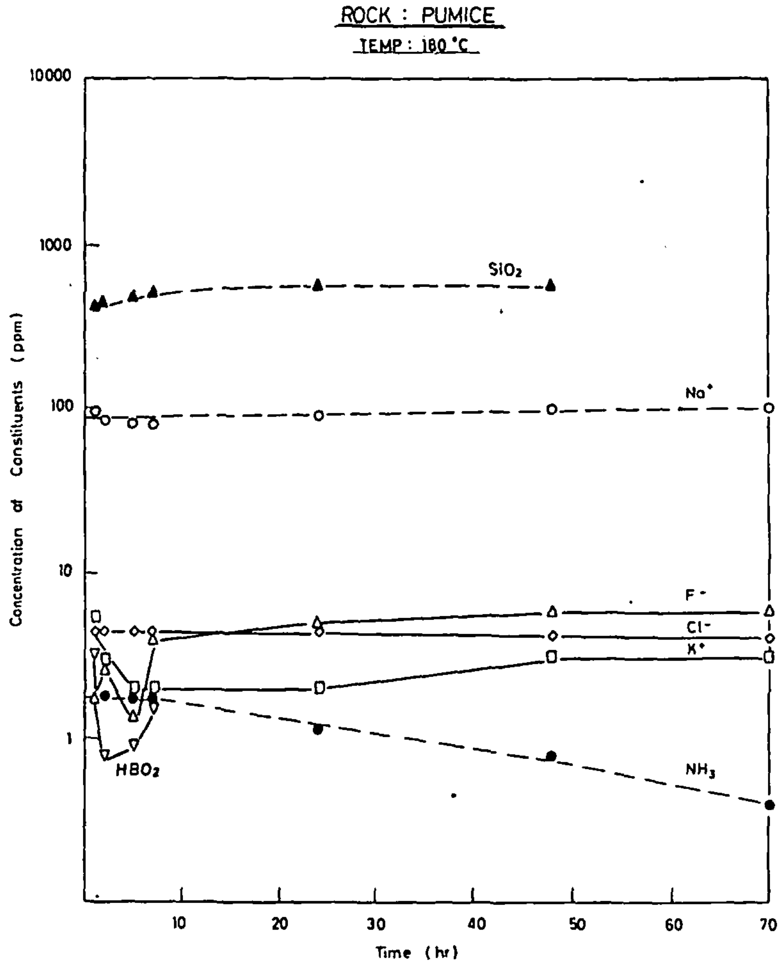

Fig. 2. Change in concentration with time of constituents dissolved from rhyolitic pumice at 180°C.

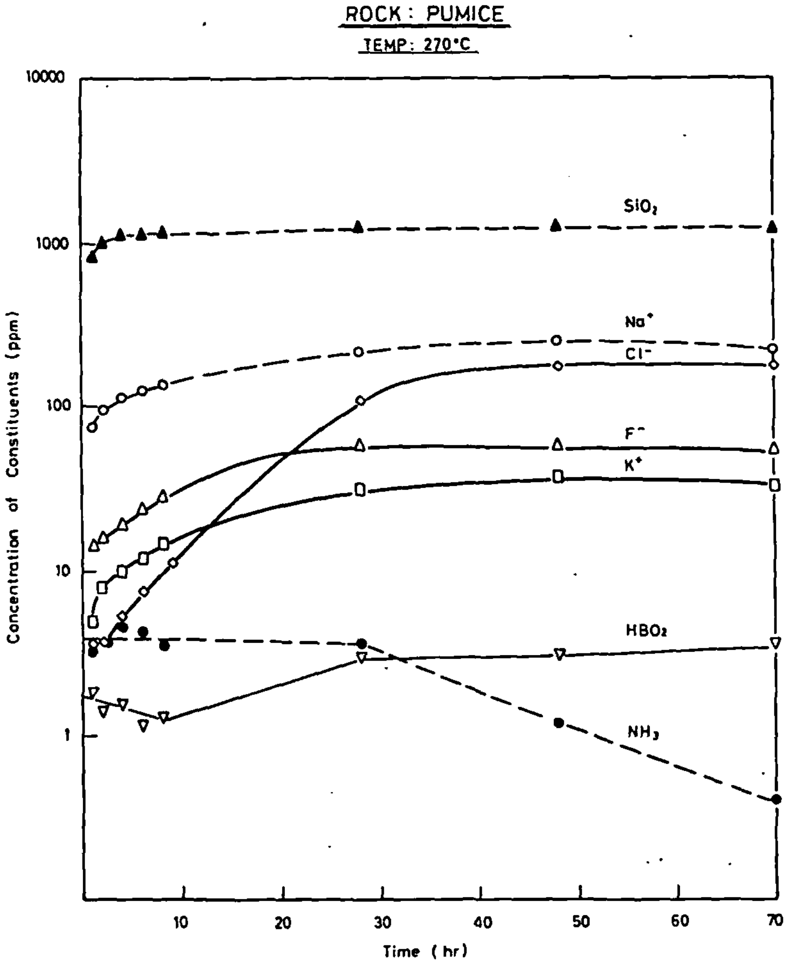

Fig. 3. Change in concentration with time of constituents dissolved from rhyolitic pumice at 270°C.

Rock type

Basalt
Obsidian
Ignimbrite
Pumice
Dacite
Andesite
Greywacke

Fig. 4.

Concentration of Constituents (ppm)

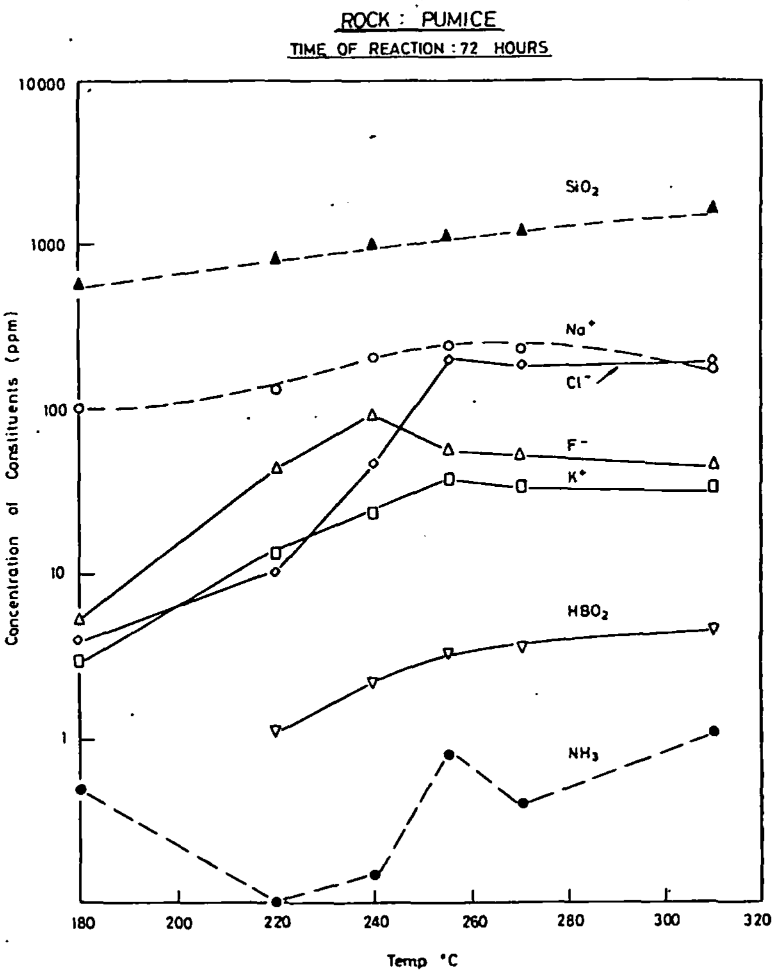

Fig. 4. Variation with temperature in the concentration of constituents dissolved from rhyolitic pumice.

Table 7

Rock type	Temperature (°C)	Time (hr)	Concentrations (ppm)			
			Mg	As	Rb	Cs
Basalt	350	300	0·20	n.d.	<0·1	<0·1
Obsidian	350	480	n.d.	n.d.	0·2	<0·1
Ignimbrite	350	480	0·03	n.d.	<0·1	<0·1
Pumice	310	72	0·17	0·85	n.d.	<0·1
Dacite	350	300	n.d.	<0·1	n.d.	n.d.
Andesite	350	300	n.d.	1·3	n.d.	n.d.
Greywacke	350	480	0·75	n.d.	n.d.	n.d.

for pumice for which slight crystallization to feldspar and quartz was apparent. The proportion of crystalline alteration product in the obsidian must have been too small to be apparent on an X-ray pattern.

The total water content of the air-dried rock particles was determined before and after exposure to water at the highest temperatures of the experiments (pumice over a range of temperatures)—see Table 8.

Only pumice and obsidian gained water, the remainder, except rhyolite, losing small amounts.

EXAMINATION OF RESULTS

(a) *General*

The tables show that the interaction of water with various rock types can liberate appreciable quantities of many of the elements characteristic of natural thermal waters. The exact concentrations in the reaction solutions are, with some exceptions, not of great significance as the effective ratio of rock to water in a natural hydrothermal system could vary widely. Also, it must be considered that a selective extraction of constituents from rock could occur during the lifetime of a natural system which consisted of a deep convective cycle of meteoric water. The results cannot be related directly to the composition of natural hot waters, but must be interpreted with reference to reaction rates, chemical equilibria and knowledge as it becomes available of the deep hydrology of thermal areas.

As the times of interaction were very short compared with the periods available for reaction in natural hydrothermal systems, the results must be interpreted by judging as far as possible what the element concentrations in the experimental solutions would be after a much longer reaction period. This can be done in some cases only by reference to known equilibria, e.g. the high silica concentrations in the reaction solutions would not persist in nature, but would decrease until equilibrium with quartz was established. In most experiments only slight alteration of the rock occurred, and it must be considered whether or not from a chemical equilibrium viewpoint an increase in the extent of alteration would increase the amount of an element in solution.

Widely different reactivities were observed for the various rock types. The relative rates at which constituents were liberated are of interest as these are a reflection of the way in which the elements are held in the rocks.

The results for each element are now reviewed, and the concentrations in the reaction solutions are compared with the total amount of the element available in the rocks to see the effectiveness of the extraction processes. As similar results for an element were often given by several rocks, it is not necessary to discuss each rock type in detail. The dilution factor of 15 per cent each time a sample was taken during a run should be remembered.

A distinction must be drawn between major and minor rock constituents. Sodium, potassium, calcium, magnesium, silica, as major constituents, are present in the rock in excess of the amounts that could be dissolved in the water under the experimental conditions, and a saturated equilibrium state defined by the rock composition, temperature and pressure should eventually be set up. Constituents such as chloride, fluoride, ammonia, arsenic, sulphur, lithium, rubidium, caesium, which are present in the rocks to the extent of less than 0·1 per cent, could, unless limited by sparingly-soluble compound formation or by inclusion in a rock alteration mineral structure, be transferred largely to the water phase. For all of the latter group of elements the equilibrium rock/water distribution coefficient is likely to favour the water phase at the temperatures of interest (e.g. (Cs/K feldspar)/(Cs/K solution) at 400° is 0·25 according to Eugster, 1955).

(b) *Individual constituents*

(i) *Chloride.* The pattern of reaction was often a fast build-up in chloride concentration which was then followed by a further, more gradual, increase in chloride concentration. The proportion of chloride in the rocks which was easily removed during the initial rise in concentration differed considerably for the various rock samples. Figure 5 shows approximately the relative proportions of "easily-removed" chloride in some of the rock types, along with similar results for boron.

For basalt at 300–350° about 75 per cent of its total chloride was easily removed by water. For andesite a rapid increase in reaction rate occurred after about 120 hr at 350°, after about 45 per cent of its total chloride content was removed into solution. The chloride content of the rock dropped from 190 ppm to 50 ppm during the 350° experiment, giving a good mass balance with the chloride found in solution.

The amount of chloride removed from the pumice in the 310° experiment after 1–3 days remained at about 25–30 per cent of the chloride in the rock, the analysis of the rock before and after 3 days exposure giving chloride concentrations of 990 ppm and 680 ppm.

The lower chloride content of the dacite was reflected in the chloride content of its solutions, but in addition, the percentage of easily-removed chloride in the rock was low (about 25 per cent). The rhyolite contained the lowest percentage (about 13 per cent) of total chloride readily available for extraction; this rock did not lose water during the reaction. Almost 40 per cent of the chloride in the ignimbrite was readily removed by 350° water, and it is of significance that this rock also lost about 2 per cent of water from its structure during the reaction and had started to devitrify. Only small amounts of chloride were extracted from greywacke but the rate of reaction was rapid even at 150°. About 50 per cent of the total chloride in the rock was readily available for solution.

A large proportion of the chloride in many of the rocks was readily available for extraction (particularly for basalt, andesite and greywacke), although the degree of reaction of the rocks with water as shown by microscopic and X-ray examination was slight in all cases except for obsidian and pumice. The water content figures in Table 8 show that the glassy rhyolitic rocks absorbed several per cent of water before crystallization occurred.

The initial rate ($dc/dt = k$) of increase in chloride concentration in solution from rhyolite pumice was examined as a function of temperature between 220–270°, and the Arrhenius activation energy, E, obtained from the equation $k = A \exp(-E/RT)$, was found to be equal to $2{\cdot}7 \pm 1$ kcal/mole. This is of the order expected for an absorption/desorption process, but is also in the vicinity of the activation energy of about 4–5 kcal/mole associated with rate control by ion diffusion in solution (Moelwyn-Hughes, 1948). The kinetics *suggest that a high proportion of the* easily-liberated chloride in this rock was held simply on surfaces in the structure,

Table 8. Total water content (%) of rocks (air-dried)

Rock	Before exposure	After exposure
Pumice	3·8	6·0 (220°)
Pumice	3·8	9·4 (260°)
Pumice	3·8	10·1 (310°)
Pumice	3·8	13·2 (3 days, 340°)
Obsidian	0·24	4·5
Rhyolite	0·14	0·14
Ignimbrite	4·3	2·5
Dacite	0·44	0·34
Andesite	0·70	0·62
Basalt	1·12	0·80
Greywacke	2·76	2·30

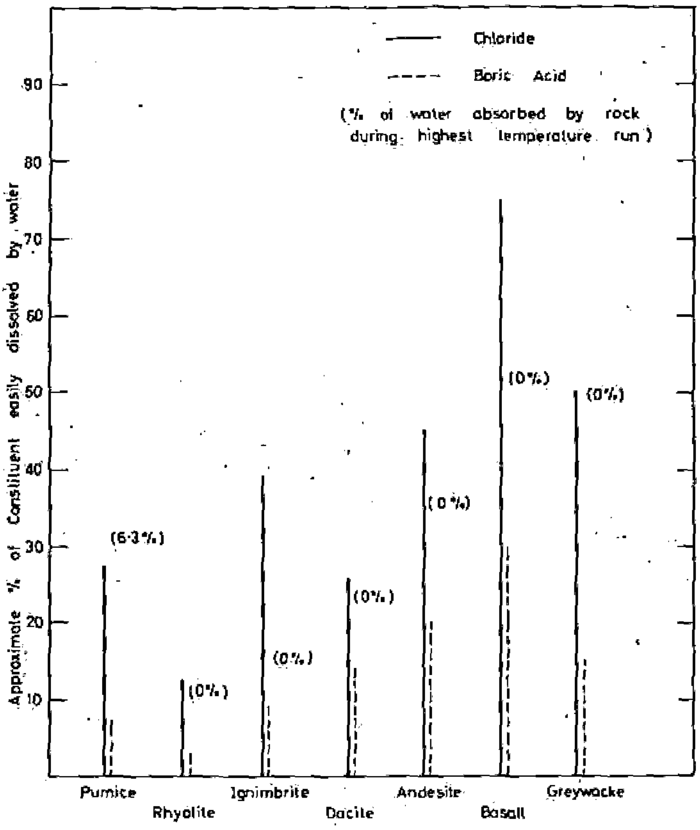

Fig. 5. Proportions of the total chloride and boron in a rock easily dissolved by hot water.

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although during the highest-temperature and largest-time experiments the slight crystallization of the pumice surface would have liberated some chloride from solid solution in the glass. However, the initial rate of liberation of chloride into solution was not controlled by either the rate of devitrification or the rate of diffusion of chloride in the pumice glass otherwise the activation energy would have been higher. The solution of such a high proportion of the total chloride from rocks such as basalt and andesite without there being any visible alteration of the rock minerals or structure is a strong indication that much of the chloride in these rocks is not held in solid solution in rock silicates, but on surfaces in the rocks. The proportion of easily-liberated chloride to total chloride varies from rock to rock and could be expected to be lowest for the massive glassy rocks. The dacite sample proved to be rather anomalous, but it is possible that the easily-leached chloride has already been washed out in nature.

The second increase in chloride concentration with time after the initial solution could be due to the permeation of water into the silicate glasses with liberation of the chloride dissolved in their structure.

(*ii*) *Fluoride.* The results for this element were included by MAHON (1963) in a paper on the chemistry of fluorine in hydrothermal systems. It was apparent that the stable concentrations of fluoride that could be retained in the reaction solutions were limited by the solubility of calcium fluoride in the silica-bearing solutions. However, when a glassy rock, such as pumice, reacted with water, high metastable concentrations of fluoride were formed in solution (see Figs. 3 and 4 compared with Fig. 6). These concentrations, given time, would decrease to the stable level, but for some rocks (particularly the pumice), and at lower temperatures, the experiment times were not sufficient for equilibrium fluoride concentrations to be achieved. For the more crystalline and calcium-rich basic volcanic rocks, high metastable fluoride concentrations were not found, the concentrations of fluoride and calcium being of the order expected from the solubility of fluorite in neutral solutions containing silica. The low concentration of fluoride in the greywacke solutions shows that the element is held within a stable mineral in the rock.

Figure 6 shows the results from recent experiments on the solubility of fluorite in water, and in water saturated with respect to amorphous silica. Earlier results on calcium fluoride solubility in water from BOOTH and BIDWELL (1950) seem too high by a factor of about two. The earlier method involved a filtration within a pressure vessel at the temperature of interest. For a substance more soluble in water at lower temperatures this procedure could lead to high values, as small particles could pass through the filter with the solution, and later dissolve when the bomb was cooled.

The present results were obtained by sampling the hot liquid phase in equilibrium with fluorite crystal chips and with silica-gel within a stainless-steel pressure vessel. The liquid was sampled from its upper volume so that solid particles were not expelled into the sampling line, and equilibrium was checked by daily sampling until constant values were obtained for the temperature. The results of ELLIS (1963) showed that it was not necessary to consider the presence of HF in the vapour phase. Iron, as evidence of corrosion, was not present in the reaction solutions.

It appears that for the fluorite/water system the solution process is essentially an ionic reaction $CaF_2 \rightleftharpoons Ca^{2+} + 2F^-$ up to about 230°. Above this temperature the quantities of fluorine liberated into solution become higher than the stoichiometric proportions required to balance the calcium. The reaction tends to become $CaF_2 + 2H_2O \rightleftharpoons Ca(OH)_2 + 2HF$ and the calcium concentrations are limited by the insoluble nature of calcium hydroxide. The addition of silica allows a more favourable equilibrium of type $CaF_2 + H_2O + SiO_2 \rightleftharpoons CaSiO_3 + 2HF$ to occur, and in this case the fluoride and calcium concentrations liberated into solution are non-stoichiometric down to lower temperatures. The ratio HF/F^- in solution depends on the solubility of $Ca(OH)_2$ or of calcium silicates at any particular temperature, and on the acid dissociation constant of hydrofluoric acid. The pH of the calcium fluoride solutions would be within about a pH unit of neutral whether or not silica was present, due to the small ionization constants of all substances present. From ELLIS (1963) the acid dissociation constant of hydrofluoric acid at 250° is approximately 3×10^{-6}.

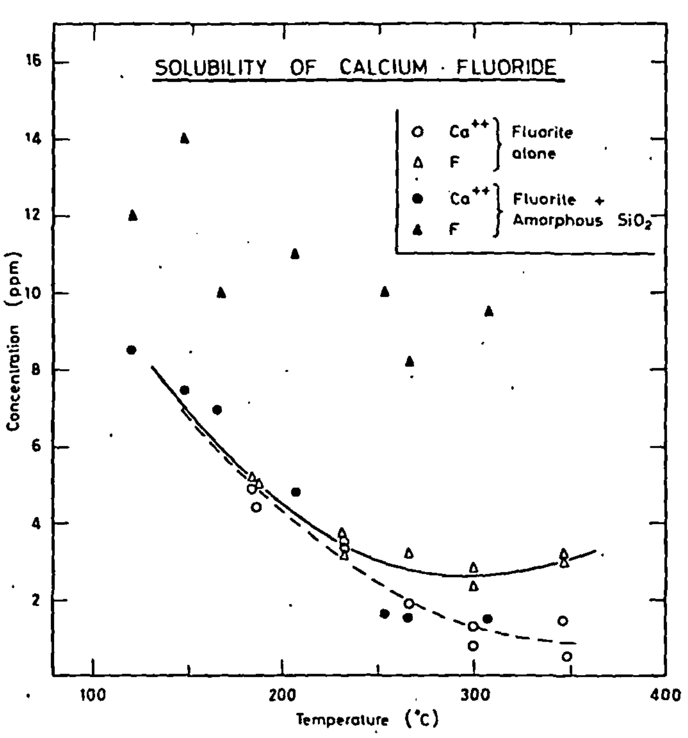

Fig. 6. The solubility of calcium fluoride in pure water and in water saturated with amorphous silica.

If the rock/water reaction solutions were appreciably acid or alkaline, their calcium and fluoride concentrations could not be expected to agree with those in Fig. 6. However, since pH measurements made on the reaction solutions showed close to neutral conditions (pH 6·5–8·0), approximate comparisons are valid.

(*iii*) *Boron.* As for chloride, certain proportions of the total boron in the rock structures were easily removed into solution. However, the fraction of total boron in this category was lower than for chloride, a higher proportion of total boron in

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rocks being apparently bound within the silicate structures. Figure 5 shows the fraction of boron in the rocks readily available for solution, in comparison with the chloride. Again the proportion was highest for basalt and andesite.

The high concentrations of boron liberated into solution at 350° from obsidian are significant, and suggest that, given time for appreciable alteration of their structure, other rocks would liberate increased amounts of boron into solution. This was confirmed by analysis of rhyolitic rock from Wairakei drill-cores showing extensive hydrothermal alteration, which had an average HBO_2 content of only 10–30 ppm, compared with 80–200 ppm in similar, unaltered rock.

The rhyolite gave boron concentrations which decreased rapidly with time during the 350° experiment. A similar behaviour was noted for greywacke. An alteration product formed on the surface of the rocks may have concentrated the boron into its structure. Some clay minerals are known to have a high capacity for boron (Harder, 1961).

The rate of boron liberation from the rocks was usually less than that for chloride, considering the proportions of the elements in the rocks. For greywacke at temperatures below about 250°, boron was liberated at a rate faster than that for the igneous rocks.

The atomic ratios of Cl/B in the solutions from the igneous rocks after the readily-dissolved constituents had been liberated ranged from about 10 for andesite up to about 45 for the pumice. Greywacke gave ratios as low as 0·35.

(*iv*) *Ammonia*. As shown in Table 4, the ammonia content of the igneous rocks ranged from 20–50 ppm, but greywacke contained 280 ppm NH_3. Only a minor proportion of the rock ammonia appeared in solution. For rocks of rhyolitic composition, the ammonia in solution ranged from 1–4 ppm, corresponding to less than 20 per cent of the content in the rocks. For basalt and andesite the concentrations ranged up to 12 ppm, or equal to up to about 30 per cent of the total in the original rock.

A characteristic pattern occurred in the ammonia concentrations in solution for runs with rhyolitic rocks and dacite. An initial period of rapid build-up of ammonia occurred until a maximum was reached, then the concentration declined at a rate greater than that due to dilution during sampling. Alteration products such as clays, zeolites or micas on the surface of the rock particles apparently absorbed ammonia into their structures. This is in agreement with the results of Wlotzka (1961) which showed high ammonia contents in these types of mineral, and with our observations of up to 1000 ppm NH_3 in hydrothermally altered rhyolitic rocks. An equilibrium between solution and alteration products is set up, and the experiments show that the equilibrium solution concentration is of the order of 1 ppm NH_3.

For basalt and andesite the concentrations of ammonia in solution did not decrease appreciably with time. This may have been due to the slower rate of formation of alteration products from these rocks, or to the alteration products having little capacity for ammonia. The basalt results show a minimum during the 300 and 350° runs which suggests that ammonia was first taken up on the rock surface by an unstable alteration product which later changed to a second phase which had a lower capacity for ammonia.

With greywacke only 12 per cent of the ammonia was dissolved from the rock at a rate comparable to that for the igneous rocks, after which the concentrations decreased slowly.

(*v*) *Sulphur*. The total sulphur content of the rocks was not determined, but earlier analyses of similar types have shown the contents to be usually in the range 100–500 ppm. In contact with hot water containing oxygen any sulphides in the rock would hydrolyse to hydrogen sulphide, then the latter would partly oxidize to sulphate. For all the rocks, the sulphate found in the reaction solutions was in the range 10–40 ppm, the highest values being at the lowest temperatures. The oxygen in the distilled water would be sufficient to create about 15 ppm SO_4^{2-} by sulphide oxidation and some additional oxygen would be held around the rock particles. Oxygen availability probably limited the sulphate concentrations in the low-temperature experiments, but at the highest temperatures a solubility equilibrium appears to be the limiting factor, probably that for calcium sulphate, as the lowest sulphate concentrations were obtained from basalt. REZNIKOV and ALEINIKOV (1953) gave the solubility of $CaSO_4$ in water at 301, 331 and 360° as 20, 9·5 and 6·3 ppm respectively, while DICKSON *et al.* (1963) showed for 100 bar pressure a solubility decreasing from 826 ppm at 101° to 56 ppm at 217°.

The pressure vessels, when opened after a run, smelled strongly of hydrogen sulphide which evidently existed to the extent of at least several ppm in the solutions. No tests for carbon dioxide were made although this gas could be formed by decomposition of carbonates and organic material in the rocks.

The higher amounts of sulphate liberated into solution from the greywacke point to the presence of sulphate in the rock. The highest temperature solutions appear to be supersaturated with respect to calcium sulphate and there is a trend with time towards lower values.

(*vi*) *Arsenic*. From the work of ONISHI and SANDELL (1955) the arsenic content of the igneous rocks used in the experiments is likely to be between 2 and 10 ppm. Rhyolitic rocks usually contain more arsenic than do dacites, andesites and basalts. The solution formed by the pumice/water reaction after 72 hr at 310° contained 0·8 ppm arsenic and for andesite after 300 hr at 350° the solution contained 1·3 ppm. An appreciable amount of this element in the rock is therefore available for solution by water.

(*vii*) *Sodium and potassium*. The concentrations of these elements in the reaction solutions depended on the temperature and the rock type. Concentrations of 200–400 ppm of sodium were taken into solution from pumice, ignimbrite, obsidian and basalt at temperatures over 200° during the reaction period. The remaining rocks generally liberated between 50–150 ppm of sodium into solution. Potassium concentrations were always lower than those of sodium.

For pumice at temperatures over 180°, sodium and potassium concentrations in the waters were about constant for the first 8 hr of exposure. With longer reaction times alkali concentrations increased and the ratios of Na/K decreased, which indicated that potassium was at this stage being liberated more rapidly than sodium. Above about 260–270° stable concentrations and ratios were attained for this rock within the experimental period. For obsidian the trends with temperature were similar to those for pumice, but the solution concentrations were lower. At 350°

the results for rhyolite were very similar to those for obsidian. For ignimbrite the concentrations were much higher, and the Na/K ratios were as low as 3·5.

The alkali concentrations in solutions in contact with andesite and dacite were low, and showed little variation with time after 24 hr exposure, or with temperature. Even at 350° after 300 hr the dacite showed little reaction, but andesite reacted to give about 200 ppm of alkalis in solution. Ratios of Na/K were mainly constant and lower than for the rhyolitic rocks. The amounts of sodium and potassium in solutions in contact with basalt increased with rising temperature, although at higher temperatures (250–350°) little further increase occurred. Na/K ratios were low (4–5) and similar to those obtained from andesite. There was a tendency for the ratios to decrease with increasing temperature.

Examples of stable Na/K ratios attained in solution for the various rocks at different temperatures are given in Table 9. For comparison, ORVILLE (1963) obtained for solutions in equilibrium with both sodium and potassium feldspars, ratios ranging from 3·3 at 600° to greater than 5·3 at 400°.

The ratios for the rhyolitic rocks and basalt will have most significance due to the appreciable solution of constituents from these rocks by water during the time of the experiments.

Table 9. Stable values of atomic ratios Na/K attained in experiments

Rock Temperature (°C)	Rhyolitic* rocks	Dacite	Andesite	Basalt	Greywacke
200	17–30	8·5	5	5·5	12–25
250	10–15	7·5–11	6	5·5	15–30
300	8·5–10	8–17	5·5	4·0	14–18
350	3·5–9	9–12	4–8	3·5	8–11

* Includes results for pumice, rhyolite, obsidian, ignimbrite.

(*viii*) *Lithium.* The concentration of lithium in the solutions from the various rocks was of similar magnitude at a given temperature. Previous analyses of several rhyolitic pumices, flow rhyolites and ignimbrites showed their lithium contents to range from 20–80 ppm. The results for greywackes were similar, but for andesites and basalts, lower contents of about 15 ppm and 5 ppm respectively, were obtained. The maximum concentration of this element found in the reaction solutions was about 1·5 ppm; the amounts were usually greatest at the highest temperature.

(*ix*) *Rubidium and caesium.* Analysis of the rocks used in the experiments showed that the caesium contents were 2 ppm or less. The rubidium contents of the four rocks of rhyolitic composition ranged from 40 to 80 ppm and in the dacite, andesite, basalt, and greywacke, the contents were 19, 16, less than 2, and less than 2, respectively. At temperatures up to 350° in the times allowed for reaction, little rubidium or caesium passed into solution. This is not surprising as these ions are presumably held in silicate lattices throughout the rock, and basalt and ignimbrite showed only superficial alteration by the solutions. An exception was obsidian at 350° where appreciable alteration occurred, and a small amount of rubidium was found in the resultant solution.

Some preliminary work was done in extending the reaction temperatures to 500–600°C. In pressure vessels of the type used by KENNEDY (1950b), rocks were reacted with water at 1500 bar pressure for a week at a rock/water ratio of unity (for pumice 0·5), and the resultant solutions were analysed after rapid cooling. The caesium concentration in the solution from the pumice after reaction at 600° was 0·6 ppm, and from the rhyolite 1·4 ppm (this solution also contained 2·0 ppm of rubidium). These additional experiments confirm that with major alteration of the rock, most of the caesium is liberated into solution, as its ion size is too large for it to be favoured as a replacement for other alkalis in hydrothermal alteration silicates.

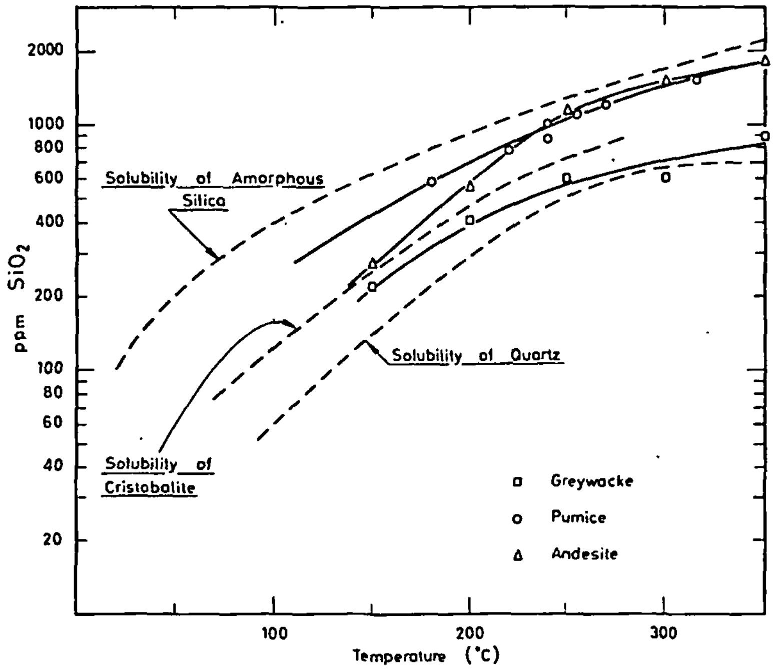

Fig. 7. The concentrations of silica in the solutions derived from the reaction of various rocks with water.

(*x*) *Magnesium*. In all the solutions examined, the magnesium concentrations were less than 1 ppm, and the concentrations showed little relationship to the magnesium contents of the rock, e.g. basalt and pumice at similar temperatures gave approximately equal solution concentrations. Magnesium is strongly sorbed into rock alteration products.

(*xi*) *Silica*. As might be expected for the major rock constituents, the concentration of silica in solution rapidly attained an initial equilibrium concentration, which for all rocks lay between the concentrations for saturation with respect to quartz and to amorphous silica. Figure 7 shows the changes in the initial equilibrium silica concentrations with temperature, and includes lines for the solubility of amorphous silica and quartz (Kennedy, 1950a) and of cristobalite (Fournier and Rowe, 1962).

The silica results for pumice and dacite followed the trend of the line for amorphous silica, but the solubilities were about 20 per cent lower. The concentrations in solutions from andesite and basalt were little different from those for pumice

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at temperatures above 225°, but at lower temperatures the concentrations were much less. The general approach to the amorphous silica solubility line reflects the essentially glassy nature of the volcanic rocks. From the silica concentrations, the activity of silica in the glasses of dacite and pumice was about 0·75 to 0·85 of that for pure amorphous silica. As the molecular fraction of SiO_2 in these glasses is about 0·77 to 0·80, a close to ideal solution behaviour is indicated for silica in the rock glasses. At temperatures over about 200°, the results for andesite and basalt tend towards the amorphous silica solubility curve.

The silica concentrations for obsidian are not shown in Fig. 7 but fell closer to the cristobalite solubility line than to that for amorphous silica. This agrees with the petrological observation of cristobalite as the first product of crystallization of obsidian, but the reason for the different behaviour of the two glasses, pumice and obsidian, is not clear.

Greywacke gave the lowest concentrations of silica in solution, the values above 250° approaching the solubility of quartz. Higher relative silica concentrations at lower temperatures suggest the presence of a small proportion of amorphous silica or cristobalite in the greywacke, which recrystallized readily to quartz at higher temperatures. However, this was not apparent from the petrological examination.

RELEVANCE OF EXPERIMENTS TO NATURAL SYSTEMS

(a) *Rock-to-water ratios*

The experimental results for water-soluble constituents such as chloride, fluoride, boric acid and ammonia showed an important fact about their occurrence in rock structures. Some of the more crystalline rocks readily liberated a high proportion of their content of these constituents before showing evidence of hydrothermal alteration, whereas the glass-rich rocks liberated smaller proportions of the elements even though some alteration of the glass occurred. The water-soluble constituents are held not only in solid solution in the silicate structures, but to a large extent exist on surfaces of grains, crystals and microfissures in the rock. A breakdown of crystal structures is not required to liberate appreciable amounts of chloride etc., into aqueous solution, and therefore pick-up of these constituents by water can occur more readily than has usually been considered.

The reaction solutions were all of about neutral pH, and much of the readily-soluble material appears to have been extracted by simple solution rather than by extensive reaction of rock minerals with water. Changing the rock-to-water ratio in a static system would change the concentrations of the solution constituents accordingly. In natural circulation systems the ratios of rock to water would be much greater than in the present experiments. From porosity measurements, ratios of ten to twelve appear to be reasonable values for recent volcanic areas, and probably still higher ratios in areas of sedimentary or metamorphic rocks. Chloride concentrations of about 50–400 ppm found in the experiments with volcanic rocks would become of the order of 200–2000 ppm if in a static system the rock-to-water ratio was ten. Similarly, boric acid concentrations would become of the order of 20–150 ppm HBO_2. These examples would be minimum figures as the rock and water reactions had certainly not gone to completion. Maximum concentrations for complete reaction are obviously limited by the element content in the rock (Table 4).

For greywacke rock, the minimum concentrations of chloride and boric acid calculated for a rock/water ratio of ten would be 50 ppm and 180 ppm, respectively.

The results from closed-chemical-reaction systems cannot as yet be applied quantitatively to natural thermal waters involving heating and convection of meteoric water. Any relevant discussion would imply knowledge that does not exist at present on the rate of turnover of natural hydrothermal systems, their age and the types of heating mechanism. As all the trace elements in the rocks are not removed with the same ease, natural circulation of hot water could cause differential extraction of the elements, e.g. chloride removed before boron. Variations in a ratio such as Cl/B between thermal areas in similar rocks could, therefore, give some idea of the relative stage of development of the natural systems. The major difficulty is that the ratio of reservoir-storage volume to the total-circulation volume of water over the lifetime of a natural thermal system is not known. It is quite possible that after the initial production of hot water, a Wairakei-type system is in a process of decay rather than of a continuing thermal-equilibrium convection cycle.

The discussion below is not taken further than to show the concentrations of the most soluble elements such as chloride and boron that could be produced in closed reaction systems at reasonable natural rock-porosity values (about a rock/water ratio of ten in recent volcanic hydrothermal areas).

(*b*) *The reaction time factor*

The results suggest that two processes are of importance in the liberation of trace elements from rocks. First, a porportion of chloride, boric acid, ammonia and possibly other constituents is held adsorbed on surfaces in the rock and is readily available for solution by water. This material is likely to be removed by hot water in a relatively short time in the geological sense. Secondly, the trace constituents which are held within silicate lattices, but are otherwise of a type favouring concentration in the water phase, would be released only when the silicates are decomposed or recrystallized by hydrothermal alteration. It is impossible to wait a sufficiently long time for complete rock alteration to occur in the laboratory at reaction temperatures much below 250–300°C, but it seems likely that where temperature-dependent solubility equilibria are not involved, the high-temperature results can be used to suggest the solution concentrations that would occur at lower temperatures if the reaction times were extended. To this extent the highest-temperature experiments were the most significant of the series. The mineralogy of drill-cores from the N.Z. hydrothermal areas (Steiner, 1958b), shows that the end product of hydrothermal alteration of rhyolitic rocks at 200–260° is an assemblage consisting of calcium zeolites, secondary potash-rich feldspars, and hydromica. Analysis of a selection of cores showed that over 80–90 per cent of the original chloride and boron in the rock are lost during natural alteration.

(*c*) *Individual elements*

The amounts of chloride and boron which can be released from the volcanic rocks during hydrothermal alteration are more than sufficient to give element concentrations in a coexisting water phase which are comparable with the levels found in the recent New Zealand volcanic hydrothermal systems. Any hot water

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that has been in contact with fresh volcanic rock must inevitably contain constituents such as chloride and boric acid. The lower availability of chloride and higher amount of boric acid obtainable from greywacke is in good agreement with the compositions of the New Zealand warm spring waters issuing from this rock.

Fluoride, sulphate, calcium and magnesium are available from the rocks in excess of the amounts required to explain their concentrations in natural waters. They are limited in concentration by temperature and pH dependent mineral/solution equilibria, particularly at high temperatures where sulphates, carbonates and fluorides are very insoluble.

The ammonia concentrations also appear to be dependent on a distribution between the solution and clay, zeolite or mica alteration minerals. With the exception of those at Ngawha, the ammonia contents of the natural waters are similar to the concentrations found in the experiments. The levels of concentration in the recent volcanic springs are little different from those in the warm springs. At Ngawha the ammonia is probably derived from the surface sediments high in organic material, through which the waters pass.

ONISHI and SANDELL (1955) concluded from their survey of arsenic in igneous rocks that the arsenic in thermal waters could not have been derived from rock/water reaction. However, the present results suggest that at a rock/water weight ratio of ten, concentrations of at least 6–8 ppm arsenic could be expected in solutions in contact with rhyolite pumice or andesite, providing that the element is not held at lower levels by solubility-product relationships.

The silica concentrations in natural waters are temperature dependent, and give little information about the origin of the waters. The high metastable concentrations of silica in the reaction solutions suggest that natural hot water migrating into fresh volcanic rock could cause extensive solution of silica and later redeposition as quartz. Considerable transport of silica could occur, depending on the relative rates of silica solution and deposition. An outward migration of a hydrothermal reservoir into fresh country may be a very slow process due to the flow channels into the cooler country becoming choked with silica or quartz deposits. The sealing of a system by silica may be important in localizing high-temperature volcanic thermal water reservoirs.

Comparison of Table 1 with Table 9 shows that the atomic ratios of Na/K in the waters at Wairakei, Waiotapu, Kawerau and Rotorua, where waters are drawn from reservoir systems in rhyolitic rock at known temperatures, are in good agreement with values obtained in the experiments. For Kawerau, Waiotapu and Wairakei the underground temperatures are 250–295°C, and for Rotorua about 150–200°C. Both experimental and field results show that an equilibrium Na/K ratio in solution exists at each temperature, and this fact was used by ELLIS and WILSON (1960) to indicate water movement within the Wairakei hydrothermal system. The concept of a reversible temperature-dependent Na/K ratio in the natural solutions probably fails below about 150–200° because of slow reaction rates, and for the same reason the experimental ratios for dacite, andesite and greywacke are probably of little practical significance.

A notable feature of the high-temperature waters from the recent volcanic areas is their high content of the rare alkalis, lithium, rubidium and caesium. The solution experiments show that these elements are dispersed throughout the rock structures, and are not concentrated to any great extent on surfaces as are chloride and boron. There is adequate lithium and rubidium in the rhyolitic rocks to account for the observed concentration of these elements in waters from recent volcanic areas, assuming that rock/water weight ratios of the order of ten can be applied, and that at least 10 per cent of the elements are liberated into solution during a hydrothermal reconstitution of the rock. To obtain caesium concentrations of up to 4·7 ppm which are found in these waters (GOLDING and SPEER, 1961), it would be necessary to have 0·5 ppm caesium in the rock at a rock/water ratio of ten, if complete extraction of caesium occurred. Analysis by an ion-exchange/flame-photometry technique indicated that the caesium content of some New Zealand rhyolitic rocks is within the range 0·75–2 ppm. The preliminary 600° experiments noted above show that with extensive alteration of the rocks by water a high proportion of the caesium can be transferred into solution.

Rare-alkali concentrations in the warm springs of New Zealand are mainly very low (Rb and Cs are negligible except at Ngawha) and there is little distinction between springs in old volcanic areas and those in greywacke or sedimentary areas. The Na/Li ratio for Maruia Spring is of a value common for recent volcanic springs, but the other results for this ratio in Table 3 are generally much higher.

Carbon dioxide and carbonate species have been neglected in this study but it was found in preliminary additional experiments that the main effect of adding carbon dioxide to the reaction vessels was to increase the rate of reaction between rock and water. Bicarbonate formed by reaction of carbon dioxide with rock until approximately neutral pH conditions for the temperature were achieved. It is intended to do further work on rock extraction with carbon dioxide solutions.

CONCLUSIONS

The laboratory experiments were designed to show to what extent the chemical composition of natural hot waters could be profitably used as evidence in working out the processes which create natural hydrothermal systems. In discussions of these systems the presence of elements such as ammonia, boron, fluoride, lithium and chloride in high concentrations in thermal waters has often been taken as evidence for magmatic water in the hot discharges. Magmatic water is defined as the water leaving a molten rock system, and some writers (including in the past the present authors) have quoted pegmatites as an analogy where elements such as lithium and boron are concentrated in a residual fluid as the parent molten rock body crystallizes.

From the present study it is apparent that the compositions of natural thermal waters can also be approached by the interaction of hot water with rock at moderate temperatures. This does not necessarily exclude the concept of magmatic water, but does show that the composition of magmatic water (for such water must at times exist in nature whether or not it has any bearing on the hydrothermal systems under discussion) is not unique. It should also be noted that magmatic water is not necessarily water that has risen from greater depths with the rock melt. KENNEDY (1955) showed that a rock melt entering a zone of high water pressure could absorb several per cent of water which would be expelled again later when the rock crystallized. Magmatic water, therefore, may be local meteoric water which has passed through a silicate melt.

The approach which appears most profitable is to assume that where rock and hot water co-exist in nature at temperatures of say, over 150°, the times of contact are sufficient for an equilibrium distribution of certain elements between phases to be established. The times available for reaction are very great compared with those in the laboratory experiments. The water phase would concentrate constituents such as lithium, caesium, chloride and boron that are not readily accommodated in secondary silicate structures. The concentration effect may be greater at moderate temperatures than at high temperatures (e.g. EUGSTER's (1955) results on the distribution of caesium between feldspar and water at temperatures of 400–800°C).

There are actually few elements present in thermal waters at temperatures of up to 300°, whose concentration is not governed by equilibria with solid phases in the confining rocks. The principal exceptions, at least at these temperatures, appear to be chloride, bromide, boron, caesium and possibly arsenic and lithium. The distribution of these elements is likely to be so much in favour of the water phase that it is doubtful if it would be possible to distinguish whether the elements in solution resulted from a process of "extraction" from solid rock at, say 200–300°C, *or* from a water-rich fluid separated from a crystallizing molten rock at perhaps 600–800°C, and which was subsequently diluted with meteoric water.

In the light of the experiments the chemical composition of thermal waters could in many cases be deduced from their temperatures for a given underground rock environment, but it is doubtful whether a unique mechanism of origin of high temperature thermal waters could be derived from their chemical composition. In rocks of a particular composition, bodies of thermal waters of similar type but different origin could exist, some containing water from a high-temperature magmatic source, yet others containing no water whose temperature had exceeded the moderate temperatures of the storage system.

A decision on which is the more likely alternative for a particular area will have to be made largely on the basis of whether or not sufficient rock/water interaction could occur to account for the transfer of chemicals. The study of rock/water stable-isotope equilibria, and of the tritium and C^{14} contents of waters as indicators of circulation times, will also be of great assistance. Unfortunately, judging from New Zealand experience, the rock environment of interest is likely to be at a depth of several miles, and can only be inferred. For hydrothermal systems in old areas of dense rock such as those at Steamboat Springs, Nevada, the magmatic-water approach adopted by WHITE (1957) appears reasonable, but for young areas of permeable volcanic rocks such as in the North Island of New Zealand the simple rock/water interaction mechanism is a possibility that cannot be ruled out on the basis of water compositions.

Concentration of elements in an aqueous residual magmatic fluid is only a special case of a distribution equilibrium which, given time, should establish itself between rock minerals and water at all temperatures in situations where complete reconstitution of the original rock occurs. In view of the current arguments over the genesis of ore-bearing fluids this should be checked by further quantitative experimentation. To this end the rock/water distribution studies at higher temperatures and sub-melting water pressures are being extended to cover a wider range of rocks and elements. The results may be of interest both in the study of hydrothermal systems and of the generation of ore-bearing solutions.

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"NONCONDENSABLES" IN GEOTHERMAL FIELDS

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ABSTRACT

The behavior of gases in geothermal fluids was studied at Republic Geothermal, Inc.'s (RGI's) East Mesa test site. Specifically, the solubility of carbon dioxide (CO_2) and nitrogen (N_2) as a function of temperature and pressure was investigated in detail by chemical analyses and theoretical evaluations.

Carbon dioxide determinations in the field were made using a newly designed sampling device. The analytical data give reliable CO_2 mass balances in the system $H_2O - CO_2$.

An attempt was made to generate a numerical model capable of describing and predicting the complicated phase behavior of CO_2 and N_2 in geothermal fluids. The thermodynamic model developed can be applied to predict the CO_2 and N_2 gas behavior in reservoirs, well bores and surface equipment. Although intended for East Mesa, it can easily be expanded to almost any geothermal system and to other gases.

Fundamentally, the model is based on Henry's Law and takes into account the nonideal behavior of CO_2 and its solubility in waters having any ionic strength. Initial comparisons of sodium bicarbonate ($NaHCO_3$) content of the fluid resulted in large errors. Thus, the new model was revised to take the $NaHCO_3$ content into account with subsequent good agreement between predicted and measured behavior.

Relative to other geothermal fields, the CO_2 concentration in the fluids at East Mesa was found to be very low (≃ 1000 ppm). Nonetheless, it will still require a significant investment in power plant extraction equipment to handle the noncondensables conventionally. The new model predicts a disproportionately high CO_2 concentration in the first stage flash and very low concentration in the second stage flash. Consequently, a simple vent process is proposed that will remove most of the CO_2 from the water before any major steam flash is taken.

References and illustrations at end of paper.

INTRODUCTION

A geothermal reservoir can contain fluids in either a single or two phase condition. The fluid in RGI's East Mesa geothermal reservoir consists of a single phase liquid, i.e., water, with no apparent gas phase. Gases dissolved in the liquid phase under reservoir conditions may, however, "break out" of solution as this liquid phase is produced. This gas evolution from the liquid phase is experienced due to temperature and pressure decreases during production; with the various types of gases (CO_2, N_2, AR, hydrocarbons, etc.) evolving at different rates. The amount and composition of this gas phase may change continuously due to temperature and/or pressure drop during the process of producing and utilizing the geothermal fluid.

The behavior of gases in the reservoir, well bores, and surface equipment during geothermal production operations is important and must be understood in detail. The objectives of the present work were to:

1) Determine the CO_2 and other gas concentrations in the geothermal fluid at various pressures and temperatures in the field.
2) Develop a computer model to calculate gas concentrations for various thermodynamic conditions.
3) Compare measured with calculated data and define the reliability of the model.
4) Suggest handling processes for noncondensables in RGI's East Mesa field and power plant operations based on model results.

CO_2 DATA AS A VITAL GEOTHERMAL PARAMETER

Carbon dioxide is a major component of most gases observed in geothermal systems and deserves special attention for the following reasons:

1) Its phase behavior often determines the pH value of the geothermal liquid, and with that the detrimental formation of carbonate scale, particularly $CaCO_3$ and $FeCO_3$.

2) Its rate of production can be very high, resulting in the need for special and expensive equipment for its removal. For example, large vacuum pumps or steam ejectors may be required downstream of a barometric condenser in a flashed steam process power plant.

3) The injected water after a flash process can have a very high pH value due to the lack of CO_2. Recombining of the separated CO_2 with the heat-depleted geothermal brine downstream of the power plant and injection of the recombined fluids may or may not be desirable from an injectivity standpoint. Lowered pH may benefit injectivity of the recombined fluids by dissolution of $CaCO_3$ around the well bore, but the compatibility between the native rock and injected fluid in the reservoir may be a problem.

4) Large volume sources of pure CO_2 are rare in the USA, and the CO_2 as a by-product of geothermal operations may become a valuable commodity.

SAMPLING AND ANALYSES OF GASES

There are a number of publications concerning various types of sampling and analytical methods for determining the concentrations of gases in geothermal operations. A comprehensive overview and literature search on this subject will be published soon by Battelle PNL[1]. Presently, it can be stated that CO_2 and other gas determinations are subject to major sampling and analytical problems. The work reported herein required development of at least partial solutions to some of these problems for its completion.[2,5]

CARBON DIOXIDE SAMPLING AND ANALYSES

The main sampling device used at East Mesa consisted of the gas absorber shown in Figure I, which can be used anywhere within the test facility. A solution of two normal NaOH is placed in both the main trap and the gas trap. The volume of the NaOH solution in the main trap is measured by fill marks. The produced mixture, condensate gas or any other geothermal fluid, is then allowed to rise to the liquid level in the main trap from one fill mark to the next, thus allowing the measurement of the dilution. Any reactive gas escaping the main trap is absorbed in the gas trap (second leg). After reaching the upper fill mark in the main trap, all valves are closed and the entire apparatus is shaken to allow for the absorption of still unabsorbed CO_2 in the dead volume gas space above the fluid level. Then, a sample is drawn from both legs of the apparatus and analyzed for CO_2 by either one of two ASTM methods:

1) Total CO_2 by Evolution[3]

2) Titration[4]

The entire method, i.e., sampling and analyses, is calibrated with a blank of two normal NaOH without a sample entering the apparatus. The CO_2 determined in these blank determinations is subtracted from the final analytical result. Typical examples of the measured CO_2 concentrations are given in Tables I and II. The first column of data (IDENTIFICATION) lists the location where the sample is taken and the volume (and ratio) of the 2N NaOH and actual sample. The fourth column (MG CO_2 PER LITER OF SAMPLE) lists the raw analytical data measured in the mixture of sample and NaOH. Finally, the fifth column (MG CO_2 PER LITER OF COOLED LIQUID) shows the calculated and true concentration of CO_2 in the sampled fluid.

The data listed in Tables I and II can be used to perform a material balance for the total CO_2 content within the geothermal test system. Assuming a water flash of ten percent and the CO_2 concentrations listed in Table I, i.e., wellhead water (1098 mg/liter), steam condensate (6746 mg/liter), and discharged water (444 mg/liter) yields an almost perfect balance. Using the CO_2 concentrations in the steam and the discharged water, the calculated CO_2 concentration in the wellhead water should be 1075 mg/liter. The actually measured concentration is 1082-1098 mg/liter. The difference between measured and calculated value is only on the order of 15 mg/liter or less than 1.3 percent of the calculated value. This almost perfect agreement shows that this analytical method gives accurate, reliable, and useful data.

The chief disadvantage of this method is that the results yield only the total CO_2 concentration in the liquid or steam. The distinction between the various species of the CO_2, i.e., physically dissolved CO_2, bicarbonate ions (HCO_3^-) and carbonate ions ($CO_3^{=}$) cannot be made by this method. On the other hand, the different ionic CO_2 species can be approximated if the pH value of the liquid[5] and the total CO_2 concentration are known by using the data given by Latimer[6] (see Table III). Using this approach yields the distribution of the various CO_2 species at 20°C and not at the higher temperatures of the fluids in the test facility. However, using the dissociation constants given by Helgeson[7], the data listed in Table III can be corrected to the in-line temperatures, thus providing a reasonable approximation of the concentration of the various CO_2 species as a function of total CO_2 concentration, temperature and pH.

SAMPLING AND ANALYSES OF OTHER GASES

There are a number of methods for obtaining gas samples for the analytical determination of gas composition in geothermal operations. The collected gas samples are analyzed by either gas chromatography or mass spectrometry.

The sampling methods used at East Mesa include a number of enrichment methods based on physical sample separation and various absorption methods, as well as modifications of the gas absorber method discussed previously. In some cases, the samples were collected by the enrichment of individual gas components with the proper choice of absorbers. In other cases, the main component (CO_2) was removed by absorption and the remaining enriched gas phase was analyzed for the components of interest.

All methods, method comparisons, and many results obtained at the RGI East Mesa test site will be treated in depth in the Battelle PNL[1] report. Some of the preliminary results are given in Table IV. The large nitrogen concentration in these gases is highly unusual for geothermal fluids. Presently, it is assumed that this high N_2 concentration is formed in the reservoir by the decomposition of NH_3 as suggested by Seward[8].

MODELING OF GAS BEHAVIOR IN EAST MESA GEOTHERMAL FLUIDS

In order to design and construct a power plant it is necessary to predict the solubility behavior of the principal gasses, i.e., CO_2 and N_2, under all practical operating conditions (temperature, pressure and brine composition). In addition, the solubility behavior of CO_2 must also be known in detail to predict any carbonate scale formation in geothermal operations. Therefore, a computational method to predict the CO_2 and N_2 phase behavior was developed. The model is a numerical simulation of the evolution of CO_2 and N_2 in a power plant utilizing the direct flash steam cycle.

The description of the model development which follows, proceeds sequentially from a very simple model to one that gets progressively more complex as the various pertinent factors are introduced.

SIMPLE MODEL FOR FLASH IN AN H_2O - CO_2 SYSTEM

The basic model describing the phase behavior of CO_2 and water in a power plant utilizing a flash cycle may be represented schematically as shown in Figure II. In developing the model, initially it is assumed that:

1) The vapor phase is a perfect gas.

2) Water and CO_2 form an ideal solution in the liquid phase.

3) There is no reaction between CO_2 and H_2O.

4) The wellhead fluid consists of distilled water and dissolved CO_2.

For this system, one can apply the heat balance, mass balance and the equilibrium conditions as shown below:

1) Heat Balance.

Enthalpy of the feed = enthalpy of the vapor + enthalpy of the liquid phase

$$FH_F = VH_V+LH_L \qquad (a)$$

Dividing equation (a) by F gives:

$$H = (V/F)H_V+(L/F)H_L \qquad (b)$$

Let

$V/F = \Psi$, the fraction of flash, then
$L/F = 1-\Psi$

Therefore,

$$H_F = \Psi H_V+(1-\Psi)H_L \qquad (1)$$

Equation (1) may be solved to obtain the value of Ψ:

$$\Psi = (H_F-H_L)/(H_V-H_L) \qquad (2)$$

2) Mass Balance.

Mass of CO_2 in the feed = Mass of CO_2 in the vapor + Mass of CO_2 in the liquid

$$FX'_{CO_2} = VY_{CO_2} + LX_{CO_2}$$

$$X'_{CO_2} = (V/F)\ Y_{CO_2} + (L/F)\ X_{CO_2}$$

$$X'_{CO_2} = \Psi Y_{CO_2} + (1-\Psi)\ X_{CO_2} \qquad (3)$$

Where

X'_{CO_2} = Mole fraction of CO_2 in the feed

3) Equilibrium Conditions.

Under the assumptions specified, the solubility of CO_2 in water is controlled by Henry's Law and is given by:

$$P_{CO_2} = HX_{CO_2} \qquad (4)$$

Assuming that the vapor phase consists of steam and carbon dioxide,

$$Y_{CO_2} = P_{CO_2}/P_T$$

Using the above equations, equation (4) becomes:

$$Y_{CO_2} = (H/P_T)\ X_{CO_2} \qquad (5)$$

Thus, the problem of calculating the amount of CO_2 emission upon flashing the reservoir fluid consisting of distilled water and CO_2 may be solved with the three equations, (2), (3) and (5).

The solubility of CO_2 in water has been studied extensively by various investigators[7,9-12] and the Henry's Law constant may be given by the empirical equation developed by Naumov, et al[13]. Their equation is modified to fit the units used in this paper and is given by the following equation:

$$\text{Log } H = -(3178.6/T)+58.9525-7.677 \ln T+ 0.299x10^{-3}T-0.225x10^{5}T^{-2} \qquad (6)$$

The value of the Henry's Law constant predicted by equation (6) agrees very well with those measured by others,[7,9-13] and is used to calculate the Henry's Law constant in this paper. The above calculations involved iterations because of the lack of the total pressure (P_T) value after flashing. Initially, the total pressure is taken to be equal to the saturated vapor pressure of water at the flash temperature. Equations (1) through (6) are used to obtain the CO_2 distribution in the liquid and vapor phases. From the mole fractions of CO_2 and H_2O in the vapor phase, the partial pressure of CO_2 in the vapor phase, and hence, the total pressure (P_T) are calculated. The new P_T values are used and the calculations repeated. The process is repeated until there is no change in the P_T value. Usually, the final values can be obtained in five iterations or less.

The calculated emission characteristics at various flash conditions covering a range of initial CO_2 concentrations of general geothermal interest and feed water temperatures of interest at East Mesa are shown in Figure III. Figure IV shows the rate of CO_2 emissions as a function of percent flash using geothermal fluid containing 978 mg CO_2 per liter wellhead water at 320°F, 335°F, and 350°F, for a 64 MW power plant.

MODIFICATION FOR NONIDEAL GAS

The nonideality of CO_2 is taken into consideration and the fugacity of CO_2 was calculated using the Benedict-Webb-Rubin[14] (BWR) equation of state. The BWR constants for CO_2 are calculated from the generalized BWR constants as derived by Su and Viswanath[15]. These values of fugacity are then substituted in place of the values of pressure in the model.

The calculated fugacity data for CO_2 as a function of temperature and pressure clearly indicate that a very small error is introduced in using the values of pressure in place of fugacity for low pressures. At relatively high pressure (above 300 atm.) and lower temperatures, the use of fugacity in place of pressure is advisable. For the analysis of CO_2 data from East Mesa field or any other known geothermal operation, this modification is not necessary. However, for the sake of completeness and to avoid any further doubt, the model includes the fugacity effect.

MODIFICATION FOR PRESSURE EFFECTS ON THE LIQUID

In this section the nonideal behavior of the liquid phase is introduced into the model through the effect of pressure on Henry's Law constant. This influence arises through the effect of pressure on Gibbs free energy of the solution. Henry's Law in the usual form is written as:

$$f_{CO_2} = H\ X_{CO_2} \qquad (7)$$

The value of the Henry's Law constant at any temperature and pressure may be determined using the equation below[16,17]:

$$\log H(T,P) = \log H(T,P=1) + (1/RT2.303)\bar{V}_{CO_2}(P-1) \qquad (8)$$

$\bar{V}_{CO_2}$ values were calculated from the empirical equation given by Naumov, et at[13].

Using equation (8), Henry's Law constant at any pressure can be calculated and is used in equations (2) and (3) to obtain the concentrations of CO_2 in the liquid and vapor phases after flashing, taking into account the nonideal behavior of the vapor phase as well as the effect of pressure on the liquid. As with the fugacity correction, the calculated CO_2 evolution characteristics taking these modifications into account for various flash conditions and a single feed water CO_2 concentration and temperature are not significantly different from those ignoring these two parameters.

MODIFICATION FOR LIQUID REACTIONS AND IONIC STRENGTH

In this section, two modifications are introduced into the model. First, the pertinent reactions that take place in the liquid phase between H_2O and dissolved CO_2 are considered in order to derive an equation for the pH of the solution. Second, the effect of ionic strength on the activity coefficients of ionic species are calculated using Debye-Hueckel theory and the resulting activities are used in place of the concentrations in the model.

The equilibrium reactions to be considered are:

$$CO_2(g) = CO_2(aq) \qquad (A)$$

$$CO_2(aq)+H_2O = H^+ + HCO_3^- \qquad (B)$$

$$HCO_3^- = H^+ + CO_3^{2-} \qquad (C)$$

$$H_2O = H^+ + OH^- \qquad (D)$$

Here *(g)* refers to CO_2 in the gas phase and *(aq)* refers to CO_2 dissolved in the aqueous phase.

The equilibrium constants of these reactions may be represented by the equations below:

$$H = P_{CO_2}/\gamma_{CO_2}M_{CO_2} \qquad (9)$$

$$K_1 = (\gamma_{H^+}\gamma_{HCO_3^-}/\gamma_{CO_2})(M_{H^+}M_{HCO_3^-}/M_{CO_2}) \qquad (10)$$

$$K_2 = (\gamma_{H^+}\gamma_{CO_3^{2-}}/\gamma_{HCO_3^-})(M_{H^+}M_{CO_3^{2-}}/M_{HCO_3^-}) \qquad (11)$$

$$K_w = (\gamma_{H^+}\gamma_{OH^-})(M_{H^+}M_{OH^-}) \qquad (12)$$

The constants K_1 K_2, and K_w are functions of temperature and are given by the following equations[21-24]:

$$\text{Log } K_1 = -2382.3/T + 8.153 - 0.02194T \qquad (13)$$

$$\text{Log } K_2 = -2730.7/T + 5.388 - 0.02199T \qquad (14)$$

$$\text{Log } K_w = -4470.99/T + 6.0875 - 0.01706T \qquad (15)$$

By a consideration of charge neutrality and a mass balance for CO_2 in the aqueous medium, the pH of the solution can be determined as a function of temperature and partial pressure of CO_2. The resulting equation may be written as:

$$M_{H^+}^3 - C_1\ M_H + -C_2 = 0 \qquad (16)$$

$$\text{where } C_1 = (K_w/\gamma_{H^+}\gamma_{OH^-}) + (K_1P_{CO_2}/H\ M_{H^+}\gamma_{H^+}\gamma_{HCO_3^-})$$

$$C_2 = 2\ K_1K_2P_{CO_2}/H\gamma_{CO_3^{2-}}(\gamma_{H^+})^2$$

A similar development for pH determination has been presented by Jackson[19] and Ryzhenko[20,21].

The activity coefficients of the charged species may be calculated by using modified Debye-Hueckel theory and in this report, the equations presented by Kharaka and Barnes[18] are used.

The coefficients for the charged aqueous species are written as:

$$\text{Log } \gamma_i(T,I) = -A(T)\nu_i^2 I^{½}\{1+a_i^{\circ}B(T)I^{½}\}+B^{\circ}(T)I \qquad (17)$$

where a_i^o = the distance of the nearest approach of ions in solution

$A(T), B(T)$ = molal Debye-Hueckel coefficients

ν_i = ionic charge

I = ionic strength

B^o = a deviation function

The constants $A(T)$ and $B(T)$ are given by

$$A(T) = 1.8246 \times 10^6 \, \varepsilon^{1/2}/(\varepsilon T)^{3/2} \quad (18)$$

$$B(T) = 50.29 \times 10^8 \, \varepsilon^{1/2}/(\varepsilon T)^{1/2} \quad (19)$$

where ε is the dielectric constant of water and is calculated using the empirical equations available[22,26]. The ionic strength (I) of the solution may be calculated by the equation:

$$I = \tfrac{1}{2}\Sigma_i M_i \nu_i{}^2 \quad (20)$$

The density (ρ) of water is calculated using the equation presented by Kell[25]

Calculations from the above show that an increase of ionic strength from zero to three would increase the emission of CO_2 by 30 percent, and 23 percent less would remain in the fluid for small flashes. However, because of the low ionic strength and low concentration of CO_2, the effect of ionic strength may be neglected at East Mesa.

CO_2 MODEL APPLICATION TO EAST MESA

In applying the model to calculate the evolution of CO_2 from geothermal fluids using a flash cycle, a distinction must be made regarding the so-called "flashable" and "non-flashable" part of the total measured CO_2 in the wellhead fluid. The measured value of the CO_2 concentration in the wellhead fluid is the sum of the flashable and the non-flashable forms of CO_2. The flashable CO_2 is that which is dissolved in the fluid in molecular form. The non-flashable CO_2 is that which is due to the bicarbonate and/or carbonate salts dissolved in the fluid. The distinction between the flashable and non-flashable forms of CO_2 has not been considered in the foregoing model development.

RGI's East Mesa waters contain large concentrations of sodium bicarbonate, as indicated by the high pH value of 9.2 after flashing and confirmed by the chemical analyses. Therefore, the application of the model as constituted thus far, assuming all the wellhead CO_2 is flashable and ignoring the presence of non-flashable bicarbonate or carbonate content in the fluid, predicts a CO_2 concentration too high in the steam and too low in the discharged water. As an example, assuming a total of 1070 mg CO_2 in the wellhead fluid is flashable, the predicted CO_2 concentration for a 228°F flash temperature is 12,220 mg of CO_2 per liter of steam condensate and 1.7 mg of CO_2 per liter of the discharged water. The measured values (see Tables I & II) are 7030 mg of CO_2 per liter of steam condensate and 440 mg CO_2 per liter of discharge water. This large difference between predicted and measured values is obviously unacceptable.

The deficiency of the model can be eliminated by calculating the flashable CO_2. However, this would require a knowledge of the pH value (or the bicarbonate and carbonate concentrations) at any flash temperature. The dissociation reactions of the bicarbonate and carbonate salts have to be taken into account and the non-flashable CO_2 concentration has to be calculated at each flash temperature.

In order to achieve an agreement between the calculated CO_2 concentrations and the observed values, two simplifying assumptions must be made:

1) The 440 ppm of CO_2 observed in the liquid phase after separation in the above example is assumed to be due to the presence of sodium bicarbonate. This assumption is reasonable considering the high pH value of 9.2[27]. The additional presence of carbonate, which requires elaborate calculation and is much less significant, is not accounted for.

2) The concentration of bicarbonate is not dependent upon the flash temperature. This assumption is not entirely valid, but is a reasonable approximation.

The approximate validity of the two assumptions may be verified by actually calculating the pH of the fluid and comparing it with the measured value. This can be done in a simplified manner by using equation (16).

Rewrite equation (16) as:

$$M_{H^+} = K_1 \, M_{CO_2}/M_{HCO_3^-}$$

at 228°F,

$$K_1 = 4.4 \times 10^{-7}$$

$$M_{CO_2} = 0.039 \text{ mole}$$

$$M_{HCO_3^-} = 10.00 \text{ moles}$$

Therefore, $pH = \log M_{H^+} = 8.8$

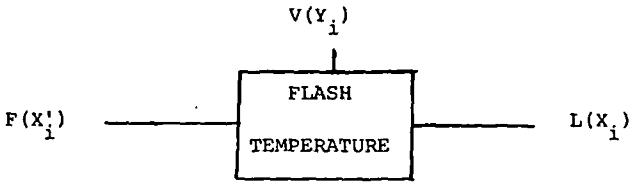
The calculated pH under the above assumptions is 8.8, whereas, the measured value is 9.0 - 9.2. Both assumptions can be removed in favor of a more rigorous treatment in a future refinement of the model.

Calculations were made using the model with the above simplifying assumptions. The CO_2 concentration in the vapor phase, as calculated using the model, agrees well (i.e., four percent higher) with the observed values in the field. Thus, pure thermodynamics (the model) indicate that slightly larger amounts of CO_2 should come out of the separator in the steamline than are actually observed.

The lower observed CO_2 concentration in the steamline can be attributed to the kinetics of CO_2 evolution. Very little information is available in the literature on the rate constant for CO_2 evolution. Thuy and Weilland[28] studied the mechanism of CO_2 desorption from aqueous solution and their work gives only a criterion for bubble desorption. When and if the values of the rate constants of the process become available, the kinetic effects can be incorporated into the model. The disagreement between the calculated and observed CO_2 values may also be due to the above simplifying assumptions made in the calculation of the non-flashable CO_2 concentration.

MODEL FOR AN H_2O - GAS MIXTURE

The model for H_2O - CO_2 may be extended to the case when more than one gas species is present in the reservoir in a manner similar to the initial procedure outlined earlier for the simple H_2O - CO_2 system:



MASS BALANCE FOR ith SPECIES:

$$X_i' = \Psi Y_i + (1-\Psi) X_i \qquad (21)$$

EQUILIBRIUM CONDITION FOR ith SPECIES:

$$Y_i = (H_i/P_i)X_i \qquad (22)$$

$$P_T = \Sigma_i P_i \qquad (23)$$

From equations (21) and (22), it follows:

$$X_i = X_i/(1+(H_i/P_T)-1)) \qquad (24)$$

$$Y_i = H_i X_i/P_T \qquad (25)$$

$$P_i = H_i X_i \qquad (26)$$

Using equations (24) through (26), the emission of various gaseous species may be computed for different flash temperatures if the Henry's Law constants are known.

The interest in the present paper is for CO_2 and N_2 in the feed waters, and the Henry's Law constant for N_2 may be computed for various temperatures using the empirical formula given by Himmelblau[29].

With the foregoing model and without considering the presence of non-flashable bicarbonates, the evolution of CO_2-N_2 mixtures for various feed concentrations and temperatures may be calculated.

GAS VENT PROCESS PRIOR TO STEAM FLASHING

Figure III clearly indicates that the magnitude of the gas emissions depends primarily upon three variables: (1) the temperature of the wellhead fluid; (2) flash temperature/pressure; and (3) the flashable CO_2 concentration in the wellhead fluid. The calculations further suggest that a major portion of the dissolved gases can be removed (vented) from the geothermal fluids prior to the final flash. Such a vent process has been suggested by Matthews[30] in a patent. However, no known published data or calculations exist in the literature on the applicability of such a vent process. In the following sections, an attempt is made to calculate the gas removal potential using a vent process for a 64 MW power plant.

CO_2 VENTING

Figure IV shows the calculated CO_2 emissions for a 64 MW power plant assuming that the CO_2 concentration in the unflashed geothermal fluid is 0.0004 Mol flashable CO_2/Mol H_2O (978 mg CO_2/liter). The concentration of CO_2 in the vapor phase is highest with a small incremental flash of the wellhead fluid, and becomes smaller as more of the water flashes and enters the vapor phase. An amount equal to 42.6 weight percent of all the flashable CO_2 can be removed from the geothermal fluid, if the wellhead temperature is dropped from 350° to 349°F. This amount increases to 47.0 weight percent if the temperature is dropped from 335° to 334°F, and becomes 51.6 for the first temperature drop of one degree if the fluid has an initial temperature of 320°F.

Similar computations were made for the case of a fluid with an ionic strength of 3.0. The model predicts a significant difference in CO_2 concentration in the steam for equivalent increments of flash relative to the zero ionic strength data. This information is presented only for general interest since the TDS at East Mesa is on the order of 2000 mg/liter, which is the equivalent of an ionic strength of only 0.02.

Figure III shows a plot of CO_2 concentration in the remaining liquid phase as a function of flash temperature for three geothermal fluids having the same flashable CO_2 concentration (0.0082 mol of CO_2 per mole of H_2O or 20,000 mg of CO_2 per liter of H_2O). The dotted lines in the figure represent the percent flash. The solid curves represent the mole fraction of CO_2 that is left in the liquid phase after a water flash has been taken. From these curves, it can be seen that if the produced water (320°F well temperature) is flashed at 300°F, a two percent water flash is obtained. The corresponding CO_2 flash is about 9 percent. Figure IV illustrates the absolute rate of CO_2 emissions expected from a 64 MW power plant. It shows that a two percent steam flash would generate 105,000 standard cubic feet (SCF) per hour of CO_2. The total CO_2 eventually liberated from the total mass flow is approximately 115,000 SCF per hour in a ten percent water flash.

The CO_2 emission behavior indicated above suggests the application of a vent process in geothermal power plants based on a flash cycle. An initial "CO_2 flash" could be applied to rid the geothermal fluid of a large portion of its original CO_2 content without taking a large loss of steam. For example, a fluid produced at a wellhead temperature of 335°F could be pre-flashed to separate a major portion of the CO_2 from the fluid. A pre-flash of only 0.1 percent steam could remove as much as 40 percent of the CO_2 from the system. This represents a substantial decrease of the CO_2 load on the vacuum pumps or steam ejectors.

Figure V shows the conditions to be expected in a hypothetical 64 MW power plant. Assuming an average wellhead temperature of 335°F and 978 mg/liter CO_2 flashable dissolved in the single phase geothermal fluid feed, Figure V gives the percent of CO_2 removed. The dotted line in the upper part of the figure (SCF/hr without venting) shows that the turbines would eventually be charged with 110,000 SCF/hr if no vent process is used. The dotted curve (SCF/hr with venting) indicates the CO_2 flow rate entering turbines if the vent process is applied.

Figure VI shows a similar example to the one above, except that a portion of the wellhead CO_2 is non-flashable in one case. This applies at East Mesa, with the exception of the low wellhead temperature of 320°F. A total of 1070 mg/liter CO_2 is contained in the wellhead fluid and 440 mg/liter of this CO_2 is considered to be non-flashable in one case. Figure VI gives the flow rate of CO_2 entering the turbines. The horizontal dotted lines (SCF/hr without venting) show that the turbines would be charged with a maximum of 126,000 SCF/hr and a minimum of 79,000 SCF/hr of CO_2 if no vent process is used. The maximum value refers to the case when the total measured CO_2 is all flashable. The other dotted curves (SCF/hr with venting) indicate the CO_2 flow rate entering the turbines if the CO_2 vent process is applied for the two cases.

CO_2 - N_2 VENTING

If more gas constituents enter the steam phase, the total gas load for the vacuum pumps or steam ejectors will be even larger. For example, Figure VII shows the CO_2 and N_2 flow rates for a 64 MW power plant as a function of flash temperature. It can be seen from Figure VII that the N_2 can be pre-flashed together with CO_2.

In summary, the obvious advantages of venting the non-condensables before they reach the turbines and condensers are the elimination of peak fluctuations and the reduction in initial investment and operating costs for vacuum pumps and/or steam ejectors. These advantages may be outweighed by the cost and technical difficulty of actually implementing the necessarily precisely controlled noncondensable flash system. Due to the low concentrations at East Mesa, this is very likely the case. However, in areas with higher non-condensable contents, serious consideration should be given to such a vent system.

RESULTS AND CONCLUSIONS

1) The geothermal fluid in RGI's East Mesa field is always single phase in the reservoir and when downhole pumps are used, is single phase in the well bore. The first occurrence of a gas phase in fluids from a pumped well is experienced when the pressure is dropped to approximately 130 psig in the surface facilities.

2) The TDS of the single phase fluid is approximately 2000 ppm; the total CO_2 concentration is on the order of 1000 ppm.

3) A new CO_2 solubility model has been developed. This model predicts the solubility behavior of CO_2 at various pressure/temperature conditions in the presence of other soluble substances for the ranges of practical field interest. The model describes equilibrium conditions only. Kinetics of the gas evolution from the liquid phase, the formation of gas bubbles and their separation from the bulk of the liquid are discussed, but incorporation into the model is not really feasible as yet on the basis of known data.

4) The CO_2 concentration in the steam flash depends not only upon how much CO_2 is dissolved in the wellhead fluid at the temperature and pressure before the flash, but also on the total dissolved solid and bicarbonate contents.

5) There are flashable and nonflashable portions of the total dissolved CO_2. The nonflashable portion of the dissolved CO_2 in the East Mesa wellhead fluid is approximately 440 ppm if the liquid is flashed down to 20 psig (228°F), and corresponds to the $NaHCO_3$ content of 840 ppm (equals 440 ppm of CO_2) in the unflashed wellhead liquid.

6) There is relatively more CO_2 in the vapor phase at higher flash pressures (temperatures). For example, the vapor phase from a first stage flash which causes the water temperature to drop 20°F contains eleven times as much CO_2 as the vapor phase in the second stage which yields an 80°F temperature drop. The CO_2 concentration in the steam from the first flash can be 42 times larger than that of the steam phase from the second flash.

7) The calculated pH value of the fluid exiting from the separator is 8.77. The measured value of the exiting value is 9.0.

8) A venting process can remove a large portion of the CO_2 before it reaches the turbines. This vent process will not eliminate the need for removal of noncondensables in a power plant downstream of the barometric condensers. However, the size of the required vacuum pumps or steam ejectros can be decreased substantially, resulting in considerable savings in construction and operating costs. This vent process will be of particular interest for geothermal fluids having CO_2 content higher than that at East Mesa. The process has another advantage in that it can eliminate the peaks in fluctuations in CO_2 concentration from the produced geothermal fluid.

NOMENCLATURE

F = feed rate (lbs/hr)

f_{CO_2} = fugacity of CO_2

H = Henry's Law constant

H_F = enthalpy of feed (Btu/lbm)

H_V = enthalpy of vapor (Btu/lbm)

H_L = enthalpy of liquid (Btu/lbm)

I = ionic strength

K = equilibrium constant

L = rate of liquid formation (lbs/hrs)

M_i = concentration of the ith species

P = pressure

P_i = partial pressure of the ith species

R = gas constant

T = temperature in ° k

$\bar{V}_{CO_2}$ = partial molar volume of CO_2 in aqueous medium

X_{CO_2} = mole fraction of CO_2 in the liquid phase

X'_{CO_2} = mole fraction of CO_2 in the feed

Y_{CO_2} = mole fraction of CO_2 in the vapor phase

ε = dielectric constant

γ_i = activity coefficient of the i^{th} species

ρ = density

Ψ = fraction of flash

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TABLE I
CARBON DIOXIDE ANALYSES
EAST MESA NO. 16-29/APRIL 6, 1978

IDENTIFICATION[A.]		DATE SAMPLED	TIME	MG CO_2[C.] PER LITER OF SAMPLE	MG CO_2[D.] PER LITER OF COOLED LIQUID
16-29	Blank	4/6/78	12:20	110[B.]	--
16-29	Wellhead 750-1500 (1:1)	4/6/78	12:30	604	1098
16-29	Wellhead 750-1500 (1:1)	4/6/78	12:40	596	1082
16-29	Downstream of Separator 750-1500 (1:1)	4/6/78	12:45	277	444
16-29	Downstream of Separator 750-1500 (1:1)	4/6/78	12:50	262	414
16-29	Steamline 1250-1500 (5:1)	4/6/78	13:35	1270	7070
16-29	Steamline 1250-1500 (5:1)	4/6/78	13:50	1216	6746

A. Date analyzed 4/11/78, see text.

B. Analyzed in triplicate. Care was taken to avoid CO_2 contamination during analysis.

C. CO_2 in all species, ionic and nonionic forms, see text.

D. CO_2 contamination of fluid in line before sample dilution and corrected for CO_2 content of blank and dilution with blank. CO_2 in all species, ionic and nonionic forms.

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TABLE II
CARBON DIOXIDE ANALYSES
EAST MESA NO. 16-29/APRIL 7, 1978

IDENTIFICATION[A.]	DATE SAMPLED	TIME	MG CO_2[C.] PER LITER OF SAMPLE	MG CO_2[D.] PER LITER OF COOLED LIQUID
16-29 Blank	4/7/78	7:40	110[B.]	--
16-29 Wellhead 750-1500 (1:1)	4/7/78	9:15	568	1026
16-29 Wellhead 750-1500 (1:1)	4/7/78	9:15	577	1044
16-29 Downstream of Separator 750-1500 (1:1)	4/7/78	8:30	276	422
16-29 Downstream of Separator 750-1500 (1:1)	4/7/78	8:35	268	426
16-29 Dwonstream of Baker Tank 750-1500	4/7/78	8:50	273	436
16-29 Downstream of Baker Tank	4/7/78	8:55	260	410
16-29 Steamline 1250-1500 (5:1)	4/7/78	7:45	1250	6950
16-29 Steamline 1250-1500 (5:1)	4/7/78	7:50	1217	6752

A. Date analyzed 4/11/78, see text.

B. Analyzed in triplicate. Care was taken to avoid CO_2 contamination during analysis.

C. CO_2 in all species, ionic and nonionic forms, see text.

D. CO_2 contamination of fluid in line before sample dilution and corrected for CO_2 content of blank and dilution with bland. CO_2 in all species, ionic and nonionic forms.

TABLE III
pH VALUES BASED ON DISSOCIATION CONSTANTS
FRACTION OF TOTAL CARBON DIOXIDE PRESENT AS

pH	H_2CO_3	HCO_3^-	CO_3^{--}
6.5	0.4232	0.5767	0.0001
7.0	0.1883	0.8113	0.0004
7.5	0.0683	0.9303	0.0014
8.0	0.0226	0.9728	0.0046
8.5	0.0072	0.9783	0.0145
9.0	0.0022	0.9530	0.0448
9.5	0.0006	0.8701	0.1293

TABLE IV
GAS CONCENTRATIONS (WELL NO. 16-29)

SAMPLE STATION	DATE SAMPLED	PRES. (PSIG)	TEMP. (^oF)	COMPOSITION OF NONAQUEOUS GAS (MOL %) CO_2	N_2	Ar/O_2	CH_4	%WATER FLASH	VOLUME %GAS
11 A	3/28/78	94	317	79.3	14.40	1.16	5.74	0	2.52
11 A	3/28/78	84	317	88.6	7.85	0.36	3.36	0	7.20
11 A	3/28/78	72	317	93.2	5.01	0.31	1.62	<1	16.10
8 A	3/25/78	8	225	92.8	6.9	0.27	0.21	≈9	ND
8A	3/30/78	8	225	91.4	5.54	0.24	2.84	≈9	ND
8A	3/30/78	8	225	89.7	7.26	0.12	2.58	≈9	ND

ND: NOT DETERMINED

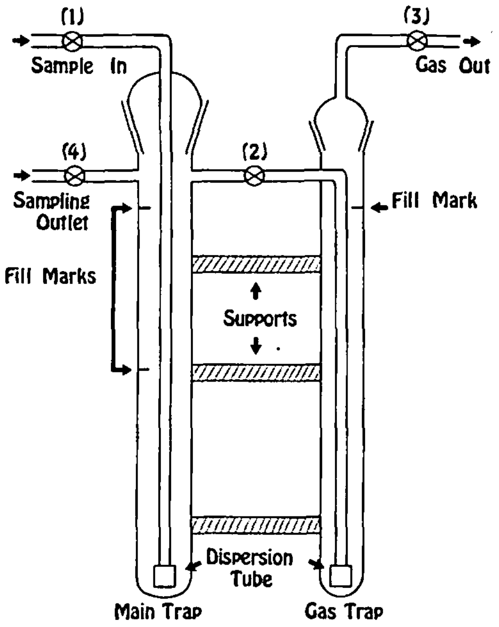

Fig. 1 - Apparatus for CO_2 sampling

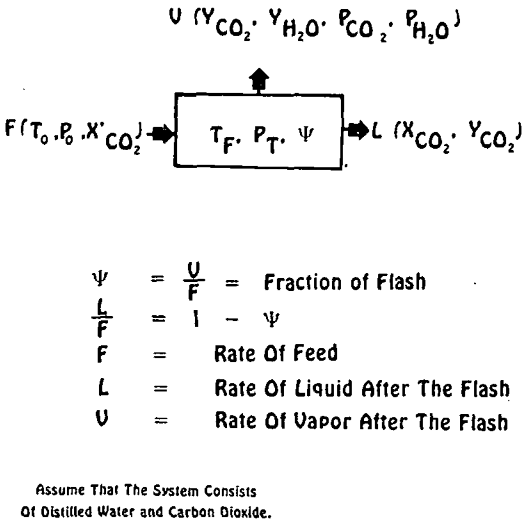

Fig. 2 - Thermodynamic model for flash in H_2O-CO_2 system

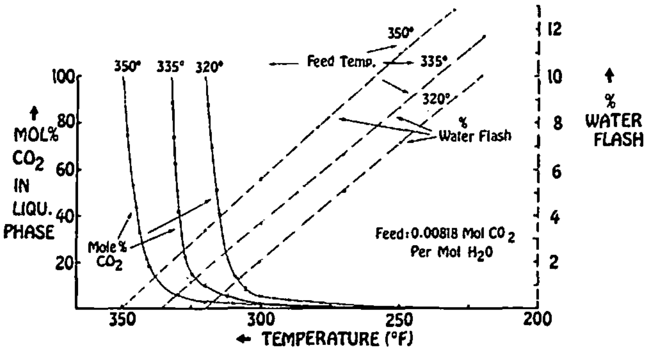

Fig. 3 - CO_2 and H_2O flash in system H_2O-CO_2

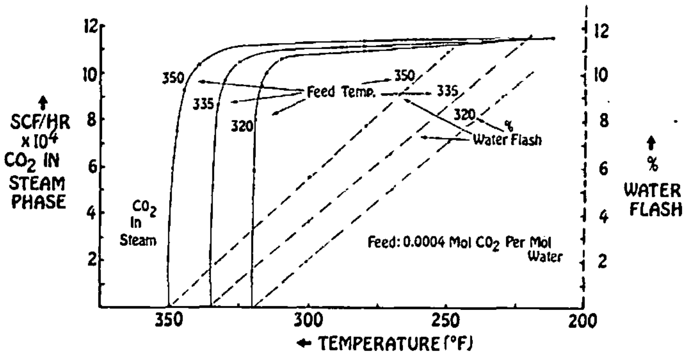

Fig. 4 - CO_2 and H_2O flash in 64 MW power plant

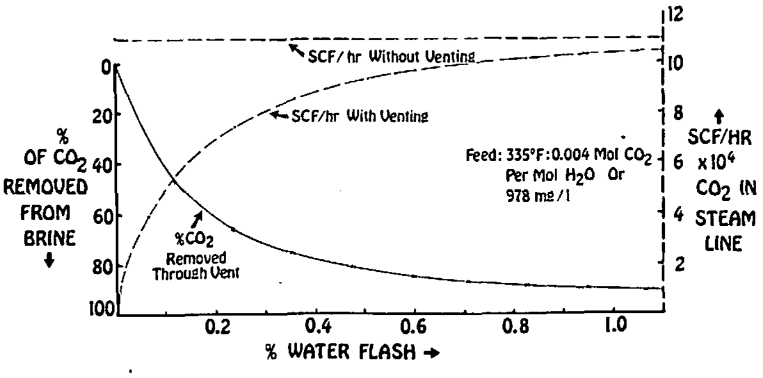

Fig. 5 - CO_2 venting in 64 MW power plant plant

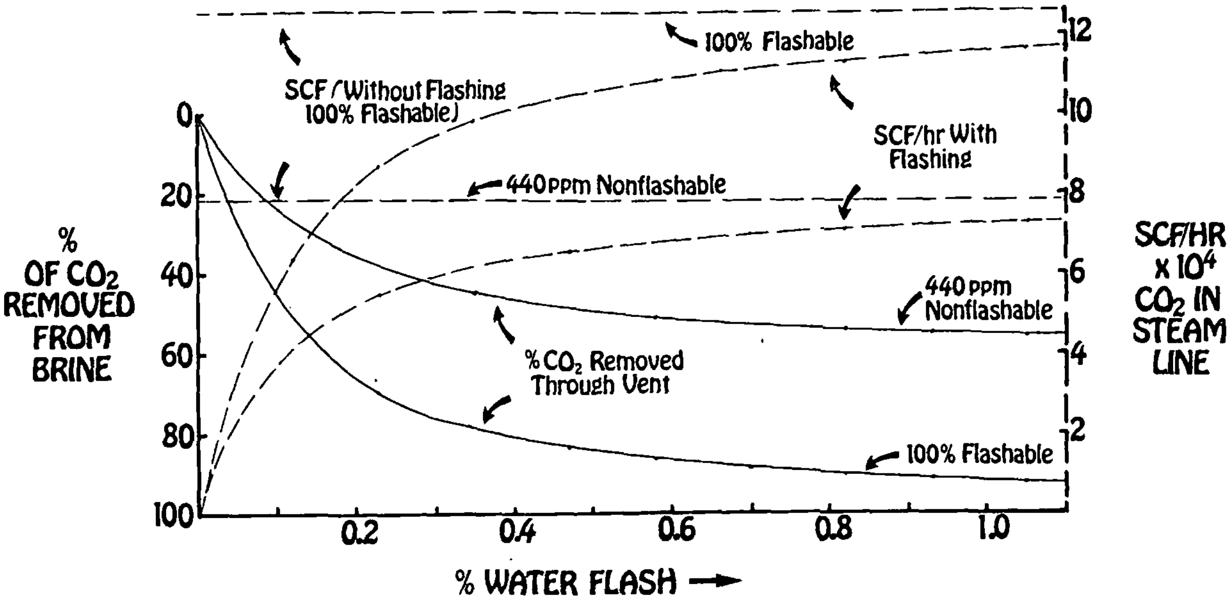

FIG. 6 - CO_2 VENTING IN 64 MW POWER PLANT

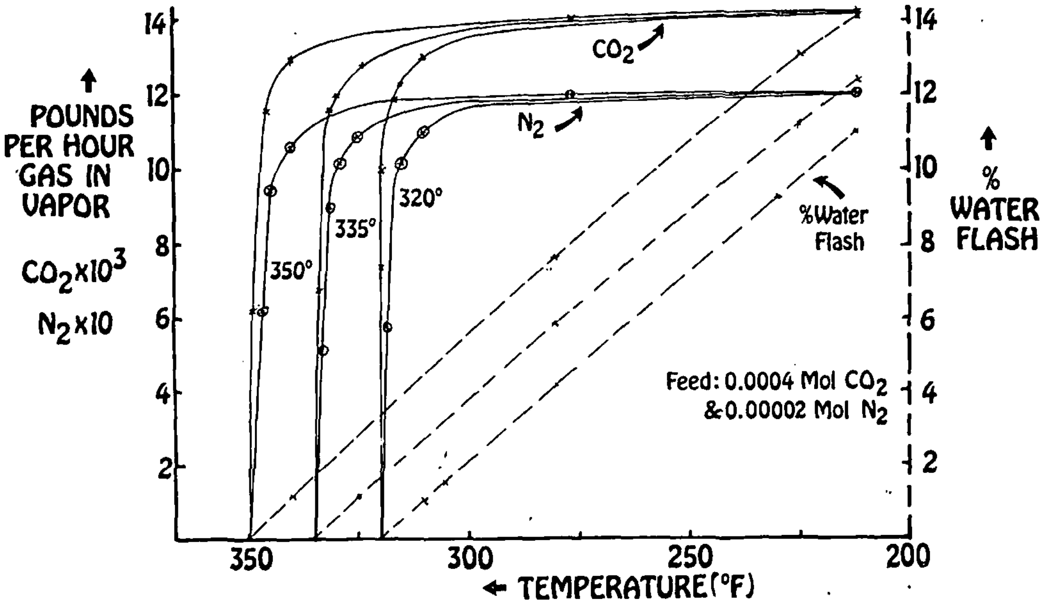

FIG. 7 - CO_2, N_2 AND H_2O FLASH IN A 64 MW POWER PLANT

⇒ SHWard

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A NATIONAL RESEARCH AND DEVELOPMENT PROGRAM FOR GEOTHERMAL INDUCED SEISMICITY

WORKING DRAFT #1

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JANUARY 26, 1979

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I. INTRODUCTION

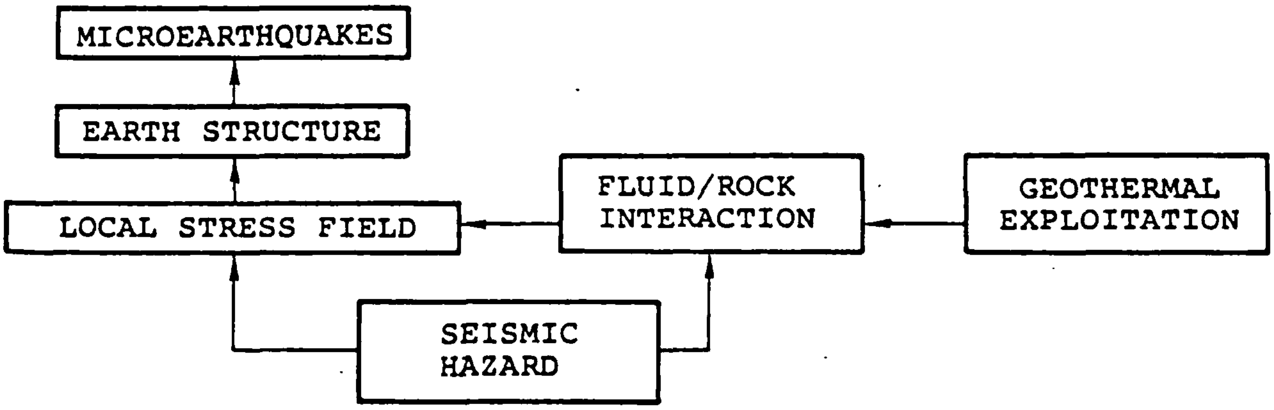
The Department of Geothermal Energy, Headquarters, has established the Geothermal Induced Seismicity Program (GISP) to develop a national research and development program plan to: (1) measure and quantify the magnitude of the problem, and (2) establish causal relationships between geothermal energy production and seismic events. The objective of the project is to gain an understanding of man-caused earthquakes resulting from the utilization of geothermal resources and the means by which such earthquakes can be predicted and safely controlled or moderated.

Seismicity induced by human activity is not unique to geothermal environments. The association of an increase in seismic activity with the filling of large reservoirs is now well documented (Bell and Nur, 1978). In several of these cases the main shock had a magnitude around six and was locally damaging. Another example of induced seismicity is the Denver earthquakes between 1962 and 1967 which were closely related to fluid injection in the Rocky Mountain arsenal disposal well in Colorado (Healy, et al., 1968). Although the injection was at only one site, several slightly damaging earthquakes occurred. Fluid withdrawal in oil fields has also been associated with several large tremors in California (Long Beach) and Texas. Finally, mining activities in underground areas have long been known to be the cause of rockbursts, which have had energy releases equivalent to magnitude five earthquakes (Jaeger and Cook, 1976).

In all these cases, the principal cause of the seismic activity was the alteration of the preexisting stress field by either fluid withdrawal or reinjection, or by removal of material from the ground. If these activities are in regions of naturally occurring seismic activity, or where there is already a dominant stress pattern, the probability of inducing earthquakes is even greater. Unfortunately, most geothermal prospects are in areas where there is active faulting. In the United States the most notable example is California, where the steam-dominated system in The Geysers and the hot water systems in the Imperial Valley both lie in regions where events greater than magnitude seven have occurred. However, almost the entire western United States is potentially seismically active, especially in geothermal areas such as Nevada, western Utah, and Wyoming. Another important case is that of the geopressurized zones of the Gulf Coast. In addition to reinjection, rapid withdrawal of fluids necessary for significant power generation may cause sudden failure and/or subsidence. Hoover and Dietrich (1969) suggested a relation between fluid removal and seismicity at the Rocky Mountain arsenal disposal well. Lastly, the extent to which hydrofracting can be controlled in hot dry rock environments is not known. The degree to which larger events may be triggered by the coalescence of smaller shocks is still uncertain.

Although induced seismicity has been studied in relation to dam sites, there are other factors which make geothermal reservoirs unique. Anomalous temperatures, pressures, strain rates, and rock types in geothermal environments all combine to alter the effective strength of the materials. In fact, geothermal prospecting involves "listening" for continuous seismic energy emitted from the system, or detecting microearthquakes caused by the dynamic processes (Liaw and McEvilly, 1979; Majer and McEvilly, 1979). The permeability necessary for the existence of a geothermal reservoir is often provided by faulting and fracturing along potentially active faults. Laboratory data on rock fracture and slip along preexisting planes or cracks suggest that the concept of effective stress (i.e., the shear strength is proportional to the difference between the normal tectonic stress and the fluid pore pressure) is the dominant effect in failure (Friedman, 1975). In producing geothermal environments where fluids are constantly being removed and reinjected at much higher than natural rates, anomalous pore pressures are inevitable. If these properties occur in regions of high stress and are coupled with the withdrawal and reinjection of fluids, then a situation exists where seismicity can easily occur. This, in addition to the fact that earthquake activity is noted in every commercially productive geothermal region indicates the need for understanding the mechanisms involved. The question seems not to be, will earthquakes be associated with fluid withdrawal or reinjection in producing geothermal regions, but how large will they be, and can they be controlled to minimize the damage to the surrounding environment and production region itself? The amount of geothermal power produced amy depend upon the induced seismicity and the extent to which it can be controlled, rather than the available heat.

The critical elements of the problem identified by the GISP panel are shown in the following schematic.



The microearthquakes which occur before and during exploitation represent the primary data base. The inversion of this data to obtain changes in the local stress field should determine the seismic hazard. An understanding of the effect of exploitation on the local stress field via fluid/rock interaction will identify the cause of the hazard and hopefully permit its control.

Each of these elements will be discussed separately in the following sections, both in terms of current status and additional research needs. Also a history of the induced seismicity and subsidence at The Geysers, California is presented as an appendix. This area will be recommended for intensive seismic monitoring and interpretation by the GISP panel.

II. DATA ACQUISITION

2.1 INTRODUCTION

Data bearing on exploitation-induced earthquake activity associated with a producing geothermal reservoir are of several types, including, of course, the details of earthquake occurrence within the field. Equally important, if we are to base an understanding of induced earthquakes on appropriate models, are the physical and chemical properties of the reservoir and their variation with time and with production. A variety of ongoing geochemical, geophysical, and geodetic measurements will be a necessary part of the development of major geothermal fields. As many of the detailed measurements involve substantial expense and manpower, it is fortunate that most are not required, and many are not in fact available, until major production begins.

2.2 PREPRODUCTION MONITORING

2.2.1 Seismic

In the preproduction period the most important measurement is that of background seismicity. Directly analogous to the now standard practice followed in the construction of major dams, where induced seismicity is a known potentiality, a high-sensitivity long-term record of natural seismicity in the project vicinity is fundamental to a meaningful analysis of any earthquake activity subsequent to field development. This preproduction monitoring program can be quite simple, e.g., a single high-quality seismograph, and it need become more elaborate only if warranted by the complexity or level of background seismicity detected in the reservoir area. Such a site-specific monitoring effort should not be confused with the general coverage provided in many areas of the western

United States by networks of seismographs (e.g., Caltech, U.C. Berkeley, USGS, University of Nevada and University of Utah, etc.) Such networks, except when concentrated for a specific study, rarely have interstation spacings less than 10 to 20 km, and thus cannot provide a long term seismicity record at very small magnitudes (less than one). Furthermore, such networks normally produce biased locations for hypocenters, with errors of several kilometers being common in areas of extreme lateral variations in crustal properties. For these reasons and because the data will be fundamental to subsequent modeling of reservoir dynamics and in the identification of induced seismicity, it is imperative that each promising geothermal prospect be instrumented on a minimal basis at such time as it becomes clear to the operators that probability is high for the development of a producing field. This timing should assure several years of preproduction monitoring.

The optimal preproduction monitoring system would seem to be a three-component downhole (at least 100 m), 4.5 Hz geophone package, operating with at least 50 Hz bandwidth and at maximum possible sensitivity into an event recorder with digital cassette recording, and located no more than 1 to 2 km from the expected field center. Such an installation is relatively inexpensive (less than $10 K, including the hole), and will provide adequate monitoring of surrounding earthquake activity. In the event that significant seismicity is seen in the immediate vicinity (within 5 km), two additional stations can be added for improved spacial resolution of the hypocenters, and subsequently the network can be expanded to the density required by the ongoing analyses of the local seismicity. In most cases, however, the single-station monitoring will suffice and data reduction will be simply a matter of cataloging a limited number of events selected by an S-P time criterion, say less than about two seconds.

2.2.2 Data Bank

The second aspect of preproduction data acquistion recommended for promising geothermal prospects involves creation of a site-specific cell in the geothermal data bank, for the prospect. Known regional and local geological, geochemical, geophysical and geothermal data can then be assigned to the prospect, and the required data base will be established for subsequent analysis as development continues.

2.3 PRODUCTION DEVELOPMENT PHASE

2.3.1 Introduction

When the prospect is shown to be economically viable and the decision is made to move the field into production, the intense phase of data acquisition should begin. Individual reservoirs will demand differing measurements, but the common goal for all is a continuous log of reservoir properties, production statistics and seismic activity, to be used in modeling reservoir dynamics for earthquake occurrence. The following list includes a wide range of measurements that would provide data crucial to the modeling efforts. It is clear that the field operator must be convinced of the need for these data if the program is to succeed.

2.3.2 Seismicity

If the reservoir area has been found to be seismically active in the course of preproduction monitoring, the network should be expanded to at least six, perferably eight to ten, stations. Interstation spacing should be no more than 1 to 2 km, and common timing with less than 10 ms error between stations is required. Individual station characteristics should be the same as those used in preproduction monitoring.

Downhole sensors should be placed as deep as is feasible. Data analysis now becomes more labor-intensive, with earthquakes to analyze on a continuing and timely basis. Routine processing should yield, in addition to precise hypocenters, source parameter estimates (fault planes, stress drops, seismic moment, rupture dimensions, etc.) and characteristics of the frequency content of the seismic waves as seen at each station. The same network can be used in experiments designed to detect changes in subsurface properties associated with reservoir exploitation. Such experiments may use local explosions or regional seismic events in monitoring wave velocities and attenuation within the reservoir volume. It is probable that the seismic network configuration will be shaped by results of the data analysis, with instruments removed or installed for specific data needs. In a seismically active field the network will thus provide a twofold service – monitoring of earthquakes, and monitoring of reservoir properties.

Should the reservoir be found aseismic throughout preproduction monitoring, the minimum requirement during production development is a single station near the reservoir center. The existing station may well suffice, if the location is correct. This minumum system is sufficient to detect the onset of induced seismic activity, at which time a full network should be installed. It may be that the utility of a seismic network in monitoring changes in reservoir properties, as discussed above, provides sufficient rationale for its installation even in aseismic reservoirs.

2.3.3 Structure

Modeling studies for production-induced earthquake occurrence will depend heavily on structural data for the reservoir. Clearly, the developer will have the most complete picture of the reservoir, and his models provide the initial framework for analysis. To the extent possible and practical, these data should be released to the data bank on the field. It is likely that inadequacies will exist that suggest specific experiments for an improved structural picture. Acquisition of such needed data (e.g., geophysical surveys, geochemical analyses, special logging surveys, rock mechanics data, etc.) could well be supported financially by the Department of Energy, for the sake of case-history development.

2.3.4 Reservoir Pressure

For the purposes of induced seismicity research it would be desirable to detect changes in reservoir pressure of a few tenths of a bar or so and to detect temperature changes greater than 0.1°C. Instrumentation with sensitivities of this order have been developed and are typically used in reservoir engineering studies. Thus, there is no need to develop new instrumentation to sense changes in these parameters. Preliminary studies should be made to determine the spatial and temporal rates necessary to adequately characterize the pressure and temperature fields in the producing reservoir. These studies should be site specific in nature since spatial and temporal variations in these parameters can be expected to differ substantially from field to field.

2.3.5 Subsidence

Preliminary calculations indicate that volumetric strains in some producing reservoirs could be as large as 10^{-3} and that the mean strain rates could be of the order of 10^{-5} per day. Thus, rather crude instrumentation could be used to monitor volumetric changes in the reservoir. Unfortunately at the present time the sensors for making observations on this scale in geothermal reservoirs is not available. Since surface subsidence is directly linked to changes in reservoir volume (reservoir compaction) the development of both direct and indirect methods for monitoring reservoir compaction is a major goal of the geothermal subsidence research program. Studies in this area were initiated in FY '78 and appear likely to continue in FY '79. Thus, there is no need to support the development of compaction monitoring methods under the induced seismicity research program. However, lines of communication should be developed to insure that the methods developed suit the needs of both the seismic and subsidence research programs.

2.3.6 In Situ Stress

Mean stress drop calculations imply that the seismicity observed at the Geysers geothermal field is associated with changes in the *in situ* stress state of a few bars to a few tens of bars. It would, therefore, be desirable to have the capability to detect stress changes as small as a bar or so. Methods and systems for monitoring the ambient state of stress on this scale have been developed and are currently being utilized in the earthquake hazards reduction program sponsored by the U. S. Geological Survey. These should be directly applicable to monitoring the *in situ* stress state in the overburden of a producing geothermal field. However, because of the high temperatures and corrosive fluids typically found in geothermal reservoirs, some adaption of existing technology will be necessary before changes in the reservoir state of stress can be reliably measured. Thus, the development of a stress monitoring system that can perform reliably in a geothermal reservoir is a legitimate field of study for the induced seismicity research program.

2.3.7 Special Requirements

The data needed can, with exception of downhole (high temperature) logging, be acquired with existing technology and equipment. Research needs are primarily in the area of using the data in modeling reservoir dynamics.

III. SEISMIC HAZARD ESTIMATES BASED ON RESERVOIR STRESS FIELD DETERMINATIONS

A deterministic approach to the estimation of the seismic hazards associated with geothermal energy production requires knowledge of the initial tectonic stress levels within the medium, plus the changes in the stresses due to production. In addition, knowledge of the strength characteristics of the material along with variations in the strength due to effects such as water weakening and fluid pressure variations would be required. With this information, one approach would be to predict failure based on stress levels relative to the strength of the material, under specified fluid injection and/or extraction conditions, using reservoir modeling methods. In this case, reservoir production would produce perturbations in the initial tectonic stress, temperature, fluid pressure and ultimately the material strength, which could be sufficient to produce significant changes in the background microseismicity and in extreme cases, especially in regions with preexisting faults under relatively high tectonic stress, sufficient changes to trigger a fairly large seismic event.

The fully deterministic approach to an estimate of the hazard involved in an active geothermal reservoir not only requires knowledge of a large number of material parameters and state variables, such as initial temperature and stress, but also knowledge of geologic structure including the fracture and fault zone geometry. Obviously acquisition of this information will require an extensive field program; and the elements of such a program are discussed in earlier sections of this report. Further, details of the production history of the field would be required in order to specify the time dependent boundary conditions for the reservoir modeling and an observational program designed to obtain surface and downhole tilt, strain, compaction and subsidence measurements with time is required in order to, at least partially, verify the modeling predictions. Finally, the rhyologic and chemical behavior of rocks as a function of stress level, temperature, fluid content, strain rate, etc. must be known with reasonable certainty for meaningful predictions of failure phenomena to be made. While considerable research in this area of rock physics is underway, in particular under other areas of the geothermal program and under the earthquake prediction program, it is premature to conclude that sufficient knowledge of rock failure under high temperature reservoir conditions is presently available for very accurate modeling predictions to be made at this time. Consequently, it is important that the present program include support for rock physics experiments designed to more precisely define rock rhyology near and at failure, as a function of temperature, strain rate, fluid content and chemistry.

Since seismic hazard estimates based on reservoir modeling can only be expected when the initial tectonic stress state of the reservoir is specified, it is critical that stress level estimates be accomplished under this program. Specification of the stress state can be achieved in part by hydrofracturing experiments in the field, but this direct measurement of the ambient stress state, while critical, gives limited information spatially and is expensive to obtain. Applications of seismic techniques for estimates of stress changes associated with the microearthquakes that constitute the background activity in tectonically active areas, is therefore of great importance in estimating the initial stress distribution within the reservoir area.

In this case, passive seismic monitoring of the region may be used to record the commonly occurring small earthquakes within a field and estimates of the stress changes produced by the events can be obtained. These stress changes are, in fact, nbe amount of local ambient stress that can be released by an earthquake (the "recoverable ambient stress") and so is an important quantity in itself. Further, methods have proposed to relate the observed recoverable stress inferred from the seismic observations to the ambient stress local to the seismic event. However, these currently provide a rather wide range of estimates which are dependent on particular earthquake model assumptions and approximations. Thus, while additional research in the use of seismic data for stress estimates is required for accurate delineation of the initial ambient stress state, it is nevertheless necessary that the program incorporate an observational seismic study designed to give both recoverable and ambient stress estimates spatially throughout the prospective reservoir in order that reservoir modeling be an effective method of predicting seismicity changes.

The seismic observations of microearthquake activity are also an important tool for the location and delineation of fault zones within the field and can be used to give stress field orientations with a rather high degree of certainty. These observations are clearly important in defining the initial state of the reservoir as well as its dynamic state during production. In this regard, continuous seismic monitoring of the reservoir region could be used to provide a basis for monitoring the changes in seismicity during production, so that modeling predictions could be checked, and so that an empirical basis for correlations between production procedures and seismic activity could be established. Equally important, this approach offers the possibility of inferring the stress field by observational means during production. Thus, an independent determination of the seismic hazard could be based on the seismicially inferred (spatially variable) stress levels, stress field orientation and seismicity levels. In this approach one would require sufficient seismic instrumentation to detect and locate the numerous small events. Further the detector array must be adequate to determine the azimuthal radiation patterns from each event and the spectral properties of the radiated seismic field. With this capability it would be possible to determine the stress drop (or recoverable stress) associated with each event along with an inferred ambient stress and the orientation of the failure plane, as well as the event location. Given a spatially distributed occurrence of small seismic events within the field which would provide a spatial sampling of the stress, then it would be possible to delineate regions of high stress and potential large scale failure during any field production program.

In view of these possibilities for quantitative seismicity estimates, it is appropriate to recommend a comprehensive program with complementary observational-empirical and modeling components designed to provide a documented basis for seismic hazards assessment. The essential elements of this program are:

1. To obtain production and seismicity data from an operating geothermal field, specifically the Geysers field, to determine the quantitative nature of any correlations between seismic activity, reservoir structure and production history. This information to be used as an empirical means of estimating expected effects, and to verify reservoir modeling predictions.

2. To employ passive seismic monitoring of geothermal field seismicity to obtain estimates of the non-hydrostatic stress, both initially and as a function of production history and to also compare these estimates with *in situ* ambient stress estimates using hydrofracturing measurements. From the combined stress data to then base predictions of future

seismicity on the stress field estimates obtained from microearthquake occurrences and available <u>in situ</u> stress measurements during production.

3. Based on quantitative material property and field structure data coupled with initial stress state estimates, use reservoir modeling methods to predict stress field variations to be expected as a function of field production programs and, from these stress predictions, to infer seismicity changes based on fault locations and rock strength properties. Finally, to also correlate the results with production histories and general time dependent seismicity data, including the seismically estimated stress state variations, in order to establish a verified, deterministic, predictive capability.

4. Based on the inferred stress levels and the material strength, which serves to define stress levels at which failure may occur, provide an estimate of the probable locations, maximum dimensions, magnitudes and expected ground motion from the largest events to be expected.

Some of the essential aspects of this program are discussed in more detail in the following sections. In particular, we address the basic questions of how geothermal reservoir energy production may affect seismicity and how the effects can be predicted by reservoir modeling. In addition, a more detailed discussion of how seismic observations are used to infer failure plane orientations and stress levels within a tectonically active region is included.

IV. PHYSICAL BASIS FOR TRIGGERING OF EARTHQUAKES BY GEOTHERMAL PRODUCTION OR REINJECTION

To understand the relationship between production or reinjection of geothermal fluids and earthquakes we require an evaluation of the perturbations in the mechanical, thermal or chemical environment caused by exploitation. These perturbations act upon rocks whose initial state is the other unknown which we need to measure, i.e., are there preexisting faults in the rocks and are they stressed to near the point of failure?

This section lays out an experimental approach to measuring the static physical parameters in an appropriate rock mass and determining the effect most likely to trigger earthquakes in that body of rock. Because it is presently seismicially active and it is the principal producing geothermal field in this country, the Geysers area offers the best laboratory for such an experiment.

4.1 THE INITIAL STATE

It is now possible to measure the absolute state of stress in boreholes where temperatures reach 250°C. The method, hydraulic fracturing, has been extensively used in recent years for this purpose, although not in the high temperature application. In addition to the unforeseen problems likely to develop in high temperature environments, the hydrofracturing technique does not work well in highly fractured rock. Otherwise, the technique has worked successfully and is the only method available for other than surface measurements.

The faulting and fracture state in the rocks can be approached by using a borehole televiewer, an ultrasonic device which maps the orientation and distribution of fractures intersecting the borehole. This device has been modified for use at temperatures up to 220°C. The radiation pattern from microearthquakes also can be used to estimate fault plane orientations, in active zones.

The fluid pressure is one of the principal parameters influencing earthquakes. The presence of a large number of drill holes at the Geysers makes it possible to determine the fluid pressure in the reservoir at the focal depths of the earthquakes easily, provided access to pressure data can be obtained. Use of the boreholes is a prerequisite to conducting the experimental plan outlined here.

The foregoing measurements, along with seismic methods designed to infer the stress changes associated with background microearthquakes, can be used to establish the ambient stress field and its variability. The strength properties of local rocks at the appropriate temperatures and pressures should then be measured, and this capability is available at several existing laboratories.

With these data, it becomes possible to estimate the likelihood that any perturbation caused by production or reinjection could lead to shear failure and earthquakes. The possible perturbations affecting seismicity are examined in the following sections.

4.2 FLUID PRESSURE CHANGES

Production of steam from the Geysers has led to a maximum reduction in the reservoir pressure of 225 psi. The reduction in fluid pressure would act to strengthen the rock against frictional failure, although the indirect effect of subsidence might ultimately trigger earthquakes. Reinjection of water apparently does not lead to significant increases in the fluid pressure except, possibly, in the immediate vicinity of the injection wells. A series of bottom-hole pressure measurements over hours to days following a period of injection should be carried out to establish the spatial and temporal extent of any such increase. Such data have not been gathered to date, but are relatively easy to obtain.

4.3 FLUID PRESSURE GRADIENTS

Local reductions or increases in reservoir pressure due to production or reinjection result in pressure gradients in the fluid or vapor phase. These gradients in turn generate stress differences in the solid medium and conceivably, may contribute to increasing local shear stress (or decreasing the normal stress) on faults sufficient to trigger earthquakes. From existing production data, the maximum gradients in the vapor phase are low, no more than 1.5×10^{-2} bars/meters so that the effect, though finite, is not large. Once fault plane orientations and slip directions are determined from focal mechanism studies, the effect of the known gradients can be estimated from the known fluid pressure gradients.

4.4 STRESS CORROSION CRACKING

The dependence of brittle fracture strength on the chemical environment needs some detailed study. Enough is known to suggest that such an effect may be important, although whether there has been sufficient change in the reservoir to affect the fracture strength significantly is only poorly understood.

4.5 THERMAL STRESS

Temperature gradients induce stress differences which might contribute to initiation of seismic activity. In a vapor dominated reservoir, gradients should be quite small and the stresses correspondingly low. However, reinjection of relatively cool water could lead to a more substantial effect. Lack of knowledge of the geometry of the fracture system into which the reinjected fluid flows will make calculation of local stress variations in discrete fractures rather crude. Although a difficult problem, some order-of-magnitude estimates need to be attempted.

4.6 SUBSIDENCE

Removal of steam has resulted in a maximu subsidence of about 15 cm since production began at the Geysers. The effect of such deformation on local stresses can be estimated provided adequate leveling data exist. As it is suspected that subsidence in oil fields may play a role in local fracturing, and that it may lead to damaging earthquakes, suggests that this effect is likely to be a significant one.

4.7 PHYSICAL MODELING

The relative effects on faults of known orientation, by the perturbation discussed above, can be estimated in the first year, at least to within an order of magnitude. It appears likely that all but one or two of the above effects can be eliminated as having little significance, particularly as the current seismicity patterns and focal mechanisms are available for comparison with expectations from the calculations. For example, the strains induced by known subsidence can be compared with the strain release pattern derived from focal mechanism studies to judge whether any reasonable relationship exists.

In the second year, it should be possible to conduct measurements of absolute stress and the fracture distribution to provide the foundation for more refined calculation of the seismogenic effects. Finally, and most important, the three-dimensional pattern of faults, stress and the relevant perturbing effects should be incorporated into a model which leads to a prediction of the maximum probable earthquakes. The latter study is critical not only to the Geysers, but to the general problem of induced seismicity.

4.8 STRESS FIELD AND FAILURE PREDICTIONS BY RESERVOIR MODELING METHODS

In many areas of the world, land subsidence and small earthquakes have been observed to accompany the production of fluids (oil, gas, water, steam, etc.) from undergground reservoirs. Subsidence is generally believed to be caused by the compaction of the semi-consolidated strata of the reservoir as the effective overburden stress (defined as lithostatic stress minus fluid pressure) is increased due to fluid withdrawal. Fluid production can also produce relatively large localized stress changes in the reservoir (and overlying) rock. The localized stress buildup has potential for activating faults. (Thus, for example, increase in horizontal stress can lead to growth of normal faults whereas a buildup in shear stress may cause shear failure in the overburden/underburden.)

The geohydrological effects described above involve thermomechanical interactions between the rock and fluid components. Theoretical models describing the thermomechanical response of the rock and fluid (water and/or steam) composite material in terms of the isolated components have been developed and are currently operational. In these models, the stress-strain equations for the rock matrix are coupled with the diffusion equations for the fluid. Some of the more advanced modeling methods appear to be adequate for analyzing subsidence and stress buildup in a geothermal aquifer undergoing production and/or injection and it appears that no new theoretical development effort is required at this stage, at least until further comparative studies are completed.

In the modeling theory, the fluid flow and the solid response problems can be decoupled if one assumes that the fluid withdrawn (or reinjected) is small, so that the overburden essentially remains constant. The restriction to uniaxial (vertical) compaction together with the assumption of constant overburden implies that the reservoir porosity can be regarded as a function of pore fluid pressure and temperature only. During the past few years, several reservoir programs (incorporating the uniaxial compaction assumption) have become available. Given basic reservoir engineering data (rock porosity, permeability, specific heat, thermal conductivity and compressibility; fluid equation of state, etc.; and the initial state of the reservoir), the reservoir simulators can be employed to yield perturbations in the fluid state (pressure, temperature, etc.) introduced by exploitation/reinjection. Several of the reservoir simulators possess considerable flexibility as far as fluid and rock properties, problem geometry and boundary conditions are concerned. Thus, for example, a current advanced reservoir modeling program can treat multiphase, multispecies (water/steam, water with dissolved methane/free methane, water with dissolved salt/steam/precipitated salt) fluid flow in one-, two- or three-dimensions. In this program each computational zone in the finite-difference grid may contain a different rock type and provisions are also made for all practical boundary conditions.

In order to model the effect of time-varying fluid flow on matrix stress in a geothermal reservoir, finite element solid equilibrium codes are employed. Any such finite element code is basically a program for solving linear elastic continuum problems; however, problems requiring treatment of nonlinear material behavior may be solved by iteration using effective elastic moduli in the element. Given rheological properties of the reservoir rocks and the fluid pressure history in the reservoir, these programs may be employed to yield the time varying stress field and the deformation in the matrix. These programs can also be used to model overburden changes. Interactive codes have also been developed that couple fluid response programs with finite element solid matrix response codes. In the coupled fluid-solid matrix computations, the system is marched through any desired number of time steps in each of which a flow cycle calculation is performed yielding values of pore pressure, temperature and fluid density at the end of the time step. This information is then used in the finite element solid matrix calculation to yield the instantaneous equilibrium condition (i.e., rock displacements, stress, etc.) as functions of rock properties and fluid variables.

Most approaches for the analysis or subsidence and stress buildup are based on decoupling the fluid flow and rock response calculations. (For example, changes in the fluid state cause perturbations in the rock stress state; however, the perturbations in the rock stress field are not allowed to affect the fluid response.) Although this procedure is computationally very efficient, it may be that, for very accurate predictions, it will be necessary to develop new computer codes which solve the fully coupled fluid flow and rock response problem. Also, one may want to calculate aseismic slip (as a result of fluid preduction/injection) on discrete faults. The numerical techniques for treating the latter problems already exist and may be adapted to these problems.

4.9 SEISMIC METHODS: STRESS ESTIMATES, FAULT PLANE GEOMETRY AND SEISMICITY LEVELS

An objective of this part of the research program is to determine the spatial and temporal variations of recoverable tectonic stress. In this context the term "recoverable tectonic stress" refers to that part of the nonhydrostatic stress field within the earth that can be released, in the form of seismic radiation, by an earthquake. This stress is therefore distinct from the absolute or ambient nonhydrostatic stress, a part of which may not contribute to the radiation from a spontaneous failure process. The recoverable stress then, is that part of the ambient nonhydrostatic stress that can be released as seismic radiation.

A second objective is to relate this recoverable stress level, which can be inferred from seismic observations of the wave radiation from small earthquakes, to the ambient stress level which acts to initiate a failure process. The relationship between recoverable stress and ambient stress is quite uncertain in that the earthquake model theory required is still being developed and in any case requires verification. In this regard, measurements of ambient stress by hydrofracturing can be compared to seismically estimated recoverable stress values obtained from events at, or very near, the ambient stress measurement. These independent stress estimates could then be used to establish a relationship between the recoverable and ambient stresses. However, given that a determination of the recoverable stress can be obtained, it may be possible to identify spatial regions as hazardous in terms of the existing recoverable stress levels alone and to also predict the size and locations of likely large earthquakes, the former in terms of the detailed nature of the seismic radiation to be expected. Furthermore, it is reasonable to expect that inferred recoverable stress levels themselves can be used to predict the time of failure, if we are able to resolve time variations of the of the stress and monitor stress buildup with time to some critical level and spatial configuration.

The approach to the estimation of the recoverable stress is to use observations of the seismic radiation from the numerous very small to moderate sized earthquakes in the tectonic region of interest and to infer the stress changes associated with these events. The stress changes are largely local to the failure zone, in view of the rapidity of stress change falloff with distance, and, for these small events, constitute perturbations to the regional stress field. The changes can, however, be used to provide a sampling of the regional stress and hence provide the desired stress sampling mechanism.

Observational and interpretational methods for estimating stress using large numbers of small events require automated procedures to cope with the large amount of data recorded. Currently employed procedures involve the following:

1. The acquistion of a large event data base spanning as long a time period as possible, with events recorded in digital form over a reasonable wide frequency range.

2. The processing of the event data, using multistation recording to determine fault orientations and locations, and extraction instrument corrected spectral data from which variable frequency, compressional (P) wave magnitudes may be computed at "low" (near 1 Hz) and high frequencies (near 10 Hz).

3. Using regional earth structure models and an appropriately general dyanmical model for the earthquakes, to generate theoretical variable frequency magnitude results for the variety of earthquake types and sizes contained in the

observed data set (this involves generating synthetic seismograms at the distance range and azimuths comparable to those from which the observations are made, and then generating the theoretical variable frequency magnitudes by the same spectral analysis procedure used with the observed data).

4. Classification of events as to type (i.e., strike-slip, thrust, etc.) and determination of both the recoverable stress and the failure zone dimensions of the observed events by comparison with the theoretical magnitude results.

The results generated by these operations include:

1. Locations of events, which define active faults or tectonic zones within the region.
2. "Recoverable stress" or stress drop determinations associated with the events, giving estimates of the background stress that can be released by an earthquake.
3. The failure zone dimensions that are associated with each event.
4. The orientation of the failure zone or fault plane for each event, which provides information on the stress field orientation as well.
5. The numbers of events versus event magnitude (or energy release).

These data would clearly provide necessary initial data for the reservoir modeling and, with continuous seismic monitoring, can provide a check on the modeling predictions of the stress field changes during production.

In addition, time variations in seismicity (cummulative numbers of events versus event magnitude), microearthquake event clustering (spatial distribution of events), and fault plane orientation at a given location, as well as the stress itself, appear, at least on occasion, to be premonitory indicators of relatively large earthquakes. Therefore the seismic monitoring results may in themselves provide important empirical results for larger event prediction.

V. RECOMMENDED PROGRAM

5.1 Background seismicity measurements prior to exploitation should begin immediately at all promising geothermal prospects. At least two years of preexploitation monitoring is recommended. The optimal monitoring system would consist of a three-component (possibly 100 m downhole), 4.5 Hz geophone package, operating with at least 50 Hz bandwidth and at maximum possible sensitivity into an event recorder with digital cassette recording, and located no more than 1 to 2 km from the expected field center. In the event that significant seismicity is seen in the immediate vicinity (within 5 km), two additional stations should be added for improved spatial resolution of the hypocenters, and subsequently the network can be expanded to the density required by the ongoing analysis of the local seismicity.

5.2 An intensive, site specific data acquisition and interpretation program should be initiated immediately at the Geysers, California. A summary of the induced seismicity and subsidence history of this area is given in the appendix. The recommended program for the Geysers is as follows.

5.2.1 Continue operation of the telemetered network to provide continuous mapping of seismicity ($M \geq 1$) as the production zone expands in 1979 and 1980. Increase station density near future power plants especially Unit No. 13, a 100 MWe unit which begins operation in FY '80. It will be located in a part of the steam field that is presently aseismic.

5.2.2 Invert the microearthquake travel time and gravity data to obtain an estimate of the elastic properties and density of the earth structure in the areas of microearthquake clustering. Constrain the inversion with all geophysical data available from the operators of the field.

5.2.3 Determine the stress drop and fault orientation of the microearthquakes. Identify the spatial and temporal variation of the these fault parameters and correlate with production and injection procedures. Delineate regions of high stress drop and estimate the potential for large scale faulting.

5.2.4 Model the effect of time-varying fluid flow on the stress in the rock matrix in the vicinity of injection and production wells. Determine if the stress buildup is sufficient to explain the observed microearthquake and in particular the stress drops associated with these earthquakes. The operators of the field should be encouraged to furnish injection and production data (bottom hole pressure measurement) and the properties of the reservoir (permeability and porosity) for this project.

5.2.5 Install strong motion recorders near critical facilities. Continue geodetic and gravity measurements. Install tiltmeters near Unit No. 13.

5.2.6 Perform hydraulic fracturing measurements in selected boreholes to determine the absolute state of stress in the field.

5.3 A site specific cell in the geothermal data bank should be created for each prospect. Geological, geochemical, geophysical and geothermal data can be assigned to the prospect for analysis as development of the prospect proceeds.

We recommend that the above elements (5.1, 5.2 and 5.3) be initiated during the first year and be assigned the highest priority. The priority of the following elements will be determined after the results of the Geysers project are evaluated.

5.4 Seismicity measurements and reservoir properties should be obtained for all prospects undergoing exploitation. The field operator must be convinced of the need for these data if the program is to succeed. Seismic monitoring is essential. For seismically active areas the preexploitation network should be expanded to at least six, perferably eight to ten, stations. Interstation spacing should be no more than 2 km and common timing with less than 10 ms error between stations is required. If the reservoir is aseismic, a single station near the reservoir center would be sufficient. If induced seismicity is detected then a full network should be installed. The USGS telemetered network at the Geysers should be reviewed and upgraded, if necessary, in order to meet the requirements of elements 5.2.2, 5.2.3 and 5.2.4. Bottom hole pressure measurements and reservoir properties including elastic constants, density, porosity and permeability will be required for each seismically active field.

5.5 The dependence of brittle fracture strength on the chemical and temperature environment needs some detailed study. This activity should be coordinated with other areas of the geothermal program and the earthquake prediction program.

5.6 Prediction of the ground motion from the largest expected events will be required. Coordination with research activities conducted by NSF, USGS and NRC is recommended. However, it is clear that the transmission path contributes a large percentage of the overall uncertainty in seismic design. The microearthquake data should be interpreted to provide a site specific calibration of the attenuation of seismic waves from the fault to critical facilities. This interpretation would also provide an estimate of changes in the Q structure of the reservoir as a function of production and injection rates.

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APPENDIX A

A SUMMARY OF INDUCED SEISMICITY AND SUBSIDENCE AT THE GEYSERS, CALIFORNIA

A.1 STEAM PRODUCTION HISTORY

The first geothermal well at the Geysers was drilled in 1921, but extensive steam withdrawal did not begin until Pacific Gas and Electric Company began generating electricity in 1960 with Unit No. 1. Power production rose from 11 MWe in 1960 to 51 MWe in 1966, expanding to the current 502 MWe in 1975. When operating at full capacity, the field production rate is approximately 8.5 million pounds (19 million kg) per hour. Pacific Gas and Electric Company is currently constructing four new power plants, which will nearly double the generating capacity (to 908 MWe) within the next year or so. Ad additional 900 MWe could be added by the mid- 1980's (Lipman, Strobel and Gulati, 1977).

A.2 EARTHQUAKES AT THE GEYSERS

The sparse northern California network of the University of California at Berkeley provides the only preproduction data on seismicity at the Geysers. The location threshold over most of this period was about magnitude 1, so little can be said about the number of smaller earthquakes at the Geysers before power production began. However, the Berkeley data does show an increase in the number of earthquakes at the magnitude 1 level since production began. In addition, larger earthquakes

Several brief microearthquake surveys have been conducted at the Geysers over the years. Results of these studies, by Lange and Westphal (1960), Hamilton and Muffler (1973) and

Majer and McEvilly (1977), suggest that microearthquake activity at the magnitude 0 level may have increased as power production increased.

In 1973 the U. S. Geological Survey extended their central California seismographic network northward to the Geysers (Figure A.1). Station density was increased in 1975 and gain in 1977 to 1978. The present Geysers network is shown in Figure A.2; average interstation spacing is 4 km. Approximately 1000 earthquakes ($M \geq 1$) have been located at the Geysers since 1975. Marks, et al., (1978) and Bufe, et al., (1979) have examined the distribution of earthquakes with respect to the steam production zones and injection wells (Figures A.3 and A.4). The contours of the two zones of decreased steam pressure are interpreted by Lipman, Strobel, and Gulati (1977) as the consequence of steam production from two reservoirs. Estimated points of water injection are also shown in Figure A.3; data on the exact points of injection and condensate injection rates have not been made available by the producers. The correlation between the two clusters of microearthquakes and the two reservoirs is compelling circumstantial evidence that the earthquakes are induced.

Marks, et al., (1978) have also compared the 1975 to 1977 regional seismicity at $M \geq 2$ to the seismicity in the early (1962-1963) days of steam production when U. C. Berkeley operated a single station at Calistoga, 30 km southeast of the Geysers. They found the number of regional events had increased from 25 a year to 47 a year. The difference of 22 a year is near the 1975 to 1977 occurrence rate at the Geysers, suggesting that seismicity at the Geysers was significantly less in 1962 to 1963.

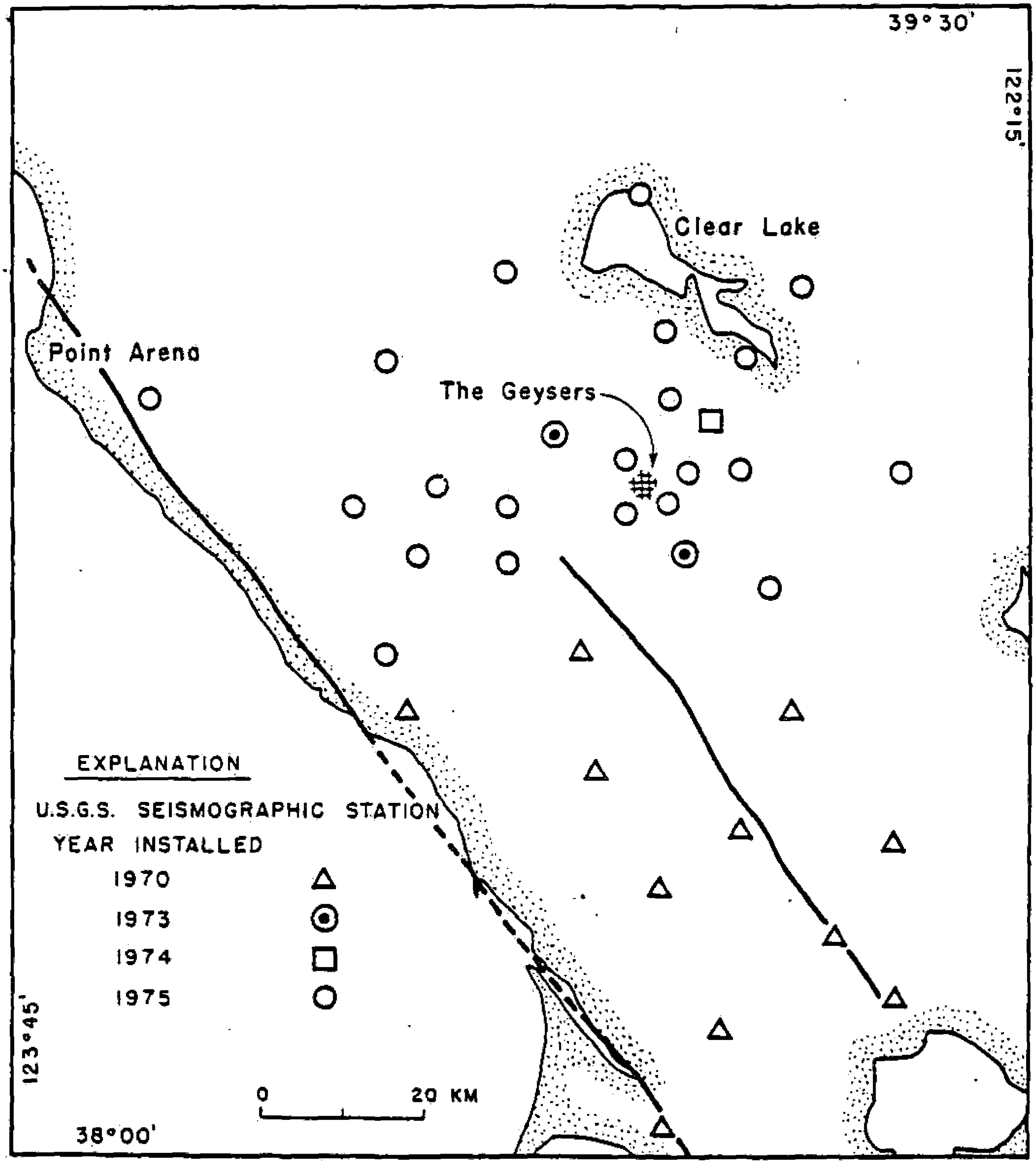

Figure A.1. U. S. Geological Survey seismographic stations, 1977. The stations immediately around the Geysers are shown in more detail in Figure A.2.

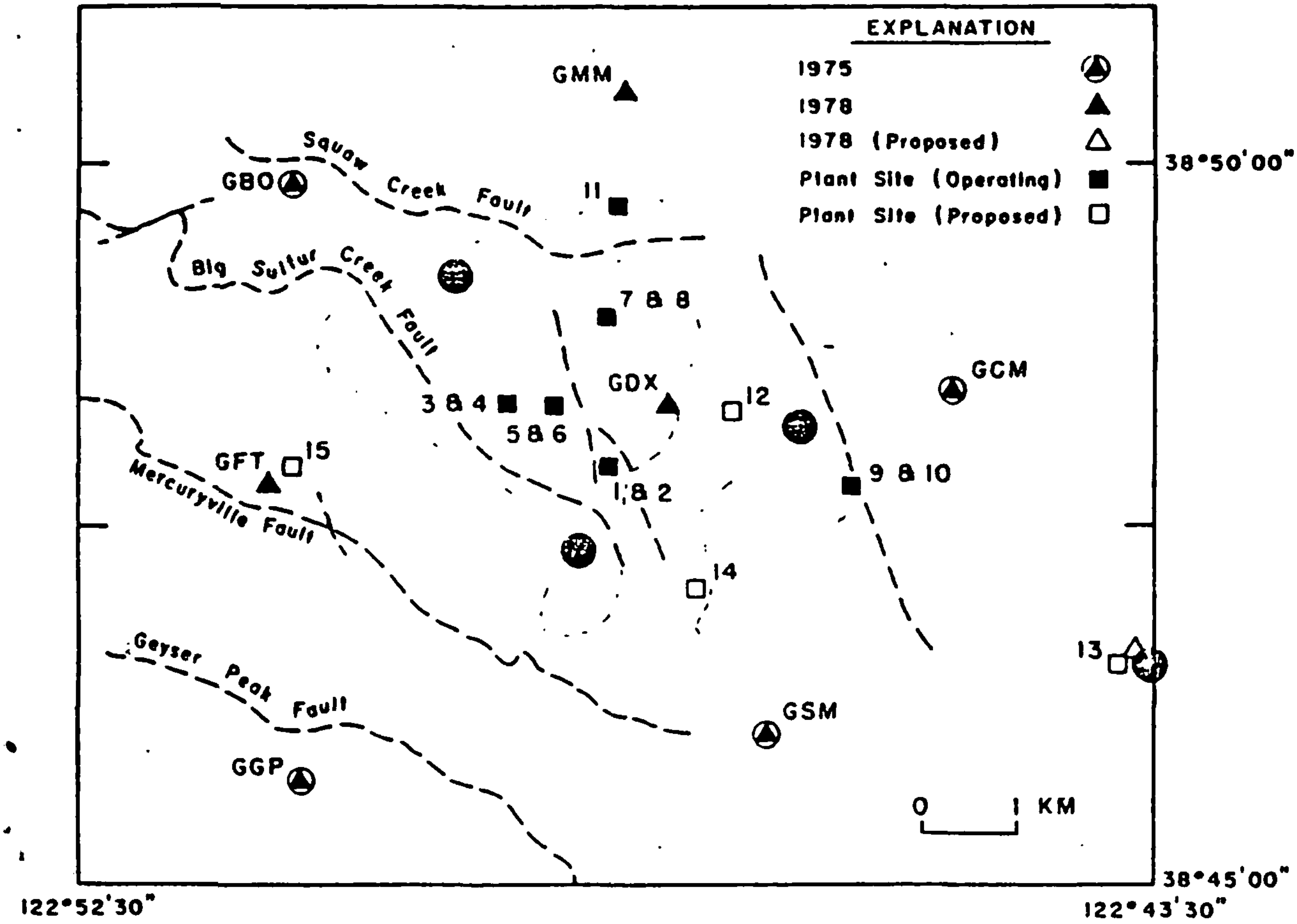

Figure A.2. Network of telemetered seismographs at the Geysers, May 1, 1978. Also shown are (numbered) geothermal power plants. Units 1 through 11 are generating power at the present; 12 through 15 will begin operation in the near future. Faults are from a compilation by R. McLaughlin of the USGS. In addition to the telemetered stations, a roving network of three-component digital seismographs is being deployed at the Geysers. Initial locations of these portable stations are indicated by solid circles.

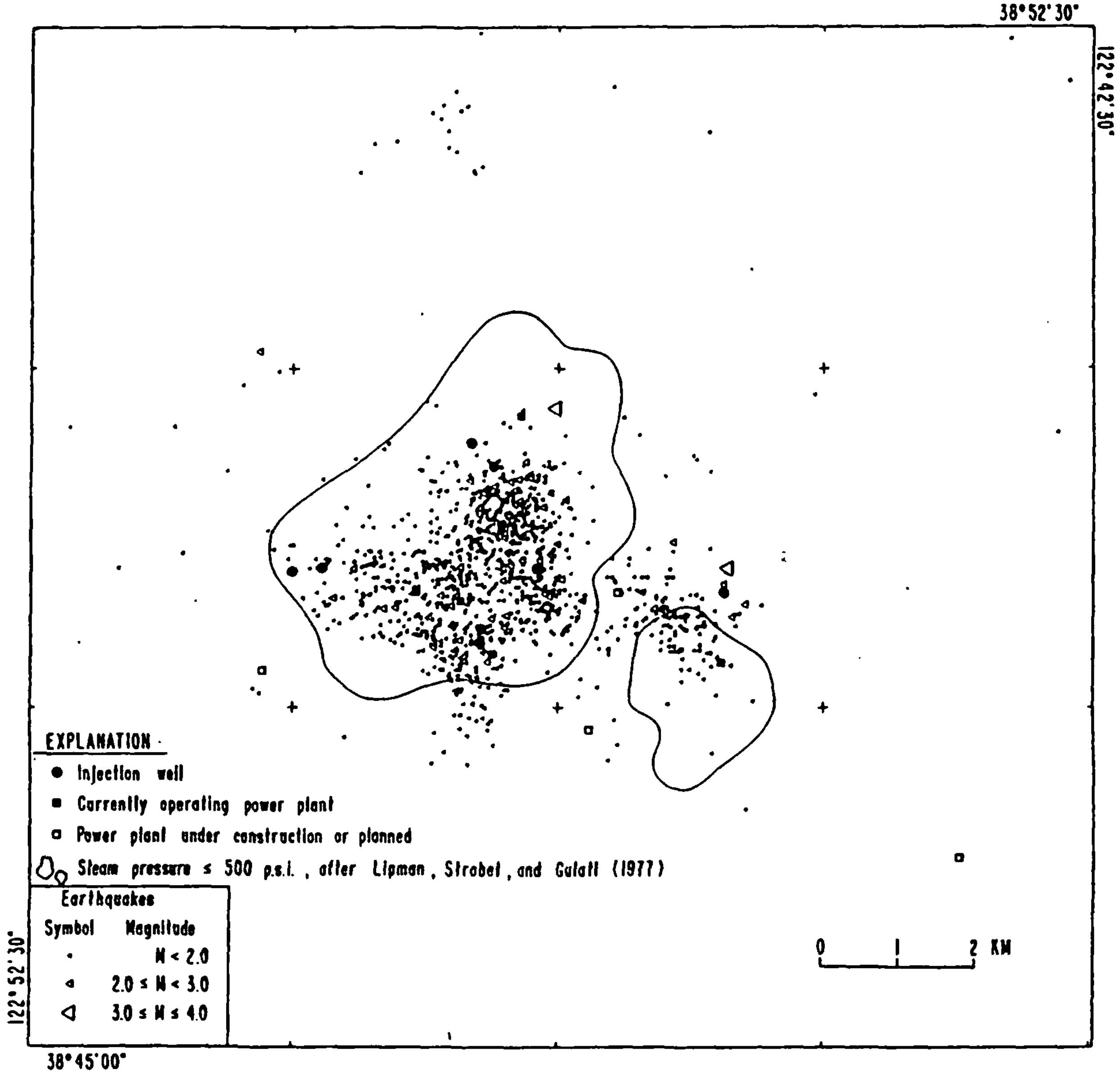

Figure A.3. Earthquake distribution and steam production zones, the Geysers Geothermal Area, California.

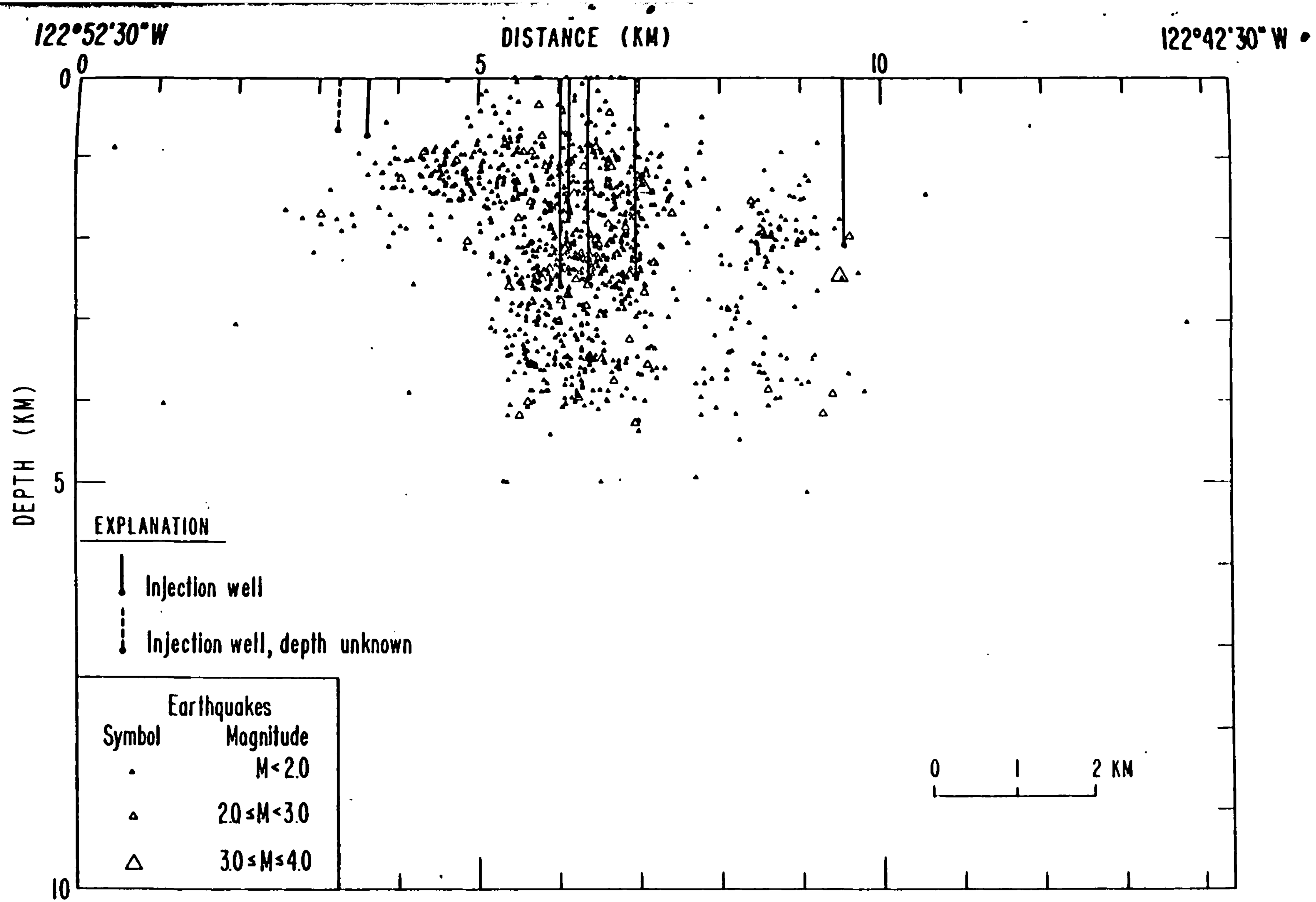

Figure A.4. Steam production zone and cross section, the Geysers Geothermal Area, California.

A.3 CHARACTERISTICS OF THE EARTHQUAKES AND THE RESERVOIR

Several studies of earthquake characteristics and reservoir properties which bear upon induced seismicity at the Geysers are in progress or have been completed. Marks, et al., (1978), conducted a comparative study of seismicity rates and b values at the Geysers and elsewhere in the Clear Lake region. They found no significant difference in b values (range 1.1 to 1.5) between the Geysers production zones and the surrounding geothermal and tectonic regimes. The earthquake occurrence rate in the production zones was found to be higher and more constant (less episodic) than in the surrounding regions.

Peppin and Bufe (1978) found no significant differences in spectral characteristics of earthquakes at the Geysers and those at Alexander Valley, 10 km to the south.

Bufe and others (1979) have detected a change in the faulting pattern at the Geysers since late 1977. Earthquakes in the lower (h > 2 km) part of the reservoir have changed from predominantly strike-slip to predominantly normal faulting. The shallower earthquakes are strike-slip or thrust, and are very simliar to mechanisms of earthquakes in the surrounding region.

Majer and McEvilly (1978) have examined the shallow crustal structure at the Geysers, using results of a seismic refraction profile and spectral studies of microearthquakes. They find the vapor dominated reservoir to be characterized by relatively high P- and S-wave velocities and low attenuation, a situation possibly reversing with depth. Iyer, et al., (1979) find large travel time delays and Ward, et al., (1979) find excessive attenuation in teleseismic P arrivals at the Geysers. Denlinger and Kovach (1979) conducted a shallow vibroseis reflection survey at the Geysers and have examined gravity data from the developed and undeveloped parts of the field.

Lofgren's (1978) 1973 to 1977 geodetic results have shown horizontal (2 cm/yr, convergence) and vertical (3 cm/yr subsidence) changes which suggest that the geothermal reservoir is being compressed both vertically and horizontally as fluid pressures within it are drawn down by production. Isherwood (1979) interprets gravity decreases as large as 120 mgal as resulting from steam withdrawal with no significant natural recharge. These results suggest a trend of decreasing porosity in the reservoir; a process reflected in the high level of microearthquake activity.

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Preliminary Assessment of a Geothermal Energy Reservoir Formed by Hydraulic Fracturing

By

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THIS PAPER IS SUBJECT TO CORRECTION

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ABSTRACT:

Two, 3-km-deep boreholes have been drilled into hot (~ 200°C) granite in northern New Mexico in order to extract geothermal energy from hot dry rock. Both boreholes were hydraulically fractured to establish a flow connection. Presently this connection has a large flow impedance which may be improved with further stimulation. Fracture-to-borehole intersection locations and in situ thermal conductivity were determined from flowing temperature logs. In situ measurements of permeability show an extremely strong dependance upon pore pressure -- the permeability increased by a factor of 80 as the pressure was increased 83 bars (1200 psi). An estimate of the minimum horizontal earth stress was derived from fracture extension pressures and found to be one-half the overburden stress.

INTRODUCTION:

A program designed to demonstrate the feasibility of extracting energy from hot dry rock has been initiated at the Los Alamos Scientific Laboratory. Basically, it is proposed that man-made geothermal energy reservoirs can be created by drilling into relatively impermeable rock to a depth where the temperature is high enough to be useful; creating a reservoir by hydraulic fracturing; and then completing the circulation loop by drilling a second hole to intersect the hydraulically fractured region, or by drilling into the immediate vicinity of the first fracture and then creating a second fracture that intersects the first one.

Thermal power would be extracted from this system by injecting cold water down the first hole, forcing the water to sweep by the freshly exposed hot rock surface in the reservoir/fracture system, and then returning the hot water to the surface where the thermal energy would be converted to electrical energy or used for other purposes. System pressures would be maintained such that only one phase, liquid water, would be present in the reservoir and the drilled holes. The concept is described in more detail by Smith, et al[1] and the mechanics of the heat extraction process have been reported by Harlow and Pracht,[2] and McFarland and Murphy.[3]

The hot dry rock concept is being investigated in a series of field experiments at a site called Fenton Hill, located on the west flank of a dormant volcano, the Valles Caldera, in the Jemez mountains of northern New Mexico. In December 1974, the first deep borehole, GT-2, was completed to a depth of 2.929 km (9609 ft) in granite, where the temperature was 197°C (386°F). A hydraulic fracture was then created close to the bottom of this

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*Work performed under auspices of the USERDA.

References and illustrations at end of paper borehole. A second borehole, EE-1, was then drilled to complete the circulation loop, but it failed to intersect the GT-2 fracture by approximately 6 m (20 ft). Communication between the wellbores was then established by initiating a fracture from EE-1. This fracture is located an average distance of approximately 6 m (20 ft) from the GT-2 fracture. Due to uncertainties in fracture orientation measurements, it is not known whether the two fractures intersect. A series of flow experiments was then conducted to determine the nature of this circulation path, and to measure fracture properties necessary to complete the design of a demonstration heat extraction experiment. The results of these experiments are described in the following sections.

ANALYSIS OF TRANSIENT WELLBORE PRESSURES:

By assuming constant, one-dimensional, permeable flow into a homogeneous porous media with constant properties, and by also assuming that the hydraulic conductivity of the fracture is very large compared to that of the rock, it can be shown that if water is injected into a fracture at a constant rate, q, the change in fracture pressure, P, is:[4, 5]

$$P = \frac{2\mu q}{kA}\sqrt{\frac{\kappa t}{\pi}} \quad . . . . \quad (1)$$

Because the hydraulic diffusivity, κ, is

$$\kappa = k/\mu\,\bar{\beta} \quad . . . . \quad (2)$$

the product of the fracture area times the square root of permeability, $A\sqrt{k}$, is given by rewriting Eq 1.

$$A\sqrt{k} = 2\sqrt{\frac{\mu}{\pi\bar{\beta}}}\;\frac{q\sqrt{t}}{P} \quad . . . . \quad (3)$$

Downhole pressure changes at the fracture face are estimated by correcting the measured surface wellhead pressure for pressure losses. These pressure losses consist of frictional losses in surface piping, flowing friction in the wellbore and, as the flow enters the fracture, an additional wellbore-to-fracture impedance (analogous to a skin effect). Since the flow rate is constant and wellbore storage effects are not significant, the total pressure loss due to these effects is also constant, and can be estimated by extrapolating the pressure curves back to zero time.

Typical data for the EE-1 fracture are presented in Figure 1. The experiment was conducted by pumping into the EE-1 wellbore at a constant rate of 2.1 ℓ/s (34 gal/min), corrected to downhole conditions. A good linear fit to the data is obtained on P versus $\sqrt{t}$ coordinates. Deviation of the later time data from the linear fit is thought to be due to pressure dependent permeability, or a "leak" from the EE-1 fracture to the GT-2 fracture via a flow connection; as will be discussed.

Since the porosity of the granite is less than 1%, the mean compressibility, $\bar{\beta}$, is essentially that of the rock which, based upon the results of sonic velocity logs, is estimated to be 2.7×10^{-5} bar^{-1} (1.9×10^{-7} psi^{-1}; 1 bar = 10^5 N/m^2 = 14.5 psi). Using available properties of water at 200°C,[6] and the above values of $\bar{\beta}$ and q, it can be shown that the $A\sqrt{k}$ value for the EE-1 fracture at the time this experiment was conducted was 2.2×10^{-5}m^3 (7.8×10^{-4} cu ft). Since this result was obtained with an initial pore pressure of zero (taking hydrostatic pressure as the baseline), the $A\sqrt{k}$ derived is more properly designated as $(A\sqrt{k})_o$, where the subscript represents the change in the initial pore pressure.

An extrapolation of the linear fit in Fig. 1 back to zero time provides an estimate of 2.8 bars (40 psi) for the pressure losses between the surface and the fracture. Although this pressure loss is probably not linear with flow rate, especially at much higher flow rates, it is instructive, for purposes of comparison, to divide it by the flow rate to yield a specific impedance. This specific impedance from the surface to the EE-1 fracture is 1.3 bar-sec/liter (1.2 psi-min/gal) which, as we will show, is small compared to the overall circulation impedance. Similar results with the GT-2 fracture indicate that its $(A\sqrt{k})_o$ is 5.2×10^{-5}m^3 (1.8×10^{-3} cu ft) and the surface to GT-2 fracture impedance is 3.9 bar-sec/liter (3.5 psi-min/gal). Potter et al[7] report that the permeability of GT-2 core specimens is 0.01 to 0.1 micro-darcy at downhole conditions of temperature and pressure, while West et al[8] report that, based upon drill-stem testing at a depth of 1.5 km (5000 ft) in GT-2, the permeability of a similar granite is approximately one micro-darcy. Taking the latter result as perhaps more representative of heterogenous rock conditions suggests that the area of the GT-2 fracture is approximately 5.2×10^4m^2 (5.6×10^5 sq ft), and if circular, has a radius of 90 m (300 ft). This is a rough estimate of course, but Albright[9] reports, on the basis of microseismic acoustic techniques, that the radius of the GT-2 fracture must be at least 50 m (160 ft).

It is found that values of $(A\sqrt{k})_o$ are most useful when they are interpreted as a parameter which characterizes a fracture. Changes in $(A\sqrt{k})_o$ indicate irreversible changes in a fracture, examples being fracture extension due to pressurization or changes in k due to potential geochemical effects such as the formation and precipitation of rock-water interaction products or the dissolution of rock mineral components, particularly silica (SiO_2).

A historical summary of the $(A\sqrt{k})_o$ for both fractures is presented in Figure 2. At the top of this figure are identified the various flow experiments (which are discussed in more detail in reference 10), while near the bottom, the maximum EE-1 wellhead pressure achieved during each experiment is indicated. Since the creation of the EE-1 fracture in October, 1975, its $(A\sqrt{k})_o$ has increased during several of these flow experiments. Furthermore, these increases have been observed only when the EE-1 pressure has exceeded 90 to 94 bars (1300 to 1360 psi). Thus, it is believed that these increases in $(A\sqrt{k})_o$ are due to increases in A (fracture extensions) and that the fracture extension pressure, P_e, is approximately 92 bars (1330 psi) above hydrostatic. Since its creation, $(A\sqrt{k})_o$ of the GT-2 fracture has not changed significantly. The maximum sustained pressure ever reached at the GT-2 wellhead was 91 bars (1320 psi), i.e., below P_e. The permeability of the rock surrounding the GT-2 fracture has apparently not changed, in spite of the potential geochemical effects cited above.

DETERMINATION OF MINIMUM EARTH STRESS:

Based upon a theory of fracture mechanics, Sack[11] has shown that the difference between the fracture extension pressure and the earth stress perpendicular to the fracture plane, S_3, (the least compressive principal stress) is:

$$P_e - S_3 = \sqrt{\frac{\pi\gamma E}{2(1-\nu^2)R}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Aamodt[12] has reported values of the properties for a granite similar to that found in EE-1 and GT-2; γ = 100 J/m^2 (6.8 lb/ft), E = 3.8 x 10^5 bars (5.5 x 10^6 psi) and ν = 0.3. Substituting these values and supposing that either fracture radius, R, is presently as small as 50 m (160 ft), it can be shown that $P_e - S_3$ is only 3.6 bars (53 psi). Thus the minimum earth stress, S_3, in the EE-1 fracture is approximately 88 bars (1280 psi) above hydrostatic. As will be shown, the EE-1 fracture is roughly centered about a depth of 2.95 km (9670 ft), so that the absolute value of S_3 is 375 bars (5440 psi) or 50% of the overburden pressure, S_1, (the maximum compressive principal stress). As expected, these fractures are vertically oriented.

PORE PRESSURE DEPENDENT PERMEABILITY:

The effects of pore pressure upon $A\sqrt{k}$ are indicated in Figure 3. The results were obtained from an experiment (No. 111) in which the sequence of operations was to first inject water into the EE-1 fracture at a constant rate until a pressure of 28 bars (400 psi) above hydrostatic was reached, and then adjust the flow rate such that this pressure was maintained constant for two hours. In such a manner a new pore pressure was established in the rock adjacent to the fracture face. Following the two-hour "soak" the procedure was repeated at the additional pressure levels shown on the figure. The start of each new change in pressure level was taken as a new zero time and the results, when plotted versus $\sqrt{t}$, yielded straight lines as shown. Using a modified principle of superposition, the $A\sqrt{k}$ for each increment of pressure can be calculated and the results are indicated on the figure. As can be seen, increasing the pore pressure from 0 to 69 bars (1000 psi) above hydrostatic resulted in a factor of 3.8 increase in $A\sqrt{k}$. Since A did not change (pressure levels were below the fracture extension pressure) the permeability apparently increased by a factor of 15.

Additional results, obtained from another flow experiment (No. 114), presented in Figure 4 indicate that the permeability increases even more sharply (up to a factor of 80!) as the pore pressure increases to 83 bars (1200 psi) above hydrostatic. These results are qualitatively similar to those of Brace, et al[13] for westerly granite and to those of Potter, et al[7] for GT-2 core specimens. If one interprets the "effective" stress holding microcracks closed as simply the difference between the earth stress and the pore pressure, then Brace, et al[13] have shown that reducing the effective stress by increasing the pore pressure tends to open the microcracks, leading to large changes in the effective permeability of the rock.

Figure 5 presents a summary of all the data we have measured pertaining to pore-pressure-dependent permeability. Included are data from the EE-1 fracture, the present GT-2 fracture (roughly centered at 2.81 km) and an early, now-inactive fracture in GT-2. Empirically we have found that the square root of the ratio of the permeability at zero wellhead pressure to the permeability at elevated pressures, $\sqrt{k_o/k}$, is reasonably linear with pressure as shown. A value of zero for the ratio $\sqrt{k_o/k}$ at the intercept with the abscissa mathematically implies infinite permeability at the face of the fracture plane. A reasonable interpretation would be that when the pressure approaches the maximum horizontal component of earth stress, S_2, (the intermediate earth stress, aligned horizontally and parallel to the fracture plane) the effective stress in the S_2 direction approaches zero with concomitant opening of microfractures. The least squares line using the entire data set has the equation:

$$\sqrt{\frac{k_o}{k}} = 1.00 - 0.0098\ P(\text{Bars}) \quad . \quad . \quad . \quad (5)$$

and the extrapolated pressure, at $\sqrt{k_o/k} = 0$, of 102 bars (1480 psi) above hydrostatic is believed to be an estimate of S_2

ANALYSIS OF FLOWING TEMPERATURE LOGS:

In Situ Thermal Conductivity. The equation describing the heat transfer in the rock surrounding a wellbore is:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{\rho c}{\lambda}\frac{\partial T}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and the equation for the flowing fluid in the wellbore is:

$$\frac{\partial T_f}{\partial t} + U\frac{\partial T_f}{\partial z} = -\frac{2}{\rho_f c_f}\left(\frac{\lambda}{r}\ \frac{\partial T}{\partial r}\right) \quad r = a \quad . \quad . \quad (7)$$

In the derivation of Eqs. 6 and 7 it has been assumed that the properties of the rock and the water are constant and that the turbulent mixing that occurs in the flowing water results in negligibly small radial temperature gradients in the water. If these equations are nondimensionalized, it can be shown[14] that a dimensionless temperature difference is a function of a dimensionless time and the ratio of the volumetric heat capacity of the rock to that of the fluid:

$$\frac{2\lambda\ (T_{of} - T_f)}{\rho_f c_f a^2 U\ dT_f/dz} = \Phi\left(\frac{\lambda t}{\rho\ c\ a^2}\right)\cdot\Psi\left(\frac{\rho c}{\rho_f c_f}\right) \quad . . . (8)$$

where T_f = fluid temperature at time t, depth z

T_{of} = initial fluid temperature at depth z

Equation 8 is valid when both the fluid velocity U, and the temperature gradient dT_f/dz do not vary significantly with time. The latter condition requires that the following dimensionless grouping be less than 0.3[14]

$$\rho_f c_f aU\sqrt{\alpha t}/\lambda z \leq 0.3 \quad . . . . (9)$$

A wellbore heat transmission computer program[15] was used to generate the functional form of Eq 8 for a value of $\rho c/\rho_f c_f$ appropriate for granite and 200°C water. The computed curve is shown in Fig. 6. This curve is essentially a type curve, and is the thermal analog to the type curve developed by Ramey[16] for pressure analysis of a single well in an infinite reservoir with wellbore storage.

All parameters except temperature and time, in Eq. 8, are assumed constant so if experimental values of log $(T_{of}-T_f)$ are plotted against log (t), the plot should have the same shape as Fig. 6. The data from the temperature logs taken in the GT-2 wellbore, at a depth of approximately 2.77 km (9100 ft), injecting at a constant rate of 0.6 liter/sec (9 gal/min) with conditions satisfying equation (9), were plotted on log-log coordinates and the results are overlayed on the type curve of Figure 6. A match of curve shape occurs and a match point at an experimental time of 10,000 seconds corresponds to a dimensionless time of 1.4. The wellbore radius is 0.087 m. Using a value of 2700 kg/m³ for the rock density, ρ, and a value of 1050 J/kg-K for the heat capacity c, the calculated value of the <u>in situ</u> thermal conductivity of the rock is <u>3.0 W/m-K</u> (1.7 BTU/hr-ft-°F). This is in excellent agreement with the laboratory results reported by Sibbitt[17] for core specimens taken from GT-2.

As a check, the temperature difference at 10,000 seconds is 2.8°C and using values:

ρ_f = 950 kg/m³ (59.2 lb/ft³)

c_f = 4184 J/kg-K (1.0 BTU/lb-°F)

q = 6 x 10^{-4}m³/sec (9 gpm)

λ = 3.0 W/m-K (1.7 BTU/hr-ft-°F)

ΔT (dimensionless) = 0.66

a value of 32°C/km (0.017 °F/ft) is calculated for the average temperature gradient dT_f/dz. This is in excellent agreement with the local measured temperature log in the interval of the wellbore near 2.77 km (9100 ft). Average measured gradients from 1 to 2.9 km (3050 to 9600 ft) depths in GT-2 are between 50 and 60°C/km (0.027 and 0.032°F/ft).

<u>Determination of Wellbore-to-Fracture Connection Depths.</u> By assuming constant rock properties and a constant wellbore radius, the ratio of the water velocity U_2 (at some depth z_2 and time t) to the velocity U_1 at a reference depth z_1 is related to the water temperature changes and water temperature gradients, $\bar{G}$, at these depths and time as:

$$\frac{U_2}{U_1} = \frac{T_f(z_2) - T_{of}(z_2)}{T_f(z_1) - T_{of}(z_1)}\ \frac{\bar{G}\ (z_2)}{\bar{G}\ (z_1)} \quad . . . (10)$$

It should be noted that the gradient, $G = \partial T_f/\partial z$, is no longer required to be constant in Eq. 10 and in fact, the gradient to be used, $\bar{G}$, is an "effective average" gradient. For short time tests with insignificant wellbore heat storage ($1<\alpha t/a^2<10$), a useful approximation for $\bar{G}$ is:[14]

$$\bar{G} = \sqrt{G(t)\cdot\frac{1}{t}\int_0^t G(\tau)d\tau} \quad . . . . . (11)$$

The results of temperature logs taken while injecting at a constant rate into the GT-2 wellbore are shown in Figure 7. These logs were taken under conditions satisfying the short time criterion Eq. 9. The data of Figure 7 were analyzed per Eqs. (10) and (11) and Figure 8 presents the relative velocity as a function of depth. The depth intervals at which water is being lost to the surrounding rock are exceptionally well defined by this technique. Furthermore, Figure 8 indicates that 80% of the water is flowing into a fracture over a more narrow interval (∿ 40 m) than is suggested by the depression in the logs of Figure 7. The relative velocities plotted in the intervals where the relative velocity changes from 1.0 to 0.2 and 0.2 to 0.05 may not be significant, since in these intervals water is flowing into the rock formation, and the rock energy equation, Eq. 6, should therefore incorporate an additional convective mode of heat transfer.

From Figure 8 it appears that the main connection between the GT-2 borehole and fracture is centered at 2.81 km (9220 ft), with a secondary connection at 2.87 km (9420 ft). The main connection occurs where the casing was damaged while "milling out" a packer and the secondary connection occurs where the casing was jet-perforated. A similar analysis of flowing temperature logs taken in the EE-1 borehole indicates that it is connected to its fracture at 2.95 km (9670 ft). Attempts to determine these fracture-to-wellbore connection points with spinner surveys have been unsuccessful because of the high temperatures at these depths.

IMPEDANCE TO FLOW CIRCULATION:

The circulation of flow through the present downhole system is characterized by high impedance. Figure 9 presents results of an experiment in which water was injected into EE-1 while GT-2 was vented. Since buoyancy effects due to temperature differences are not important in short term experiments the net pressure difference is simply the EE-1 pressure; while the net, circulated flow is simply the flow rate measured at the surface outlet at the GT-2 wellbore As can be seen, a linear relationship exists between the pressure difference and the circulated flow (at least at these low flow rates) and the slope of the line yields the specific impedance, which for this experiment was 142 bar-sec/liter (130 psi-min/gal).

The results of many flow circulation tests indicate that flow appears at the venting wellbore in two or more stages suggesting that two or more paths of communication exist between the fractures. In the first stage, flow appears at the venting wellbore less than ten minutes after the start of pumping into the other wellbore This response is so fast compared to the calculated response time for the low permeability granite between the two fractures, which are estimated to be 6 m (20 ft) apart, that we conclude that this early-stage of flow must be via a set of natural fissures, or a zone of locally very high permeability, or even possibly by means of an intersection of the two hydraulic fractures.

Following this early-arriving flow, a slowly increasing flow rate is observed, possibly caused by permeation of water through the rock separating the two hydraulic fractures. As expected, this additional increment of flow rate varies with time and the pressure levels at the two boreholes as well as the size of the fractures. Because permeability so greatly increases with pore pressure, (see Figure 4) this second path of communication controls the major flow fraction, particularly for long-term tests where both wellbores are pressurized to high levels.

Figure 10 summarizes the impedance data to date. The circled data points represent the initial (first stage) impedance while the vertical bars represent the full range of transient impedance exhibited during each long-term test.

Anomalous transient pressure curves obtained during experiments 102 and 106 suggest that the declines in initial impedance observed during these experiments are due to the removal of impedances in the fractures; possibly a "flushing out" of rock/water/drilling fluid interaction products which had partially closed the fractures to flow.

Figure 10 indicates that the lowest impedance measured to date is approximately 28 bar-sec/liter (25 psi-min/gal). Because of uncertainties in the area of overlap of the two fractures, and the distance between the two fractures, and the extreme variation of permeability with pore pressure, it is difficult to estimate the minimum value of impedance attainable with the present system. However, very approximate calculations suggest that if both boreholes were maintained at 90 bars (1300 psi), i.e., slightly below P_e, the impedance of the rock between the two fractures might ultimately drop to 5 bar-sec/liter (5 psi-min/gal), i.e., comparable to the other impedances in the system.

DISCUSSION:

System Potential As A Demonstration Heat Extraction Experiment. The measured in situ permeability, even at high pressures is low enough that "leak off," requiring the continuous replenishment of water to the system, is not a serious problem. Both fractures appear to be located deep enough so that their temperatures should exceed 185°C (364°F). At the present time both fractures have a computed radius of 90 m (300 ft) or more. The in situ thermal conductivity is 3 W/mK, which is as high as can be expected from competent granite.[17]

Calculations of the sort described in reference 3 indicate that with the conditions described above either one of the two fractures could provide enough energy for a demonstration heat extraction experiment. Initially, 10 MW (thermal) power could be extracted, but the power would decline in a short period of time (∿ months). A relatively fast drawdown of power is actually preferred, since this results in cooler rock temperatures, with subsequent contraction and cracking of the rock, and, hopefully, enhancement of the heat transfer area. Field measurements of the effects of thermal stress cracking are particularly desirable, since at present, we have available only the theoretical results of Harlow and Pracht[2] to guide us in the design of high performance (∿ 100 MW(t) for ∿ 30 years) reservoirs which continuously grow due to thermal stress cracking.

Unfortunately, a 10 MW (thermal) demonstration heat extraction experiment would require a flow rate of 15 liters/second (240 gal/min) so that even if the present total circulation impedance was approximately 10 bar-sec/ℓ (9 psi-min/gal) as a result of very high permeability, the pressure loss would be 150 bars (2200 psi). This is not realistic since the injection wellbore would be pressurized above the fracture extension pressure while the other would be operated at low pressure, with a lower permeability and higher impedance effect.

Flow Impedance. The explanation we have offered for the observed impedance behavior is a simple one, and therefore appealing. Nature is not often so simple however, and therefore other theories can rightfully be proposed. One alternative theory maintains that flow communication is by means of two intersecting fractures and that the observed flow impedance is primarily due to fractures which are collapsed or nearly closed.

The fractures can stay closed, near the wellbore even at pressures above S_3 because of stress concentrations at the wellbore. Changes in impedance are effected by pressurizing the fractures, forcing them to open somewhat. Such a theory is not in accord with the observed transient pressure data, which depends, for its validity, upon an infinite conductivity fracture; unless it is assumed that the permeability in question is not that of the rock, but that of the fracture. If the latter case were true, then one calculates from the apparent $(A\sqrt{k})_o$ of the fracture, that the fracture aperture must be so large that it should be considered to have an infinite hydraulic conductivity compared to the granite rock. Unfortunately, there are enough uncertainties that these calculations cannot be performed with complete confidence and it is difficult to unequivocally verify one model or the other.

Propping the fractures open with suitable particles, which have high strength and are resistant to 200°C water, is being considered as a technique for reducing the flow impedance. An alternate possibility is chemical treatment with an aqueous solution of sodium carbonate (Na_2CO_3) to preferentially dissolve the quartz component of the granite reservoir and thus increase the rock matrix permeability and fracture conductance and hopefully reduce the total impedance. Should neither of these techniques work, a redrilling operation to actually intersect one of the fractures will be necessary.

CONCLUSIONS:

Two vertical hydraulic fractures have been created in hot, dry granite. The fracture initiated from the EE-1 borehole has been extended on several occasions so that presently both fractures are approximately 90 m (300 ft) or more in radius. In situ measurements of the effect of pore pressure upon rock permeability confirm, qualitatively, laboratory studies on core specimens, and suggest that large increases in permeability occur as the pore pressure approaches the intermediate principal earth stress, S_2. The two horizontal principal stresses, S_2 and S_3, differ only by 14 bars (200 psi), but they both differ considerably from the vertical stress; so that lithostatic conditions do not prevail at this depth, at this site.

Both fractures are situated deep enough (2.8 km) so that the rock temperature exceeds 185°C (364°F), high enough to be useful for energy extraction. The in situ thermal conductivity is 3 W/mK (1.7 BTU/hr-ft-°F) which compares favorably with laboratory measurements on competent granite core specimens. This combination of favorable rock temperatures, thermal conductivity and fracture radii is sufficient that either fracture could serve as a demonstration heat extraction experiment. Before this is accomplished however, the borehole which is not directly connected to the chosen fracture will have to be cemented off and redrilled so as to directly intersect the fracture selected for exploitation; or else further stimulation (propping or leaching) will be required to attain a low impedance path between the two fractures, in which case heat can be extracted from parts of both fractures. The latter situation may be more advantageous, since, with thermal fracturing, this system may evolve more quickly into one in which heat is being removed by the water from a rock volume, rather than a planar fracture.

NOMENCLATURE:

A = Area (both sides) of fracture
a = wellbore radius
c = specific heat capacity at constant pressure of the rock
c_f = specific heat capacity at constant pressure of the water
E = Young's modulus of elasticity for the rock
$\bar{G}$ = "effective average" water temperature gradient
k = permeability of rock
P = pressure change in the fracture
P_e = fracture extension pressure
q = volumetric flow rate entering the fracture
r = radius coordinate
R = maximum fracture radius
S_1, S_2, S_3 = maximum, intermediate and minimum compressive earth stress, respectively
T = rock temperature
T_f = water temperature
T_{of} = initial (before start of flow) water temperature
t = time
U = velocity of water in the wellbore
z = depth
α = thermal diffusivity of rock ($=\lambda/\rho c$)
$\bar{\beta}$ = mean compressibility ($=\phi\beta_f + (1 - \phi)\beta_r$)
β_r = compressibility of rock
β_f = compressibility of water
κ = hydraulic diffusivity ($= k/\mu\bar{\beta}$)
γ = fracture surface energy
λ = thermal conductivity of rock

μ = viscosity of water
ν = Poisson's ratio
ρ = density of rock
ρ_f = density of water
τ' = dummy variable of integration
ϕ = porosity
Φ, Ψ = functions of nondimensional groupings

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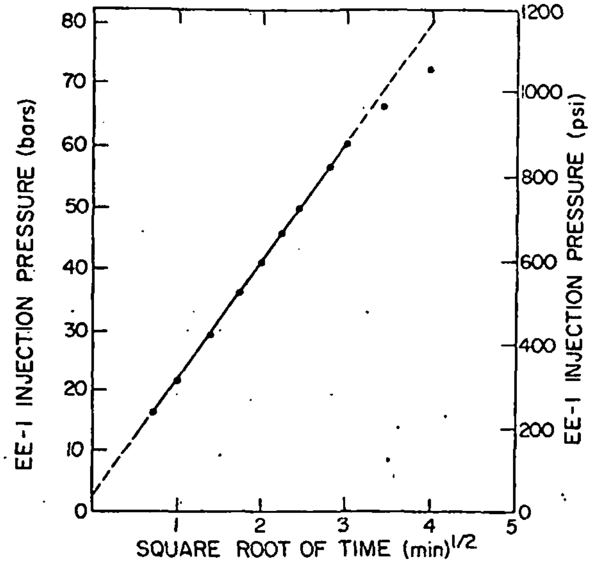

Fig. 1 - Transient increase in wellhead pressure due to water injection.

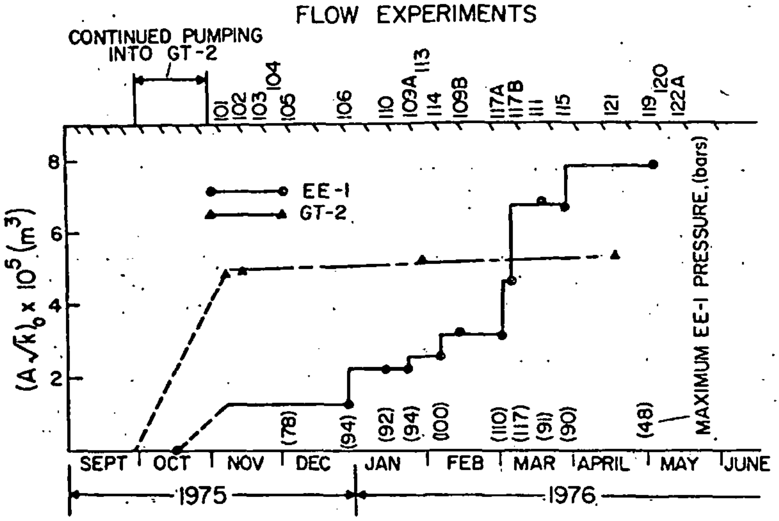

Fig. 2 - Variation of $(A\sqrt{k})_o$ product.

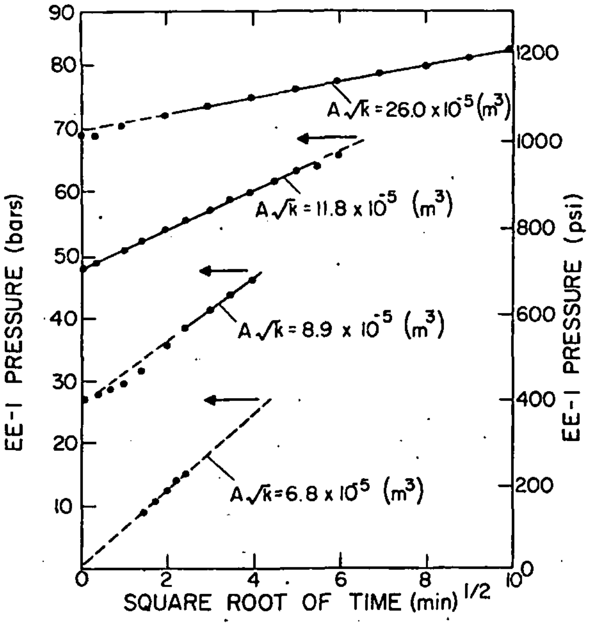

Fig. 3 - Transient pressure increases at elevated pore pressures.

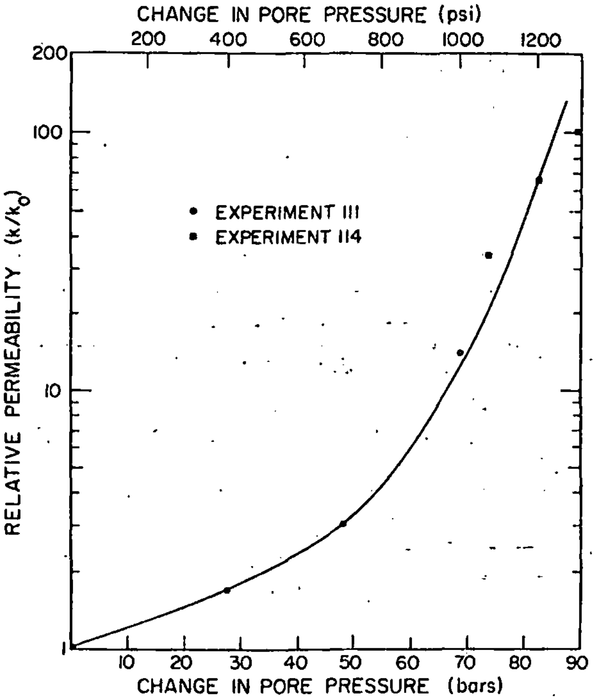

Fig. 4 - Effect of pore pressure on permeability.

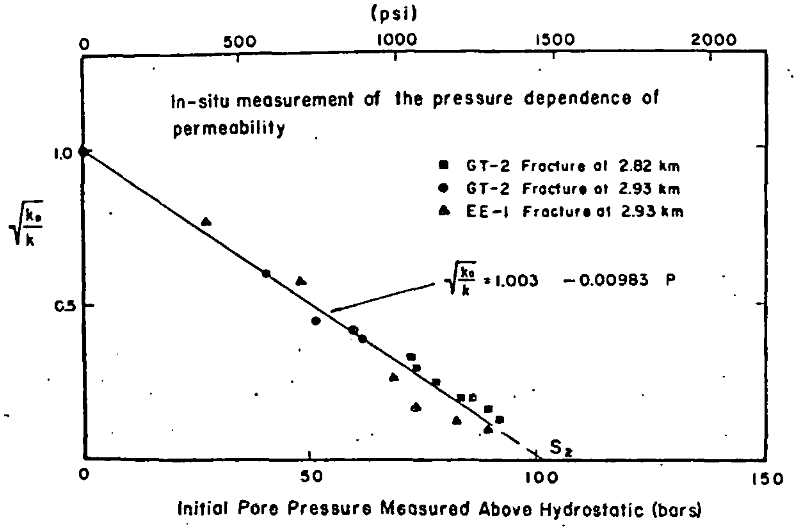

Fig. 5 - Summary of all pore pressure dependent permeability data and extrapolation to intermediate principal stress.

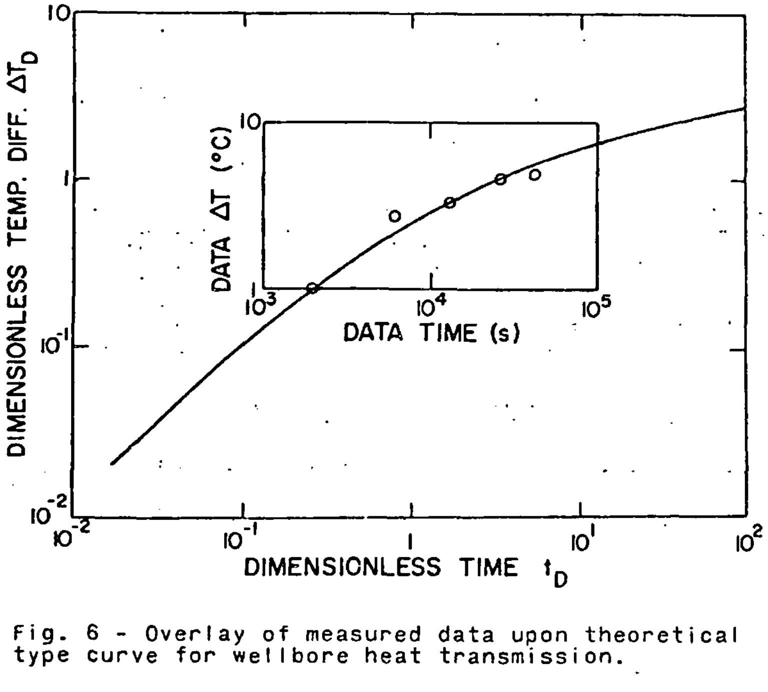

Fig. 6 - Overlay of measured data upon theoretical type curve for wellbore heat transmission.

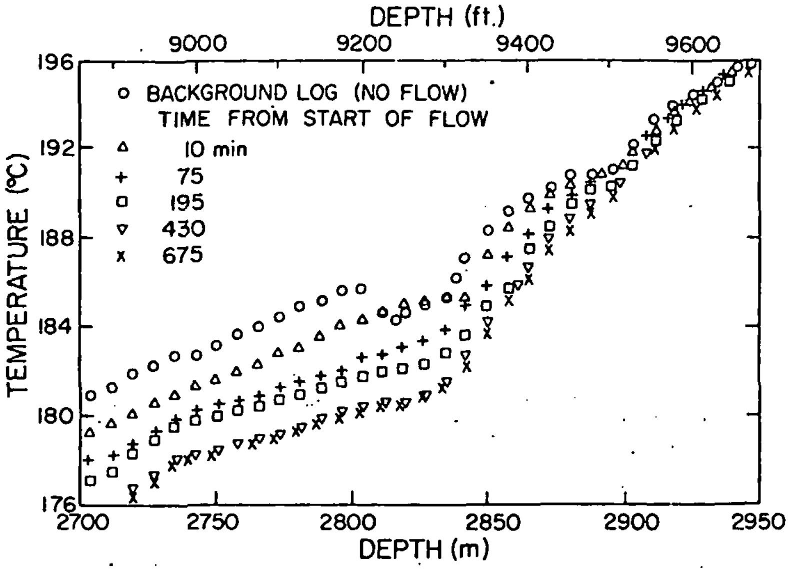

Fig. 7 - Temperature log data.

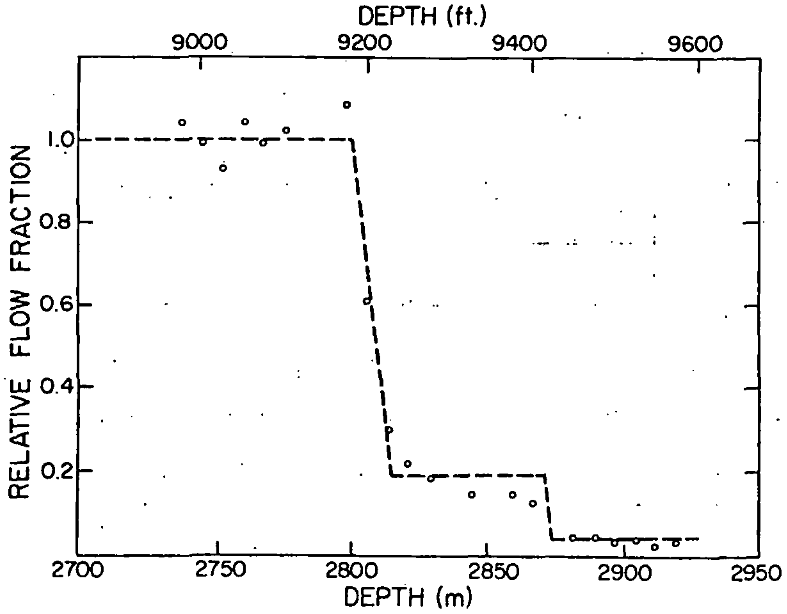

Fig. 8 - Relative water velocities, showing wellbore-to-fracture connection intervals.

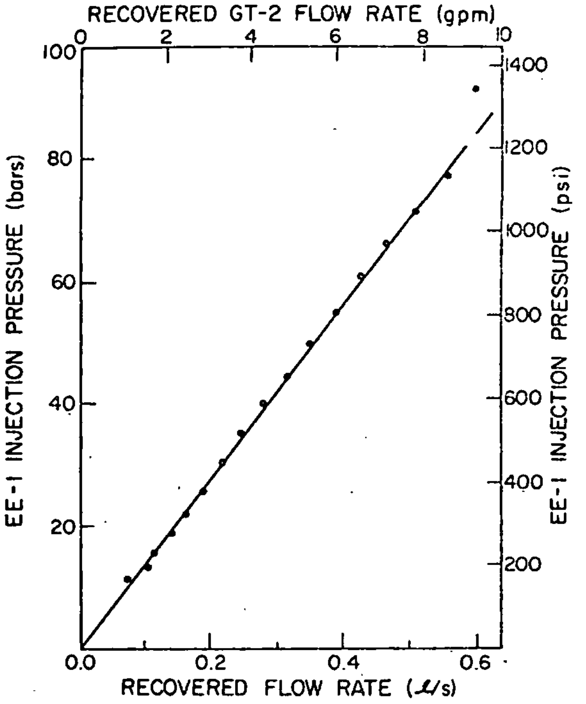

Fig. 9 - Relation of overall pressure losses to circulating flow rates.

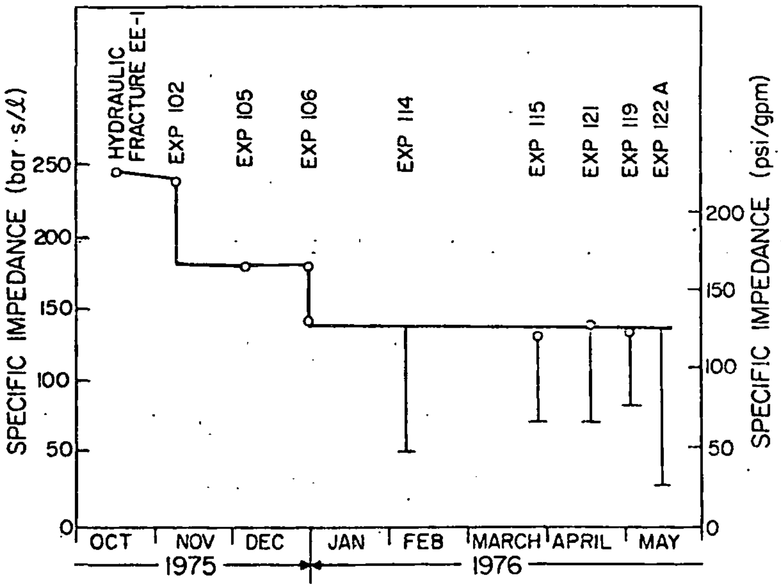

Fig. 10 - Variation of circulating flow impedance.

Progress in geothermal energy

(see last page bottom)

J. D. Garnish

Man has been using the heat from the Earth on a small scale, in the form of natural hot springs, for many centuries. Only recently, however, has geothermal energy been exploited on a commercial scale and the concept that it could become a significant contributor to the world's energy supplies is only now beginning to emerge as a practical reality. This article reviews the economic and technological factors involved in exploiting this source of energy and its possible future contribution to the total demand for energy.

It would not be realistic in this brief review to attempt to offer a blow-by-blow account of the development of existing geothermal technology, nor would it be necessary. With the rapid increase in interest in geothermal topics all over the world (59 countries were represented at the last major conference on the subject) has come an increase in the literature available, and the reader who is interested in particular aspects of the subject is recommended to consult some of the references listed in the bibliography at the end of this article. A particularly good summary of the technical aspects of current geothermal energy use has been published recently by H. C. H. Armstead [1]. The aim of the present article is rather to indicate the state of the art, to outline some of the general factors which restrict the availability of geothermal energy, and then to describe in more detail two recent developments which, in the opinion of the author, have major implications for the more widespread use of heat from the Earth.

Present usage of geothermal sources

Over the centuries, man's use of geothermal energy has progressed through a series of stages, each representing an advance in technology and a resultant increase in that part of the resource which could be considered a reserve. Use in the earliest times was limited to those instances where the Earth's heat was brought naturally to the surface by hot springs, a locally useful but globally insignificant amount of energy. With the development of drilling technology by the oil industry came the ability to tap more useful amounts of energy, though it should be realized that even today our ability to exploit geothermal sources is limited to the depth which such drilling can achieve—currently about 10 km. Not until the second half of the nineteenth century was any extensive use made of geothermal waters, for space heating in Hungary and the USA. Although electricity was first generated from geothermal steam in Italy in 1904, the rate of development was very slow until the 1950s. Since then, and particularly in the last decade, the pace has accelerated considerably. The current position of the major users of geothermal energy is summarized in Table 1 (see p. 71). It will be seen that the countries most involved are those situated on or near the major crustal plate boundaries (figure 1), and that the most common use of geothermal sources at present is to generate electricity. The question is: What are the prospects for geothermal development in those countries—the majority of the world, in fact—that are remote from the boundary zones?

The accessibility of the Earth's heat

The fundamental parameter which restricts the accessibility of geothermal energy is the low rate of heat transfer through the materials which make up the outer layers of the Earth's crust. Although the interior of the Earth (below a depth of 100 km) is estimated to be at temperatures ranging from 1500°C to over 3000°C [2], the outer crustal rocks are such poor conductors that heat can flow outwards only very slowly. In fact, the average rate of outward heat flow through the surface of the Earth is only 60 mW/m^2, several thousand times less than the rate at which solar energy reaches the Earth.

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Joined the United Kingdom Energy Authority in 1966, having trained as a physical chemist at Bristol University. He worked on a variety of materials problems at AERE Harwell before joining the Energy Technology Support Unit at its formation in 1974. As a member of the Unit, he is responsible for supplying technical advice to the U.K. Department of Energy on geothermal matters and is the Project Officer for the Department's geothermal R & D programme.

Beneath the land masses of the world the average crustal thickness is some 35 km, well beyond the limits of drilling technology. There is little chance, therefore, of penetrating to the hotter (and possibly molten) material beneath the crust. At the present time, the prospects of exploiting the Earth's heat can be best understood by considering the crust as a giant storage medium in which heat has accumulated over geological periods of time and from which it may be 'mined' as a non-renewable but very large source of energy. The problem then resolves itself into two components: How can heat be extracted at a useful rate from a mass of poorly-conducting rock, and where can the processes be applied most economically?

To deal with the second question first, it can in most cases be rephrased as: Where can the highest temperatures be found at the shallowest depths? The heat in the crust has accumulated from a number of sources, primarily by transfer from beneath and from heat generation processes within the crust itself (radioactive decay, frictional and chemical effects, for example). These effects occur non-uniformly across the surface of the Earth; for example, heat transfer by convecting magma (molten rock) to shallow depths is greatly enhanced in the volcanic and seismic zones (which reflect the processes occurring at the plate boundaries). Thus, although the 'geothermal gradient' (the rate of increase of temperature with depth in the upper layers of the crust) shows a world-wide average of 25–30°C/km, giving rise to the average heat flow of 60 mW/m^2 mentioned earlier [3], in some regions the gradient is considerably greater than this—80°C/km or more.

The other question posed above was how to extract heat from the crustal rocks. First of all, some heat transfer medium is needed; to date, water has been the only serious candidate for this role. Secondly, because rocks are poor conductors of heat, large heat transfer surfaces are required. These two conditions occur naturally where ground waters are able to circulate through permeable rocks such as sandstones or limestones. Up to the present, all exploitation of geothermal energy has made use of the natural combination of deep-circulating ground waters with porous rock. The higher the natural geothermal gradient the greater will be the temperature of the water at a given depth (and, frequently, the easier it will be for such water to return to the surface as a hot spring or a geyser). Equally, the shallower will be the drill-holes needed to extract the hot water or steam and hence the lower the capital outlay in the development project. It is not surprising, therefore, that most of the major projects to date have been sited in those regions of the world where the geothermal gradient is unusually high.

How can geothermal sources be used?

One further factor is significant; the porosity and permeability of rocks decreases generally with depth, so it is uncommon for water to be able to circulate freely at depths much greater than about 4000 m. For this reason alone the temperature of geothermal water and steam rarely exceeds 300°C, even in the most favourable areas, and is often significantly less. This temperature limitation has several implications for the exploitation of geothermal energy. The useful thermal energy (above 10°C) obtainable from hot water, even at 300°C, is less than 0.1 per cent of the chemical energy content of a similar quantity of oil. It is therefore a very much less valuable product and the amount of capital which can be spent on exploration and drilling is reduced accordingly. Again, the cost of transmitting the water over any distance rapidly exceeds the value of the energy available, so the use of steam or hot water is generally limited to those sites where a market for the heat can be developed within a few kilometres of the well-head. Finally, the relatively low temperature, though useful, does restrict the range of application.

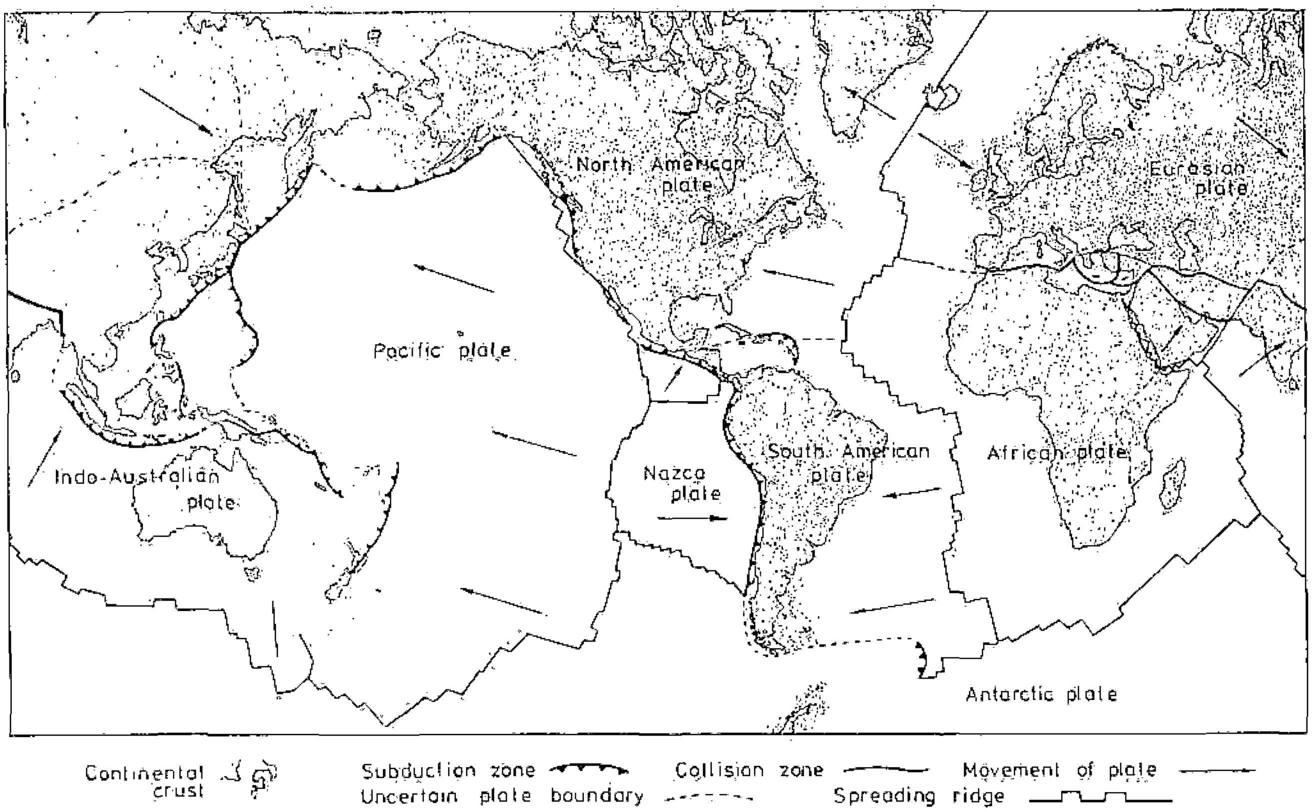

Figure 1 The Earth's crust consists of a set of rigid plates which are moving relative to one another. The resulting stresses at the plate boundaries give rise to earthquakes and active volcanos. Heat flow and geothermal gradient in these regions is higher than average.

For these reasons, geothermal sources have been used wherever possible for electricity generation, with modest size turbogenerators (10–100 MWe (megawatts electrical)) installed close to the well site. 'Wherever possible' means, in practice, where the temperature is high enough. The decreased efficiency of power generation from lower temperature sources sets a lower limit on the practical source temperature; this is an economic rather than a technical constraint but it is generally accepted at present to be about 150°C [4]. Below this temperature it is generally more profitable to seek direct uses for the heat obtained rather than to accept generating efficiencies of 10 per cent or less. This constraint on usage becomes significant in considering the implications for geothermal exploitation in the 'normal gradient' areas of the world; that is, those where the geothermal gradient is less than about 40°C/km. The reduction of permeability with depth means that water flows will rarely be encountered with temperatures in excess of 150°C in these areas and, because the depth required to reach a given temperature will be greater, the high cost of drilling will make it even more important to maximize the returns from such a well. This results in a need to locate a direct heat usage (thus eliminating generating losses) where the well can be operated on as high a load factor as possible. The first question is whether heat at such temperatures has any value at all. Perhaps surprisingly, the answer is 'yes'. In those countries where space heating is required for some part of the year the proportion of the primary energy supply which is used to provide low-grade heat ($T \leqslant 100$°C) often exceeds 20 per cent [4]. Where a source of low-grade heat exists, there is a clear incentive to use this rather than premium fuels—provided it can be done economically.

Use of low-temperature sources in France

The minimum size of a development is one well and, in a normal gradient area where a well depth of 1500 m or more is necessary to achieve a minimum useful temperature (say, 55°C), the minimum economic output from such a well will be of the order of 5 MWt (megawatts thermal). This limits the practical applications of direct heat uses to schemes on the scale of a district heating network or a commercial glasshouse operation rather than individual domestic supplies. Geothermal waters have been used for space-heating and for horticulture for many years, but the majority of the developments have been in high-gradient areas where drilling costs have been correspondingly low. Before similar schemes can become widespread in the less favourably

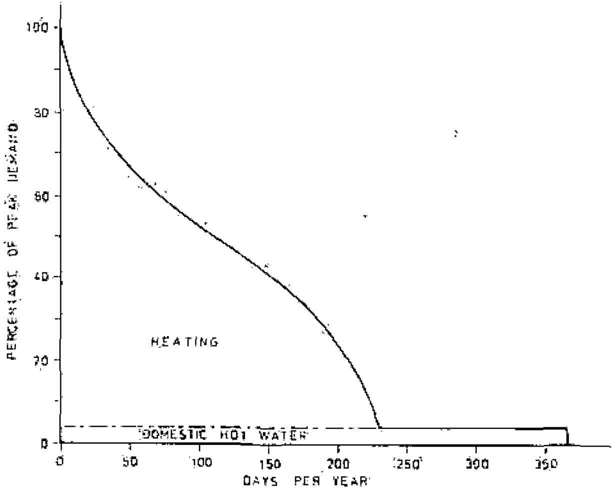

Figure 2 The typical variation in the heat load of a building as a function of time. In this particular example, heat sources with a power rating of 30, 40, 50, and 60 per cent of the peak demand could meet respectively 57, 73, 85, and 91 per cent of the total heat requirement.

situated areas, techniques have to be demonstrated which optimise the utilization of the geothermal well (which is the major item of cost in the installation), maximizing its load factor and the amount of heat extracted from the geothermal source. In this context, work in France within the last decade has been particularly significant [5]. It has resulted in a series of geothermal district heating installations being built in the Paris region and these are important in two respects: first, they represent the first large-scale demonstration of the process in a 'normal gradient' area (the geothermal gradient in the Paris region is 30–35°C/km), and, second, they have demonstrated the feasibility of re-injection as a means of disposing of the water after use.

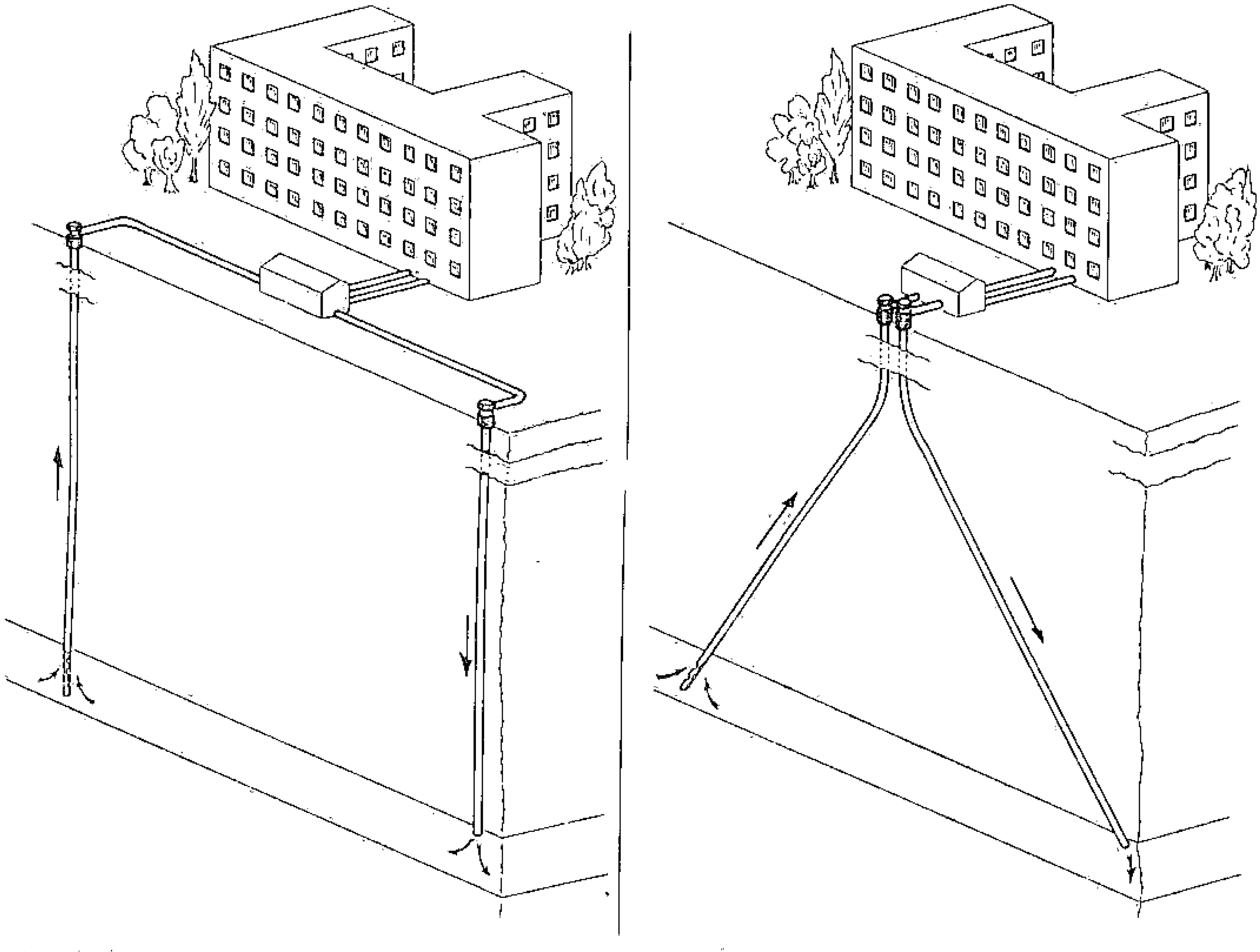

Figure 3 Alternative layouts of a production and reinjection well. The extra cost of 'whipstocking' the two wells from a common drilling pad is compensated by savings in surface transmission pipe.

There are at present four such installations around Paris, serving some 13,000 dwellings. The prototype scheme at Melun was commissioned in 1970 while those at Villeneuve-la-Garenne, Creil, and Mée-sur-Seine have been brought into operation within the last two years. Complete evaluation of the costs and benefits of these schemes is complicated by the fact that they use a mixture of pre-existing and purpose-built plant and equipment, but the best estimates suggest that the overall running costs (including amortization of capital) will be some 13–16 per cent lower than the costs of comparable oil-fired plant [6]. Plans are already in hand for further installations to serve some 25,000 dwellings in the region and it is expected that some 4–500,000 dwellings all over France will be heated from geothermal sources by 1990, resulting in a saving of about 1 million tonnes of oil per year [5].

The Paris installations draw their water from the Dogger, a sandstone stratum that lies at depths of 1500–2000 m below the city. The water temperature varies from one site to another between 57 and 75°C. With wells of this depth costing (with their associated equipment) some £300,000 apiece, it is clearly necessary to maximize the output obtained during the life of the system, and this has been achieved in several ways. Perhaps the most important step has been to analyse the heat demand of the buildings as a function of time; this results in a curve similar to that shown in figure 2. Inspection of this reveals that it is often possible to supply over 80 per cent of the total load using a heat source rated at only about 50 per cent of the peak system demand. By installing auxiliary boilers fired by fossil fuel to meet the peak load (which occurs for only a small fraction of the heating season) the size and number of geothermal wells required can be reduced and their load factor maximized. This principle has been adopted in all the French installations, resulting in the anticipated economies mentioned already. The demonstration of practical systems of this type over the next few years will in itself do much to assist in the introduction of geothermal energy to other 'normal gradient' countries.

The installation at Creil, a complex of about 4000 dwellings sited 30 km north of Paris, incorporates another interesting feature. By using heat pumps to reduce further the temperature of the water returning from the first stage of the heating network, the final temperature of the water rejected from the installation can be kept as low as 7°C. The total amount of heat obtained from the geothermal fluid is thus almost double that which could otherwise be extracted from a given well flow and the savings achieved more than compensate for the additional capital and running costs of the heat pumps.

The third item of interest about these schemes is their pioneering use of reinjection, a process which has implications for all future geothermal developments, whether in high or low gradient regions. Water from deep aquifers invariably contains quantities of dissolved solids, silica in the case of high temperature sources and salts in the case of lower temperatures. In Paris, for example, water from the Dogger contains about 25 g/l. of dissolved solids (mainly sodium chloride). The Creil scheme alone uses about 200 m³/h of this water and thus has to dispose every day of waste fluids containing 120 tonnes of salt. Clearly no surface drainage system or river could carry this loading without severe environmental problems, and so reinjection into the ground has great benefits. If the water is actually reinjected into the same formation from which it has been extracted, the process also offers the possibility of more efficient heat extraction from the reservoir rocks. Only about 25 per cent of the total heat content of the reservoir is contained in the water, the remainder being contained in the rock matrix. Recharge of the aquifer offers, in principle, the possibility of a second or even a third sweep through the system, thus extracting heat from the rock matrix as well.

Reinjection is not without its problems, of course. Additional wells must be drilled and pumps installed and operated, all adding to the costs of the system. There are risks that precipitation from the cooled water could choke up the rock formation, or that the reinjection pressures required might cause fracturing of other strata in the well, thus risking contamination of fresh water resources in other shallower aquifers. Above all, there is the risk that a 'short circuit' could develop which would allow cooled water to reach the point of extraction too quickly, thus shortening the useful life of the development. Most of these difficulties can be minimized by careful planning of the installation, but this in turn requires a thorough understanding of the characteristics of the aquifer in question. Many of these points are illustrated in figures 3 and 4, the latter showing the results of a computer simulation of one possible configuration of wells for one of the French schemes. The work in France will give valuable information about the real advantages and problems of reinjection systems, which seem likely to be used more and more widely in future geothermal developments.

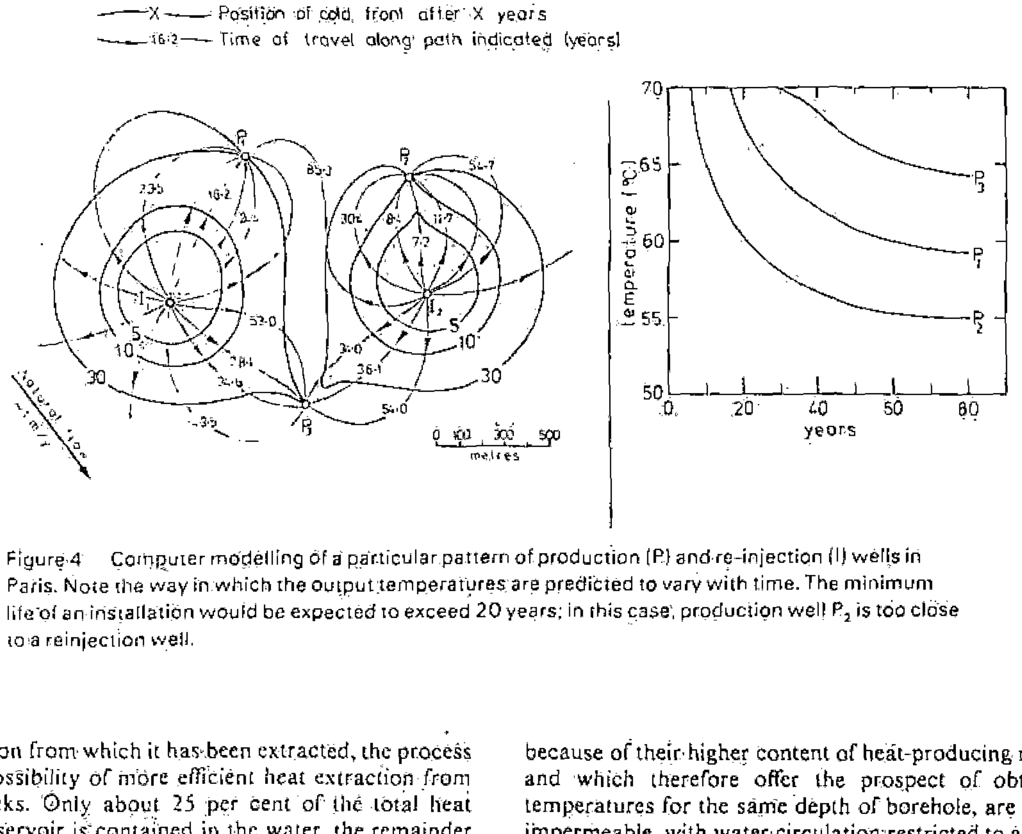

Figure 4 Computer modelling of a particular pattern of production (P) and re-injection (I) wells in Paris. Note the way in which the output temperatures are predicted to vary with time. The minimum life of an installation would be expected to exceed 20 years; in this case, production well P_2 is too close to a reinjection well.

The 'dry rock' problem

With the French work in 'normal gradient' areas (figure 5) complementing that in countries like the USA, Iceland, and Japan on high temperature sources, it seems likely that every country in the world could, in principle, exploit some fraction of the heat beneath it. All these developments have one factor in common, however—they rely on the presence of a permeable rock formation at a suitable depth. Unfortunately, the majority of the rocks in the Earth's crust fail to meet this condition of permeability. The deeper (and therefore hotter) sedimentary rocks have been compacted by the weight of material above them and their permeability reduced accordingly. Granites, which are usually hotter than the surrounding rocks at the same depth because of their higher content of heat-producing radio-elements and which therefore offer the prospect of obtaining higher temperatures for the same depth of borehole, are usually highly impermeable, with water circulation restricted to a few randomly orientated cracks and fissures. If geothermal energy is ever to make a major contribution in those parts of the world which are remote from crustal plate boundaries then some method must be developed to obtain heat from these 'hot dry rocks'.

The problem again reduces to one of forming a sufficiently large area of underground heat transfer surface. One solution which has been studied in detail would be to use an underground nuclear explosion [7] but the major difficulty appears to be the seismic effects which would be associated with an explosion powerful enough to produce an adequate volume of shattered rock. These would restrict the practical applications of the technique to regions remote from large centres of population and therefore, in general, remote from centres of energy demand. Of much wider potential application is an important experiment currently under way at Los Alamos Scientific Laboratory in New Mexico. This is designed to test the concept that a crack of adequate surface area and suitable hydrodynamic properties can be formed deep in a granite mass by hydrofracturing. In principle, if water is pumped under pressure into a deep borehole in a uniform impermeable rock, a single vertical disc-shaped crack should be formed which can be grown in a controllable manner to a radius of several hundred metres. If this crack is then intersected by a second borehole, water can be circulated around the loop so formed in such a way as to sweep evenly over the faces of the crack and extract heat from the rock [8]. The work at Los Alamos, which is illustrated schematically in figure 6, has demonstrated that such cracks can indeed be formed in deep hot granite (though it seems probable that the initial single fracture rapidly links up with previously sealed joints in the rock to form a more complex fracture volume). A trial loop has been completed, with a second, directionally-drilled borehole intersecting the crack at a depth of about 3000 m where the temperature is 200°C. Circulation of water around this loop was achieved in May 1977. This experiment, which is the subject of considerable international interest, will be closely monitored over the next two or three years. Questions to be answered about the process will include

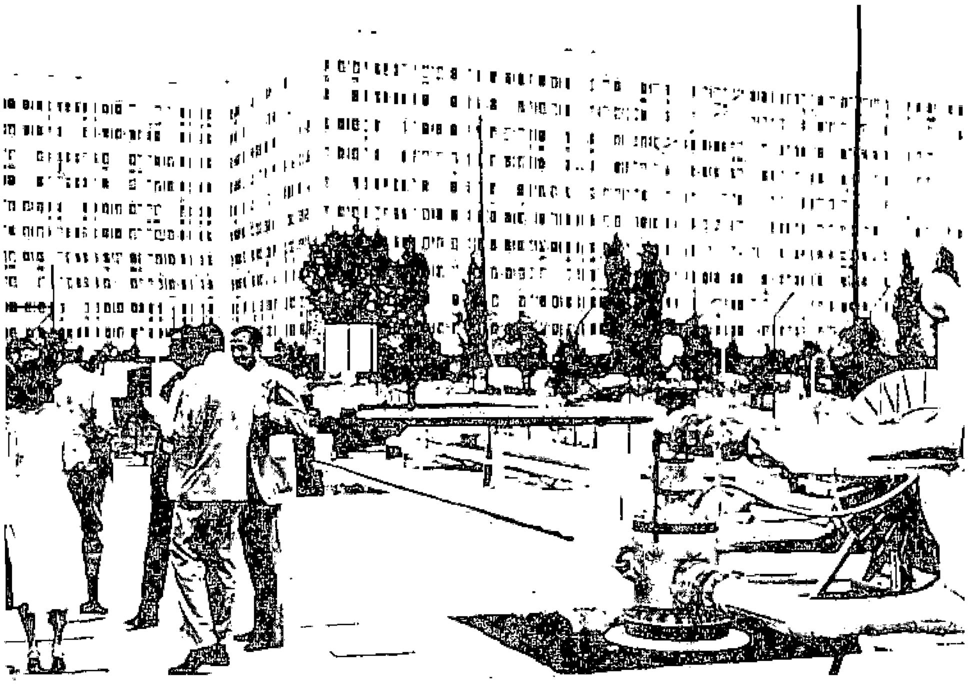

Figure 5 The geothermal installation at Villeneuve-la-Garenne. The well in the foreground supplies geothermal water for space-heating to a 1700-apartment complex, part of which may be seen in the background. The other well is used for reinjection.

—will the cracks remain open sufficiently to ensure adequate circulation rates at the pressures employed (100–125 kg/cm^2), and will leakage rates from the system be acceptable?

–how will the system be affected by the chemical reactions that are likely to occur at this temperature and pressure between the rock and the water?

—and, most important of all, how will the power output of the system vary as a function of time?

The significance of this last question is that calculations suggest that the original crack surface will cool relatively rapidly and power output could be declining quite sharply within one year of the start of operation. It is predicted, however, that as the original crack surface cools, thermal contraction of the rock will lead to fresh cracks forming at right angles to the original surface, thus extending the zone of water circulation and heat exchange into fresh volumes of hot rock. If this mechanism does indeed operate, and it seems that the viability of the system will depend on such an event occurring, then the early decline in power output should be reversed and power should then increase steadily over the remaining life of the system [9]. It will take several years, therefore, to test all aspects of the design but the outcome will be awaited with interest by many workers. If all goes well, it seems

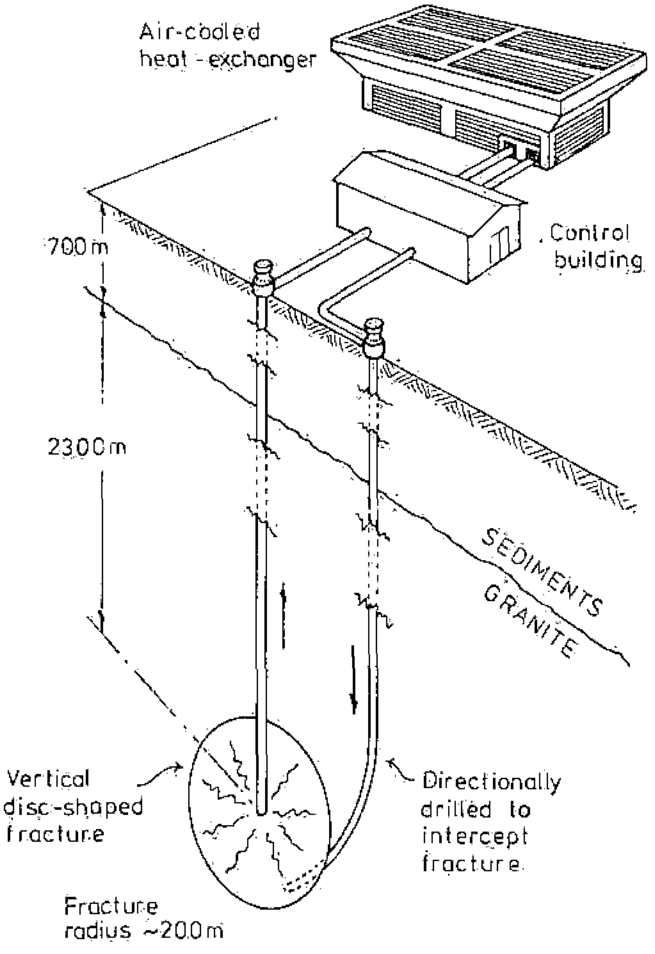

Figure 6 A schematic diagram of the 'hot dry rock' experiment at Los Alamos.

TABLE I. THE PRESENT STATE OF GEOTHERMAL DEVELOPMENT

Country	Electrical generating capacity (MWe) Installed (1976)	Estimated (1985)	(2000)	Non-electrical uses in 1976 (MWt) Residential & commercial	Agricultural	Industrial
USA	522	6,000	20,000	1.5	—	—
Italy	421	800	—	—	1	20
New Zealand	202	400	1400	215	small	125
Mexico	78.5	400–1,400	1500–20,000	—	—	—
Japan	70	2,000	50,000	10	5	small
Philippines	—	300	—	—	—	—
El Salvador	60	180	—	—	—	—
Nicaragua	—	150–200	300–400	—	—	—
Iceland	2.5	150	500	350	39	50
Costa Rica	—	100	—	—	—	—
Guatemala	—	100	—	—	—	—
Honduras	—	100	—	—	—	—
Panama	—	60	—	—	—	—
Taiwan	—	50	200	—	—	—
Portugal (Azores)	—	30	100	—	—	—
Kenya	—	30	60–90	—	—	—
Guadeloupe	—	30	—	—	—	—
Spain	—	25	200	—	—	—
USSR	5.7	20	—	114	5,011	—
Turkey	0.5	10	—	100 (planned)	—	—
Canada	—	10	—	—	—	—
Hungary	—	—	—	770	363	—
France	—	—	—	40	—	—

probable that several similar projects will be initiated in different parts of the world within the next five years.

Conclusion

Certain aspects of geothermal development are already in commercial operation on a limited scale and the more favourably situated countries are planning rapid expansions, especially in power generating capacity. Meanwhile demonstration projects, especially in France, are paving the way for a wider application of direct heat uses in many other parts of the world. In the longer term, but most important of all, there are indications that it will indeed prove possible to extract heat from 'dry' rock, thereby opening up the prospect of greatly increased exploitation of the heat in the crust at virtually any point on the Earth's surface.

The views expressed in this article are the author's own and do not necessarily represent those of the UK Department of Energy.

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Electron coincidence spectroscopy: a new way of looking into matter

Ian E. McCarthy and Erich Weigold

In electron coincidence spectroscopy, kinematically complete measurements are made of symmetric ionising collisions initiated by an electron beam on a gaseous atomic or molecular target. The reaction measures the shapes of individual orbitals, and provides a sensitive measurement of the charge density far from the atomic nuclei. The technique promises to be of outstanding importance in developing an improved understanding of molecular structures.

The title of this article is almost identical to that of an earlier *Endeavour* article by K. Siegbahn [1] on photoelectron spectroscopy. The inclusion of the word 'coincidence' in the present title is, as we shall see, of extreme significance, since it allows the determination of the dynamic structure of atoms and molecules, which is not possible by conventional electron spectroscopy.

Conventional atomic and molecular spectroscopy uses photons in the various parts of the electromagnetic spectrum to measure energy-level differences. The photons can be either emitted or absorbed in transitions between quantum states in the system under investigation. More recently photo-electron spectroscopy [1] has become a well-established tool for obtaining information on the electrical structure of atoms, molecules, and solids. This was brought about largely by technical developments in nuclear β-ray spectrometry, where the main effort was devoted to obtaining high resolution spectra of the electrons emitted from radioactive nuclei. In the photo-electric effect, which was first explained by Einstein in 1905 in a paper which was crucial in the development of quantum theory, an incident photon ejects an electron from the sample, all the photon's energy being absorbed in the process. If the incident radiation is monoenergetic, the emitted electrons will have energies corresponding to their different binding or separation energies. Those electrons ejected from more tightly bound molecular or atomic orbitals will have less kinetic energy. The energy spectrum of the emitted electrons is, therefore, characteristic of the molecule and of the elements of which the molecule is comprised.

The processes of photoelectron spectroscopy may be symbolised as

$$h\nu + A \rightarrow A^+ + e \qquad (1)$$

where the atom or molecule A is ionised by an incident photon, with release of an electron. The corresponding energy conservation equation is given by

$$E_e = h\nu - \epsilon_f \qquad (2)$$

where E_e is the kinetic energy of the emitted electron, $h\nu$ the energy of the absorbed photon, and ϵ_f the separation energy of the electron leaving the residual ion in the state f. The recoil energy of the ion is small due to its large mass, and may be ignored. Since the incoming photon has very little momentum (because of its zero rest mass), the momentum of the ejected electron is essentially equal and opposite to that of the recoiling ion. The momentum of the ejected electron is, of course, given by $\sqrt{2mE_e}$. In a simple knockout picture, in which the emitted electron is a plane wave, this means that the incident photon ejects a bound electron of momentum

$$q = \sqrt{2mE_e} \qquad (3)$$

from the target. In other words, only electrons which have momentum q can be ejected from the target. Since E_e is determined by energy conservation (eq. 1), q is also fixed for a given photon and separation energy (ignoring the small momentum h/λ of the photon). Furthermore, for normal emitted electron energies (100–1000eV) q is very large compared to the average momentum of electrons in the valence orbitals. It is only for the most tightly bound (inner) orbitals that the electrons have an appreciable probability of having the momentum q. For the valence orbitals, therefore, photoelectron spectroscopy only gives us information about the very high momentum components of the electron wave function.

The development of electron coincidence spectroscopy—or as it is more frequently called (e,2e) spectroscopy [2]—has overcome these kinematical limitations. In an (e,2e) reaction an incident electron ejects an electron from the sample, the two outgoing electrons being measured in coincidence to ensure that they originate from the same ionising event. The process may be symbolised as

$$e + A \rightarrow A^+ + e + e. \qquad (4)$$

Particular electronic quantum states f of the residual ion can again be isolated by resolving their separation energies ϵ_f, this being the difference between the incident and summed emitted electron energies. However, since the momenta of both electrons emerging from the ionising collision are also measured, one is free to obtain for each final state f a profile of ion recoil momentum $-q$ by measuring the electron coincidence count rate for different arrangements of detector angles and energies which define a set of values of $-q$.

At sufficiently high energies the incident electron knocks out a target electron in essentially a clean manner; the incident, ejected, and scattered electrons interact only very weakly with the electrons in the residual system. The continuum (i.e. incident and emerging) electrons are then described by plane waves having straight line trajectories. We can consider the interaction as taking place between three bodies, the incident electron, the target electron, and the residual ion; the residual ion plays the role of an inert spectator. In order to conserve momentum the ion must have a momentum equal and opposite to that of the bound electron in the target system.

The (e,2e) cross section therefore depends on the product of only two factors, the electron–electron scattering cross section and the probability of finding an electron of the momentum q. The momenta of the detected emerging electrons may be varied, allowing one to measure the cross section as a function of q. This q-profile is, therefore, essentially given by the square of the momentum space wave function of the struck electron. We can, therefore, completely determine the dynamic properties of the electron in its orbital. The measured momentum profiles can be compared with structure wave functions calculated by the

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Gasifying coal underground

P. N. Thompson

With growing concern for adequate sources of energy in the future there has been a revival of interest in the underground gasification of coal. This article describes current activity in this field and discusses the technological and economic factors involved. It concludes that although this means of utilising coal is only marginally attractive at present, it could yet prove valuable—especially for exploiting very deep coal seams, as in Belgium—in changing economic circumstances.

In recent years there has been renewed interest in the underground gasification of coal (UCG). Considerable work was carried out in the Soviet Union from about 1930 onwards, and pilot scale trials took place in the United States and Britain during the 1950s; there were smaller experiments in several other countries. However, most of this work ceased around 1960 for economic and political reasons consequent upon the flood of cheap oil and natural gas coming on to the energy market. Only in the Soviet Union were two existing commercial-scale sites kept going, producing gas in sufficient quantities to generate 100 MW of electricity at each site.

Following the Yom Kippur war there was a revival of interest in additional sources of energy, of which UCG was one. In addition, the passing of the Federal Coal Mining Health and Safety Act in the United States caused attention to be paid to methods of producing energy from coal that would not require miners to go underground. New work was begun also in Canada, Belgium, and West Germany. In Britain, the National Coal Board carried out a re-assessment of the process [1] and the Soviet Union began to sell its technology on a licensing basis.

UCG has always had popular support, although some of this support is based upon misunderstanding of its limitations. It may be as well to dispose immediately of three major misconceptions.

(a) The process is not suitable for gasifying thin, poor quality seams that would not be worth mining by conventional means. Early Soviet work showed that the calorific value of gas produced dropped sharply for seams less than 1 m thick, because heat losses to the surrounding strata became relatively much more serious than in thicker seams. The economic effects of ash content are the same whether the coal is burned on the surface or underground, so that seams which are not worth mining because of their ash content are not worth gasifying either.

(b) Far from being unobtrusive the process has considerable environmental effects, although these are different from those of conventional mining. These arise from the considerable amount of drilling necessary for gas generation on any sizeable scale. With present technology a borehole would be required every 30 m, so that even for a small site capable of providing gas for a 100 MW generating station 20–50 hectares of land would be in use per year: this is about six times that covered by the average British opencast site. There is no doubt that this land could be rapidly reclaimed, but the visual impact of the numerous drilling rigs upon areas of scenic beauty would be considerable.

(c) The gas produced is dirty and of low calorific value. Normally this has been about 4–5 MJ/m^3, nowhere near the 20 MJ/m^3 of the old 'town gas' made by carbonising coal in retorts, that many people expect UCG to produce.

The basic process

The basic process of UCG is shown in figure 1. Air is blown down a borehole, the coal is ignited at the bottom, and gases resulting from the combustion are drawn off at another.

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The combustion of coal in air is a complex series of reactions involving carbonisation, distillation, and combustion of the by-products, but for our purpose it is sufficient to consider the reactions as being represented by the two basic equations:

$$C + O_2 \rightarrow CO_2 + \text{heat}$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat.}$$

Although the coal will have been completely gasified the resulting gases are incombustible and once they have lost their sensible heat they will have little or no value. However, if the hot gases are constrained to remain in contact with further coal after all the oxygen has been consumed, secondary reducing reactions occur:

$$C + CO_2 + \text{heat} \rightarrow 2CO$$

$$C + H_2O + \text{heat} \rightarrow CO + H_2.$$

These endothermic reactions use the heat of combustion to produce a combustible gas which can be used as a fuel. Some methane is also produced both by combination of hydrogen with coal

$$C + 2H_2 \rightarrow CH_4$$

and by pyrolysis of the coal beyond the reducing zone.

A typical gas composition, using air as the gasifying agent, is as follows:

	mole %
CO	10
H_2	12
CH_4	2
CO_2	15
N_2	60.

The nitrogen acts as diluent, resulting in a gas with a calorific value of about 4 MJ/m^3. If this nitrogen were not present—if, for example, pure oxygen were used as the gasifying agent—then the calorific value would be around 7.5 MJ/m^3.

The two-stage gasifying process postulated is, of course, the basis of the producer and water gas reactions that have been used for generating industrial fuel gas in surface producers for many years. Essentially, UCG involves transferring this process into producers or gasifiers constructed in the seam. Control of the product with a naturally variable raw material, such as coal, is difficult enough on the surface. The problems are magnified underground, with remote operation and no possibility of raking or moving the bed. Little is known at present of the manner in which the process is influenced by the many different factors involved. Among the important variables that have been identified are air injection rate, water intrusion rate, and seam thickness. Laboratory experiments have indicated that, for any seam thickness, there is an optimum water/air ratio that gives a maximum calorific value for the gas produced. However, with present knowledge this is virtually impossible to reproduce underground. Much more data—derived from the instrumentation of the 'space-age' type, currently being used at Hanna, Wyoming (see below)—would be required before any precise control of the product could be possible.

To allow the combustion front to proceed in the required direction a linkage channel has to be established between the two boreholes. Several methods have been tried in the past.

(a) Hydro-fraccing. This is a process, much used in oil production, where high-pressure water is injected to open up natural breaks in the coal.

(b) Electro-linkage. A high voltage (200V) is applied to electrodes at the bottom of the holes. The current first dries out, and then carbonises, the seam, leaving a permeable path of coke between the holes.

(c) Pneumatic linkage. High pressure air (about 70 bar) supplied to one borehole percolates to the other and eventually an enlarged air passage is formed. This has proved effective in lignites, which are relatively soft, but is much slower in bituninous coal.

(d) Reverse combustion. Air is supplied at high pressure at one hole and the coal is ignited at the other. The flame front progresses towards the injection hole, against the airflow. When a linkage channel has been formed the air flow, at normal gasification pressure (2 bar), is reversed.

Utilising the gas

The low quality of the gas produced has already been mentioned. Because of the high cost of storage and transport which would be associated with this low quality gas, its utilisation, without upgrading, would be restricted to electricity generation or process heating on the spot. Cost analyses demonstrate that gas of low calorific value can be competitive with grid gases of high calorific value only at distances less than about 15 km from the point of production.

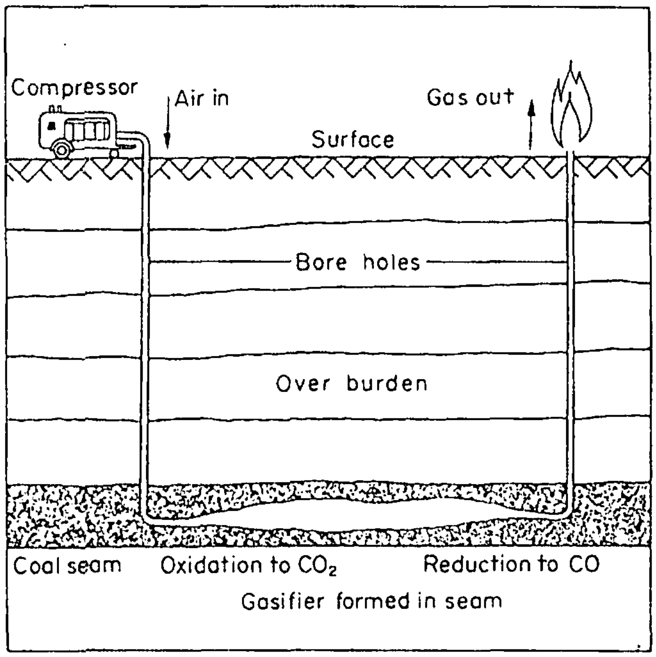

Figure 1 Basic concept of underground coal gasification.

The only use which has in fact been made of the gas so far is for electricity generation. During the last trial at Newman Spinney, in Britain, in 1959 a small generating station was built and an average of 1½ MW of continuous power was produced during the 108 days of the test [2]. Some larger scale sites have been used for electricity generation in Russia and, as has already been mentioned, two sites producing gas in sufficient quantities to generate 100 MW each are currently in operation. These are the only instances so far in which the gas has been put to some practical use. Naturally, however, renewed interest in UCG has led to reconsideration of possible applications.

Two major problems stand in the way of utilising the gas for power generation, at least so far as Britain is concerned. The first consideration is the potential scale of generation. Because of the amount of land required and the area of coal to be gasified it is most likely that present UCG technology would only sustain power stations with capacities in the 100–500 MW range (depending upon the thickness of the coal seam). The present policy of the Central Electricity Generating Board is to construct very large stations—up to 3000 MW—to feed the national grid. A change of policy would therefore be required if small stations were to be constructed to supply individual towns or industrial complexes.

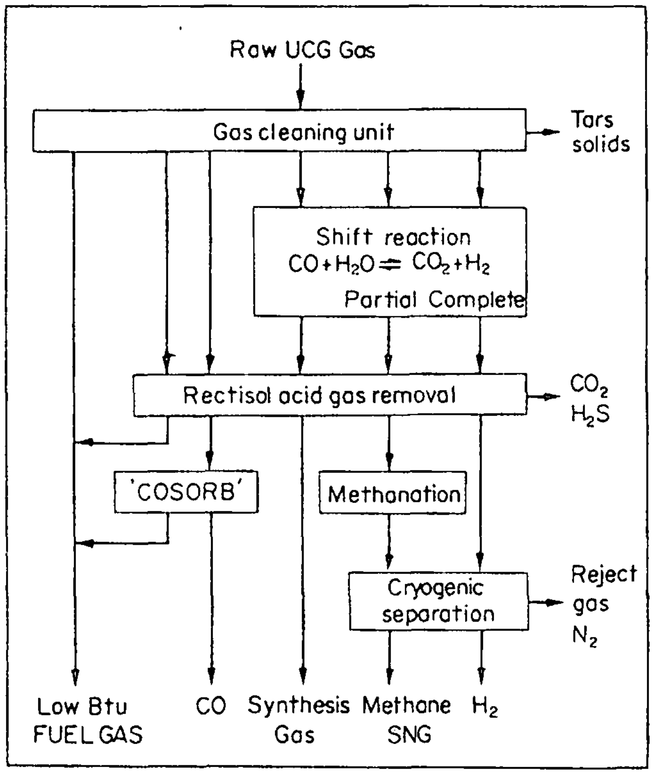

Figure 2 Possible paths for up-grading UCG.

The second consideration is that the nature of UCG, in its present form, is such that any station linked to a gasification site would have to operate at a high load factor. How far the rate of burn could be controlled to keep in line with demand is virtually unexplored. If this proves to be impracticable, then UCG schemes for power generation would be brought into direct competition with nuclear power for base load generation.

The gas could conceivably be used for process heating, but three basic requirements would have to be satisfied. First, the consumers would have to be grouped fairly close together near to the UCG site, so as to minimise gas transmission costs. Second, means would have to be devised of operating the site to give a fairly constant product; there would be a very real problem in using gas with a variable calorific value, as at present. Third, some special grouping of consumers would have to be contrived so as to give a steady load factor.

In considering utilisation of the gas, by far the greatest attention has been paid in recent years, especially in the United States, to the possibility of up-grading it to produce a gas of pipeline quality. This has obvious attractions in the light of the rapid rundown of natural gas supplies expected over the next two decades. Basically, there are two ways in which this might be done: to use gasifying agents other than air or to treat the gas on the surface.

Nitrogen is the major diluent of the gas produced when using air. If oxygen were used instead of air, the calorific value would in theory be virtually doubled. Experiments have been made in the past but the accumulated experience has not been particularly encouraging, mainly through the difficulty of controlling the process so as to ensure that combustible, rather than non-combustible, gases are produced. In addition, two other major factors have to be considered. The scale of oxygen consumption—2000 tonnes/day for a 100 MW site—is such that an oxygen production plant with a capacity well in excess of any at present operating would be required. The other obstacle is that of cost. Estimates show that using oxygen rather than air would make the gas approximately twice as expensive.

Steam or steam/oxygen injection has also been proposed and, on a small scale, tried in the past. Introduction of water should increase the proportion of hydrogen, and has been shown to do so to some extent. This could have important consequences for up-grading the gas, as will be shown later. What is unlikely to happen is a sharp increase in the proportion of methane produced, as has sometimes been claimed. Undoubtedly reactions such as:

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

do occur, but they require temperatures of about 400° C and residence time of about one hour. Combustion temperatures in practice are around 600° C and residence time, once linkage has been established, is a matter of minutes.

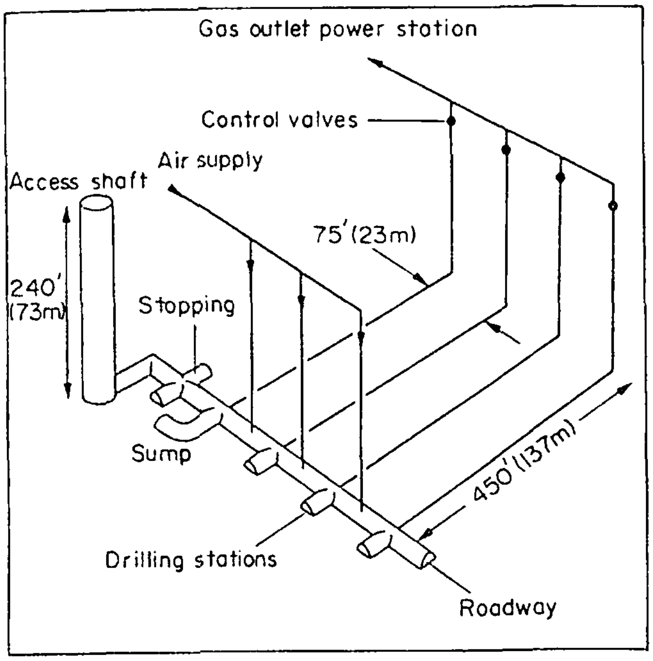

Figure 3 Diagrammatic representation of final trial at Newman Spinney.

However, a mixture of carbon monoxide and hydrogen produced by gasification with air, constituting as it does a basic synthesis gas, does form a useful building block for up-grading the gas to, say, substitute natural gas (SNG) quality or for a chemical feedstock. A number of options may be open (figure 2).

(a) Up-grading to a clean fuel gas by scrubbing and then removing all the carbon dioxide and hydrogen sulphide present.

(b) Up-grading to SNG by partial 'shifting' to increase the H_2:CO ratio; removing the carbon dioxide and hydrogen sulphide; methanating the synthesis gas; and, finally, cryogenically separating the methane.

(c) Up-grading to hydrogen by the shift reaction and cryogenic separation.

(d) Production of carbon monoxide by the COSORB process.

The first option involves little more than the removal of acid gases and the 'Rectisol' process would seem to be suitable. This has been operated successfully for over 20 years at the SASOL Fischer-Tropsch plant in South Africa. The second option uses the shift reaction to increase the H_2:CO ratio to a more acceptable value (about 3:1). Methane is then synthesised from the raw synthesis gas to give a gas of the following approximate analysis:

	mole %
CO	0.1
H_2	0.0
CH_4	11.5
CO_2	0.5
N_2	86.5.

Reasonably pure methane might then be recovered from the gas at this stage by cryogenic separation. This conjecture is based upon a plant designed by Petrocarbon Developments Ltd., and commissioned in Poland, which is removing nitrogen from a crude natural gas initially containing 56 mole per cent of nitrogen. For the third option the shift reaction is pushed to completion to convert all the available carbon monoxide to hydrogen, which is then cryogenically separated. The difficulty of cryogenically separating carbon monoxide from nitrogen has led to consideration of the COSORB process in the fourth option. This would produce a 97.5 per cent pure carbon monoxide stream and a stream of gas of low calorific value, which is the residual hydrogen and nitrogen.

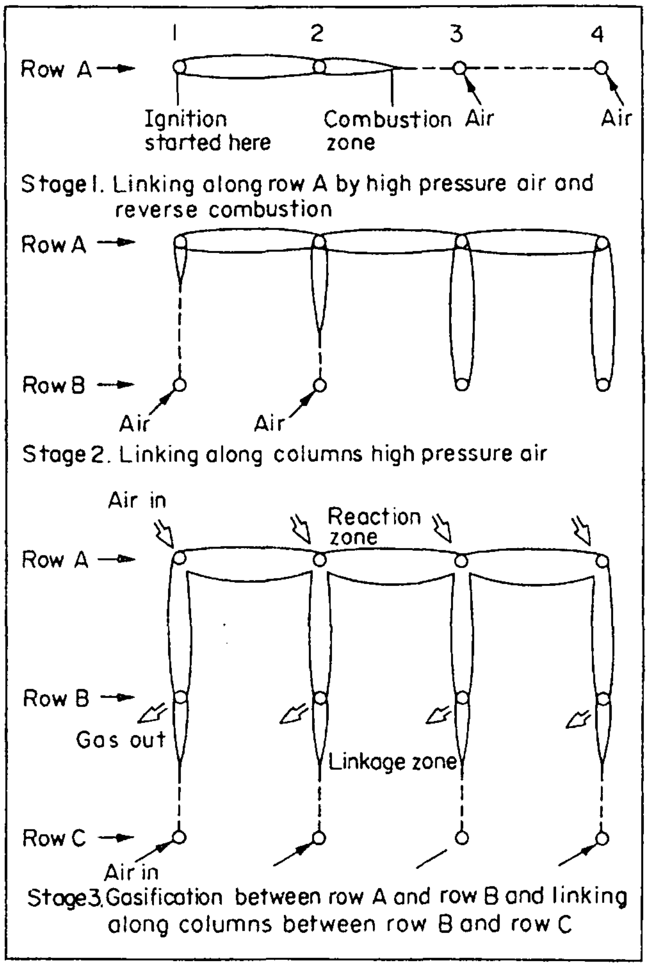

Figure 4 Vertical drilling method for UCG.

A preliminary analysis of the process costs involved has shown that this gasification with air, followed by up-grading on the surface, may well be a better proposition economically than gasification with oxygen or oxygen/steam. However, the costs involved require much more analysis and the final product, if it were SNG, would, of course, be considerably more expensive than natural gas. This would hardly justify any large scale investment in UCG at present.

The utilisation of the gas has been discussed at some length because the possible contribution to a future energy pattern must obviously be borne in mind when considering the possible advantages of the process. Let us now turn our attention to an outline of the mechanics of production and its likely economics.

Methods of underground gasification

Many methods of gasification have been tried in the past—the variations depending upon seam thickness, angle of dip, and depth. However, they amount basically to two methods:

(a) those involving some preliminary mining, and
(b) those depending entirely upon drilling from the surface.

The preliminary mining method was epitomised by the final trial (known as P.5) at Newman Spinney (figure 3). A shaft was sunk, from the bottom of which a gallery was driven in the coal. Horizontal boreholes were drilled out from this gallery, and their ends were contacted by vertical holes drilled from the surface. The whole of the gallery was ignited and the resultant gas drawn off from the vertical holes. While this system was fairly successful, in that it produced gas over a period of 108 days, nevertheless it has not been taken up since. All current proposals incorporate drilling from the surface alone, in spite of the fact that the P.5 method would probably produce a cheaper product gas. However, it would suffer from the disadvantage of requiring some men to work underground, which might not be possible at great depths.

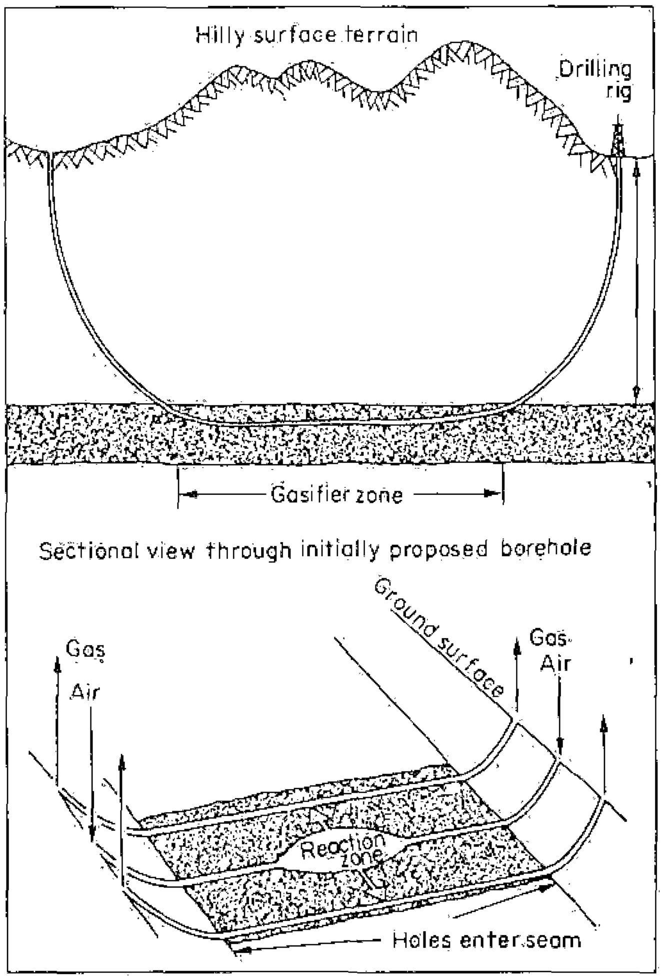

Figure 5 Longwall generator proposed by Morgantown Energy Research Center.

The vertical drilling method is essentially that adopted by the Soviet Union for gasifying brown coal. The stages of development are shown in figure 4. Air at 6 bar pressure, supplied to one vertical hole, passes through the body of the coal seam and appears at a second hole 25 m away. With the air flow established, ignition is begun at the bottom of the receiving hole and the linkage path is burned open by reverse combustion. By repeating the process between successive holes in the selected pattern, a gasifier of almost any shape or size can be created. This basically is the method adopted in those Soviet sites currently working. The technology and design involved is now being sold under licence, and has been bought by a Texan utility company for gasifying the lignites in the Gulf area. A trial burn was made in the winter of 1976; this was successful and further application is proceeding.

In the USA most trials are financed by the Federal Energy Research and Development Administration. The Soviet system has also basically been adopted in the trials being conducted at Hanna, Wyoming, under the direction of the Laramie Energy Research Center. This is the only site that has been consistently operating, albeit on a small scale, outside the Soviet Union since 1972. Various hole configurations and methods of operation have been tried, but eventually the preferred method has been the 'linked vertical well' system on the same lines as the Soviet one. The latest complete trial, during the summer of 1976, produced gas that would have been sufficient to generate 6 MW of electricity over a 30-day period. This is in a seam of sub-bituminous coal 10 m thick at a depth of 100 m [3].

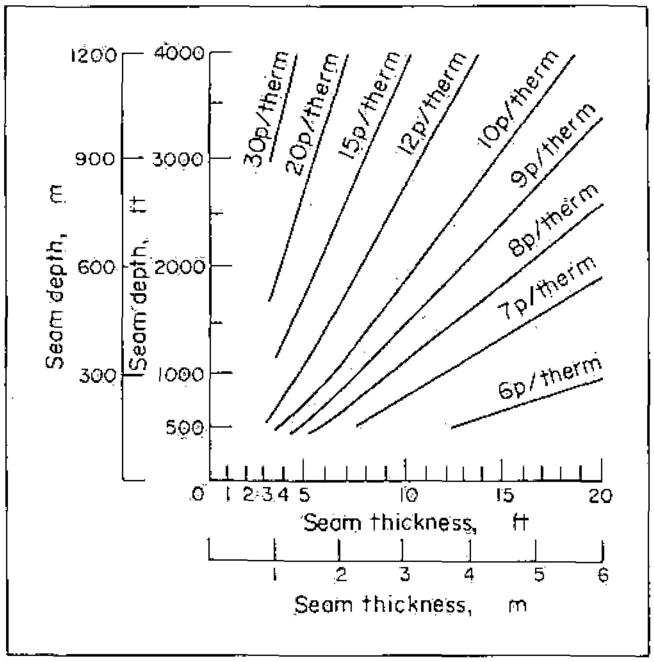

Figure 6 Graphical representation of variation of cost of UCG for different seam thicknesses and depths.

Another concept in the United States is that of the 'longwall generator' put forward by the Morgantown Energy Research Center, West Virginia, and illustrated in figure 6. Boreholes would be drilled from the surface, intersect the seam, pass along it for about 200 m, and then rise to the surface again. The concept was subsequently modified to one in which the hole did not emerge from the seam but was contacted by a vertical borehole. In the event one of these directional holes was drilled, but proved to be extremely costly [4]. The present programme at Morgantown is for a trial to be conducted along the Hanna lines to test the feasibility of gasifying thin (3 m) Eastern bituminous coals at a depth of 300 m.

One of the problems encountered has been that of permeability of the coal seam. In an effort to overcome this problem, and to enhance the permeability, the Lawrence Livermore Laboratory introduced the concept of the 'rubblised bed', according to which large amounts of explosive placed at the bottom of concentric rings of boreholes would be fired. It was hoped that the coal seam would be so fractured that a broken bed would be produced, approximating to that in a surface gasifier [5]. In the event, a test in a 7 m seam in Wyoming resulted in the opposite effect. While there was considerable fracturing around the hole itself, the permeability in the body of the coal was actually reduced because the force of the explosion closed up the natural fractures. Currently the possibility of using shaped charges to establish linkage between holes is being investigated, but for the time being the trials at the Wyoming site will be based on 'linked vertical wells', as at Hanna. In Canada a trial burn has been conducted in Alberta on the same basis but the results have not yet been published.

From the British point of view, the most interesting results could come from the scheme put forward by the Belgian *Institut National des Industries Extractives* (INIEX) to exploit their coal reserves at depths (in excess of 1000 m) which are considered unmineable by conventional means. It has five essential features:

(a) Air injected at a pressure higher than 20 bar.
(b) Alternately cycled phases of increasing pressure up to 50 bar, followed by a drop down to 20 bar.
(c) Gas off-take holes equipped with water-circulation heat exchangers to give an additional steam output derived from the sensible heat of the gas.
(d) Methane drainage from the upper seams as they are broken up by the subsidence from below.
(e) Electricity generation from a combined gas/steam cycle power station using the low calorific value gas from UCG, high calorific value gas from methane drainage, and steam generated from the outlet holes and gas turbine exhaust.

It is claimed that use of high-pressure air as the gasifying medium will allow very high flow rates through small diameter holes, so keeping down the drilling cost, and that the high-pressure energy will be recovered in a gas turbine with very little loss [6]. All this remains to be proved, as preliminary drilling began only in 1977.

A similar proposal has been put forward in West Germany for the same reasons. They aim to produce a gas of medium calorific value so the effects of using hydrogen, oxygen, and steam, as well as air, will be studied. Progress so far has been limited to laboratory studies.

The economics of UCG

Opinions as to whether the economics of UCG are favourable vary from country to country, reflecting the different conditions that exist. Thus Lawrence Livermore studies show that gas of pipeline quality could be produced via UCG at a lower cost than via the Lurgi process. However, this estimate is based on thick seams (30 m) at relatively shallow depths (300 m) and a high proportion of methane (11 per cent) in the raw gas [7]. Cost estimates by INIEX indicate that UCG could provide the cheapest source of energy in Belgium. This arises from the extremely high cost of deep-mining there, and on the assumption that the use of high pressure gasification would enable boreholes to be more widely spaced, 75 m apart instead of 30 m.

On the other hand, a recent National Coal Board assessment indicated that for Britain UCG, while not being wildly expensive, nevertheless lay at the upper end of the energy cost spectrum. Figure 6 shows the variation of cost for different seam thicknesses and depths. A reasonable range for gas costs is 7–24 p/therm. As a basis for comparison, deep-mined coal for power stations cost 4–12 p/therm, depending on the colliery, and opencast coal an average of 3 p/therm. (all costs refer to beginning 1976.) These costs do not suggest that UCG is an immediate economic proposition. In general, it would be cheaper to mine any given seam by conventional means rather than try to gasify it. By far the major proportion of the costs is that of drilling (60 per cent). Drilling costs could be reduced by, amongst other things, increasing the distance between holes. However, the assessment was based on proven existing technology. In particular, borehole spacing was taken to be 30 m. This is the maximum that has yet been achieved, although it must be stressed that there does not seem to have been any systematic work aimed at increasing the distance. This forms part of the programme of work at Hanna over the next two years. If the spacing could be increased to 60 m, then costs would be reduced by about 80 per cent.

UCG technology remains, therefore, in a rudimentary stage although current activity may produce significant developments. There seems to be no immediate reason why it should be taken up again in Britain, but it is certainly an option that should be borne in mind for the future in view of the possible need to develop our deep-lying coal reserves, which it might not be possible to mine by present-day methods. Problems arise in working seams at depths below 1000 m, especially with regard to high temperatures. The National Coal Board is currently considering ways, including UCG, in which these seams might be exploited if it were to become necessary.

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June 1978

PROGRAM AND OBJECTIVES OF THE INTERAGENCY GEOTHERMAL STREAMLINING TASK FORCE

The Interagency Geothermal Streamlining Task Force was formed to assist the Interagency Geothermal Coordinating Council (IGCC) in carrying out its mandate:

> "for assessing legal, environmental, regulatory, and other aspects of Federal, State, and local government policy as they relate to geothermal energy and for developing recommendations for changes and improvements in related laws, policies and procedures, and for examination of other institutional aspects of geothermal energy, including non-governmental aspects."

Specifically, the Task Force is developing recommendations to IGCC for appropriate action to implement the President's commitment to Congress that:

> "The Departments of the Interior and Agriculture will streamline leasing and environmental review procedures to remove unnecessary barriers to development of geothermal resources."

This objective was included in the President's comprehensive energy program submitted to Congress in April 1977. The commitment was prompted by the fact that although the Geothermal Steam Act was passed nearly seven and one-half years ago, there is still no commercial production of this resource on Federal lands.

There are many reasons for the lack of a viable geothermal industry -- such as the unknowns of the resource, the less-than-perfect technologies for utilizing and disposing of it, high-risk capital investment, and inequitable tax* and price structures. However, it is widely believed that the cumbersome Federal leasing and permitting program constitutes a major deterrent to timely development. As long as the inhibiting influence of the regulatory program clouds the rate of development on Federal lands, the effects of other impediments cannot be fully and accurately assessed.

The Geothermal Streamlining Task Force has undertaken a study which includes 1) a comprehensive analysis of the elements of the present

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*New geothermal tax provisions are pending in a House/Senate conference committee and are described in a Comparative Committee Print entitled "Conference Comparison of the Energy Tax Provisions of H.R. 5263."

program designed to identify the sources of delay and quantify delays which are actually occurring; and 2) to determine the potential effects upon program performance of a series of options for program modification. The effectiveness of alternative options will be assessed in terms of their relative ability to support the Department of Energy's projected geothermal power-on-line schedule while adequately protecting the public interest and the environment.

The study will also incorporate input provided by the public, industry, environmental groups, and state agency officials through a series of workshops to be held in the western states in June. The schedule for these meetings is being finalized and is being widely publicized in order to obtain the broadest participation possible. The public meetings have been announced in the Federal Register.

The Task Force has developed a series of options for modifying the geothermal leasing and permitting program, described below, and comment on them will be requested from the above groups. In addition, suggestions for additional alternatives will be solicited.

The discussion of the options is preliminary and tentative and has not been reviewed by the attorneys of the Department of the Interior, the Department of Agriculture, or the Department of Energy. It is intended only to focus, for purposes of further discussion, on the problems which generated the suggestions for change and the remedial effects which may be exerted by the proposed options.

Option I

Improve the present system through changes in regulations and administrative procedures.

The Task Force is concentrating the largest bulk of its effort on Option I since improvements developed in the present system will almost certainly benefit the workability of any other option as well. This approach would maintain the basic features of the pre- and post-lease environmental reviews, but would increase the efficiency and uniformity of this major program function. Program modifications which will be considered include, but are not limited to, the following:

A. Use regional or areawide environmental analyses in pre-lease review and conduct site specific studies only during the post-lease permitting process.

The use of regional areawide analysis in the pre-lease situation would tend to reduce manpower/budget requirements and timeframe of performance. This approach would first permit more dependence on existing or in-progress Management Framework Plans of the Bureau of Land Management (BLM) or Land

Management Plans of the Forest Service (USFS), (which are discussed below under Option 2), or other resource-inventory type documents. This use of such documents is consistent with the new draft Council on Environmental Quality (CEQ) guidelines for implementing the National Environmental Policy Act (NEPA) (December 12, 1977) which encourage "integrating the requirements of NEPA with other planning and environmental review procedures required by law or by agency practice so that all such procedures, to the fullest extent possible, run concurrently, rather than consecutively." The draft guidelines would also require agencies to use "program, policy, or plan environmental statements and tiering from statements of broad scope to those of narrower scope to eliminate repetitive discussions of the same issues." While actual environmental statements per se are not necessarily at issue in this proposed program modification, it is felt that the language of this mandate is equally applicable to other types of environmental review documents.

In the absence of an existing plan, more generalized data gathering would still reduce time requirements and manpower utilization, freeing personnel for other work. Site specific studies at the post-lease stage would then identify the particular sensitivity of areas proposed for drilling, roads, and other permanent surface features.

Pending determination by the Solicitor of the Department of the Interior, this approach appears to be consistent with the BLM regulations on preleasing procedures. Section 3200.6, CFR Title 43, requires the Director, when an area is initially considered for geothermal leasing, to request reports from other interested agencies describing the resources contained "within the general area and the potential effect of geothermal resources operations upon the resources of the area and its total environment." (Emphasis added.)

The subsequent paragraph dealing with environmental impact evaluation, prior to final selection of tracts for leasing, calls for evaluation of the potential effects on the various resources of the entire area. There is no specifically stated requirement for site specific evaluation.

History shows that less than 1 out of 25 lease applications may be expected to result in any surface disturbing operations. Thus, the low intensity pre-lease broad based assessment proposed in this approach would be appropriate to the majority of lease application areas. Detailed site specific environmental analyses would be done on the relatively few leases that would undergo surface disturbing exploration or development as a prelude to actual operation.

The major advantages of utilizing fewer environmental analyses of broader scope are:

- Less overlapping and redundancy and thus lessened manpower, time, and dollar requirements.

- Lower printing and publications costs

This approach is used by BLM in Nevada on geothermal lease applications and USFS oil and gas leasing in North Dakota on the Little Missouri Grasslands. Estimated time and dollar savings are at least 60% when compared to the "piece mealing" methods used in other areas such as BLM California and USGS Washington-Oregon.

This option is in accord with current U.S. Forest Service policy under the National Forest Management Act. A policy decision on the part of other agencies would be required.

B. <u>Set time limits or timeframes (through administrative directive and/or regulations) for issuance of leases and permits</u>.

The draft CEQ guidelines for implementing NEPA note that while the Council considers universal time limits for the entire NEPA process too inflexible, it encourages all Federal agencies to "set limits if an applicant for the proposed action requests them, provided they are consistent with the purposes of NEPA and other essential considerations of national policy."

The only action in the geothermal pre- and post-lease approval process which is subject to a time constraint under the existing regulations is the Notice of Intent (NOI) to conduct exploration operations which the authorized officer is directed to approve or disapprove within 30 calendar days. This offers precedent for imposition of time limitations on other actions in the process.

A major advantage of this approach is that adherence to a realistic mandated schedule determined according to the criteria set forth in the draft CEQ guidelines would serve to generally reduce the length of time required for each action in the leasing and permitting process, although a precise estimate of time savings cannot be made at this time. It is felt, however, that when faced with realistic deadlines the backlogging of applications would diminish. Another advantage is that the approach would provide for more uniformity in processing schedules, an occurrence which would enhance more efficient developer planning. Failure to meet the scheduled timeframe would require a report of accountability to the applicant. In summary, this approach makes the process timing sensitive and visible.

A disadvantage is that the approach would require increased budgets and manpower in some BLM/FS field offices and in the responsible GS office.

On the other hand, it would at the same time provide a more concrete basis for projecting budget/manpower needs than the present system which tends to function, at lease in some office, in response to available resources rather than to needed resources. In other words, this program modification would provide a mechanism for establishing firm priorities.

C. Improve coordination in all phases of pre- and post-lease activities.

Since the geothermal program is jointly implemented by BLM, USFS, and U.S. Geological Survey (USGS) with still another review element in the Fish and Wildlife Service (FWS), there is significant opportunity for process delay in routine steps such as repetitive notifications, approvals, signatures, and transmittals. Improving the coordination between these agencies for the purpose of expediting the leasing and post-lease programs is consistent with the similar objective established for the Geothermal Energy Coordination and Management Project in the related area of geothermal research, development, and demonstration. The Project is composed of members from a number of involved departments and agencies, including the Departments of the Interior and Agriculture. P.L. 93-410, the Geothermal Energy Research, Development and Demonstration Act of 1974 and P.L. 95-238, Department of Energy Act of 1978 -- Civilian Applications, give to the Project the overall responsibility for the provision of effective management and coordination with respect to the Nation's geothermal research, development, and demonstration (RD&D) program.

The Project is directed to "make such recommendations for legislation or administrative regulations as may from time to time appear to be necessary to make Federal leasing, environmental, and taxing policy for geothermal resources consistent with known inventories of various resource types, with the current state of technologies for geothermal energy development, and with current evaluations of the environmental impacts of such development, and with current evaluations of the environmental impacts of such development." While the streamlining goal of the Task Force does not fall under the RD&D program umbrella per se, consistency in coordination in the regulatory program is warranted. There appear to be several methods for accomplishing this goal.

One is to establish in each agency field level coordinators for the geothermal program. A previous related study found that developers in general feel that program performance improves as the process becomes more localized — i.e., that their needs are better attended by responsible personnel on the scene who are already intimately familiar with the locale, its resources, and problem areas. This situation would be further enhanced by the presence of personnel of all responsible agencies with geothermal activities as their primary program concern who could interact locally.

The need for such personnel is especially apparent at the regional level in some regions of the USFS, and a multi-regional coordinator located at the center of activity is badly needed. It would be desirable that USFS and BLM coordinators be housed at the same location (Boise appears most logical) so as to facilitate communications.

Another potential approach to improved coordination is to consider modifying the existing Memorandum of Understanding (MOU) so as to establish guidelines for interagency cooperation among the Departments of Energy, Interior, and Agriculture in implementing the geothermal program. The MOU is the basis for the large bulk of the steps shown in Figures 1 and 2 which indicate the numerous opportunities for process slippage. Forest Service activities, which are not included in the MOU and are not shown in Figures 1 and 2 add other comment, approval, and transmittal steps to the process when forest lands are involved in KGRA lease sales and non-competitive lease applications.

Specific steps should be taken by the Departments to identify time limits for communication between their agencies. For example, KGRA clearlisting should require no more than 10 working days, and responses on approval of a Plan of Operation should also reach USGS within a similar timeframe.

The groups within the agencies charged with the writing of regulations and directives for the geothermal program should be adequately staffed and funded so that badly needed minerals program management may be carried out in a timely fashion. The need for a higher priority in manpower funding is exemplified by the fact that the geothermal power plant siting regulations were 2 years in preparation. With adequate manpower, such regulations could be proposed within 6 months.

D. Improve uniformity and consistency of policies and procedures with respect to lease stipulations among the involved agencies.

Two separate steps appear to offer the best potential for optimum improvement through this route. The first is to establish uniform policy and guidelines for special lease stipulations. In current practice, the surface management agencies sometimes attach stipulations which are unacceptable to the USGS Area Geothermal Supervisor's office and considerable time may be lost in negotiating the final stipulations. Uniform policy agreed to in advance by the involved agencies could reduce the frequency of this source of delay and alleviate to some extent developer uncertainty on special stipulations.

Another means of increasing interagency efficiency is to standardize special lease stipulations of similar nature and intent -- i.e., archaeological, endangered species, etc. The reasoning here is that past experience indicates some "one-upmanship" or pride of authorship in writing stipulations which creates unnecessary confusion and requires legal review of word changes. Not only should this delaying situation be avoided but the standardized stipulations should be expressed in language immediately comprehensible to all levels of government and industry personnel who must be concerned with them. The potential for delay in erroneous interpretation or time wasted in seeking the correct interpretation is readily evident.

Revision of the geothermal lease form to incorporate standardized stipulations appears to be the best method for implementing this change which would avoid repetitive legal review of word changes. At the same time the lease form could be combined with the application form (as is now the case in oil and gas leases) which would save an estimated 30 days per application and eliminate one form.

No disadvantages in this approach are foreseen. Its implementation would require 2 man months and no changes in regulations or policy.

E. Institute formal nomination procedures for KGRA's and non-competitive areas.

The BLM regulations provide for receipt of nominations, or public expressions of interest in leasing certain described areas, either on an individual voluntary basis or upon the Secretary's call for nominations to lease. This provision has never been implemented, however, in that BLM has neither prepared an approved form (43 CFR, 3220.2) for receiving nominations nor issued calls for nominations (3220.1). It has instead treated non-competitive lease applications as nominations and has entertained requests for lease sales through letter correspondence or oral communication.

A formal nomination procedure would probably not have substantial effect on non-competitive areas, but an advantage could possibly accrue if such a procedure were used to identify, on the basis of expressed industry interest, the priority areas for completion of baseline studies needed to expedite competitive lease or no-lease decisions and in turn guide the location of competitive lease sales. A common industry justification for lack of development is that much of the land it considers most promising is not available under the present system. If this assertion is valid, development would be expedited by prioritizing activity in the areas which industry's nominations indicate are most likely to be developed if the acreage is made available.

In past experience, the less environmentally-sensitive prospect areas, and therefore the easiest to study, have often been investigated first only to generate little or no interest in the subsequent lease sale. In those instances, the effort would have been more productive if it had been applied to the more promising areas.

The success of this program change would hinge on industry's willingness to submit nominations and on amendment of the existing procedures for classifying land as KGRA's. Developers have previously stated their reluctance to nominate acreage because of their fear that nominations would result in an increase in KGRA designation.

Potential advantages of this proposal would be to focus agency attention on competitive areas industry feels most desirable and to effect a minor time savings in developing planning priorities. Costs of this proposal would be negligible, and since some benefit might accrue, it is recommended that the involved agencies attempt to solicit nominations for planning purposes.

F. Allow no-surface-occupancy leases in wilderness study areas and other special areas where requested.

Some benefits would be gained from issuance of no-surface-occupancy leases in areas of mixed land ownership (areas composed of intermingled tracts of federal, private, and state lands), or in wilderness study or other special areas where leases on the federal lands cannot be issued.

If no leases are issued on the Federal portions pending the outcome of the study, any operator proceeding to discovery on adjacent or nearby non-Federal land risks facing a KGRA designation of the Federal tracts (43 CFR 3200.0-5k(2)). He would then be faced with competitive bidding as his only access to desired tracts in the Federal acreage if the land is not locked into no-lease status. In view of the fact that his own discovery would tend to attract other serious bidders, he risks losing to competitors those lands which are primarily valuable because of his own discovery.

A no-surface-occupancy lease could benefit him in two ways. First, it would protect his competitive interest throughout the study and decision-making period and, second, depending on engineering and economic feasibility, make recovery of the resource from this type of lease achievable through directional drilling. Certain types of non-surface disturbing activities would be allowed as appropriate on the particular lands under this type of lease.

The potential disadvantage of this approach to industry is that the lessee takes the risk of being unable to develop the lands that he has leased. Thus, there is potential for future litigation if a discovery is made. In addition, supervision of the lease by surface management agencies would be required which would not be necessary if the land were not leased. The additional costs and workload appear minimal, however, and the proposal is consistent with current law and regulation.

G. Modify KGRA regulations.

KGRA's are classified by geologic criteria and also by "competitive interest" (43 CFR 3200.0-5(k)(3)), caused by overlapping of applications filed within the same period. Lands in either type of KGRA can only be leased through competitive bidding. A recent study of all geothermal leases issued shows that the pace of competitive leasing is far behind that of non-competitive. The most recent summary shows that 1081 non-competitive leases have been issued on over 1.85 million acres of land, as compared to 239 competitive leases on 339,000 acres. Bids received number less than half the tracts offered, and about 30 percent of the sales have produced no bids at all. The total number of tracts of interest was even less than the number of bids received since multiple bids were made on the same tracts in some cases.

The reasons for this situation are not clear at present. They may reflect developer contention that the desirable tracts are not being offered, as discussed above, or the cost of competitive leases vs. non-competitive may be an inhibiting factor. The numbers do indicate, however, that the existence of KGRA's, which by definition should be more desirable than non-KGRA lands, are impeding the pace of leasing. Thus, the potential effect of amendments to the BLM regulations (43 CFR, 3200.0-5(k)) to change KGRA criteria is being investigated.

Three approaches are under consideration. They include:

- Reclassification of geologic KGRA's and competitive interest areas after they have been through unsuccessful lease sales.
- Abolish the competitve interest regulations (43 CFR, 32.00.0-5(k)(3)). The competitive interest concept is an impediment to an orderly non-competitve leasing program, and has caused delay in leasing with little financial return to the government.
- Provide for direct thermal utilization areas, to encourage use of low temperature geothermal waters.

There are several rationales for separate treatment of direct thermal utilization, or non-electric use of the resource, as opposed to electric power production. First, the requirements of the resource itself are different — temperature, pressure, and reservoir size requirements are less demanding for most direct uses than for power generation although in some cases a purer resource is required — and the type and degree of environmental impact will vary with the use. In general, the potential impacts from power production or industrial use may be expected to be more severe than those associated with domestic or agricultural use.

In addition, many if not most municipalities would be precluded, by their charters or financial responsibility requirements, from bidding on competitively-offered tracts. Thus, the most likely users of direct heating systems could not gain access to the resource on a KGRA, which in some instances might be designated because of a municipality discovery on adjacent or near-by state or private lands.

Since some of the geologic KGRA's and competitive interest areas draw no bids on being offered several times, it appears that revision of the criteria for classification in the regulations is needed -- i.e., the current KGRA standards may or may not be realistic in the light of present knowledge.

Reclassification of KGRA's and competitive interest areas lies under the authority of USGS and its area geologists. To date, no KGRA or competitive interest area has ever been reclassified.

Advantages of modifying the KGRA regulations would be more orderly development and more efficient use of the resource. Time would be saved in that leases could come on line more rapidly. No disadvantages are recognized, and costs and impacts upon manpower would be minimal.

H. Allow issuance of non-competitive leases unless the area is in a KGRA at time of application.

In present practice, non-competitive leases are not issued if the acreage involved is in a designated KGRA when the adjudication process is completed, and the applicant has signed the lease form. The KGRA clear list report is the last step in the procedure before the lease is issued, and the lease may be rejected at this late point on the basis of the clear list report. When this happens, the adjudicatory effort has been wasted. If the above change were effected, a change in KGRA status during the adjudicatory process would not affect issuance of the lease.

This approach would alleviate applicant uncertainty as to possible classification of lands during the adjudication process, and would allow applicants to commence exploration on adjacent non-Federal lands without risk of having the applied-for lands classified as a KGRA as a result of his work. Elimination of the clear list report would also speed up lease issuance.

The disadvantages of the approach include a potential loss of revenue due to loss of bonus-bids and decreased rentals, and the fact that legal modification and changes in regulations may be required. No staffing or direct budget impact are seen.

I. Provide budgets in proportion to workloads, organizational needs, and priorities.

The new draft regulations to implement NEPA require all agencies to "have sufficient capability, including personnel and other resources," to comply with Section 102 of the Act and Executive Order 11514, Protection and Enhancement of Environmental Quality. The geothermal programs of the involved agency field offices have commonly been short of this goal in their share of overall budgets.

Specifically, the pace of environmental assessment preparation and the various types of land management planning has been impeded by the inadequate budgets, and it is felt that a budgetary remedy must be a primary focus of any streamlining effort. The minerals management effort has historically been underfinanced and understaffed.

Option II

Base leasing decisions on areawide environmental assessment in combination with land management plan.

This option is based primarily on the existence of the planning requirements imposed by the Federal Land Policy and Management Act of 1976 (P.L. 94-759) and the National Forest Management Act of 1976 (P.L. 94-588) on BLM and the Forest Service, respectively.

The former requires BLM to prepare and maintain on a continuing basis an inventory of all public lands and their resource and other values, giving priority to areas of critical environmental concern. Just such a priority has been needed in the geothermal program, as discussed above, so that lease or no-lease decisions can be made on this type of area which includes geothermal among its resources. The inventory itself does not preclude leasing since the Act states that: "The preparation and maintenance of such inventory or the identification of such areas shall not, of itself, change or prevent change of the management or use of public lands." (Section 201(a)). The use of public lands is covered by a further requirement for formulation of plans "which provide by tracts or areas for the use of the public lands." These plans are to cover all public lands regardless of whether such lands have been previously classified, withdrawn, set aside, or otherwise designated for one or more uses. (Section 202(a)). No completion date is mandated for these plans.

The National Forest Management Act directs the Secretary of Agriculture to incorporate the standards and guidelines provided by the Act for National Forest System Resource Planning (Section 6) into plans for units of the system" as soon as practicable after enactment..." and to "attempt to complete such incorporation for all such units by no later than

September 30, 1985." Until such time as a unit is subject to a plan developed in accordance with the Act, its management may continue under existing land and resource management plans.

The various plans completed under this relatively new legislation, or previously, will provide "on-the-shelf" information for application in planning competitive geothermal lease sales and in processing non-competitve lease applications. Such information is necessary, it is believed, before the geothermal program can move on with sufficient speed for prudent development and with appropriate environmental safeguards.

Where the land management plans have been completed, Option 2 is actually in effect. Many of the forest management plans are completed or near completion and all National Forest Plans are to be completed by 1983, and will be fully operational under this system by 1985. In Nevada, where an initial land plan has been completed for most areas by BLM, leasing has proceeded very rapidly. Where land management plans are not complete, or where the existing plan does not consider geothermal energy production and utilization, two alternatives are available:

- Completing or amending the land management plan to consider geothermal development with environmental assessment as appropriate.

- Designing an environmental assessment specifically for incorporation into the management plan at the next revision. This process would recognize the existing plan's limitations while providing supplementary information which could fulfill needs on a limited area for immediate leasing decisions. The area to be considered would be the area which might reasonably be assumed to be affected prior to scheduled revision of the plan.

The comprehensive nature of the data gathering done in construction of the land management plan will reduce the pre-lease and post-lease data gathering and environmental review requirements considerably.

The advantage of this option is that it makes full use of the land management plans as they are now being developed, and makes allowance for the consideration of all resources and uses in their proper perspective on the lands in question. With an adequate land management plan, the additional environmental analysis needed to implement any action on those lands can be done very rapidly and cheaply. In the overall picture, this method is more effective with respect to manpower and dollars.

The disadvantage is that initially this process would require longer front end delay.

Option III

Provide for separate environmental analysis of exploration and development phases, with initial review of exploratory impacts only and comprehensive review only after a discovery is made.

At present, most pre-lease environmental analyses assume the "worst-case" level of potential impact -- that of full scale development for power generation. However, the potential impact of the exploratory phase alone is minor compared to full development, and on a large majority of leases activity will cease with exploration and restoration of the site because no exploitable resource will be found.

Thus, it is felt that efficiency in time and manpower utilization can be achieved, and the environment adequately protected, by applying the environmental review in the pre-lease period to exploration alone. One proposed method of implementing this policy would be through issuing leases granting full rights for the exploration and testing phases, but conditional rights only to commercial development contingent upon further detailed environmental analysis. It is believed that development rights could be held in abeyance in the lease through the use of special lease stipulations.

This approach stems from recent consideration of issuing oil and gas leases in potential wilderness ("roadless") areas. At an April 18, 1978, meeting in Denver attended by representatives of the Department of the Interior and industry, it was proposed by the Department that leases be issued with the restriction, via a special lease stipulation, that exploratory wells only could be drilled, with production and full-scale development contingent upon whether the acreage is eventually excluded from the Wilderness System. The important concept here is that a "two-stage" lease is contemplated to be legally accomplished with a special stipulation in the lease and no change in existing law.

If the concept proves workable, it should likewise prove applicable for any geothermal leasing situation where separation of the two phases would be advantageous. Pending further review, the basic approach appears feasible without amending the Geothermal Steam Act although 43 CFR 3200.0-6 may require modification to make this option feasible.

In addition, in order to permit the lessee to identify the resource and determine whether it is commercially exploitable, the two-stage concept envisions redefining "exploration operations" to include the drilling and testing of one or more deep wells. If an exploitable discovery were made, the special stipulation for development would not be removed until a comprehensive environmental review, considering the nature of the resource and the plans of the lessee indicated the suitability of the area for development.

In addition to achieving efficiency and providing adequate environmental protection, any version of Option 3 adopted must also consider the lessee's right to develop -- i.e., such a program must be implemented in a manner which will encourage development. Present thinking envisions this option as an elective choice approach, with a one-stage lease still available to developers if they prefer the existing system.

This option would reduce time spent in pre-lease, environmental assessment, and would require no more time for post-lease analysis than at present since these post-lease analyses are being done in sufficient detail now. The biggest time saving might occur in sensitive areas although these areas represent the greatest chance for denial or limitation of development.

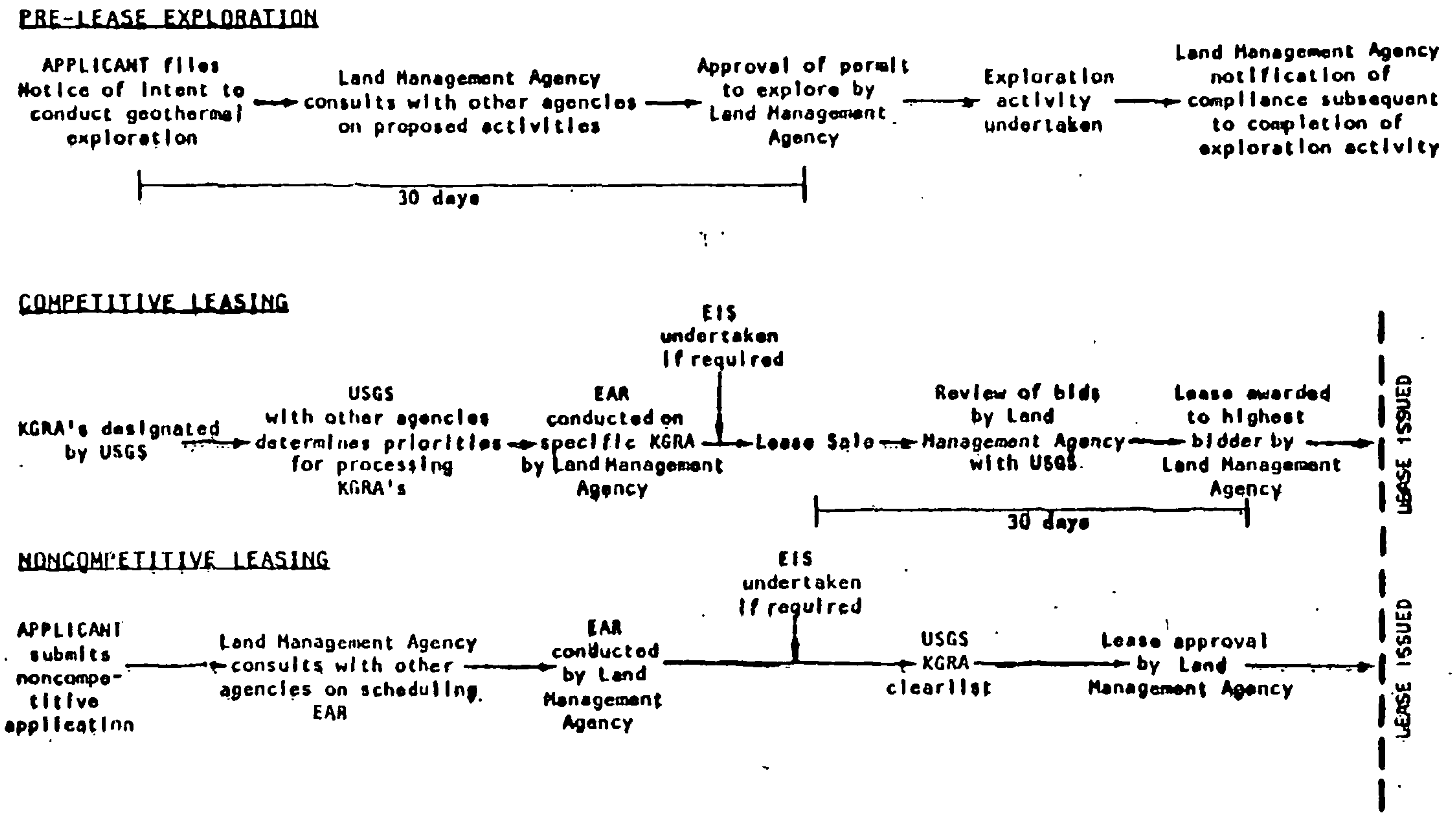
The major advantage which would accrue to the lessee is that after discovery and testing, the extent and potential value of the resource is much better known, and positively located in relation to surface values, making management trade-off value analysis much more knowledgeable and easier -- i.e., both the surface and subsurface values are now known.

The principal disadvantages to the lessee include the potential for unreasonable denial of development and the adverse economics of being unable to develop a commercially viable resource.

Written comments should be addressed to:

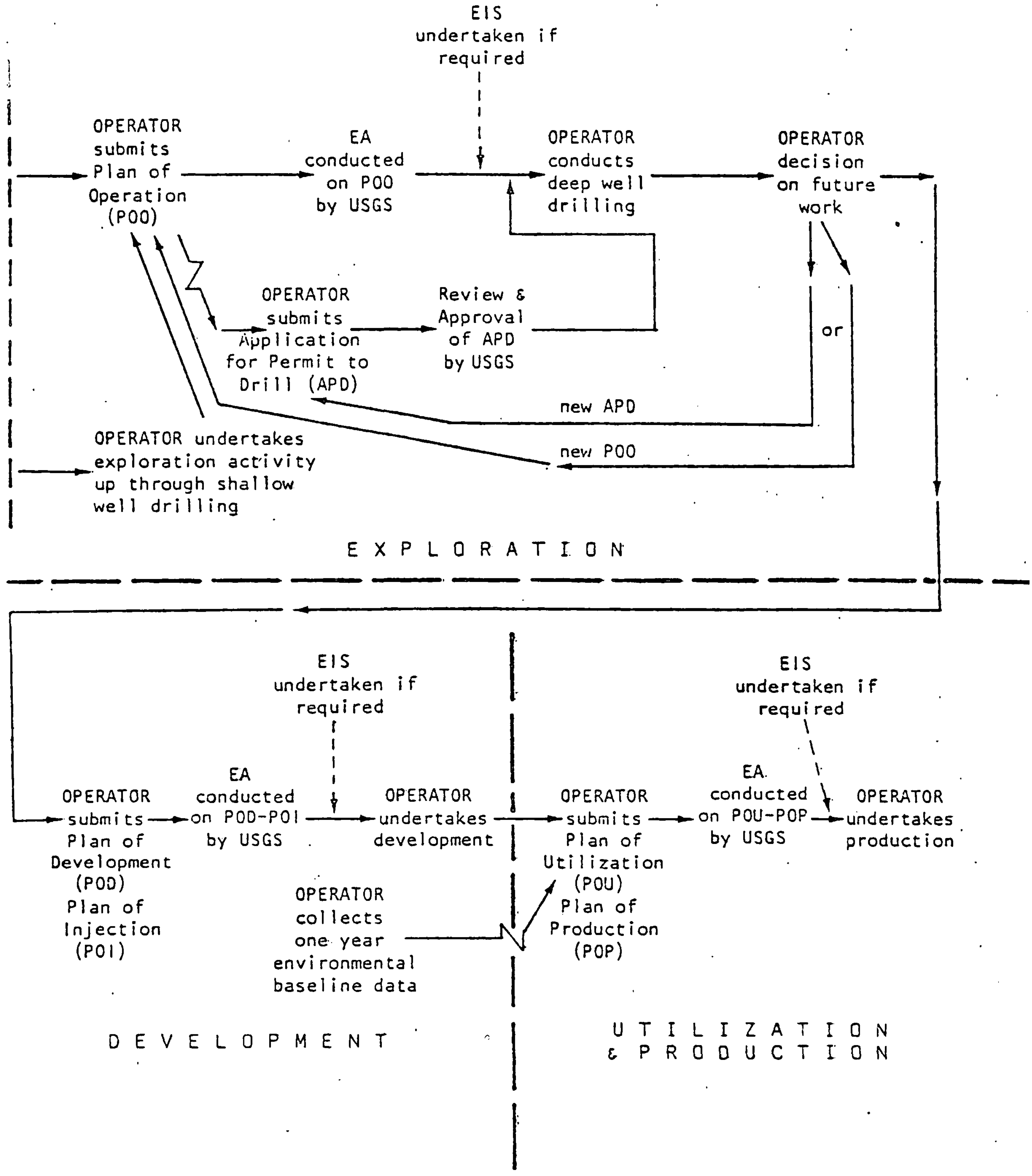
Winston B. Short
Chairman
Geothermal Streamlining Task Force
Interior Building
19th & E. Streets
Washington, D.C. 20240

EXISTING
GEOTHERMAL REGULATORY PROCESS
Principal Pre-Lease Activities



EXISTING

GEOTHERMAL REGULATORY PROCESS
Principal Post-Lease Activities



JUNE 1978

CUMULATIVE
SUMMARY OF NON-COMPETITIVE GEOTHERMAL LEASING
(BY QUARTER FROM 1974 TO PRESENT)

		BUREAU OF LAND MANAGEMENT				FOREST SERVICE			
	MONTH	TOTAL APPLS.	APPLS. WITHDRAWN, REJECTED OR REFUSED	APPLS. PENDING	LEASES ISSUED	TOTAL APPLS.	APPLS. WITHDRAWN, REJECTED OR REFUSED	APPLS. PENDING	LEASES ISSUED
1974	1	1744				712			
	3	2542				1038			
	6	2870				1172			
	9	2965				1211			
	12	3117				1273			
1975	3	3188	1077	2087	24	1359	420	939	0
	6	3334	1394	1720	220	1430	505	925	1
	9	3560	1722	1462	376	1467	520	942	5
	12	3711	1794	1491	426	1526	569	943	14
1976	3	3766	1979	1339	448	1552	706	831	15
	6	3827	2022	1164	641	1596	733	848	15
	9	3880	2231	924	725	1640	740	885	15
	12	4066	2259	1021	786	1684	740	925	19
1977	3	4163	2418	933	812	1715	744	952	19
	6	4290	2487	918	885	1753	745	989	19
	9	4395	2575	881	939	1765	746	988	31
	12	4560	2580	1002	978	1858	813	1012	33
1978	3	4649	2685	924	1040	1882	885	956	41

BLM NONCOMPETITIVE GEOTHERMAL LEASING
AS OF DECEMBER 31, 1977

	NO. OF APPLICATIONS	NUMBER ISSUED	NUMBER PENDING
ARIZONA	57	4	17
CALIFORNIA	674	10	260
COLORADO	86	43	7
IDAHO	564	111	164
MONTANA	33	6	1
NEVADA	1399	409	129
NEW MEXICO	574	85	146
OREGON	657	102	189
UTAH	497	208	57
WASHINGTON	0	0	42
WYOMING	19	0	56
EASTERN STATES	0	0	0
TOTALS	4560	978	1068

JUNE 1978

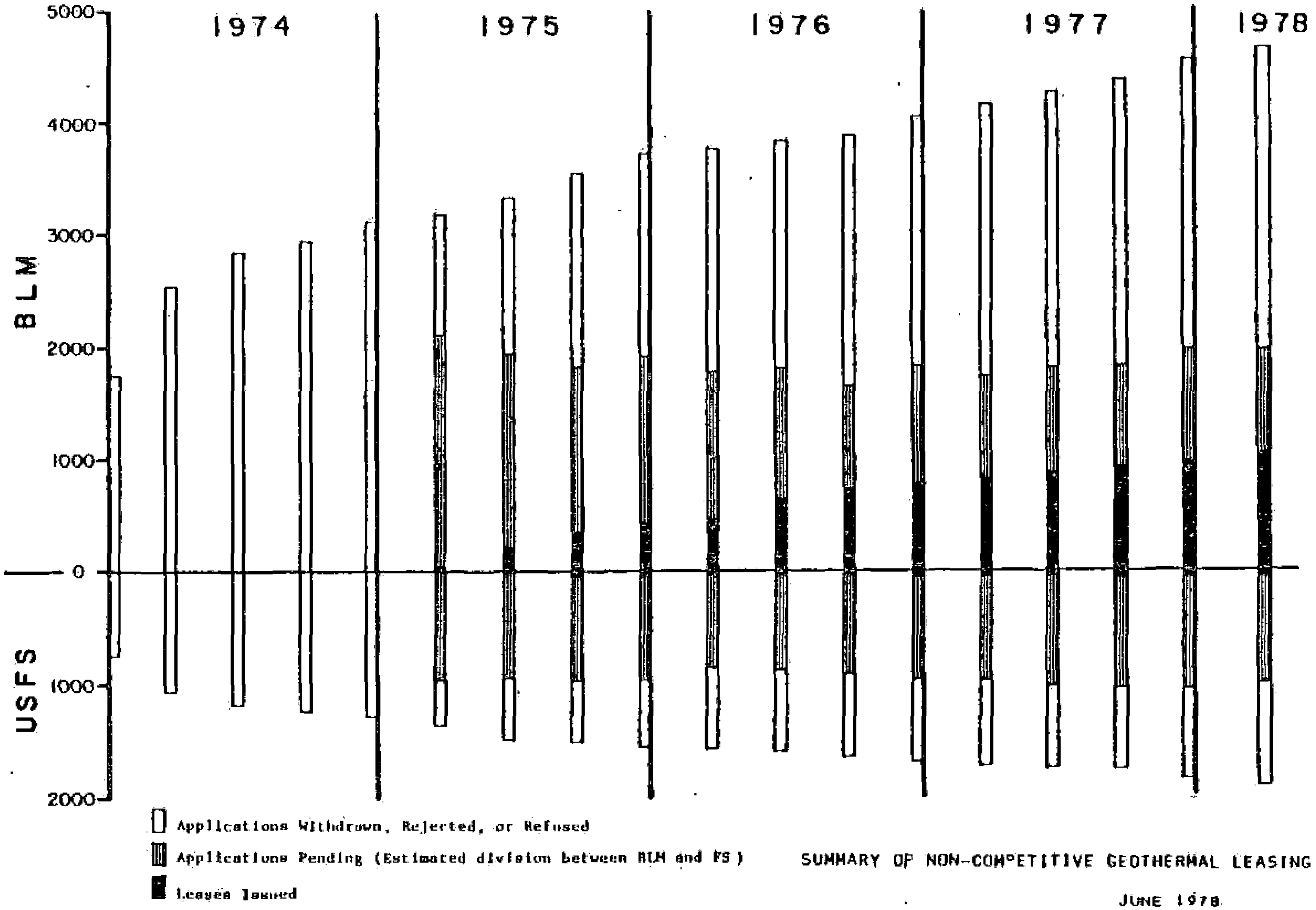
FOREST SERVICE NON-COMPETITIVE GEOTHERMAL LEASING
AS OF DECEMBER 31, 1977

	NO. OF APPLICATIONS	NUMBER ISSUED	NUMBER PENDING
ARIZONA	67	1	55
CALIFORNIA	397	0	169
COLORADO	73	0	34
IDAHO	317	1	208
MONTANA	55	0	11
NEVADA	13	3	15
NEW MEXICO	42	0	27
OREGON	378	3	218
UTAH	106	10	35
WASHINGTON	277	0	100
WYOMING	121	4	19
EASTERN STATES	12	11	0
TOTALS	1858	33	891

JUNE 1978

AGE OF NON-COMPETITIVE LEASE APPLICATIONS STILL PENDING (as of 4/78)

	5 mo. or less		6-11 mos.		12-17 mos.		18-23 mos.		24-35 mos.		36 mos. or more		Totals	
State	BLM	USFS	BLM	USFS	BLM	USFS	BLM	USFS	BLM	USFS	BLM	USFS	BLM	USFS
Ariz.	3	0	2	27	11	0	0	0	2	26	7	1	25	54
Colo.	0	0	0	0	0	0	0	0	0	0	9	27	9	27
Calif.	11	10	16	17	42	0	9	3	27	18	177	123	282	171
Idaho	44	1	46	17	1	0	9	1	27	52	62	143	189	214
Mont.	0	0	0	0	0	0	0	0	0	0	2	12	2	12
Nev.	35	1	18	0	3	0	4	0	17	1	197	8	274	10
N. Mex.	23	6	11	5	24	0	0	0	8	3	144	28	210	42
Oreg.	10	17	10	7	13	25	10	17	40	28	144	424	227	518
Utah	16	1	22	1	23	9	11	6	9	3	135	41	216	61
Wash.	0	20	0	0	0	0	0	0	8	16	0	3	8	39
Total	142	56	125	74	117	34	43	27	138	147	877	810	1442	1148



SUMMARY OF NON-COMPETITIVE GEOTHERMAL LEASING

JUNE 1978

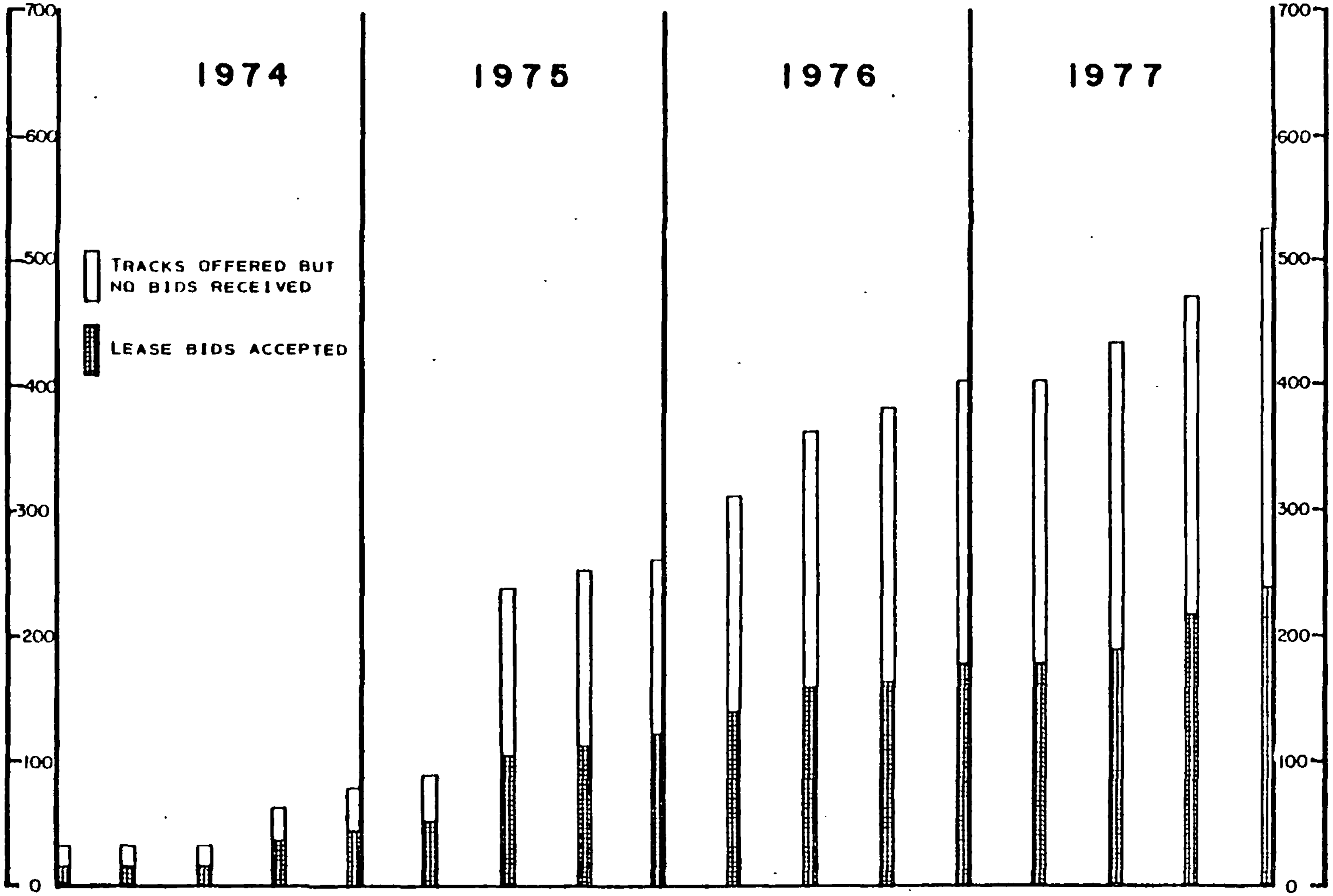
STATUS OF LEASE SALES ON KGRA'S

State	Total Federal Acreage		Theoretically Available For Leasing		Acres Offered		Acres Bid On		Acres Accepted		Federal Acres Remaining for Lease	
	BLM	FS	BLM	FS	BLM	FS	BLM	FS	BLM	FS	BLM	FS
Ariz.	3,240	0	3,240	0	780	0	0	0	0	0	3,240	0
Calif.	387,374	394,582	353,054	394,582	90,167	0	40,235	0	39,449	0	313,605	394,582
Colo.	19,045	1,780	11,271	1,513	11,271	0	5,036	0	5,036	0	6,235	1,513
Idaho	103,500	42,500	52,500	40,500	48,500	0	32,000	0	32,000	0	20,500	40,500
Mont.	8,861	29,170	8,861	29,170	320	1,280	0	0	0	0	8,861	29,170
Nev.	326,802	4,160	326,802	4,160	201,988	2,560	148,163	0	145,682	0	181,120	4,160
N. Mex.	190,320	1,316,004	190,320	1,224,004	101,693	29,375	62,482	18,050	62,482	18,050	127,838	1,205,954
Oregon	198,495	62,125	198,495	61,605	155,910	0	68,873	0	63,911	0	129,210	61,605
Utah	83,215	15,572	83,215	15,572	78,966	10,852	77,277	10,852	77,277	10,852	7,138	4,719
Wash.	0	19,001	0	13,187	0	0	0	0	0	0	0	13,187
Wyo.	0	0	0	0	0	0	0	0	0	0	0	0
TOTALS	1,320,852	1,884,894	1,227,758	1,784,293	689,595	44,067	434,066	28,902	425,837	28,902	797,747	1,755,390

CUMULATIVE
SUMMARY OF COMPETITIVE GEOTHERMAL LEASING

	MONTH	TOTAL TRACTS OFFERED	TRACTS OFFERED BUT NO BIDS RECEIVED	LEASE BIDS ACCEPTED
1974	1	33	15	18
	3	33	15	18
	6	33	15	18
	9	65	27	38
	12	80	33	47
1975	3	91	35	56
	6	240	132	108
	9	253	138	115
	12	262	139	123
1976	3	313	171	142
	6	365	204	161
	9	382	215	167
	12	405	226	179
1977	3	406	227	179
	6	434	243	191
	9	471	253	218
	12	523	284	239

JUNE 1978



SUMMARY OF COMPETITIVE GEOTHERMAL LEASING

(BY QUARTER FROM 1974 TO PRESENT)

JUNE 1978

SUMMARY OF RESPONSIBILITY IN THE FEDERAL GEOTHERMAL LEASING AND PERMITTING PROGRAM

BLM - BUREAU OF LAND MANAGEMENT
DOE - DEPARTMENT OF ENERGY
FS - FOREST SERVICE
FWS - FISH AND WILDLIFE SERVICE
GS - U.S. GEOLOGICAL SURVEY
IGCC - INTERAGENCY GEOTHERMAL COORDINATING COUNCIL

LAND MANAGEMENT PLANNING	BLM/FS
COMPETITIVE LEASE SALE SCHEDULING	BLM/FS/ GS/INDUSTRY/ IGCC
SCHEDULING FOR NON-COMPETITIVE LEASING	BLM/FS (PRIMARY) GS/FWS (CONSULTING)
PRE-LEASE ENVIRONMENTAL ANALYSES	BLM AND/OR FS (PRIMARY) GS AND FWS (CONSULTING)
POST-LEASE ENVIRONMENTAL ANALYSES	GS (PRIMARY) BLM/FS/FWS (CONSULTING)
COMPETITIVE LEASE SALES	BLM (PRIMARY) FS/GS/FWS/DOE (CONSULTING)
NON-COMPETITIVE LEASE APPLICATIONS	BLM (PRIMARY) FS/GS/FWS (CONSULTING)
DEVELOPMENT OF LEASE STIPULATIONS	BLM/FS/GS/DOE
ISSUANCE OF LEASE	BLM/DOE
PRE-LEASE BLM EXPLORATION PERMIT OR FS PROSPECTING PERMIT	BLM/FS (PRIMARY) GS AND FWS (CONSULTING)
POST-LEASE EXPLORATION PERMIT	GS (PRIMARY) BLM/FS/FWS (CONSULTING)

JUNE 1978

Sample Leasing EAR Schedule

Field Inventory – Data Analysis	6 Months
Drafting and Internal Review	5 Months
State Office Review	2 Months
Public Review	3 Months
Publication	1 Month
	17 Months

Expected Annual Federal Regulatory Workload

(Preliminary)

(Moderate Growth Scenario)

	1977	1980	1985	1990
Leases	200	200	300	600
Well Permits	100 (20)	75	400	1,000
Power Plants	2	5	30	150

SUMMARY OF ENVIRONMENTAL AND CONSERVATION LAWS IMPACTING THE FEDERAL GEOTHERMAL LEASING AND PERMITTING PROGRAM

GEOTHERMAL STEAM ACT OF 1970

NATIONAL ENVIRONMENTAL POLICY ACT OF 1969

FEDERAL LAND POLICY AND MANAGEMENT ACT OF 1976

NATIONAL FOREST MANAGEMENT ACT OF 1976

FISH AND WILDLIFE COORDINATION ACT

ENDANGERED SPECIES ACT OF 1973

NATIONAL HISTORIC PRESERVATION ACT OF 1966

FEDERAL WATER POLLUTION CONTROL ACT, AS AMENDED

CLEAN AIR ACT, AS AMENDED

RESOURCES CONSERVATION AND RECOVERY ACT

NOISE CONTROL ACT OF 1972

COASTAL ZONE MANAGEMENT ACT OF 1972

WILD AND SCENIC RIVERS MANAGEMENT ACT

OTHER CONSERVATION STATUTES WHICH LIMIT OR PRECLUDE DEVELOPMENT ON WILDERNESS, WILDLIFE REFUGES, AND OTHER PROTECTED LANDS

Geothermal Leasing Streamlining
Opinion Survey

(Please feel free to respond only to selected questions as you wish.)

Return to: Winston B. Short, BLM, Department of the Interior, 18th and C Streets, NW., Washington, D.C. 20240.

Meeting Attended____________________Date____________

Name (Optional)______________________________

Affiliation or Interest

Energy Production or Marketing________

Energy Regulation ____________

Environmental/Ecological/Cultural_____

Governmental Policy____________

Other__________________

General Questions

1. Do you feel that geothermal leasing and development on Federal lands are proceeding at an appropriate rate?

Too fast__________Adequate________Too Slow__________

Comments:______________________________

____

____

2. Do you feel that environmental (including cultural and ecological) factors are being adequately considered and protected in present operations?

Generally Yes__________Variable_______Generally No _______

Comments:______________________________

____

____

3. Do you feel that geothermal leasing and development can be accelerated without significant adverse environmental effect?

Yes _____ No _____

Comments:____

____

____

Questions related to location and cause of delays in geothermal leasing and permitting on Federal lands:

4. Do you feel that there are unreasonable delays in:

a. Land management planning decisions? Yes ____ No______

b. Leasing decisions? Yes ______ No _______

c. Plan of operation approval? Yes ______ No ______

d. Drilling Permit (APD) approval? Yes ______ No ______

5. Do you consider that any of the following are sources of delays? (M--major; S--slight)

a. Conflicts between development and environmental issues. ____

b. Federal environmental protection and land management laws. ______

c. Policies of Federal land management agencies. _______

d. State and local laws and regulations. _______

e. Lack of national policy and priorities on geothermal energy. ______

f. Newness and uncertainties of geothermal development. _______

g. Low level of interest by industry. _______

h. Too much speculative interest. _______

i. Special studies and management proposals. _______

j. Tax and price control policies. _______

k. Other ____

____

____

Questions related to possible measures to streamline geothermal leasing and permitting on Federal lands. Granted that streamlining is needed and desirable:

6. Should emphasis on environmental analysis be increased or decreased at each of the following stages?

	Increase	Decrease
a. Land-management planning	_______	_______
b. Prelease environmental analysis	_______	_______
c. Plan of operation analysis	_______	_______

Comments:____

____

____

7. Should time limits be established for specific administrative steps? Yes _____ No _____

Comments:____

____

____

8. Should geothermal leasing and development be given increased priority?

a. By increased Federal budget? Yes _____ No _____

b. In relation to other energy programs? Yes _____ No ___

c. In relation to other resource management programs?

Yes _____ No _____

Comments:____

____

____

9. Should more standards and conditions be incorporated into the lease forms? Yes ______ No ______

Comments:____

____

____

10. Would a nomination procedure be a useful means for scheduling KGRA sales? Yes _____ No _____

Comments:____

____

____

11. Should there be a limitation on the number of lease applications, or acreage applied for? Yes _____ No _____

Comments:____

____

____

12. Should competitive-interest KGRA's be eliminated?
Yes _____ No _____

Comments:____

____

____

13. Should no-surface-occupancy leases be routinely granted, where requested, in special study areas and prior to completion of land-management plans? Yes _____ No _____

Comments:____

____

____

14. Would non-occupancy leases be acceptable except where private or State lands allow the establishment of a land position?
Yes ____No ____

Comments:____

____

____

15. Should competitive-interest KGRA's be declassified after lack of bids at lease sales? Yes _____ No _____

Comments:____

____

____

16. Should KGRA's for direct thermal utilization be differentiated from KGRA's for electrical generation? Yes _____ No _____

Comments:____

____

____

17. Are comprehensive land-management plans and prelease environmental analyses justified in saving time on further analyses of plans of operation? Yes _____ No ______

Comments:____

____

____

18. Should phased leasing be allowed, with separate environmental analyses and agency decisions at prelease, exploration, and development stages? Yes _____ No _____

Comments:____

____

____

19. Would phased leases granting exploration rights and tentative development rights pending an EIS after any discovery be acceptable? Yes ______ No _____

Comments:____

____

____

20. Can you suggest practical means of streamlining the geothermal program, including changes in laws, regulations, or administrative procedures?____

____

____

____

____

Questions related to environmental aspects of possible measures to streamline geothermal leasing and permitting process.

21. For each question, 6 through 20, please evaluate the environmental impact of the suggested or implied change in the procedures.

____

CHRONOLOGICAL MILESTONES IN THE FEDERAL GEOTHERMAL LEASING AND PERMITTING PROCESS

- GEOTHERMAL STEAM ACT (P.L. 91-581) PASSED 12/24/70
- IMPLEMENTING BUREAU OF LAND MANAGEMENT AND U.S. GEOLOGICAL SURVEY REGULATIONS BECAME EFFECTIVE 1/1/74 (43 CFR, GROUP 3200 AND 30 CFR, PARTS 270 AND 271)
- GENERIC ENVIRONMENTAL IMPACT STATEMENT COMPLETED 10/73
- FIRST ENVIRONMENTAL ANALYSIS RECORD COMPLETED, SURPRISE & WARNER VALLEY, CA TRANSMITTAL TO STATE OFFICE 1/24/75
- FIRST NON-COMPETITIVE APPLICATIONS FILED 1/74
- FIRST LEASE SALE HELD 1/22/74 (CA)
- FIRST NON-COMPETITIVE LEASE ISSUED 1/16/75 (NV)
- FIRST ENVIRONMENTAL ANALYSIS COMPLETED 8/26/74 (USGS, CA, GEYSERS)
- FIRST PLAN OF OPERATION (EXPLORATION) APPROVED 9/6/74
- FIRST DRILLING PERMIT ISSUED 9/9/74
- FIRST PLAN OF OPERATION (DEVELOPMENT) RECEIVED 10/18/77 (REPUBLIC EAST MESA)
- FIRST PLAN OF OPERATION (INJECTION) RECEIVED 10/28/77 (REPUBLIC EAST MESA)
- FIRST PLAN OF OPERATION (UTILIZATION) RECEIVED 6/23/77 (MAGMA EAST MESA)
- FIRST PLAN OF OPERATION (PRODUCTION) EXPECTED 9/78

PLANT SUPPORT CAPABILITIES OF A GEOTHERMAL FLUID

Frank E. Robinson*, Kirpal Singh*, Wade Berry**,
and Terry R. Thomas***

*University of California, El Centro, CA
**University of California, Los Angeles, CA
***Republic Geothermal, Inc., Santa Fe Springs, CA

ABSTRACT

Geothermal fluids and shallow groundwater from Republic Geothermal, Inc. lease area of East Mesa in Imperial County, California were used successfully to irrigate sugar beet, alfalfa, asparagus, date palm, tamarisk, and desert climax vegetation. Chemical characteristics of the two irrigation fluids differed, but total dissolved solids content of the fluids were similar and within the 2000 mg/l range. The geothermal fluid contains elements which could be harmful to irrigated plants or plant consumers.

INTRODUCTION

The East Mesa KGRA in Imperial County, California is recognized as having geothermal fluids with relatively low concentrations of dissolved solids. Geothermal fluids produced on the Republic Geothermal, Inc. leasehold are representative of the East Mesa geothermal resource with a total dissolved solids content approximating 2000 mg/l. Saline tolerant crops and selected perennial plants, are known to succeed when irrigated with waters of similar salt content; however, the chemical characteristics of the East Mesa geothermal fluid are significantly different than the characteristics of typical irrigation waters and may contain specific chemical constituents which would make it nonsuitable as an irrigant. Conversely, the geothermal fluid may be an acceptable irrigation water for selected species and could prove to be a valuable alternative water resource in an arid region where water availability is limiting to economic growth.

Geothermal exploration and development in the desert community presents the added ecological concerns associated with land clearing and revegetation in a harsh desert environment. Pipeline transport of the geothermal fluid from production well to power plant and back to injection well also results in a continuing potential for accidental release of the geothermal fluid into the surrounding desert community. As such, it is of interest to determine whether or not the East Mesa geothermal fluids could be used to facilitate revegetation efforts in areas denuded for geothermal development; or, whether or not long-term adverse impacts to the native climax vegetation may be expected from accidental spills of the geothermal fluid. The continuing research reported in this study was undertaken as an attempt to resolve some of these questions.

PROCEDURE

A one-half hectare site was selected on Republic Geothermal, Inc.'s East Mesa lease area. The coarse hummocky sand surface was leveled and roads were constructed to service the test plot area. Six creosote bushes (Larrea tridentata) were protected within the plot area during site construction so they could be utilized in the study. Twenty-four basin irrigated plots of 0.001 hectares were constructed for the study. Half of the plots were irrigated with geothermal fluid cooled to ambient temperature and stored on-site in a 30,000 liter steel tank, and half of the plots were irrigated with shallow groundwater stored on-site in a similar 30,000 liter steel tank. Geothermal fluid was provided from Republic's East Mesa operations via a nearby injection well pipeline, and shallow groundwater was provided from Republic's 100 meter water well located adjacent to the study site. Chemical characteristics of geothermal fluid and the groundwater typically used during the study are presented in Table 1.

TABLE 1

CHEMICAL CHARACTERISTICS OF THE IRRIGATION FLUIDS

Chemical Constituent	Groundwater(1) (mg/l)	Geothermal(2) Fluid (mg/l)
PO_4	0.5	0.62
Na	410	575
K	12	30
Ca	68	9
Zn	0.1(3)	0.02
Cu	0.04(3)	<0.1
Ti	0.34(3)	0.17(3)
Fe	0.1	0.09
Ni	0.05(3)	<0.15
Mn	0.13(3)	<0.06
Mo	0.13(3)	0.12(3)
B	0.9	2.2
Al	1.43(3)	<0.8
Si	10	181
Cr	0.13(3)	<0.03
Ba	0.66(3)	<0.4
Li	---	0.6
Pb	0.06(3)	<0.5
Cd	---	<0.03
Cl	760	475
CO_3/HCO_3	80	454
SO_4	9	165
F	0.5	4
NH_4^+	---	4
Mg	19	0.2
As	0.03(3)	0.12
Br	0.9(3)	<0.2
Sr	2.45(3)	0.4
Se	---	<0.5
Hg	---	<0.002
Sb	---	<0.5
Ag	---	<0.06
V	0.33(3)	0 18(3)
Rb	0.14(3)	0.1(3)
Zr	0.07(3)	0.07(3)
TDS	1600	1880
pH	8.3	9.2(4)

(1)Groundwater from RGI Water Well No. 1

(2)Available injection water from Republic's East Mesa geothermal operations

(3)Preliminary single sample analysis (8/8/79)

(4)Post-flash pH

A randomized block design was used in triplicate. The plots contained one of the following: (a) creosote bush, one clump per plot; (b) a fallow area to observe regrowth of desert species; (c) selected trees, three each per plot including salt cedar (*Tamarisk articulata*), date palm (*Phoenix dactylifera*), and Mondell pine (*Pinus brutia*); and (d) one row of sugar beets (*Beta vulgaris*, USH-11), one row of asparagus (*Asparagus officinalis*, UC-157), and two rows of alfalfa (*Medicago sativa*, CUF-101). The creosote bushes were irrigated with 6 cm of water once per month. The trees were rooted in a greenhouse prior to transplanting on March 21, 1979, and then watered three times per week through the summer months, twice per week in the fall, and once per week in the winter months. The trees were planted over a 10 cm bore hole two meters deep that was backfilled with a mix of one part clay loam, one part peat moss, and two parts sand. Fertilization was 110 kg/ha N, 220 kg/ha P, and 100 kg/ha Ca in gypsum.

The alfalfa, asparagus, and sugar beets were planted on October 15, 1979. Fertilization was 150 kg/ha of N, 150 kg/ha of P, and 100 kg/ha of Ca preplant and two sidedressings of 50 kg/ha N for the asparagus and sugar beets. Irrigation was daily for the first 10 days and three times a week until winter to maintain the seedings. Irrigations were approximately 3.8 cm each. Emergence counts were taken eleven days after planting in the alfalfa and sugar beets, and six weeks after planting of the asparagus owing to the slower germination. Seeds had been counted electronically and placed in envelopes to ensure the same number of seeds in each plot.

Because of the loose sand substrait, it was necessary to place bales of straw around the plots to prevent wind storm sandblasting. Elongation of the creosote branches was recorded for each irrigation source and compared to the unirrigated bushes in the desert immediately surrounding the study site. The appearance and number of desert plants in the fallow plots were recorded monthly while being irrigated at two-week intervals. Samples of all plants, each of the irrigation waters, and the soil to 150 cm were collected for elemental analysis.

RESULTS AND DISCUSSION

Creosote Bush: The creosote bush comparison of elongation of three branches per bush showed no significant differences between the two water plots or the unirrigated plots. The average elongation in six months was 8.0 cm from June to December.

Fallow Plots: *Palafoxia linearis* was the predominant species. Most of the *Baileya pauciradiata* had dried by September with a few surviving the winter. A single *Euphoria micromera* and a single *Coldenia plicata* were observed in the plots. Several other species grew in the plots before the irrigation began and then completed seed formation while being irrigated. These were *Baileya pauciradiata*, *Bouteloua bartata*, *Cryptantha augustifolia*, *Dithyrea californica*, *Mentzelia affinis*, and *Palafoxia linearis*. It was observed that plants growing in the leveled area were larger than those in the surrounding desert even prior to irrigation. It is speculated that this was due to nutrients released by moving the sand or due to better penetration of the infrequent light rains. There was no significant difference between the two irrigation sources.

Tree Plots: The tamarisk demonstrated the most vigorous growth rate, growing from the initial 30 cm at planting to over 2 m in 10 months. Either of the waters used in this study could be used to support salt cedar wind breaks between cultivated areas or along highways. There was no apparent growth difference between the two waters. The palm trees showed a vigorous appearance and development of mature fronds with each water treatment. The Pinus brutia showed poor adaptation during the first year in each water treatment; however, the poor adaptation may be a result of other desert conditions than the quality of the irrigation waters. More recently, the condition of the pines has improved but it is still too early to evaluate their success.

Crop Plots: Table 2 shows the emergence percentage when irrigated with the two waters. Vigorous growth appearance continues in all three crops. Yields will be recorded for plot comparison and tissue will be collected at harvest for elemental analysis.

TABLE 2
PERCENTAGE SEEDLING EMERGENCE IN PLOTS IRRIGATED WITH GROUNDWATER AND GEOTHERMAL FLUID.

	Crop		
	Sugar beet	Asparagus	Alfalfa
Date counted	10/26/79	11/26/79	10/26/79
Geothermal Fluid	59.4%	22.0%	68.2%
Groundwater	67.8%	10.7%	84.7%
Significance level	NS*	1.0%	5.0%

*Not significant Fisher F test

A preliminary chemical analysis was completed of tissues taken from each of the tree species, the sugar beets, and from the first cutting of alfalfa. The results of these early analyses are presented in Table 3.

CONCLUSIONS

The two irrigation waters seem to have minimal effect upon the climax vegetation up to the present time. There was no significant difference in elongation rate of the creosote bush branches between those irrigated with geothermal water and those irrigated with groundwater nor between the irrigated and non-irrigated bushes. Several plant species completed their life cycle while being irrigated with no apparent adverse effects. Additional time will be required to study desert plant seed germination and subsequent growth while being irrigated.

It is apparent that tamarisk could be grown successfully with East Mesa geothermal fluids. The date palms also appear vigorous and additional time will indicate the practicality of their irrigation with these fluids. The crop plants are growing vigorously. Final analysis of plant tissue after harvest will indicate whether or not uptake and concentration of the potentially toxic elements present in the water will restrict the utilization of the plant species that might be grown. Preliminary tissue analysis of the first cutting of alfalfa suggests that Molybdenum uptake and concentration in the tissue of the plant may require special handling of the alfalfa to make it suitable as a livestock feed. It is interesting to note that Molybdenum concentrations in the tissue of alfalfa irrigated with geothermal fluid appear significantly greater than alfalfa irrigated with shallow groundwater in spite of the observation that Molybdenum concentrations in the two waters are similar. Further study should clarify this early observation.

ACKNOWLEDGEMENT

The ongoing study is supported by Republic Geothermal, Inc. We wish to thank the Laboratory of Nuclear Medicine and Radiation Biology of the University of California at Los Angeles for their assistance with portions of the chemical analyses.

TABLE 3
PRELIMINARY ELEMENTAL ANALYSIS OF LEAF TISSUES SAMPLED
(parts per million or percent)

	Creosote		Salt Cedar(5)		Date Palm		Alfalfa		Sugar Beet	
Element	Groundwater	Geothermal	Groundwater	Geothermal	Groundwater	Geothermal	Groundwater	Geothermal	Groundwater	Geothermal
P	1511	818(1)	925	669(1)	1321	1388(1)	2809	3369(2)	3051	2310(1)
Na	1188	1132(3)	7333	2642(4)	73	581(3)	4355	4426(1)	3.18%	3.82%(1)
K	1.20%	0.92%(4)	1.34%	1.10%(2)	1.12%	1.33%(1)	1.60%	2.01%(1)	1.27%	1.78%(3)
Ca	1.44%	1.51%(1)	2.34%	3.49%(1)	6593	3574(2)	2.68%	1.66%(1)	1.27%	1.14%(1)
Zn	10.9	11.2(1)	16.0	13.6(3)	213	190(1)	16.6	21.3(2)	15.8	20.2(1)
Cu	1.87	3.97(3)	9.5	7.0(2)	2.8	2.4(1)	2.8	2.7(1)	4.9	3.5(1)
Ti	70.8	49.2(1)	8.7	13.9(1)	3.0	4.2(1)	6.65	2.05(1)	161	177(1)
Fe	283	325(1)	91.9	135.4(1)	100.0	101.4(1)	95.9	63.7(1)	197	183(1)
Co	Detectable	Detectable	2.1	2.6(1)	Trace	Trace	6.0	3.97(3)	Approx 3.0	Approx 3.0
Ni	1.8	2.6(1)	0.48	1.7(1)	14.1	13.3(1)	6.2	3.0(3)	Trace	Trace
Mn	29.8	45.8(4)	49.5	27.0(4)	10.1	9.3(1)	7.28	4.40(1)	70	31(3)
Mo	Trace	-0-	13.2	19.7(1)	-0-	-0-	7.7	26.2(2)	0.03	0.5(3)
B	92.5	71.6(4)	139.7	189.4(1)	4.0	6.0(1)	27.1	18.8(1)	50	68(1)
Al	398	778(4)	192.1	343.3(1)	143.0	161.0(1)	262.7	224.9(1)	300	276(1)
Si	1900	2530(1)	262	442(1)	7780	6972(1)	497	484(1)	1079	771(1)
Cr	3.3	1.7(1)	0.1	0.5(1)	-0-	-0-	0.93	0.40(3)	-0-	-0-
Ba	23.1	16.6(4)	6.7	7.6(1)	3.0	4.1(1)	20.1	16.6(1)	36.6	16.0(2)
Li	9.6	7.5(1)	4.0	7.0(1)	Trace	Trace	26.5	53.3(2)	25.6	35.8(3)
Pb	Trace	—	25.8	24.0(1)	-0-	-0-	Trace	-0-	6.3	6.2(1)
Be	Detectable	Detectable	Trace	Trace	Detectable	Detectable	Trace	Trace	Detectable	Detectable
Cd	-0-	Trace	Trace	Trace	Detectable	Detectable	Detectable	Detectable	Detectable	Detectable

(1) No significant Difference, Fisher F test
(2) Significantly Different at 1% level, Fisher F test
(3) Significantly Different at 5% level, Fisher F test
(4) Significantly Different at 10% level, Fisher F test
(5) Not Washed

SubJ
GTHM
QRGS

Quarterly Report

Geothermal Studies in Montana

by

Kardidus P. Lupindu
John Gogas
Janet Peterson

John Sonderegger
Charles Wideman

Period: April through June, 1983

In April, the 300 foot deep shallow test well at Warm Springs State Hospital was filled with cement and abandoned as per agreement with the Department of Institutions; also, written and oral testimony requested by the Department of Natural Resources was presented at a Water Rights Hearing concerning the Ennis geothermal system.

May and June were spent primarily working on manuscripts for a series of final reports on the program results. An abstract dealing with the Ennis system was submitted and accepted for the fall AAPG regional meeting. A field investigation was conducted two miles north of Medicine Hot Springs at the request of the landowner; however, the water temperature was due to poor drainage behind landslide deposits combined with solar effects.

Geophysical progress is as follows:

(1) Gravity Investigation of the White Sulphur Springs Area

This investigation incorporated a reconnaissance gravity survey of the greater White Sulphur Springs area and a detailed gravitational survey of the hot springs area within the city of White Sulphur Springs. Gravity readings for the reconnaissance survey were obtained at approximatley every 1 mile. Elevations were determined from U.S.G.S. 7.5' x 7.5' quadrangles. Gravity readings for the detailed survey were taken on a 35 point grid with approximately 700 feet between each grid node. Grid node elevations were determined to 0.1' by surveying.

Field work for this project has recently been completed. All data, except for 10 stations, has been reduced and terrain corrected.

The final draft of a gravity contour map of the total survey area has been started, and a geologic map compiled from Ross (1964), Birkholz (1967), Phelps (1969), and Gierke (1982) covering the same area has been completed. Final drafts of two more maps which cover the hot springs area in detail are also in preparation.

Interpretation of the data is still in the early stages. A gravity forward-modeling program utilizing a gravitational attraction algorithm for a two dimensional polygon, as developed by Talwani (1959), is up and running on our computer. This program incorporates interactive graphics which speeds up interpretations. At this time a second derivative map of the hot springs area is also planned.

(2) A Self Potential Survey of the Norris Hot Springs

The natural electrical potential of the hot springs area have been measured using the self potential (SP) geophysical method. Data have been collected along several lines which form a rough grid over the region of interest. Station spacings of 100 meters have been used along the lines. Preliminary plotting and interpretation of the SP data shows an anomaly at the hot springs location. More field work is anticipated for better anomaly resolution.

(3) Results of Resistivity Surveys Near Bozeman Hot Springs and White Sulphur Springs

The thesis of Mr. Kandidus Lupindu is attached as an appendix to this report.

ELECTRICAL RESISTIVITY STUDIES
NEAR
BOZEMAN HOT SPRINGS OF GALLATIN COUNTY
AND
WHITE SULPHUR HOT SPRINGS OF MEAGHER COUNTY
MONTANA

by

Kandidus P. Lupindu

A thesis submitted to the
Department of Physics and Geophysics
Montana College of Mineral Science and Technology
in partial fulfillment of the requirements
for the degree of
Master of Science in Geophysical Engineering

Montana College of Mineral Science and Technology
Butte, Montana
July 1983

ABSTRACT

Electrical resistivity surveys have been conducted using Schlumberger arrays. The purpose of the surveys was to investigate the occurences of Bozeman Hot Springs and White Sulphur Hot Springs.

The interpreted resistivity soundings show:

1. A low resistivity zone, apparently consisting of a single layer of 2-8 ohm-m resistivities, at a depth of approximately 20 m below the surface and near the Bozeman Hot Springs. Thickness of the conductive layer may exceed 80 m.
2. A low resistivity zone, consisting of up to 3 layers of 1-8 ohm-m resistivities, almost at the surface and near the White Sulphur Hot Springs. Total thickness may be more than 100 m.

ACKNOWLEDGEMENTS

This work carried out in 1982 was partially supported by Department of Energy under contract #DE-FC07-701D12033 and by A.I.D., under the Conventional Energy Program # 936-9997-1. Planning and directing of this work by Dr. Charles Wideman is sincerely appreciated. Thanks are extended to Mr. Mike Stickney who allowed his seismic refraction profile be included in this work.

Several valuable discussions with Mr. John Gogas, on the geology and spacial correlation of gravity anomalies of his preliminarily interpreted gravity map and resistivity anomalies mapped at White Sulphur Springs, are gratefully appreciated. A debt of gratitude is also owed Mrs. Janet Peterson and Ms. Lynn Miller, who read through and contributed in editing the manuscript of this work.

CONTENTS

LIST OF ILLUSTRATIONS

TABLES

I. INTRODUCTION

A. PURPOSE AND SCOPE

The geophysical study of Bozeman and White Sulphur Hot Springs (Figure 1) involved: 1. Conducting electrical resistivity surveys in the summer of 1982; and, 2. Interpreting from the observed electrical soundings the subsurface configuration of the hot springs and possibly, on their origin. The method employed for the surveys was the Schlumberger direct current technique as described by Keller and Frischknecht (1966), Telford, et.al., (1976), Heiland (1968), and Parasnis, (1979).

Locations of the soundings are shown in Figures 2 and 3. A total of 23 soundings included 9 at Bozeman, with a maximum separation AB/2=300 m and 14 at White Sulphur Springs, with a maximum separation AB/2=500 m.

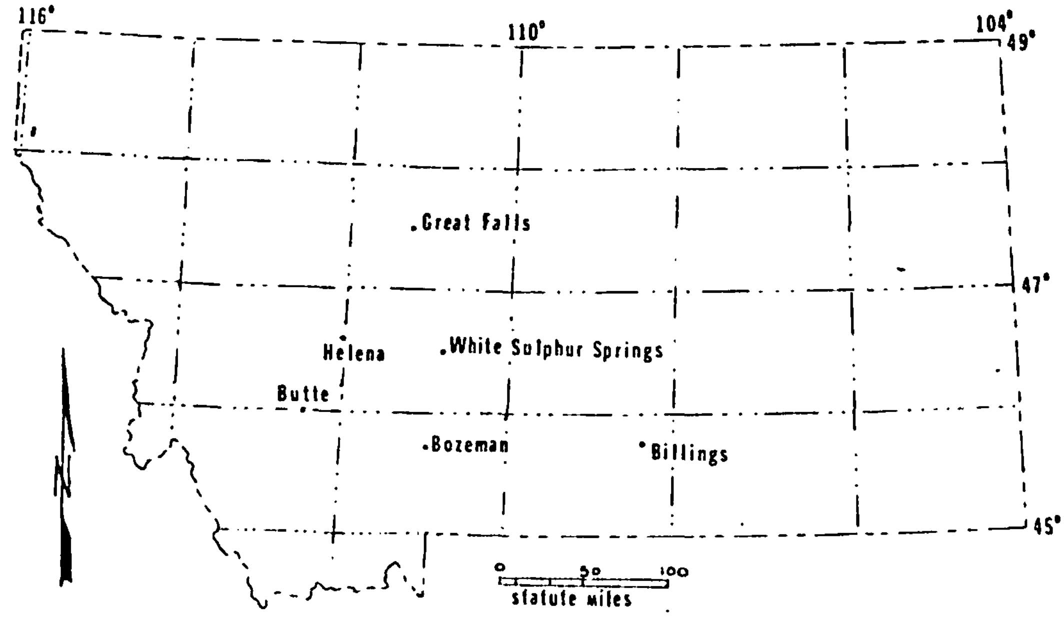


Figure 1. Index Map of Montana, Showing Bozeman and White Sulphur Hot Springs.

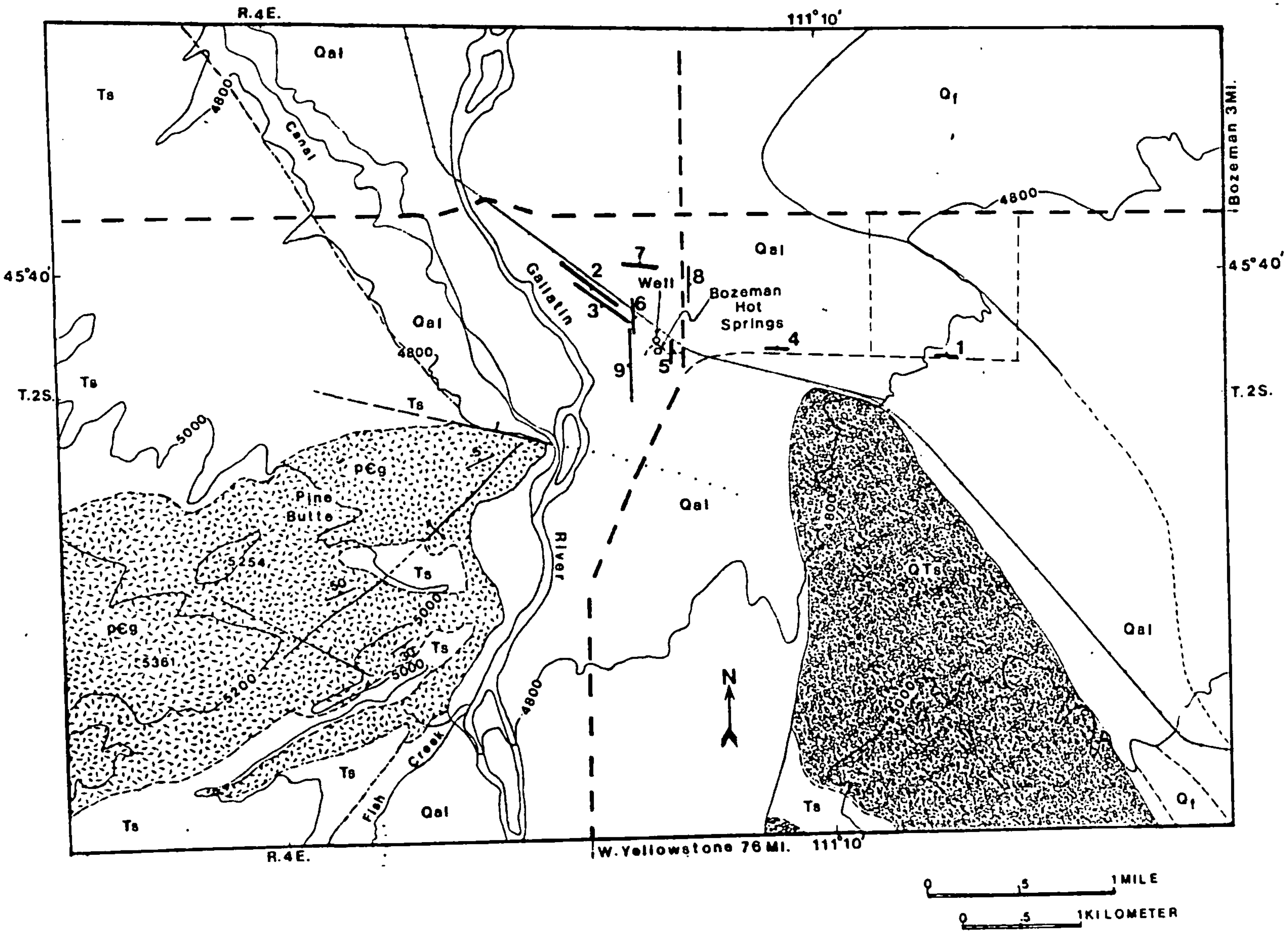
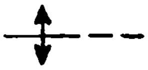
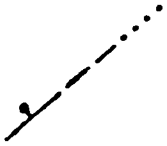


Figure 2. Geologic Map of Bozeman Hot Springs Area, Adapted from Hackett, et.al., (1960), and Chadwick and Leonard (1979), Showing Station Locations.

EXPLANATION
(Fig. 2)

Qal	Quaternary	Alluvium, predominantly stream-laid deposits
Q_f		Alluvium, predominantly alluvial-fan deposits
QTs	Quaternary-Tertiary Alluvium, stream-laid and fan deposits	
Ts	Tertiary Sediments	
pЄg	Precambrian Gneisses	
	Contact - dashed where inferred	
	Anticline with direction of plunge; dashed where inferred	
	Fault - dashed where inferred; barbells on downthrown side	
	Strike and dip of foliation	
	Sounding Station-line indicates maximum Spacing AB Surveyed; dot at the center	

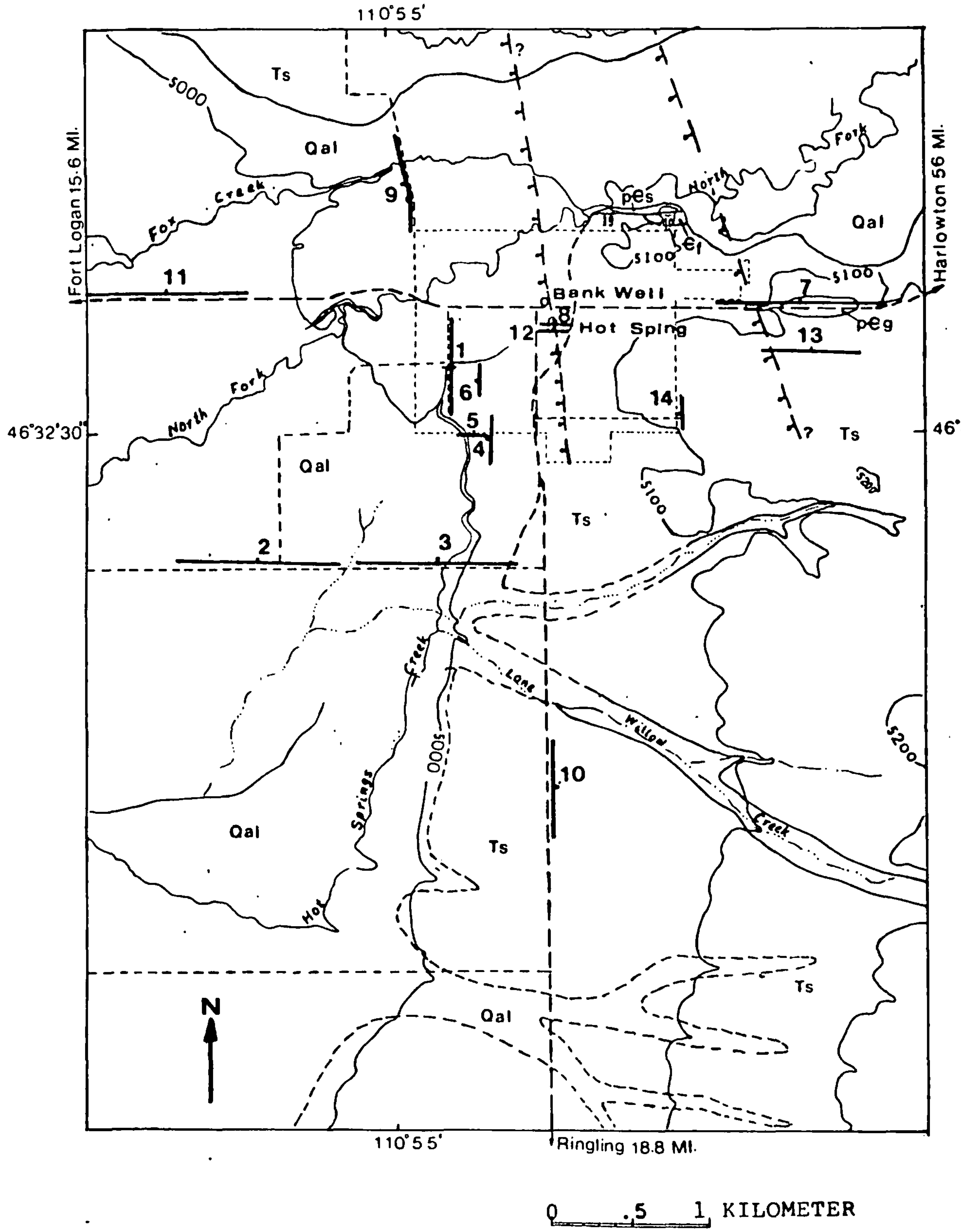
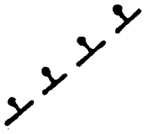
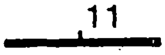


Figure 3. Geologic Map of White Sulphur Springs, Adapted from Gierke (1982), Showing Station Locations.

EXPLANATION

(Fig. 3)

Qal	Quaternary Alluvium
Ts	Tertiary Sediments
Ꞓf	Flathead Sandstone
pꞒs	Spokane Shale
pꞒg	Greyson Shale
——— – – –	Contact - dashed where inferred
	Inferred Normal Fault - barbells on downthrown side
	Sounding Station - line indicates maximum Spacing AB Surveyed; dot at the center

B. GEOGRAPHIC LOCATION

Bozeman and White Sulphur Hot Springs are situated in the Gallatin and Smith Intermontane Basins respectively. The Gallatin and the Smith Basins belong to the Rocky Mountains Province.

The Gallatin Basin is almost entirely within Gallatin County. It is flanked on the east and south by the Bridger and Gallatin Ranges. The Horseshoe Hills form the northern boundary, and topographic divides, between the Madison and Gallatin Rivers, bound the basin on the west.

A principal part of the Gallatin Basin, in which lies Bozeman Hot Springs, is between the Gallatin River and the East Gallatin River and Bozeman Creek. Bozeman Hot Springs is situated about 10 km west of the city of Bozeman, and is located in the S.E. 1/4 sec. 14, T. 2 S., R. 4 E. 1 km east of a point where the Gallatin River makes a northwest turn from its general northern flow.

The Smith Basin is located in Meagher County. The White Sulphur Hot Springs are situated in the town of White Sulphur Springs, whose location is N.W. 1/4 sec. 18, T. 9 N., R. 7 E. Big Belt and Little Belt Mountains bound Smith Basin on the west and east respectively.

C. PHYSIOGRAPHY

Part of the Gallatin Basin, bounded on the west by the Gallatin River, and on the north and east by the East Gallatin River and Bozeman Creek, ranges in gradient of land surface from about 30 m/km at the extreme southern end to less than 12 m/km near the northwestern end. Altitude ranges from about 1650 m in the south to about 1250 m in the northwestern corner.

The White Sulphur Springs area is near the contact between basin fill sediments with older rocks. Its slope is generally to the southwest, toward the Smith River. The North Fork of the Smith River is the major river draining the White Sulphur Springs area. It flows to the southwest from the Little Belt Mountains. Willow Creek, about 5 km northeast of the hot springs site, is a tributary to the North Fork of the Smith River.

D. PREVIOUS WORK

(i) Bozeman Hot Springs. Results of shallow water wells drilled in the Gallatin Valley (Hackett, et.al., 1960) show that the ground water is usually at a depth of about 3.0 m. Chadwick and Leonard (1979) suggest structural control of the Bozeman Hot Springs as being an intersection of a N. 45° E. trending anticlinal axis in Precambrian gneisses, with a N. 85° W. striking normal fault about 1 km southwest of the spring (Figure 2). Bouguer gravity anomaly map (Davies, et.al., 1965) shows that two lows are separated by a gravity high region, stretching from the Gallatin-Madison rivers divide, to the east and then to the proximity of Bozeman. The aeromagnetic map by Davies (ibid.), shows a pronounced gradient of northeast trending contours in the springs area. The high gradient may indicate existence of a northeast striking fault associated with the springs in the area.

Preliminary interpretation of gravity surveys by Mike Stickney (personal communication,1983) shows, that, in the vicinity of the hot springs, a pronounced positive nose exists and is compatible with the east-west trending anticline reviewed by Chadwick and Leonard (1979).

A Seismic refraction profile (Figure 4, Stickney, personal communication,1983) shows a low velocity layer with an apparent velocity of 1075 ft/sec (328 m/sec) and thickness of 9.7 ft (3.0 m), and an intermediate layer with apparent velocity of 7576 ft/sec (2310m/sec) and thickness of 586 ft (179 m), and a basement layer with apparent velocity of 20044 ft/sec (6111 m/sec). The low velocity layer corresponds to a near-surface, weathered zone. The intermediate layer probably is a basin-fill material saturated with ground water, and the basement layer probably is gneisses underlying the basin-fill material. The seismic refraction mapped two interfaces: one between the near-surface loose gravel (weathered zone) and the unweathered basin-fill material; and the other between the basin-fill material and the underlying gneisses.

A thermal water well at the Bozeman Hot Springs intersected from the depth of 10 m (Dunn,1981, and Figure 5), 6 m of surfacial gravels of Precambrian gneisses and amphibolites, and Tertiary basalts; 10 m of clay, 25 m of loose sand, soft sandstones and siltites; 91 m of clay, and 24 m of gravels. Figure 5 also shows an expected resistivity variation with the established lithology. The last 24 meter interval of gravels is suggested by Dunn (1981) to represent weathering deposits on an ancient topography, before deposition of basin fill materials.

(ii) White Sulphur Springs. Chadwick and Leonard (1979) suggest that the hot springs are a result of an inferred N. 30° W. range-front fault intersecting a sedimentary aquifer (fractured Belt argillite and sandstone basin fill) slightly to the west of the hot springs.

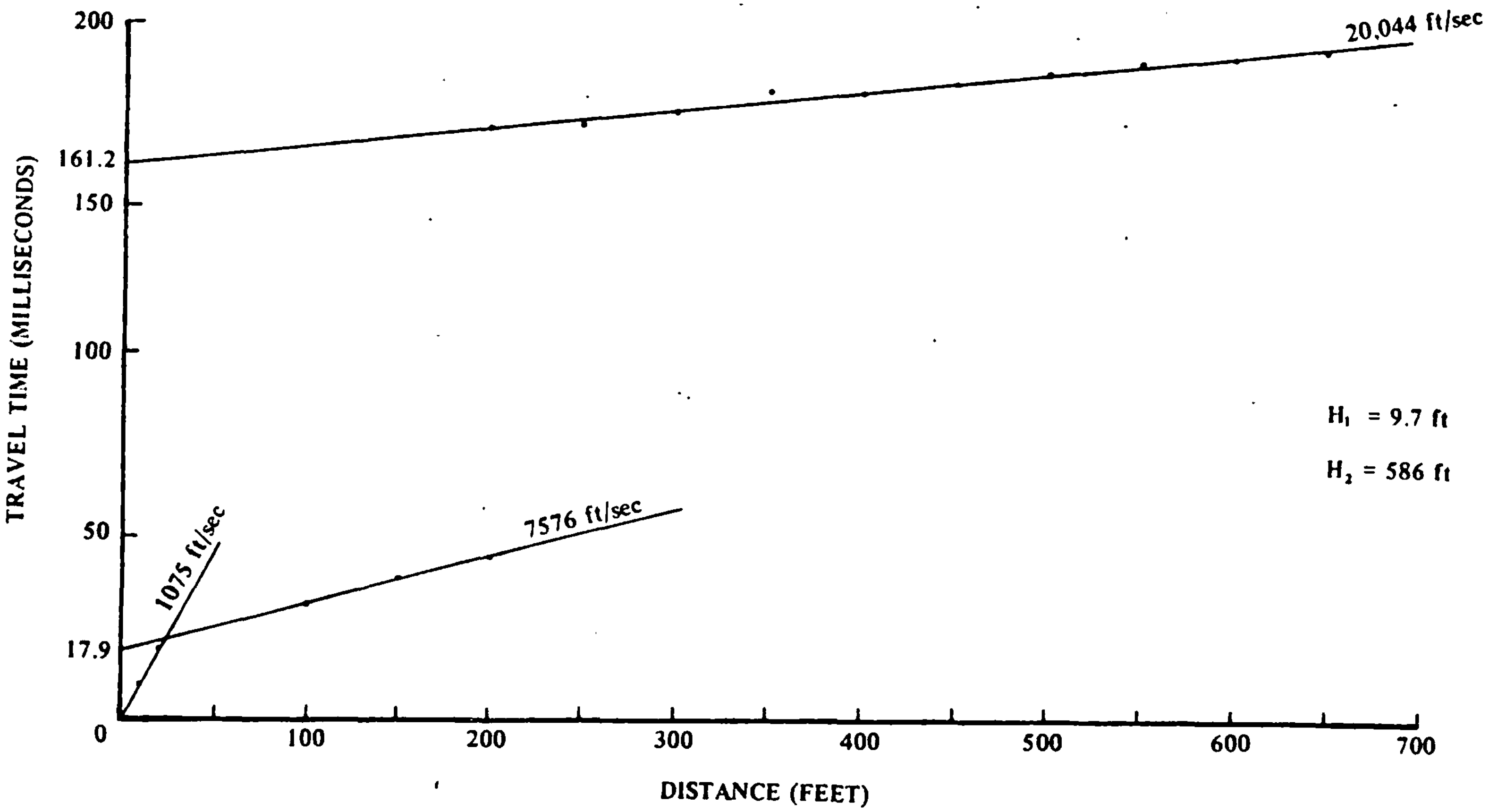


Figure 4. Seismic Refraction Profile Across The Bozeman Hot Springs Area (Stickney, 1983, Personal Communication).

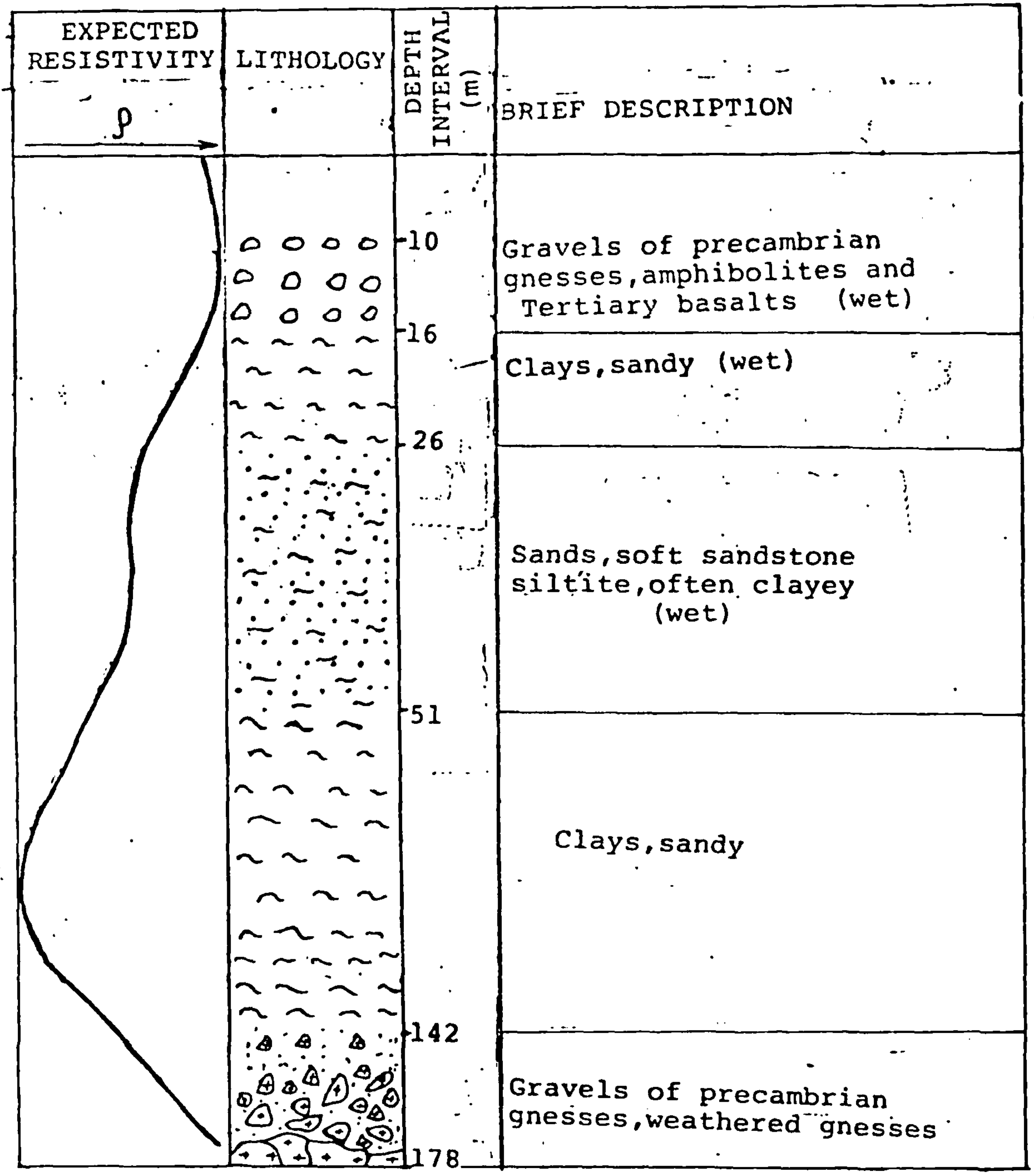


Figure 5. Schematic Geologic Log of Bozeman Hot Springs Thermal Water Well, Adapted From The Bozeman Hot Springs Thermal Water Well Geologic Report (Dunn, 1981), Showing Expected Resistivity Variation With Depth.

They further point out that thermal water possibly ascends fractures parallel to the adjacent range front fault. Gierke (1982) postulates, however, a N. 10° W. normal fault at the hot spring (Figure 3).

Two thermal wells have been drilled at the hot springs: one, at the First National Bank of White Sulphur Springs, to a depth of 270 m, and the other at the White Sulphur Springs General Hospital, to a depth of 90 m. The lithology established by these wells is from bottom of the well, fractured Belt argillites, basin-fill argillite, siltite, argillite, sandstones and gravel (Figure 6). Figure 6 also shows an expected resistivity variation with the established lithology.

Four temperature logs (Dunn,1978) were documented in the well of the First National Bank of White Sulphur Springs in both static and pumping regimes (Figure 7). In the static regime, the temperature rises sharply from 30°C on the surface to 45°C at a depth of 33.5 m and remains at about 45°C to a depth of 121.9 m, whereas in the pumping regime, the temperature is 45°C from the surface to approximately 152.4 m. Below noted depths in both methods, the temperature drops to 32°C and 33°C respectively. This lead Dunn (1978) to conclude that thermal water flows horizontally through the permeable sandstones and the fractured argillites from a thermal ground system from a source at depth.

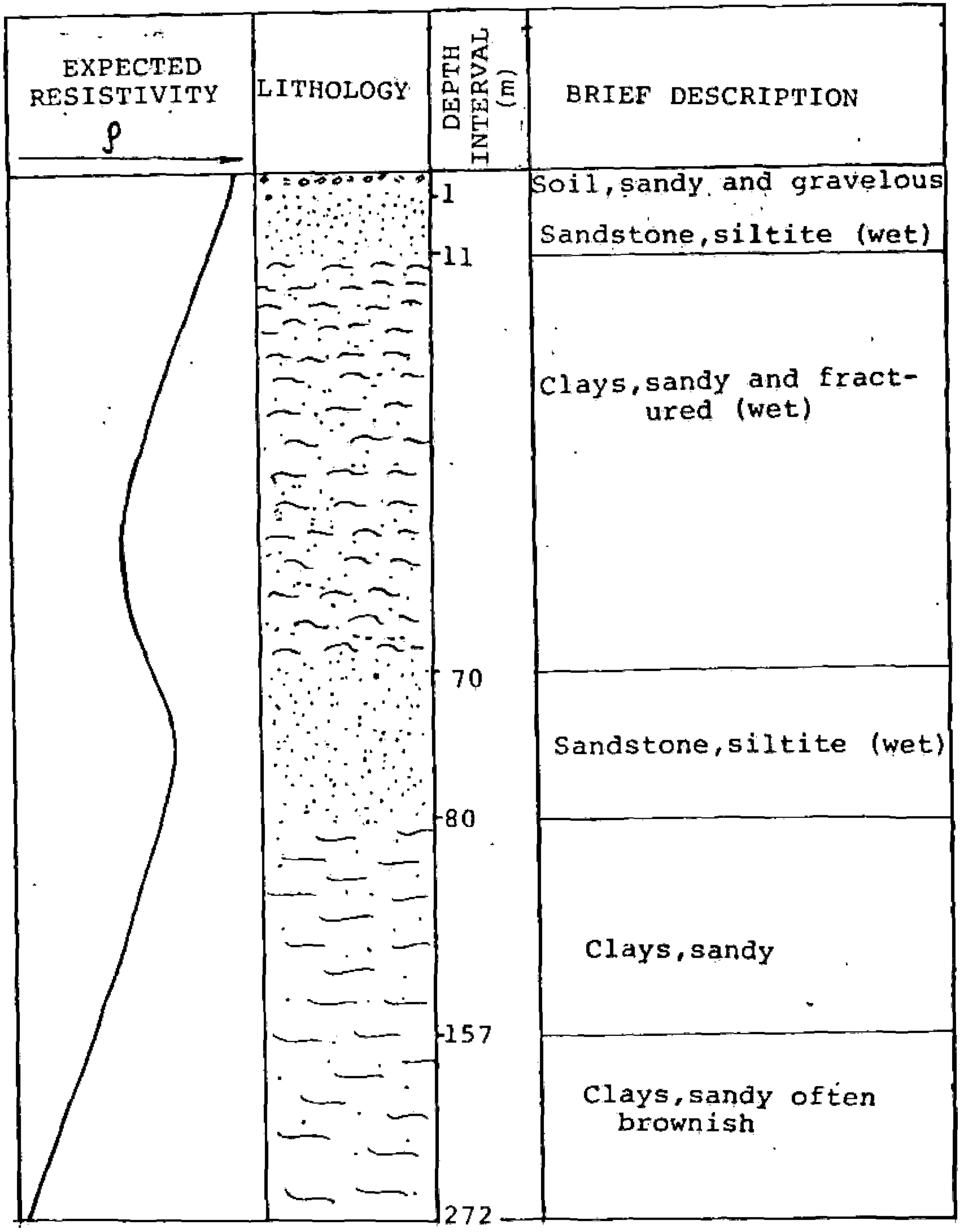


Figure 6.

Schematic Geologic Log of The First National Bank of White Sulphur Springs Thermal Water Well, Adapted From The First National Bank of White Sulphur Springs Thermal Water Well Geologic Report (Dunn, 1981), Showing Expected Resistivity Variation With Depth.

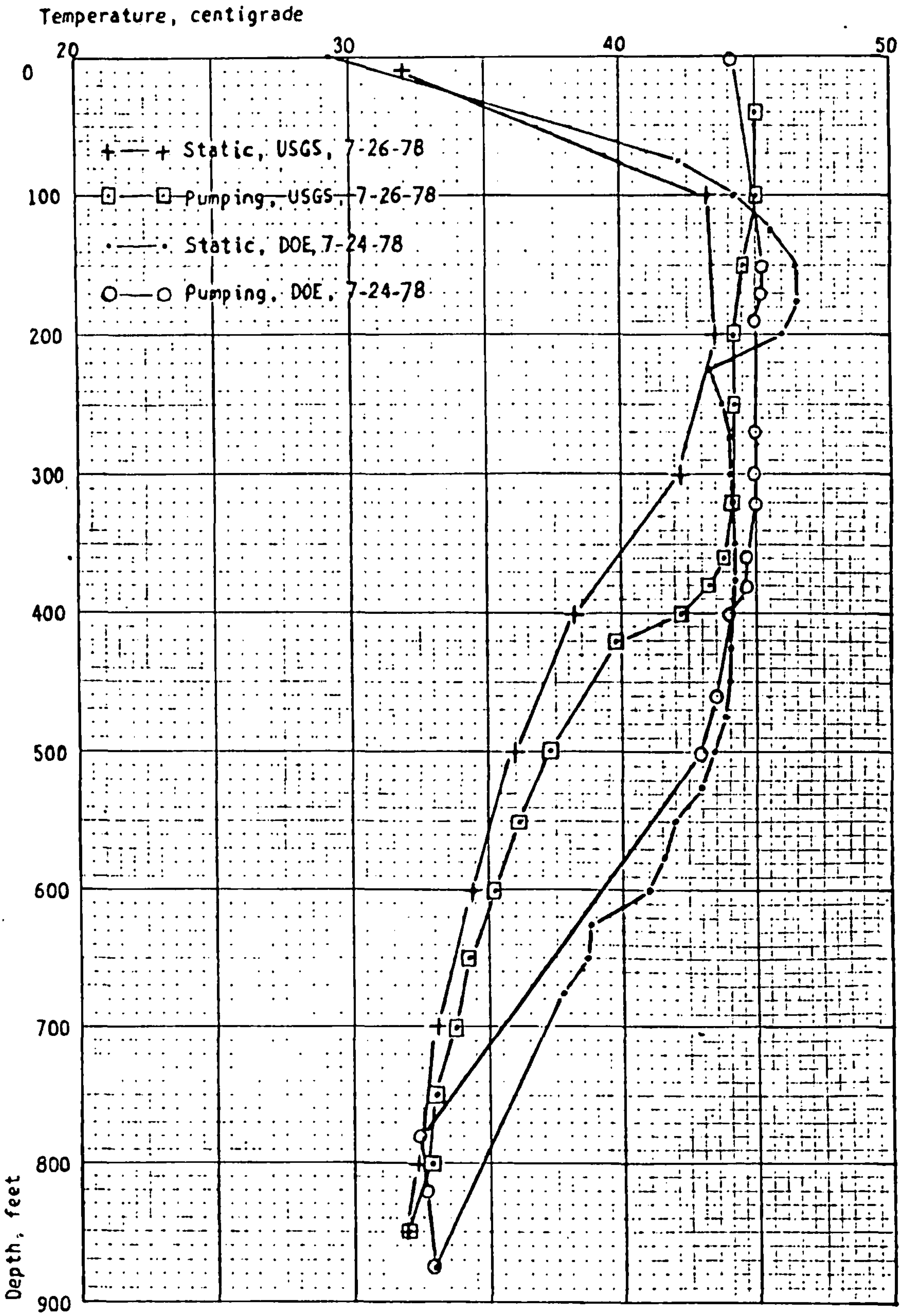


Figure 7.

Temperature Logs of The First National Bank of White Sulphur Springs Thermal Water Well (Dunn,1978).

II. GEOLOGY OF THE AREAS OF THE HOT SPRINGS

A. BOZEMAN HOT SPRINGS

(i) Lithology and stratigraphic units. The following is a summary from Hackett and others (1960), who postulate that Precambrian gneisses (pre-Beltian complexes), and Precambrian sediments (Belt Series) underlie Cenozoic sediments, respectively, in the northern and southern parts of the Gallatin Valley. Rock units in the springs area include therefore, Precambrian gneisses and Cenozoic sediments. Gneisses outcrop in the Camp Creek Hills, 1 km southwest of the springs. Cenozoic sediments constitute valley fill of Tertiary and Quaternary ages. Tertiary rocks outcrop in the Camp Creek Hills. They are composed of conglomerate, tuffaceous sandstone, siltstone, claystone, marl and volcanic ash. Undifferentiated Tertiary-Quaternary alluvial-fan and stream-channel deposits form a high benchlike fringe which is skirting the Bridger and Gallatin Ranges. The sloping surface of these deposits often terminates in an escarpment. The alluvial-fan deposits are composed essentially of poorly sorted rock fragments in a matrix of sand, silt, and clay. Rock fragments are often gneisses. The stream-channel deposits however, consist of rounded cobbles. Quaternary deposits include terrace gravel, alluvial-fan and stream-channel deposits. Remnants of terrace gravel formed by the Gallatin River are present along the east margin of the Camp Creek Hills. Alluvial fans extend into the Gallatin Valley from the foot of the slopes of the bordering Gallatin and Bridger Ranges. These deposits were formed by streams that cut into fans of older alluvium higher on the slope. They are composed of heterogeneous mixture of course-grained and fine-grained sediments (gravels, cobbles, scatered boulders, sand, silt and clay). Stream-channel deposits along the Gallatin River consist of cobbles and gravel intermixed with sand, clay, and silt. Most of the cobbles, gravel and sand grains are fragments of gneisses and dark volcanic rocks. Thicknesses of alluvial-fan and stream-channel deposits are inferred respectively to be 51 m and 25 m. Quaternary Alluvial-fan and stream-channel deposits overlie Tertiary sediments. The character, extent, and thickness of the alluvium underlying the valley between the Gallatin and East Gallatin Rivers, indicate that the alluvium was deposited concurrently with glaciation of the Gallatin and Madison Ranges.

(ii) Structural Setting. The Gallatin Valley owes its formation, as many other basins in southwestern Montana, to block faulting, which many workers believe started in Late Cretaceous (after the Laramide Orogeny) and continues spasmodically to the present (Hackett, et.al., 1960, Chadwick and Leonard, 1979). Within the Gallatin-Madison block numerous faults and folds developed presumably contemporaneously with block faulting (Hall, 1961). Movements along faults resulted in formation of the Gallatin Basin in downthrown sub-blocks within the Gallatin-Madison block. Range-front faults bound the Gallatin Valley to the south and east from the Gallatin and Bridger ranges respectively.

Figure 2 shows a postulated relationship of Bozeman Hot Springs to the intersection of a N. 85° W. fault, 1 km to the southwest, with a N. 45° E. anticlinal axis in Precambrian rocks (Chadwick and Leonard, 1979).

B. WHITE SULPHUR SPRINGS

(i) Lithology and stratigraphic units. The lithologic units generalized at the White Sulphur Springs area are Precambrian to Cretaceous sediments, Tertiary intrusives, volcanics, and sediments, and Quaternary alluvium (Gierke, 1982, Dahl, 1971, Phelps 1969).

Three outcrops of Precambrian and Paleozoic sediments (Greyson Shale, Spokane Shale and Flathead Sandstone) have been mapped by Gierke (1982) close to the hot springs. The Basin is essentially filled by Tertiary and Quaternary sediments. Tertiary sediments overlie Precambrian and Paleozoic sediments at the hot springs. The rest of the hilly area to the east and north of the hot springs site is built of rocks of all ages from Precambrian to Quaternary, with Tertiary sediments on slopes and Quaternary alluvium in river valleys.

(ii) Structural setting. The Smith River Basin, in which lies the White Sulphur Springs, may owe its formation to block faulting. It is bounded to the east and north by the southeasterly trending branch of the Disturbed Belt (a zone of thrust faults: Craig, Volcano Valley and the Willow Creek Faults). The western boundary is formed by a fault which displaces basin-fill sediments against Belt Super Group sediments of the Big Belt Mountains. A combination of east-west transverse and thrust faults form the southern boundary of the basin. Gierke (1982) postulates that the hot springs sit on a N.W.-S.E. trending normal fault whose western block is downthrown against the eastern block.

III. METHOD OF SURVEY

A. THEORETICAL BACKGROUND OF THE METHOD

(i) Brief discussion of resistivity. The theory of the electrical resistivity methods is extensively examined in geophysical literature. Here it is noted briefly that, although electric conduction in rocks is by electrolytic conduction, resistivity of a rock sample is calculated as for electronic conduction in metals as

$$\rho = R\ A/L \qquad \text{(III-1)}$$

where is electrical resistivity of a cylindrical solid of length L and cross-sectional area A, having a resistance R (ohms) between the end surfaces. Resistance R is defined as for ohmic materials as

$$R = V/I \qquad \text{(III-2)}$$

where, V (in volts) is applied voltage across the ends of the cylinder and I (in amperes) is the current flowing through it. Combining the two equations, we get

$$\frac{1}{\rho} = (I/A)/(V/L) = J/E = \sigma \qquad \text{(III-3)}$$

where σ is electrical conductivity, J is current density , E is electrical field. When the unit of length is in meters, ρ is in of ohm-meters, (abbreviated as ohm-m)

(ii) Factors varying resistivities. Generally factors include: elementary and mineral composition; granularity, porosity, pore fluids, and temperature. The temperature effect is the most predominant in geothermal fields. A discussion on the temperature effect by Malik (1977) is summarized below:

> Extreme ranges in temperature may affect the resistivity of a water bearing rock significantly, particularly if the temperature is high enough to vaporize the water or low enough to freeze the water in the pore spaces of the rock. Between these extremes, the dependence of

Denoting A for L, that is for AB/2, and b for 2 that is for MN, expression (III-5) becomes

$$\rho = (\pi A^2)/b \ x \ (\Delta V/I) \qquad \text{(III-8)}$$

Telford, et.al., (1976) state:

> Over homogeneous isotropic ground this resistivity will be constant for any current and electrode arrangement. That is, if the current is maintained constant and the electrodes are moved around, the potential V will adjust at each configuration to keep the ratio $(\Delta V K_g/I)$ constant.
>
> If the subsurface is inhomogeneous (this is always the case in practice), and the electrode spacing is varied, or the spacing remains fixed while the whole array is moved, then the ratio will, in general change giving a different value of ρ_a for each measurement. This measured quantity is known as apparent resistivity, ρ_a.

Assuming that the earth model consists of horizontal beds (Telford, et. al., 1976), the resistivity ρ_a becomes a function of depth.

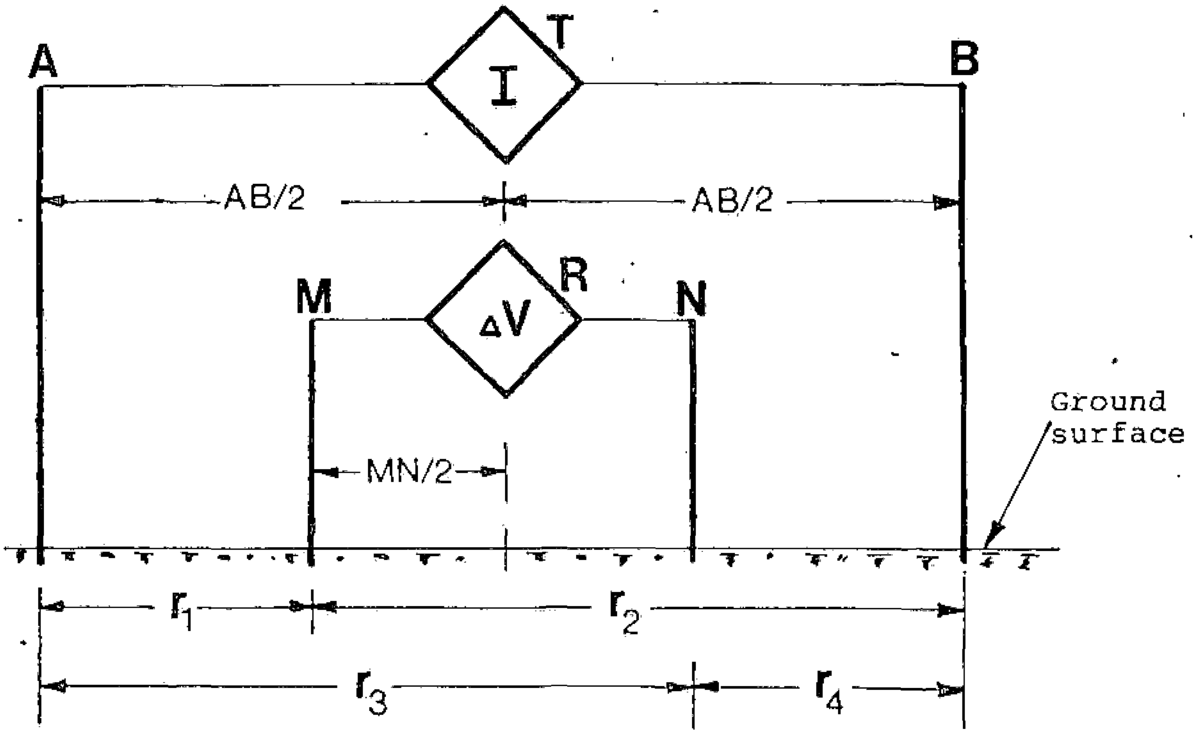


Figure 8. Symmetrical Schlumberger array

resistivity of temperature for either a electrolyte or a rock saturated with an electrolyte is given by the equation

$$\rho_T = \rho_{18^\circ} / \{ 1 + \alpha_T (T - 18^\circ)\} \qquad \text{(III-4)}$$

where ρ_{18° = resistivity is measured at a reference temperature of $18^\circ C$ (arbitrarly chosen), T = ambient temperature and α_T = temperature coefficient of resistivity, whose value is about 0.025 per degree centigrade for most electrolytes.

Moreover, the hotter the water, the greater is its dissolving power resulting in increased pore space. As a result of increased salinity of pore water and increased pore space, electrical resistivities are greatly reduced in hydrothermally altered rocks and in geothermal fields. In geothermal fields, the effect increases from the periphery to the center. In this way, the electrical resistivity contrast is amplified between a geothermal system (where it exists) and the surrounding rocks.

Classical geothermal systems typically have less than 5 ohm-m resistivity. However, one source of ambiguity in using such criteria is the presence of clay, shale and other highly porous but impermeable rocks in areas of interest.

(iii) Apparent resistivity. In a resistivity survey, the general formula for calculating resistivity values for a single layer (single overburden) from a measured ΔV and I is as follows:

$$\rho = (V/I)K_g \qquad \text{(III-5)}$$

where

$$K_g = 2\pi / (1/r_1 - 1/r_2 - 1/r_3 + 1/r_4)$$

is the electrode geometry factor (Figure 8). In Figure 8, we see that, by setting

$AB/2 = L$ and $MN/2 = \ell$, we have

$r_1 = r_4 = L - \ell$ and $r_2 = r_3 = L + \ell$

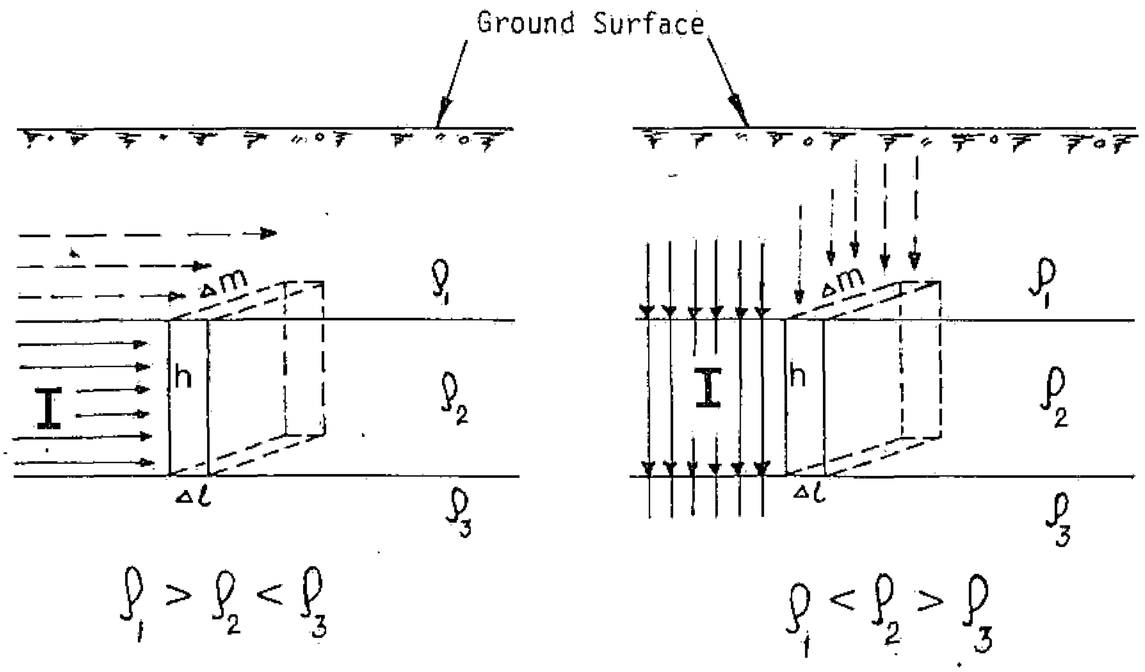
and hence

$$K_g = (\pi L^2 - \ell^2)/2\ell \qquad \text{(III-6)}$$

Since $L \gg \ell$ then

$$K_g = (\pi L^2)/2\ell \qquad \text{(III-7)}$$

(iv) Principles of equivalence and suppression. Principle of equivalence is summarised from Parasnis (1979) where, it is illustrated by considering for example, a relatively thin layer sandwiched between two layers whose resistivities are much higher or lower than that of the sandwiched layer (Figures 9a and 9b).



(a)

(b)

Figure 9. Principle of equivalence
(Modified from Parasnis, ibid).

If the sandwiched layer is much less resistive than the sandwiching layers, the current flow in the earth will then tend to concentrate into the sandwiched layer, and the current will be almost parallel to it (Figure 9a). The resistance of an elementary block of length and cross-section h m to such a current flow is

$$R = \rho_2 \Delta l/(h \Delta m) \quad \text{(ohms)} \qquad \text{(III-9)}$$

Assuming R, Δm and Δl are constant, and by rearrangement of equation (III-9) we get

$$h/\rho_2 = \Delta l/R\ \Delta m = \text{Const} = S \qquad (\text{mhos-m}^2)$$

Where, S is conductance, that is the measure of the ratio of the thickness of a conductive layer between two insulating layers to the resistivity of the conductive layer.

On the other hand, if the sandwiched layer is much more resistive than the sandwiching layers, the current flow in the earth will then tend to avoid it and take the shortest route across it. The current will be almost perpendicular to the layer (Figure 9b). The resistance of an elementary block to this current flow will be

$$R = \rho_2 h/(\Delta m \Delta l) \qquad (\text{ohms}) \qquad \text{(III-10)}$$

Assuming again that $R, \Delta m$ and Δl are constants, and by reaarangement of equation (III-10) we get

$$\rho_2 h = R\ \Delta m \Delta l = \text{Const} = T \qquad (\text{ohm-m}^2)$$

Where T is Transmittance (Transverse reistance), that is the product of the thickness and the resistivity of the resistive layer.

The same parameters S and T may respectively be ratios and products of several pairs of resistivities ρ_2 and thickness h. In this case, all layers for which the ratio or product is the same are electrically equivalent so that, h and ρ_2 cannot be determined separately.

On the principle of suppression, Parasnis (1979) states:

> If a thickness of a layer is very small compared to its depth (and its resistivity is finite) its effect on the ρ_a curve is so small that the presence of the layer will be suppressed.

In a general sequence of several layers most h and ρ_2 parameters are subject to principles of equivalence and suppression but the parameters can, in general, only vary within certain limits (Parasnis, ibid). These limits can be found by the optimization procedures of the methods of interpretation as discussed in the section of the computer modelling- interpretation of Chapter IV.

B. FIELD SURVEY TECHNIQUE

In the surveys described in this paper, the array chosen was the Symmetrical Schlumberger array, whose advantages over other arrays (Wenner, gradient and dipole-dipole) have been well presented by Malik (1977).

The Symmetrical Schlumberger linear four electrode array (Figure 8) was arranged with two closely spaced potential electrodes MN, placed midway between two current electrodes AB. Power source T measured current it injected into the ground through electrodes A and B. The potential difference established in the earth by this current was measured with the receiver R connected between the potential electrodes M and N. For each sounding, potential differences ΔV and currents I were measured at certain successive logarithmically spaced AB/2 separations. The distance MN is in principle infinitely small; but, since in practice MN cannot be made infinitely small, it is kept as small as commensurate with the measuring instruments and the potential being measured (Zohdy, 1974). Starting values for each sounding were AB/2 = 1 m and MN = 20 cm, and maximum values were AB/2 = 500 m and MN = 40 m. These values are consistent with the usual requirement for Schlumberger arrays, namely, that MN/2 is less than or equal to one-tenth of AB/2, and that MN spacing depends on current density and sensitivity of the measuring instruments.

From the measured ΔV, I, AB/2 and MN, ρ_a was calculated by formula

III-8, using a hand calculator, and plotted against the half separation AB/2 (m), on a log-log paper, with ρ_a on the ordinate and AB/2 on the abscissa. Plotting of the ρ_a was done with smoothing of the data by bringing down to initial level, all points of discontinuity arising when expanding inner potential electrodes (MN).

C. INSTRUMENTS

Necessary components for making resistivity measurements include a power source (transmitter), receiver, electrodes, cable and reels. The transmitter and receiver used had analog meters to indicate the current (in Amperes) injected into the ground and potential difference (in volts)is developed across the subsurface. Surveys were done with an IPC 7/25W lightweight, battery-powered transmitter and an IPR 7 Newmont-type receiver.

To avoid the effects of electrolytic polarization caused by unidirectional current, the d.c. polarity was reversed periodically in the transmitter every 8 sec. The spontaneous potentials were compensated for by the compensating voltage noted on the receiver before the current was switched on.

IV. INTERPRETATIONS

A. INTRODUCTION

(i) General. For this thesis, the interpretation of observed electrical resistivity sounding curves is accomplished in four stages. The first (curve matching) and second (computer modeling) stages involve obtaining resistivities and thicknesses from the observed sounding curves. For the lowest mapped layer in each sounding curve, only its resistivity is determined while its thickness remains indeterminate. Most of the observed and interpreted sounding curves show the last mapped layer to be conductive. Thickness of the last conductive layer may be estimated as illustrated below. Thirdly, geoelectric plans and sections are constructed to show the configurations of the resistivity anomalies (i.e conductive zones). The fourth stage is a discussion and presentation of results from the former three stages.

In all sounding curves illustrated, dots represent raw field data, stars represent smoothed data, and lines represent corresponding theoretical sounding curves.

(ii) Curve matching. Manual curve matching of the smoothed field curves with standard curves (Orellana and Money 1966, Zohdy, 1965) was done to obtain for each sounding curve, a set of layers and their resistivities and thicknesses, as initial input into computer programs. Two-layer master curves were used for complete matching of the two-layer observed sounding curves. Partial curve matching was employed for observed sounding curves which indicate more than two layers.

(iii) Computer modeling-interpretation. The computer interpretation involves first, calculation of a theoretical sounding corresponding to an input set of layers and their resistivity and thickness values, then, a least-square fitting of the theoretical sounding with the observed sounding. All this, is done by a computer program CAIES (Crous, 1971) described in detail by Malik (1977) and modified by Crase (1982) for use on the newly installed VAX system. Toward the end of the processing, the author used a modified version of CAIES by Gogas (1983).

Output from the CAIES program includes the number of mapped layers, resistivity and thickness of the first layer, resistivity of the last layer and, alternatingly transmittance T and conductance S of the layers between the first and last layers. The output includes also, calculated sounding and an error of fit of the calculated sounding to the observed sounding. In the curve fitting technique, the last layer in each set of inputs is treated by the CAIES program as basement of an infinite thickness. Accuracy of curve fit is then determined by the resistivities of all layers (including the basement) and the thicknesses of all layers except the basement.

As a measure of the accuracy of fit, Crous used the root-mean square (RMS) error (Malik, 1977):

$$e = \sqrt{1/N \sum_{i=1}^{N} (M_i - O_i)^2}$$

in percentage, where N = the total number of points in M (theoretical curve) and O (observed curve). 100% represents the distance of one decade of the usual logarithmic scale. An RMS of 1% is then equal to distance of 0.625 mm per decade. Crous, therefore assigned an upper limit of 1% to the RMS error in his program CAIES. When e = 1%, the iteration stops.

After the first input of the curve matching results, the interpreted resistivities of the first and last layers, and the thickness of the first layer were subsequently varied until the error reached a certain minimum. Then, using the transmittance T and

conductance S of the previous output, pairs of resistivities and thicknesses were selected for subsequent inputs. Pairs which produced smaller error and better fit than the others were treated as adequately interpreted. In this paper, all interpretations were made to less than 1% RMS error.

For convenience of discussion and presentation, the interpreted soundings are categorized into: 1.) soundings showing low resistive layers of 1-8 ohm-m; and, 2.) soundings showing relatively high resistivities of more than 10 ohm-m.

B. BOZEMAN HOT SPRINGS

(i) Sounding curves. A total of eight sounding curves are shown for the Bozeman Hot Springs area. Because of relatively high resistivities of approximately more 30.0 ohm-m or more, of their interpreted layers, sounding curves BOZ 1, BOZ 4 and BOZ 7, (surveyed farthest from the hot springs, Figures 10 and 2) show probably the typical resistivity values of the basin fill material. On the other hand, soundings BOZ 5, BOZ 6, BOZ 8, and BOZ 9 (near the hot springs, Figures 11 and 2) show lower resistivities (2-5 ohm-m) than those shown by the former soundings at similar depths of approximately 20 m below the surface. Consequently, sounding curves BOZ 5, BOZ 6, BOZ 8, and BOZ 9, are mapping a conductive zone at the hot springs. Sounding BOZ 2 (about 1 km northwest of the hot springs, Figures 10 and 2) shows a resistivity of 8 ohm-m at a similar depth of 24 m.

Sounding Boz 3 was not interpreted. Noise associated with a nearby power line is believed to have affected the results of this sounding.

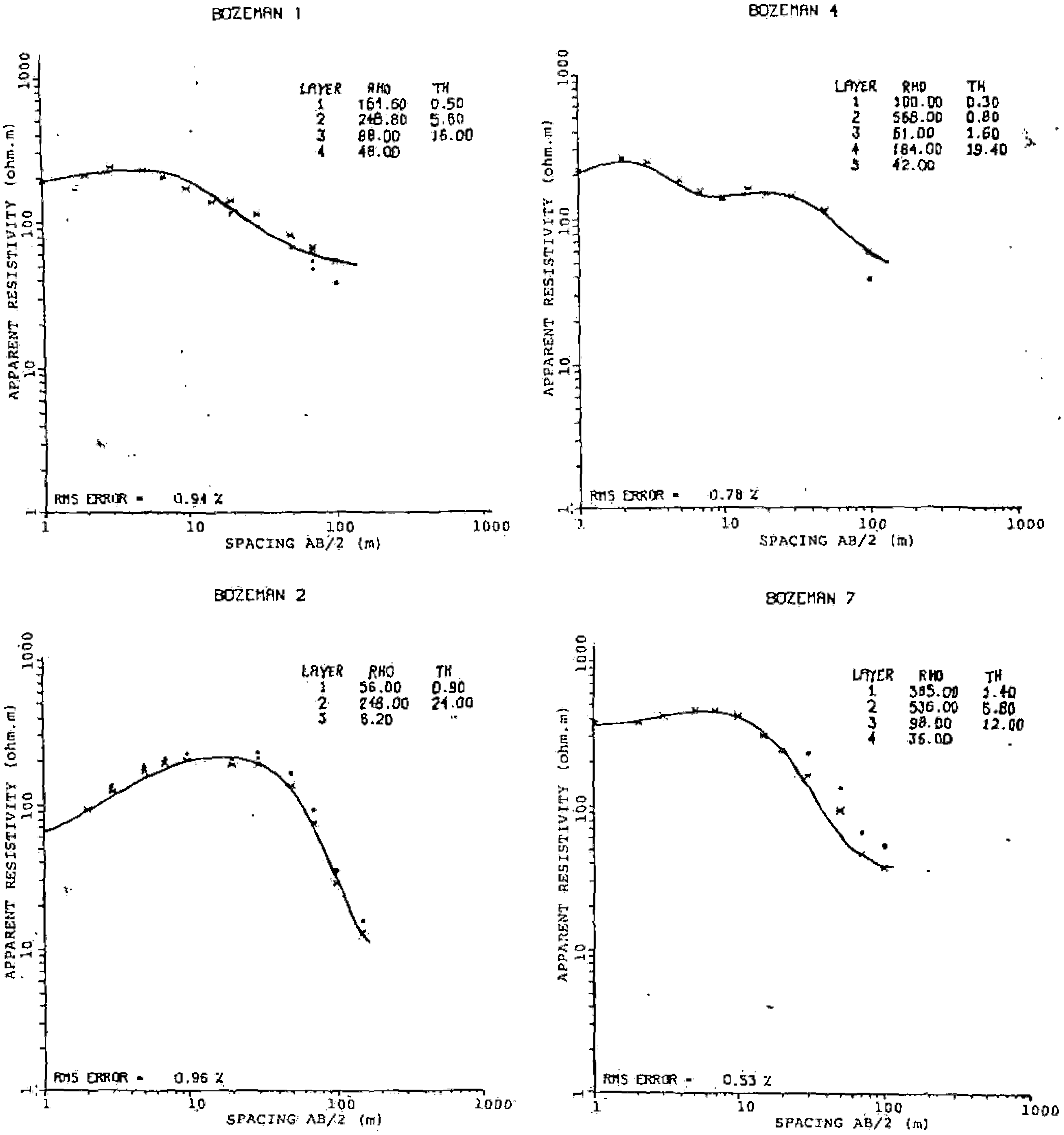


Figure 10 Sounding Curves for Stations 1, 4, 7 and 2, Showing Layers and Their Interpreted Resistivities and Thicknesses.

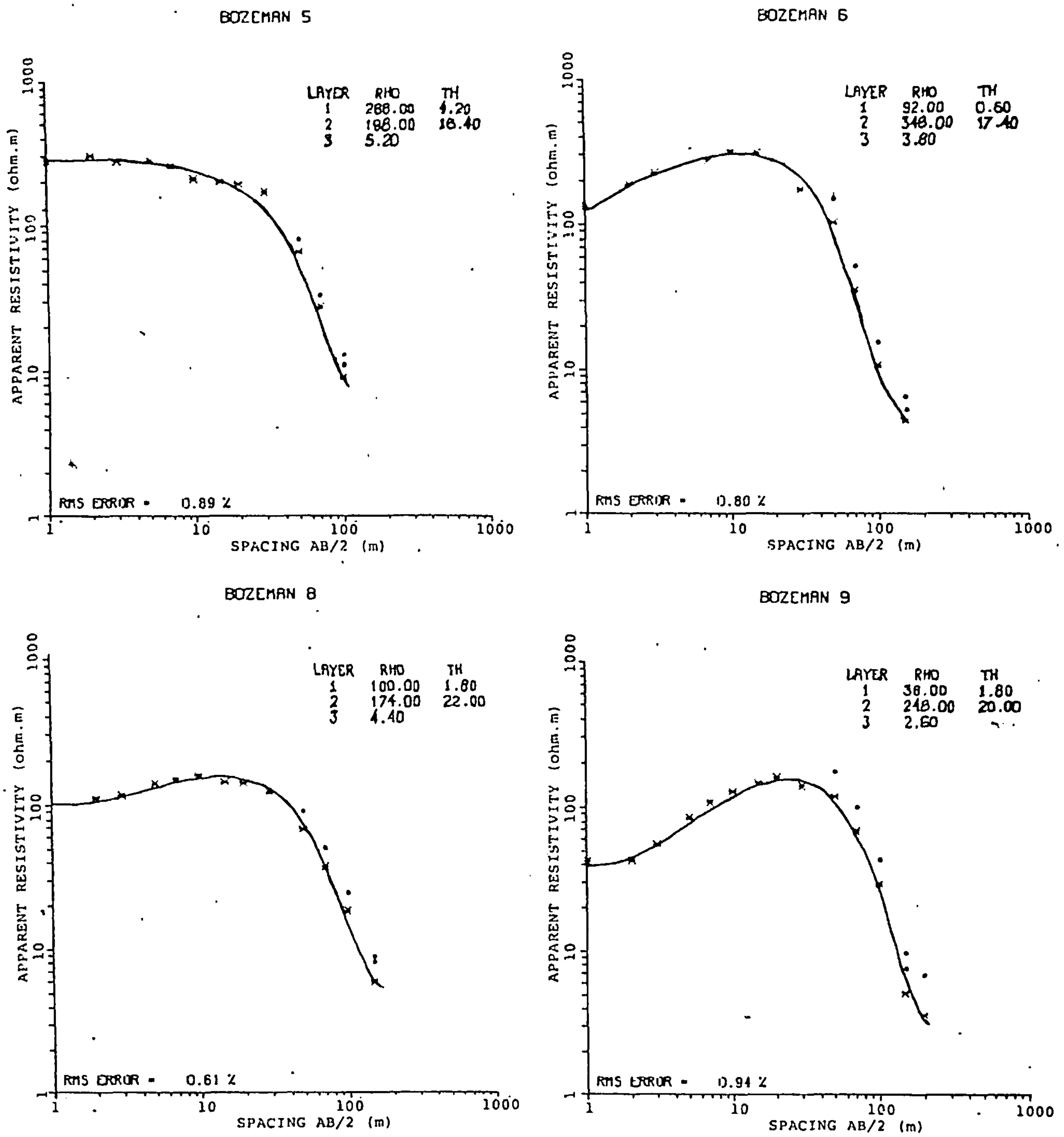


Figure 14. Sounding Curves for Stations 5, 6, 8 and 9, Showing Layers and Their Interpreted Resistivities and Thicknesses.

Maximum spacings AB/2, which in a homogenous and isotropic medium correspond to maximum theoretical penetration depths and total observed thicknesses of mapped layers, are summarised in Table 1 for all sounding curves.

TABLE 1
MAXIMUM SPACINGS AB/2 AND DEPTH TO LAST MAPPED LAYER.

Sounding curve	Maximum spacing AB/2 or Maximum theoretical penetration depth (m)	Depth to last mapped layer (m)
BOZ 1	100	22.1
BOZ 4	150	22.1
BOZ 7	100	20.2
BOZ 5	100	20.6
BOZ 6	150	18.0
BOZ 8	150	23.8
BOZ 9	200	21.8
BOZ 2	150	24.9

(ii) Thickness Estimation. Estimation of thickness of the conductive zone and resistivity of the underlying material is illustrated for sounding curve BOZ 5. First, it is assumed that the conductive zone is underlain by resistive materials. Hence, the observed sounding curve is fitted with a theoretical sounding curve of a four-layer case instead of formerly a three-layer case. Four resistivities are assigned to the fourth, relatively resistive layer. Only the thickness of the conductive zone and the resistivity of the underlying interval are varied.

Resistivities of 10, 30, 50, and 100 ohm-m are assigned to the fourth conductive layer whose thickness is varied from 30 or 50 to 150 m. Thickness of the conductive zone is estimated for each assigned resistivity by the best fit of the theoretical sounding curve to the observed sounding curve. The best fit is realized between 50-70 m of thickness when 10 ohm-m. of resistivity is used for the underlying interval. For the other resistivities, the best fit is reached with a thickness of 70-100 m. Resistivity of materials underlying the conductive zone is estimated at 30 ohm-m, again by a best fit and low RMS error (Figures 12-15 and Table 2). With a resistivity of 30 ohm-m for the underlying material, the thickness of the conductive zone was estimated at 70-100 m. Preferably, the thickness was estimated at 80 m with RMS error of 0.73%. An 80 m thickness of the conductive zone makes a total penetration depth of approximately 100 m mapped by sounding BOZ 5.

(iii) Geoelectric plan. Geoelectric plan (Figure 16) is constructed for spacing AB/2 = 100 m using apparent smoothed observed data. A low resistivity area of less than 10 ohm-m, is delineated by sounding stations BOZ 8, BOZ 6, BOZ 9 and BOZ 5. A steep gradient of contours exists between sounding stations BOZ 9 and BOZ 5. Additional sounding curves are recommended to the northeast, southeast and west of the hot springs, so that contours may be more accurately mapped.

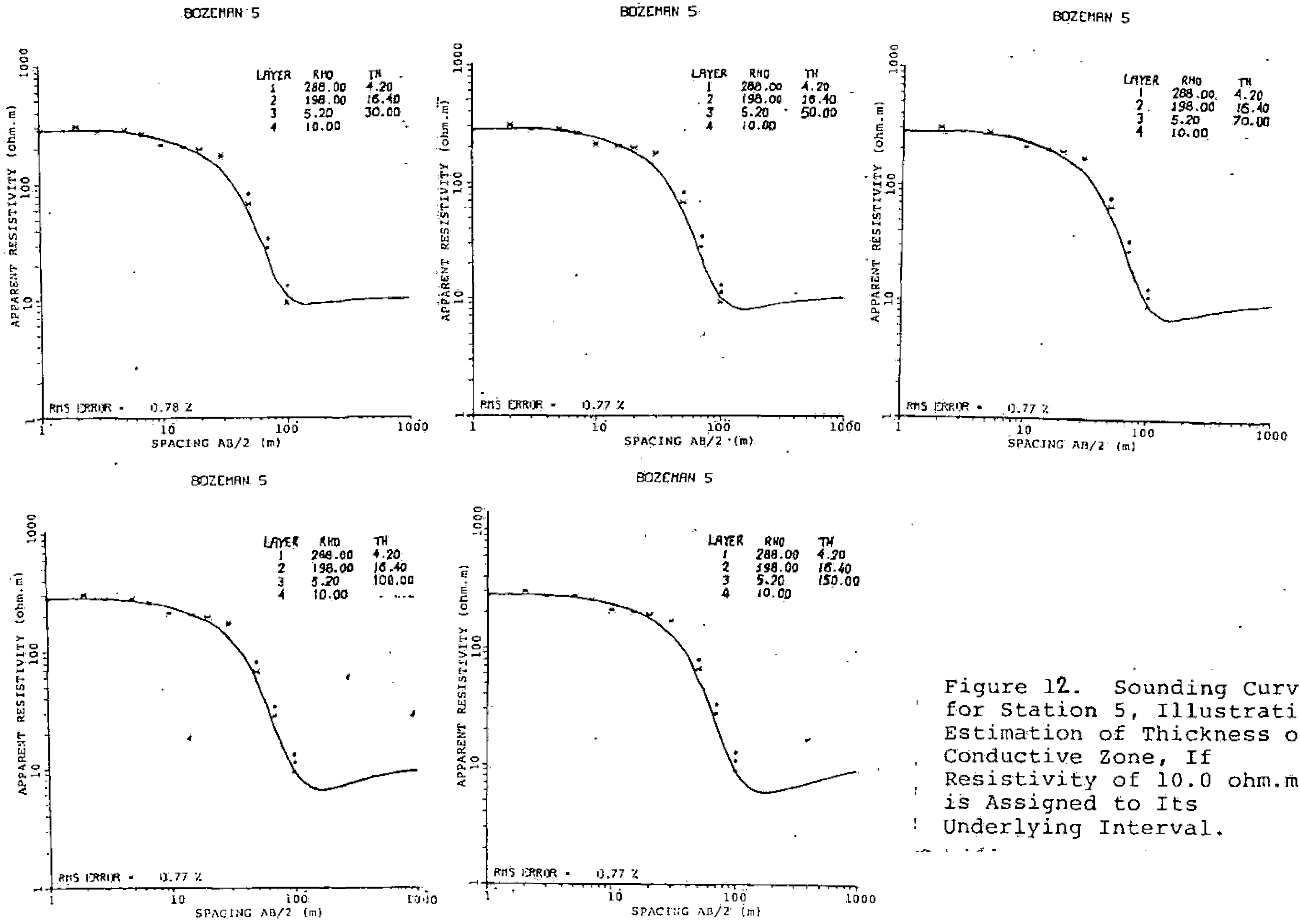


Figure 12. Sounding Curves for Station 5, Illustrating Estimation of Thickness of Conductive Zone, If Resistivity of 10.0 ohm.m is Assigned to Its Underlying Interval.

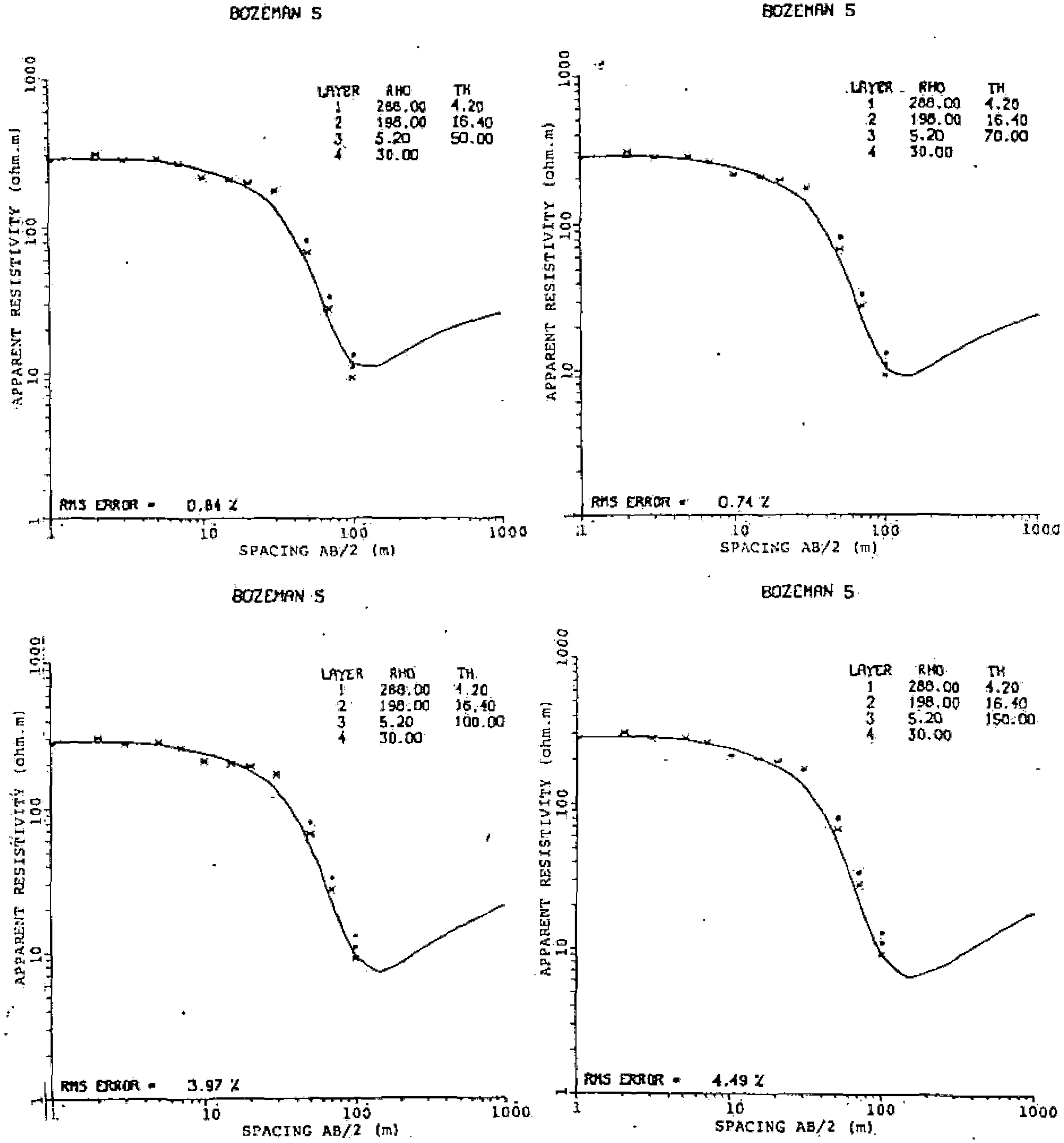


Figure 13. Sounding Curves for Station 5, Illustrating Estimation of Thickness of Conductive Zone, If Resistivity of 30 ohm.m is Assigned to Its Underlying Interval.

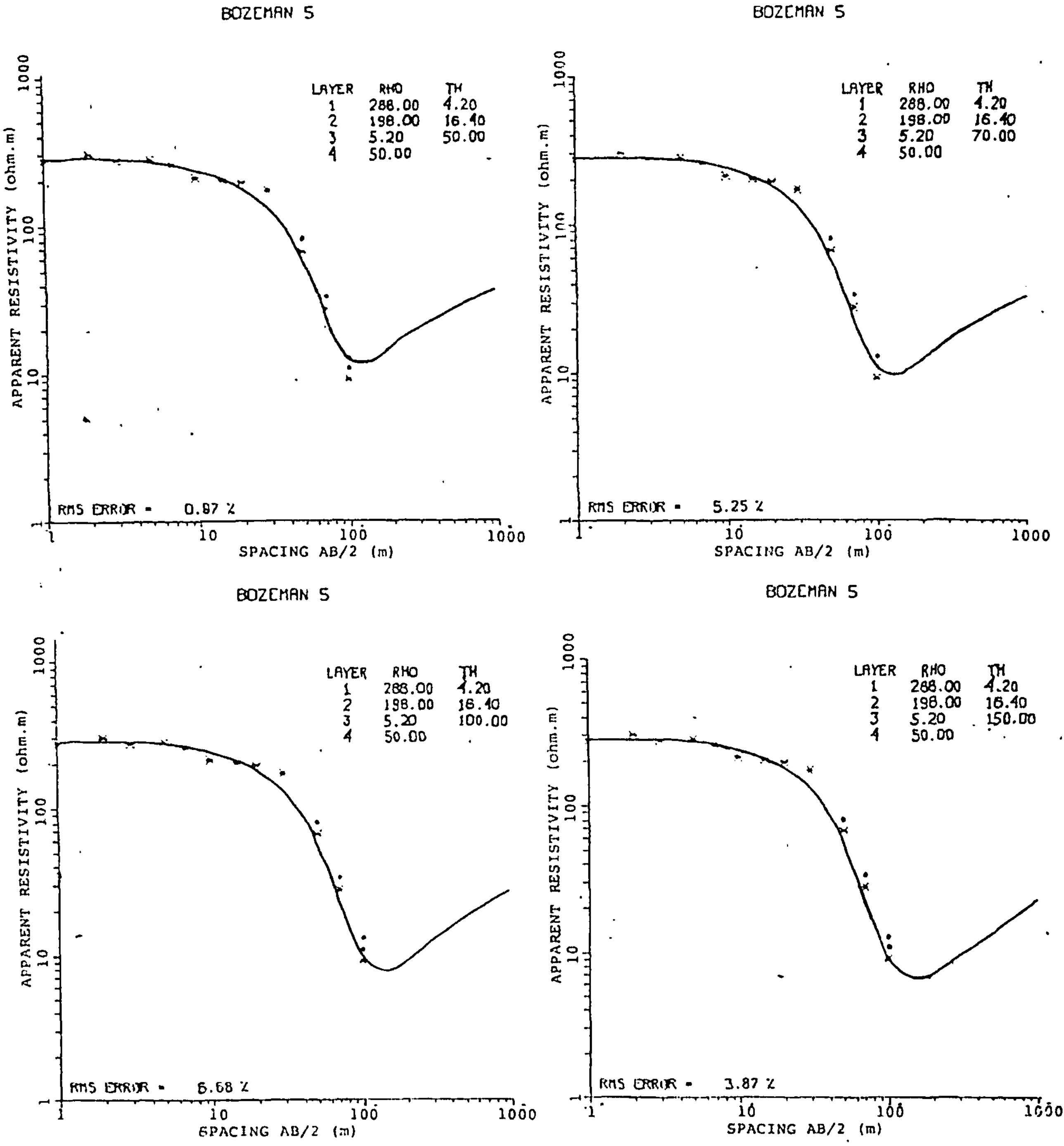


Figure 14. Sounding Curves for Station 5, Illustrating Estimation of Thickness of The Conductive Zone, If Resistivity of 50.0 ohm.m is Assigned to Its Underlying Interval.

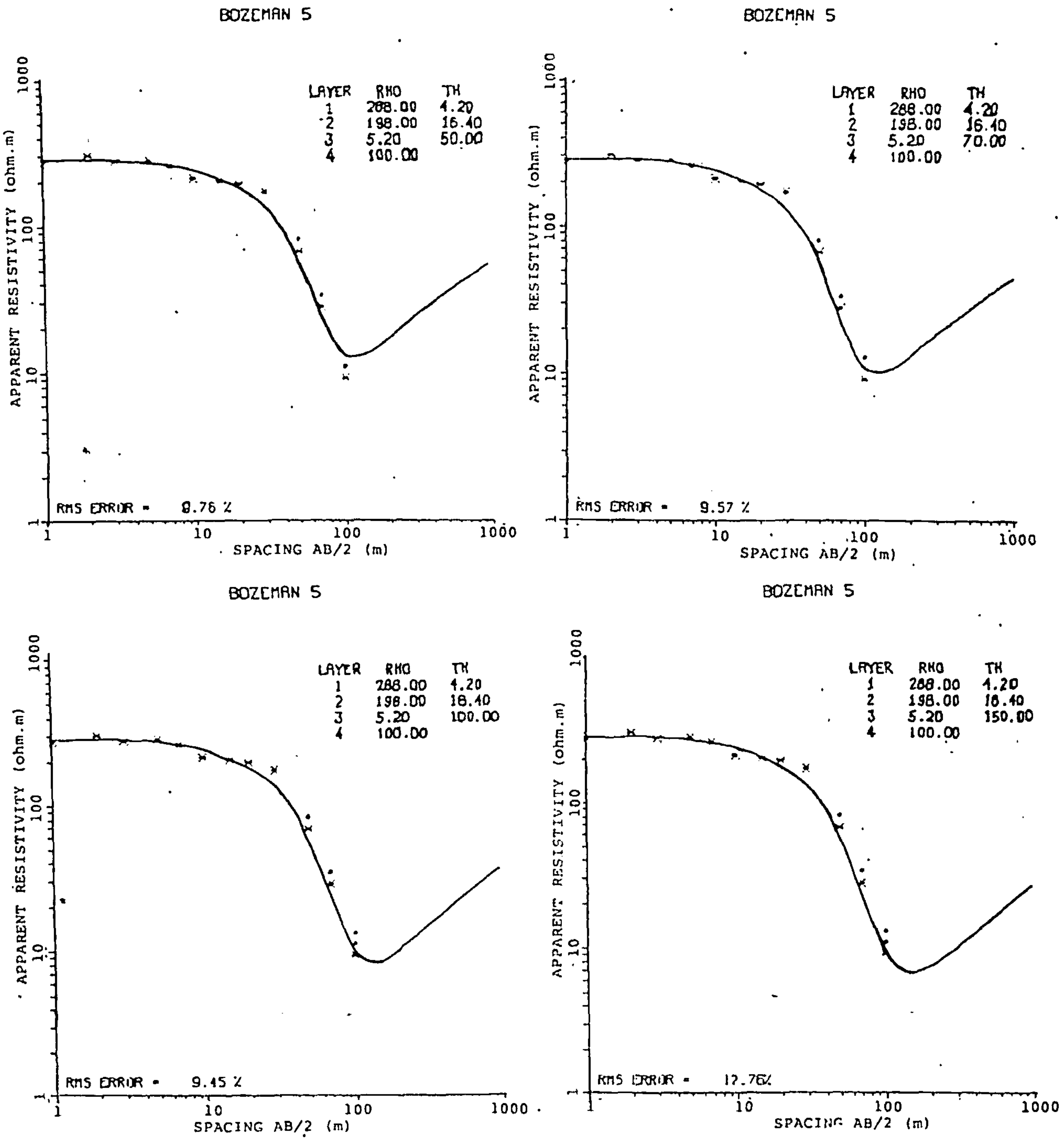


Figure 15. Sounding Curves for Station 5, Illustrating Estimation of Thickness of The Conductive Zone, If Resistivity of 100.0 ohm.m is Assigned to Its Underlying Interval.

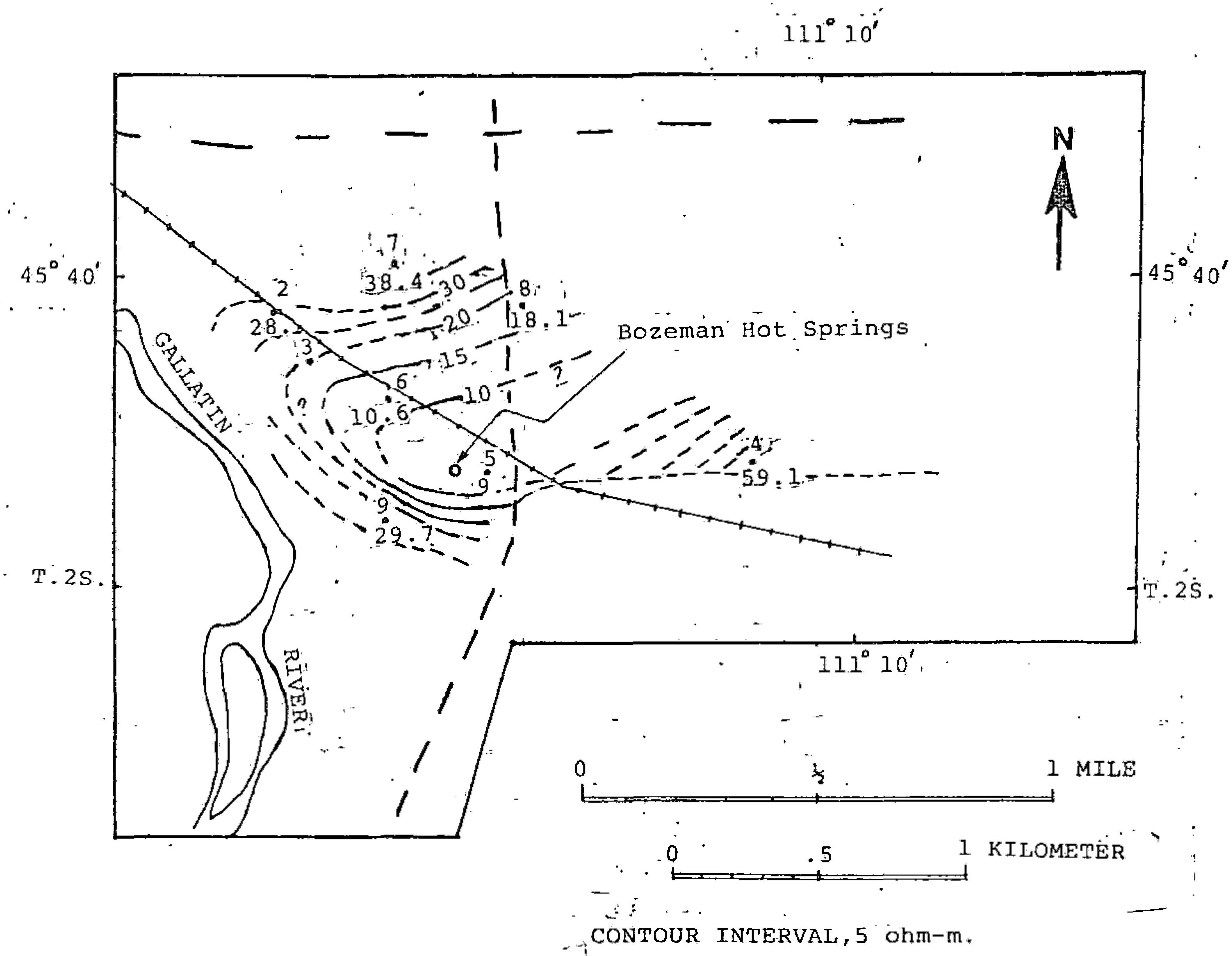


Figure 16. Apparent Geoelectric Plan, AB/2=100 m.

TABLE 2
THICKNESS ESTIMATION RESULTS FOR BOZEMAN 5

Layer (m)	Resistivity (ohm-m)	Thickness (m)	Estimated thickness of conductive interval, (m)	RMS error (%)
1	288	4.2		
2	198	16.4		
3	5.2	50-70	50-70	.77
4	10.0			
1	288	4.2		
2	198	16.4		
3	5.2	70-100	70-100	.74-4
(3	5.2	80)	80	.73
4	30.0			
1	288	4.2		
2	198	16.4		
3	5.2	70-100	70-100	3-7
4	50.0			
1	288	4.2		
2	198	16.4		
3	5.2	70-100	70-100	9-13
4	100			

(iv) Geoelectric sections. Figure 17 shows a geoelectric section constructed from sounding station BOZ 2 through BOZ 6 and BOZ 5 to BOZ 4 (Figure 2) using apparent smoothed observed data. Contours at the 10 ohm-m interval, below a depth of approximately 50 m, tend to rise to sounding station BOZ 5 from both sides, probably indicating that a low resistivity zone at the hot springs area is closer to the surface at sounding station BOZ 5 than at the rest of the sounding stations. Generally, resistivities decrease with depth, whereby, the first near-surface interval of approximately 20 m is more resistive than the underlying interval.

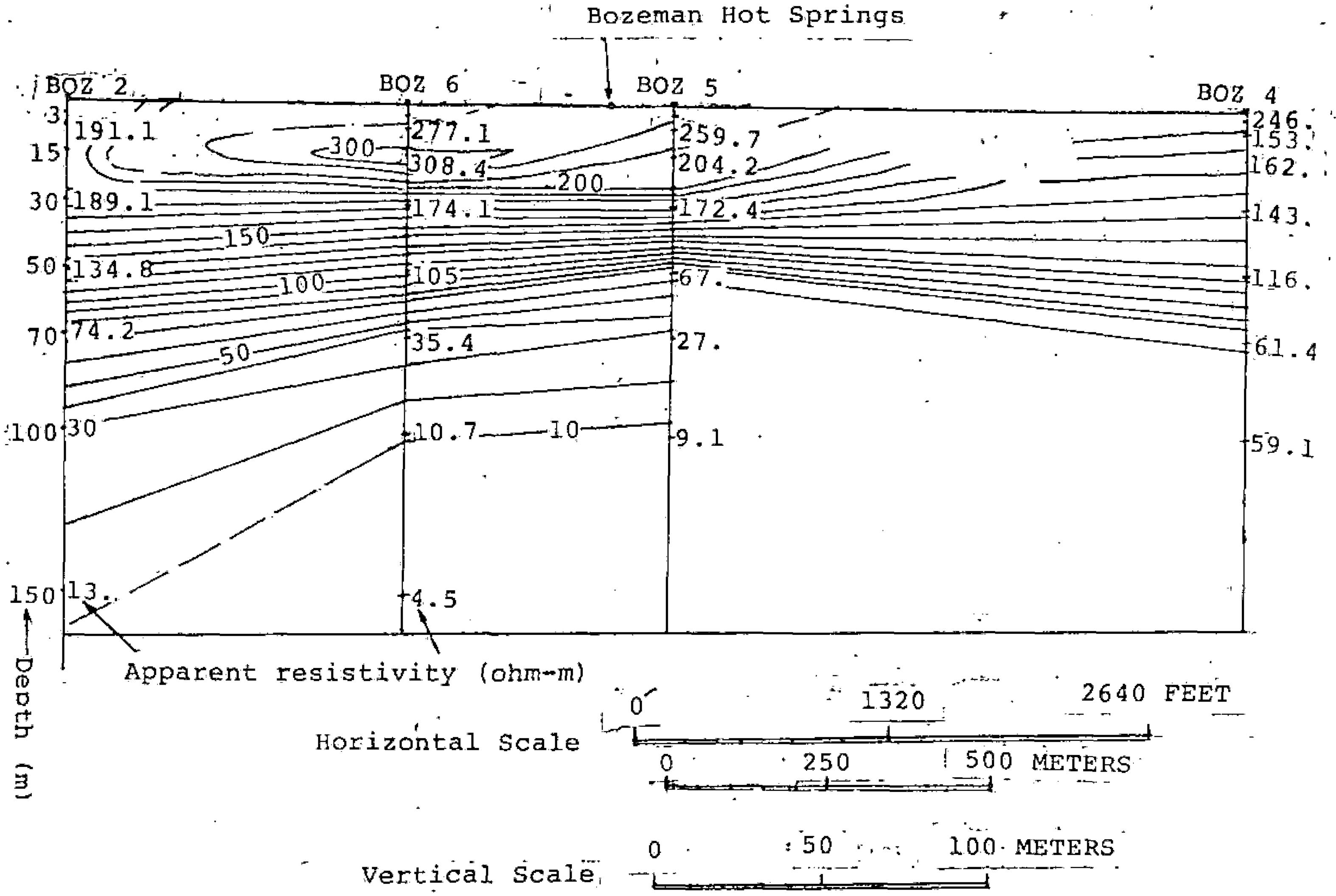


Figure 17. Apparent Geoelectric Section Across Stations 2, 6, 5 and 4.

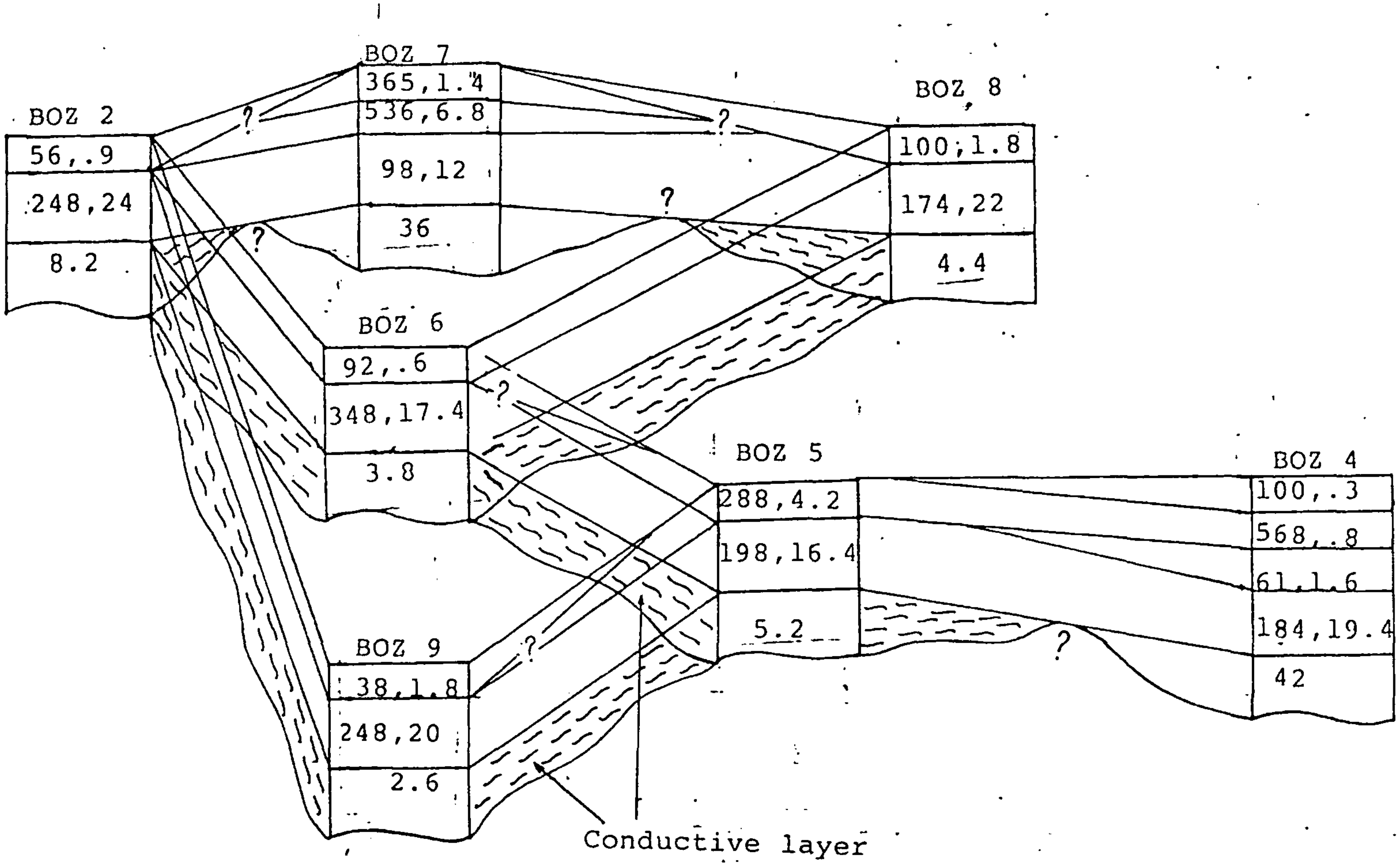
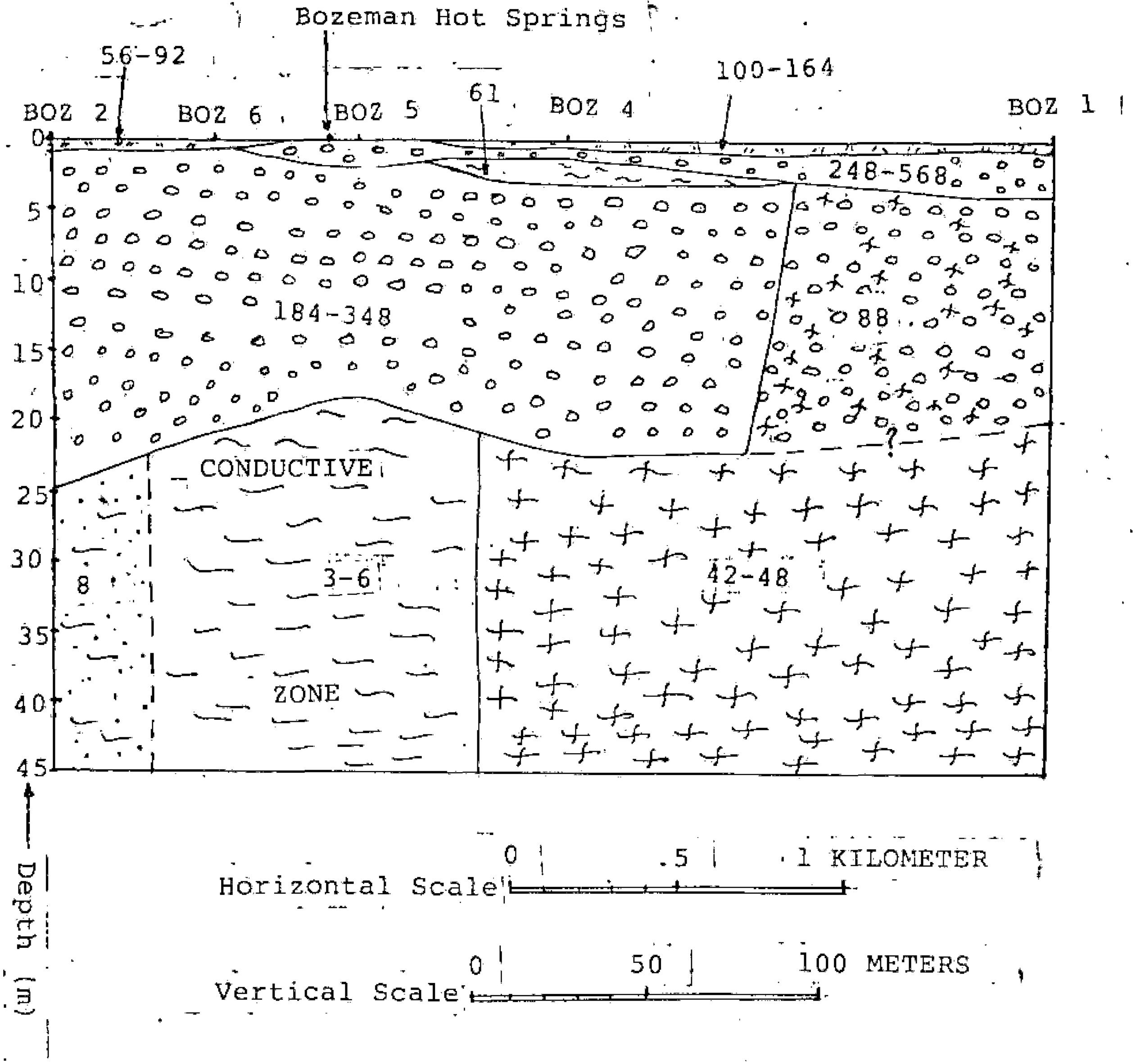


Figure 18. Schematic Diagram of Geoelectric Sections Around The Conductive Zone.



3-6 Interpreted Resistivities (ohm.m)

Figure 19. Geoelectric Section Across Stations 2, 6, 5,4 and 1.

Figures 18 and 19, constructed using interpreted resistivity and thickness values, show that the conductive zone around the hot springs site is approximately 22.0 m below the surface and is overlain by a resistive near-surface material. Figure 19 shows further, that the conductive zone (3-6 ohm-m) is flanked on the east, about halfway between sounding stations BOZ 5 and BOZ 4, by a relatively high resistive zone (42-48 ohm-m) and on the west by an intermediate resistive zone (8 ohm-m). The conductive zone and its two flanking zones are overlain by a more resistive zone of 88-348 ohm-m. A small lense-like body (less-resistive of 61 ohm-m and of 1.6 m thickness) is shown around sounding BOZ 4 below a surface layer (100-568 ohm-m.), wedging both eastward and westward.

C. WHITE SULPHUR HOT SPRINGS

(i) Sounding curves. A total of 14 sounding curves are shown for the White Sulphur Springs area (Figure 3). Two east-west soundings, WSS 8 and WSS 12 were surveyed at the hot springs site, with WSS 8 to the north-east of WSS 12. Of the remaining soundings, soundings WSS 1, WSS 4, WSS 5, WSS 6 and WSS 14, are closest to the hot springs, with their centers about half a kilometer away. The farthest soundings from the hot springs include WSS 11, WSS 2, WSS 3, WSS 10, WSS 13 and WSS 9. Based on their location with respect to the hot springs and on their apparent correlation of interpreted, subsurface parameters, four groups (WSS 2, 7, 10, 11, 13; WSS 3, 14, 9; WSS 1, 4, 5, 6; and WSS 8, 12 are described below.

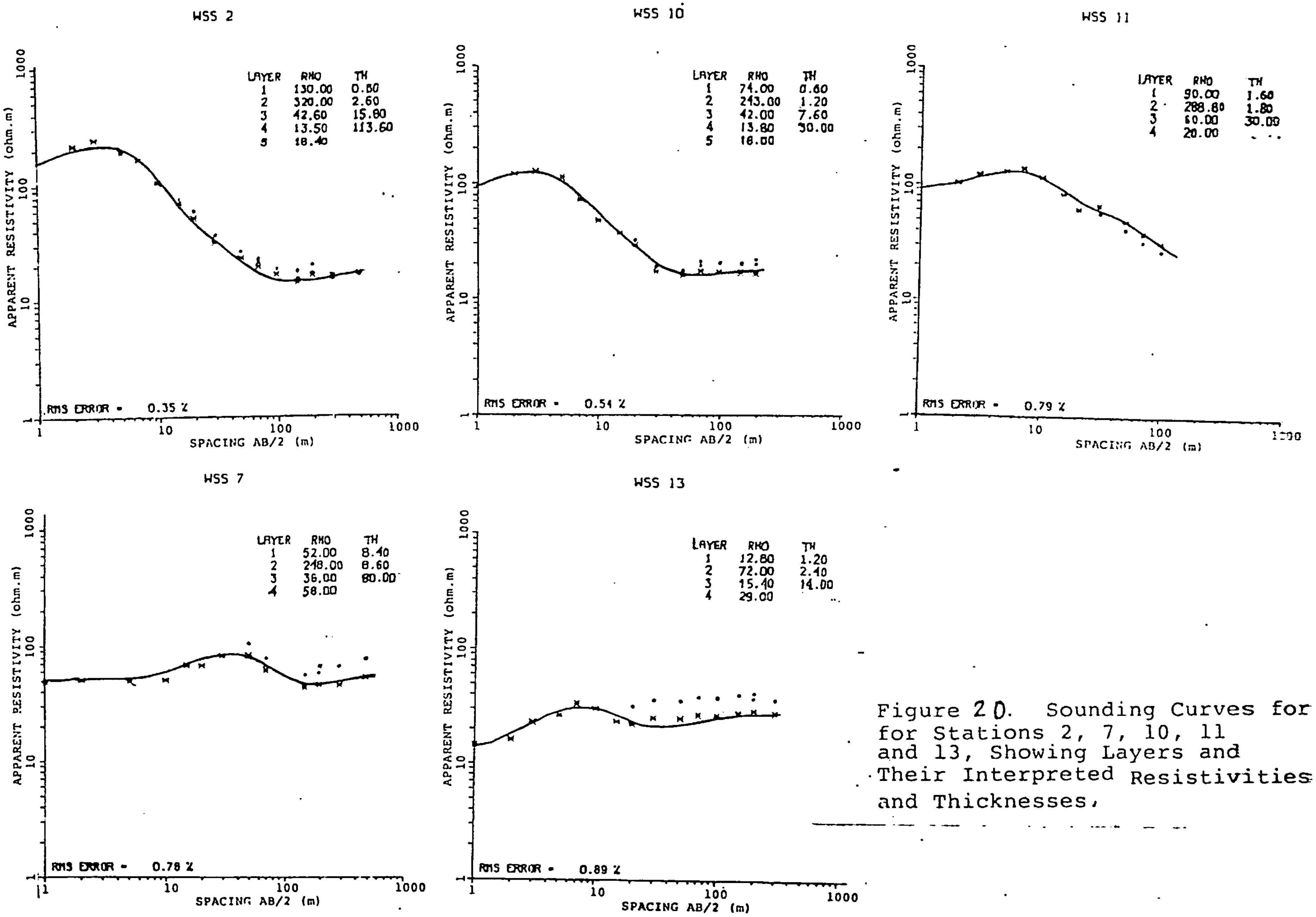


Figure 20. Sounding Curves for for Stations 2, 7, 10, 11 and 13, Showing Layers and Their Interpreted Resistivities and Thicknesses.

Relatively high resistivities of more than 10 ohm-m, show relatively resistive subsurface materials at stations WSS 2, 7, 10, 11 and 13 (Figure 20 and 3), away from the hot springs.

Soundings, (WSS 1, 4, 5, and 6, Figures 21 and 3) show relatively less resistive layers below the slightly resistive surface layer. Three such layers have been mapped at WSS 1, where from top to bottom, the resistivities are 5.2 ohm-m, 8.0 ohm-m and 3.0 ohm-m and the thicknesses are 6.0 m and 22.5 m.

Relatively resistive surface material with resistivity of 12-38 ohm-m, at WSS 4, WSS 5, WSS 6, and WSS 1, is underlain by two less resistive layers, which from the top have resistivities respectively of 8.8 ohm-m and 3.0 ohm-m (WSS 4), 6.8 ohm-m and 2.8 ohm-m (WSS 5), and 6.4 ohm-m and 3.0 ohm-m (WSS 6). Of the two layers, the top layer has a thickness of 16.0 m (WSS 4), 28.0 m (WSS 5) and 18.0 m (WSS 6),and the bottom one is of an indeterminate thickness. Sounding curve WSS 5 shows in addition, a low resistive surface material of 5.6 ohm-m and 1.1 m thickness overlying a slightly resistive layer of 25.0 ohm-m. Low resitivities indicate conductive materials existing southwest of the hot springs.

Although close to each other, soundings WSS 12 and WSS 8, surveyed at the hot springs site, show apparently different subsurface resistivities (Figures 22 and 3). A surface layer at WSS 12 of 132.6 ohm-m resistivity and 0.51 m thickness, is more resistive and thinner than a similar surface layer mapped at WSS 8. At WSS 8, the surface layer possibly consists of two layers of which the top layer of 6.8 ohm-m resistivity is less resistive than the succeeding layer of 30.0

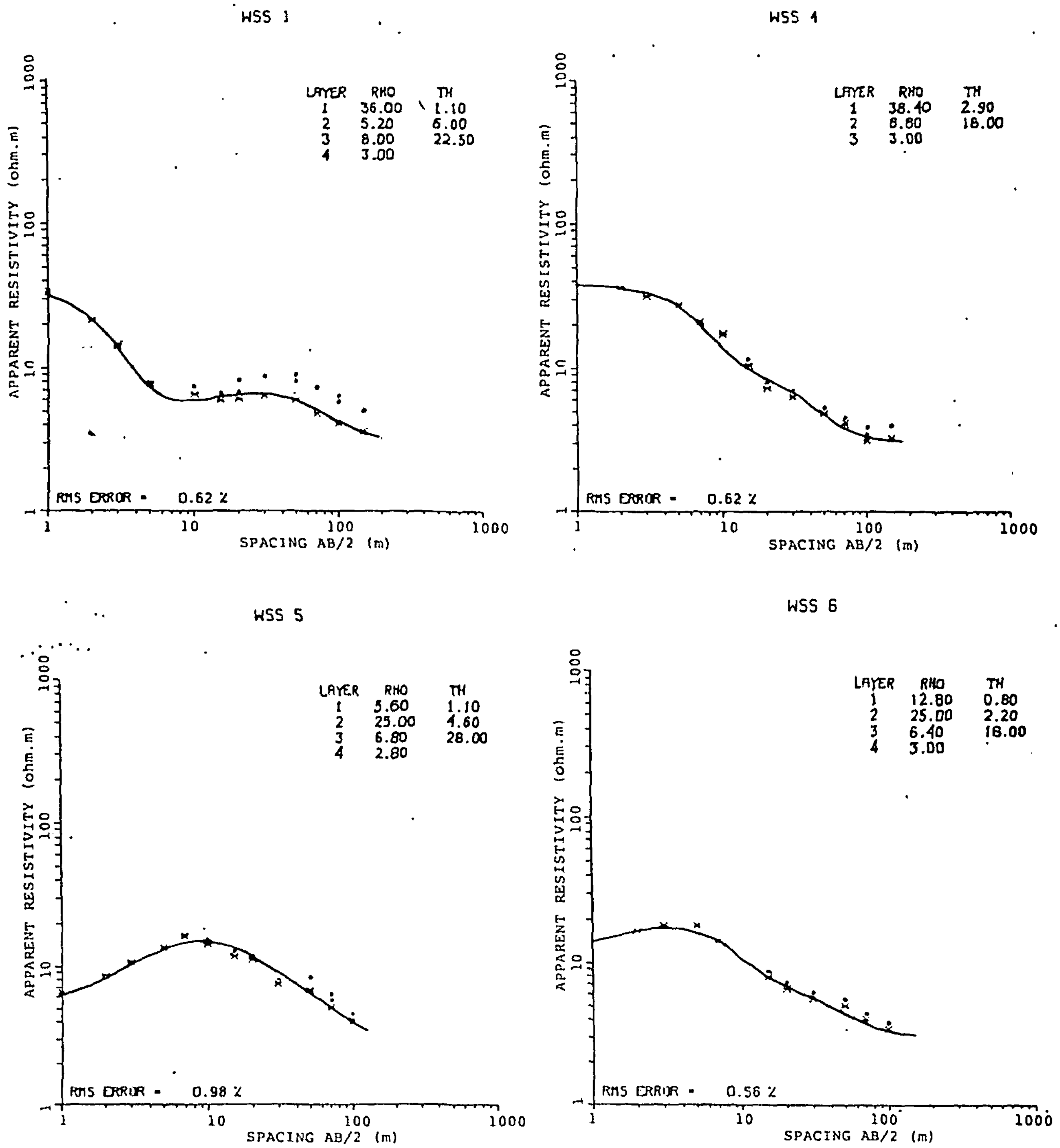


Figure 21. Sounding Curves for Stations 1, 4, 5 and 6 Showing Layers and Interpreted Resistivities and Thicknesses.

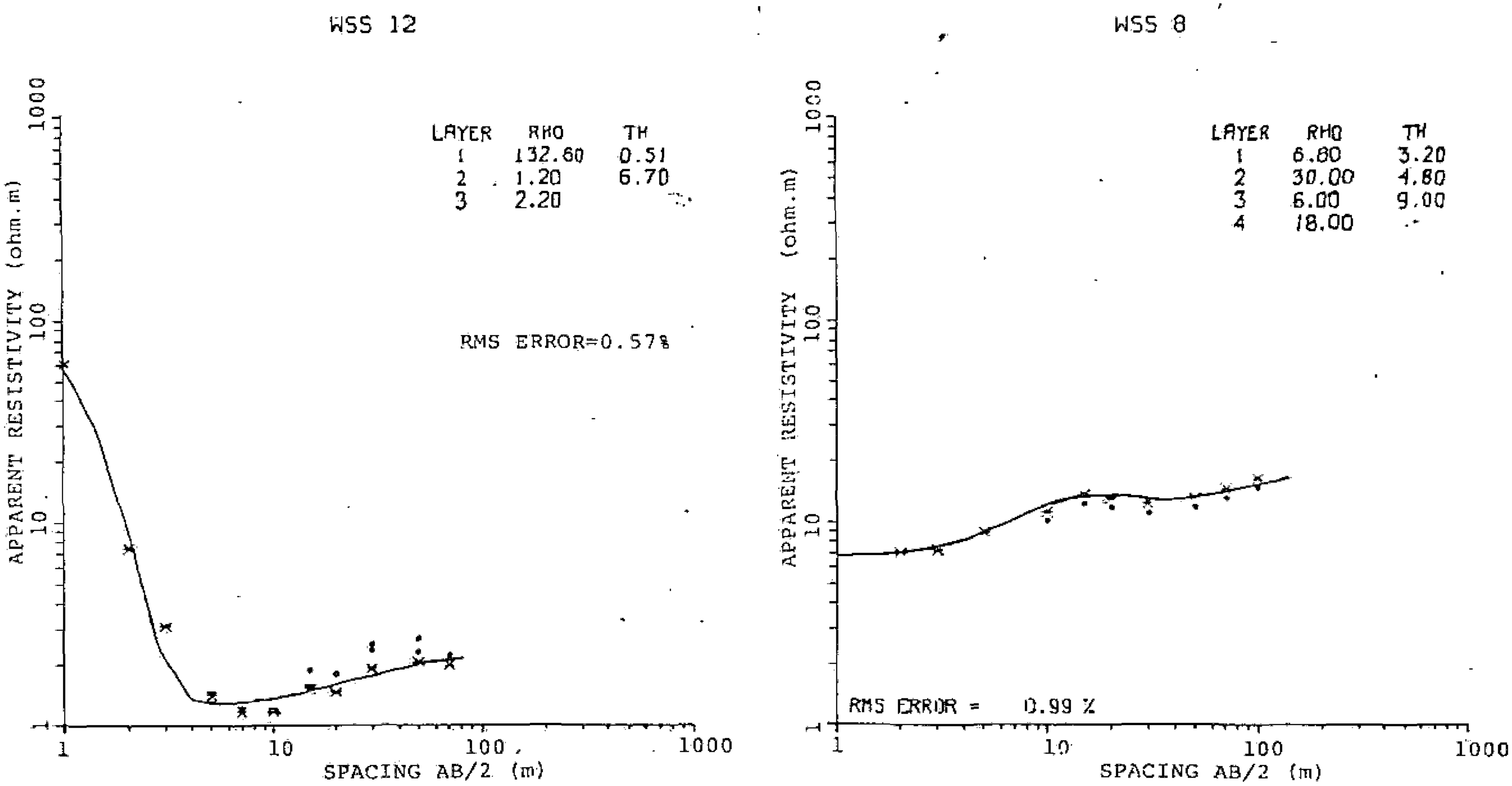


Figure 22. Sounding Curves for Stations 12 and 8, Showing Layers and Their Interpreted Resistivities and Thicknesses.

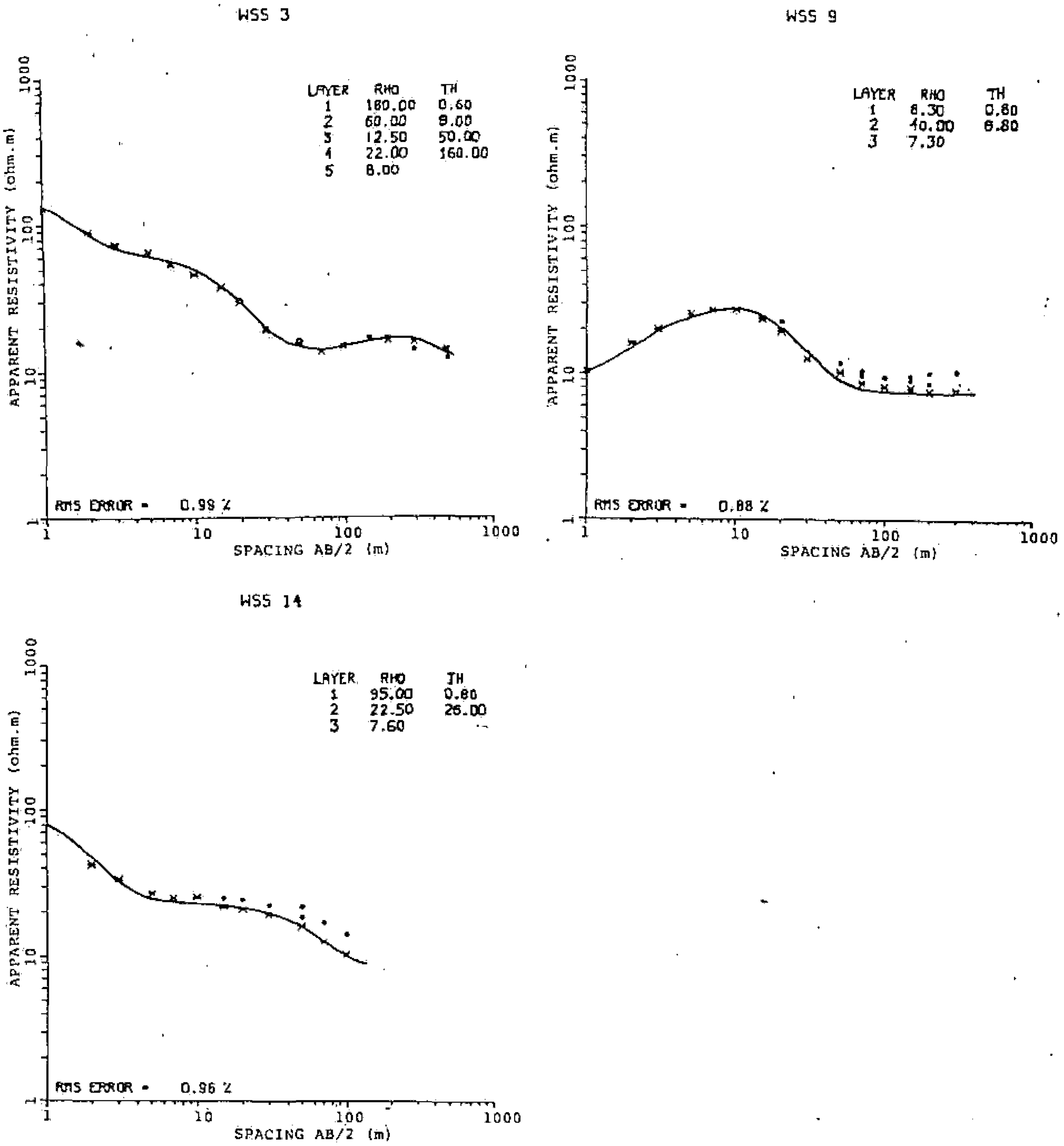


Figure 23. Sounding Curves for Stations 3, 9 and 14, Showing Layers and Their Interpreted Resistivities and Thicknesses.

ohm-m resistivity. The 6.8 ohm-m resistivity surface layer of 3.2 m thickness (WSS 8) is tentatively correlated with conductive layer 2 (WSS 12), which is of 1.2 ohm-m resistivity. Sounding WSS 8 shows a conductive layer 3 of 6.0 ohm-m resistivity and 9 m thickness, between relatively resistive layer 2 (30.0 ohm-m resistivity and 8.0 thickness) and the underlying, last layer 4 (18 ohm-m resistivity). Great difference in resistivities and their distribution with depth between soundings WSS 12 and WSS 8, in spite of their closeness to each other, suggests that they were surveyed on two geologically different environments. The subsurface material at WSS 8 are substantially less conductive than at WSS 12. Such a discontinuous distribution of resistivities may have been caused by a northwest-southeast inferred fault (Gierke, 1982) hosting the White Sulphur Hot Springs (Figure 3). If the fault exists at the hot springs, then sounding WSS 12 is on the western block and WSS 8 is on the eastern block.

Relatively low resistivities of 8, 7.3 and 7.6 ohm-m at sounding stations WSS 3, 9 and 14 (Figure 23), indicate existence of conductive layer in their subsurface, at the respective depths of 218.6, 7.6 and 26.8 m below the surface.

Maximum spacings AB/2, which in a homogeneous and isotropic medium correspond to maximum theoretical penetration depths, and the total observed thicknesses of mapped layers, are summerised in Table 3 for all soundings.

TABLE 3
MAXIMUM SPACINGS AB/2 AND DEPTH TO LAST MAPPED LAYER.

Sounding curve	Maximum spacing AB/2 or Maximum theoretical penetration depth (m)	Depth to last mapped layer (m)
WSS 2	500	132.6
WSS 7	500	97.0
WSS 10	200	39.4
WSS 11	100	33.4
WSS 13	300	17.6
WSS 1	150	29.6
WSS 4	150	18.9
WSS 5	100	33.7
WSS 6	100	21.0
WSS 8	100	17.0
WSS 12	70	9.2
WSS 3	500	218.0
WSS 9	300	7.6
WSS 14	100	26.8

(ii) Thickness Estimation. Estimation of thickness of the conductive zone is illustrated for sounding curve WSS 5, with an assumption that the conductive zone is underlain by a relatively more resistive interval. Procedures employed here are exactly the same as those used for estimating the thickness of the conductive zone at Bozeman Hot Springs. A fifth layer underlying the conductive zone, is added to the four layers previously intepreted. Three resistivities

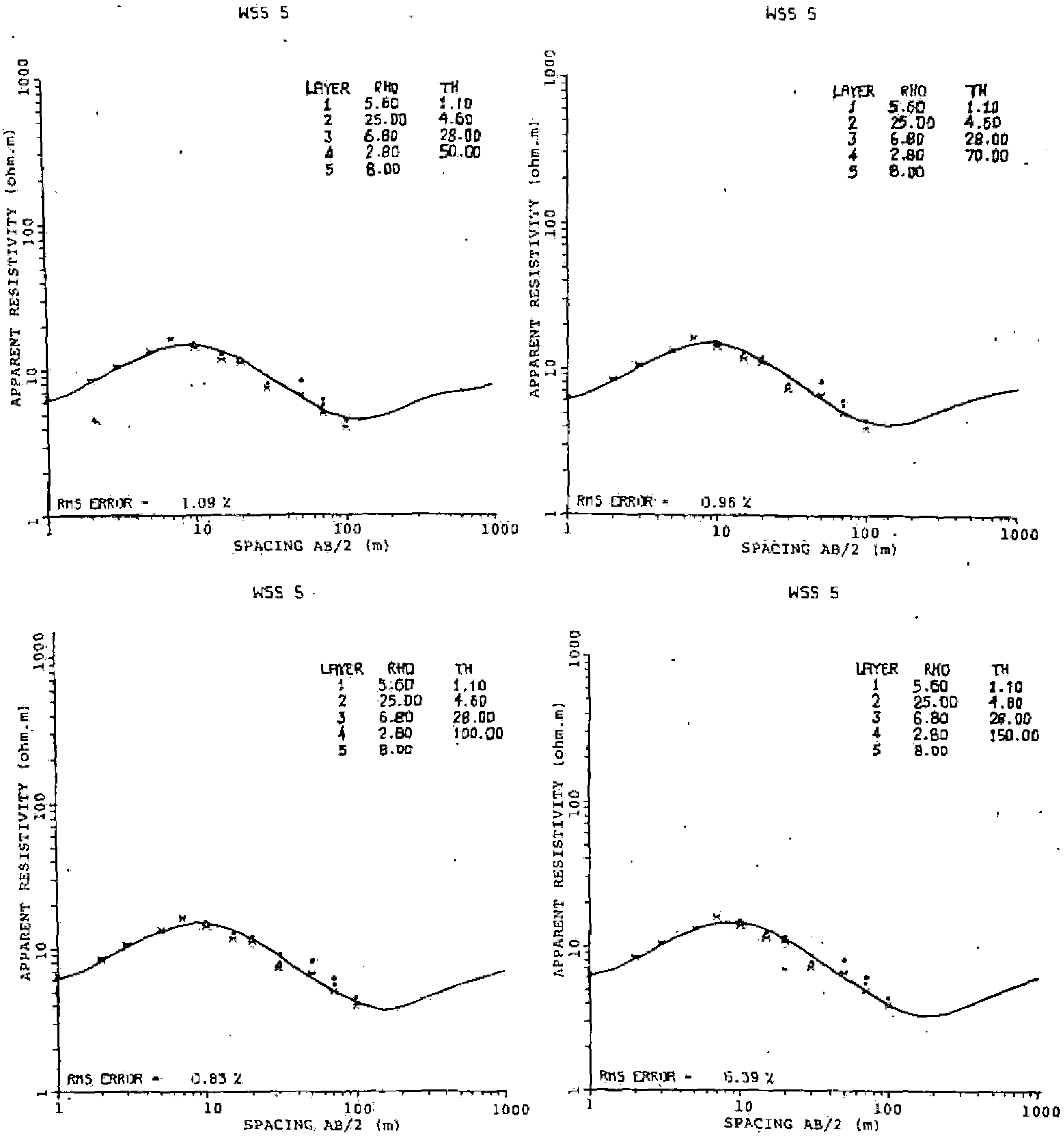


Figure 24. Sounding Curves for Station 5, Illustrating Estimation of Thickness of The Conductive Zone, If Resistivity of 8.0 ohm.m is Assigned to Its Underlying Interval.

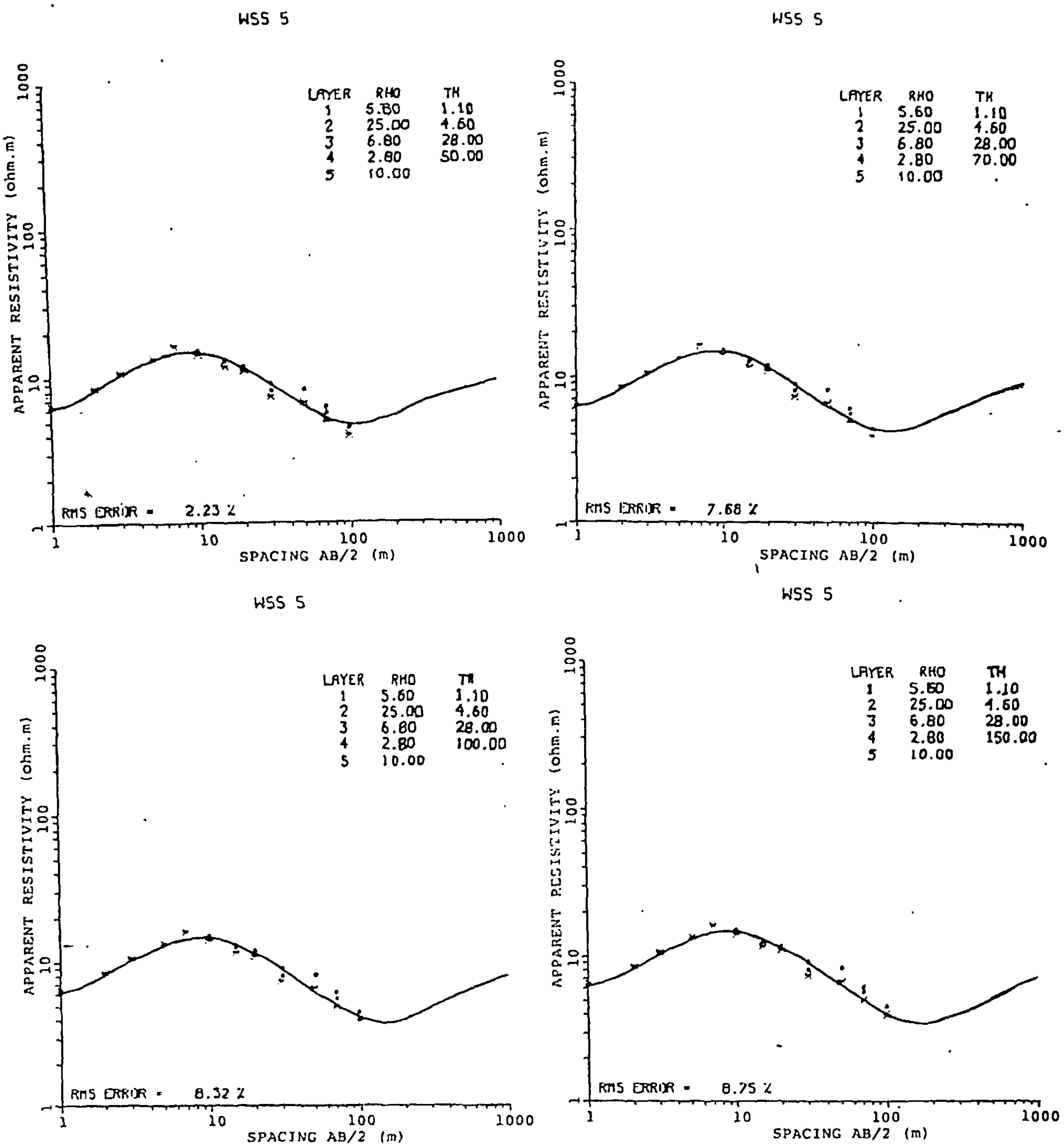


Figure 25. Sounding Curves for Station 5, Illustrating Estimation of Thickness of The Conductive Zone, If Resistivity of 10.0 ohm.m is Assigned to Its Underlying Interval.

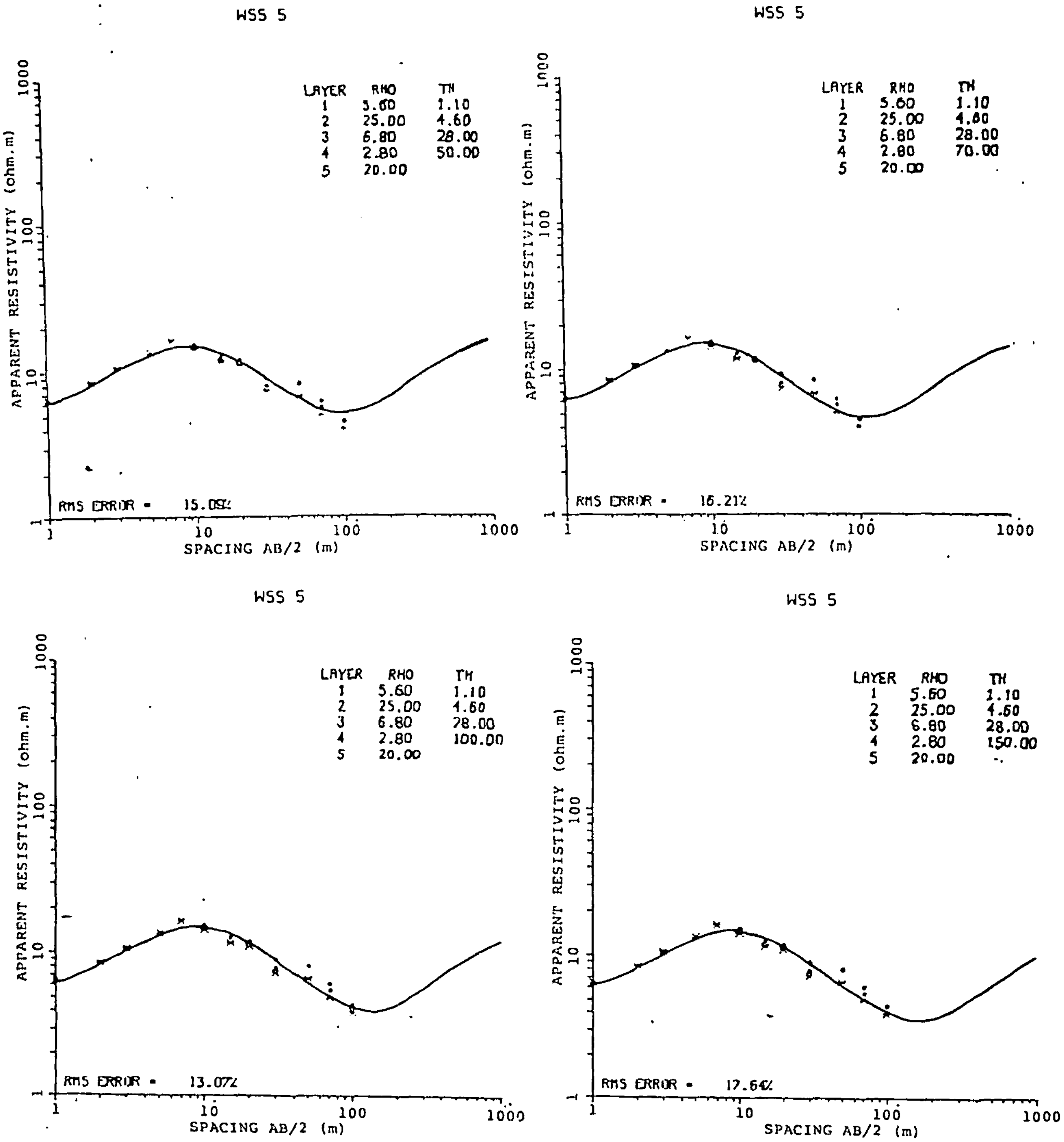


Figure 26. Sounding Curves for Station 5, Illustrating Estimation of Thickness of The Conductive Zone, If Resistivity of 20.0 ohm.m is Assigned to Its Underlying Interval.

of 8, 10 and 20 ohm-m are assigned to this fifth layer. These are chosen based on the assumption that materials of the conductive zone and the underlying interval are almost of the same composition as shown by the geologic log report and temperature logs of the Bank of White Sulphur Springs geothermal well (Dunn, 1978). All assigned resistivities show the conductive zone may be 100-150 m thick at minimum (see Figure 24-26 and Table 4). Taking into consideration the maximum theoretical penetration depth of 100 m for maximum spacing AB/2 = 100 m of sounding WSS 5, 100 m for minimum thickness of the conductive zone, may be a good approximation. Resistivity of the underlying interval probably is 8 ohm-m, as indicated by low RMS error of 0.96%. With 100 m thickness of the conductive zone, a total depth of approximately 130 m may have been mapped by sounding WSS 5. Materials, at such depths, are shown by the geologic log (Figure 6) to be basin fill clays, hence, a resistivity of approximately 8 ohm-m may be appropriate for the interval underlying the conductive zone.

TABLE 4
CONDUCTIVE ZONE THICKNESS ESTIMATION RESULTS FOR WSS 5.

Layer (m)	Resistivity (ohm-m)	Thickness (m)	Possible Thickness of conductive interval (m)	RMS error (%)
1	5.6	1.1		
2	25.0	4.6		
3	6.8	28.0		
4	2.8	100-150	100-150	.96-.83
5	8.0			
1	5.6	1.1		
2	25.0	4.6		
3	6.8	28.0		
4	2.8	100-150	100-150	7-8
5	10.0			
1	5.6	1.1		
2	25.0	4.6		
3	6.8	28.0		
4	2.8	100-150	100-150	16-13

(iii) Geoelectric sections. Figures 27 and 28 show that the mapped conductive zone is composed of two layers, at WSS 4, 6, 12, and WSS 8, whereas, it consists of 3 layers at sounding stations WSS 1 and possibly WSS 5. Sounding stations WSS 14 and 9 have then mapped the conductive layer of 7.6 and 7.3 ohm-m resistivity, probably corresponding to layer 2 of WSS 4 with resistivity of 8.8 ohm-m and to layer 3 of WSS 5, WSS 1, WSS 6, and WSS 12 with respective resistivities of 6.8, 8.0, and 2.2 ohm-m. The conductive zone is covered by a thin soil layer at stations WSS 1 and WSS 12, while at stations WSS 5 and WSS 8 it is at the surface. It is vertically flanked by relatively resistive zones of 13 ohm-m, and 18-30 ohm-m to the southwest and southeast respectively. Figure 28 shows further, possible existence of a conductive zone southeast of the main one mapped at the hot springs.

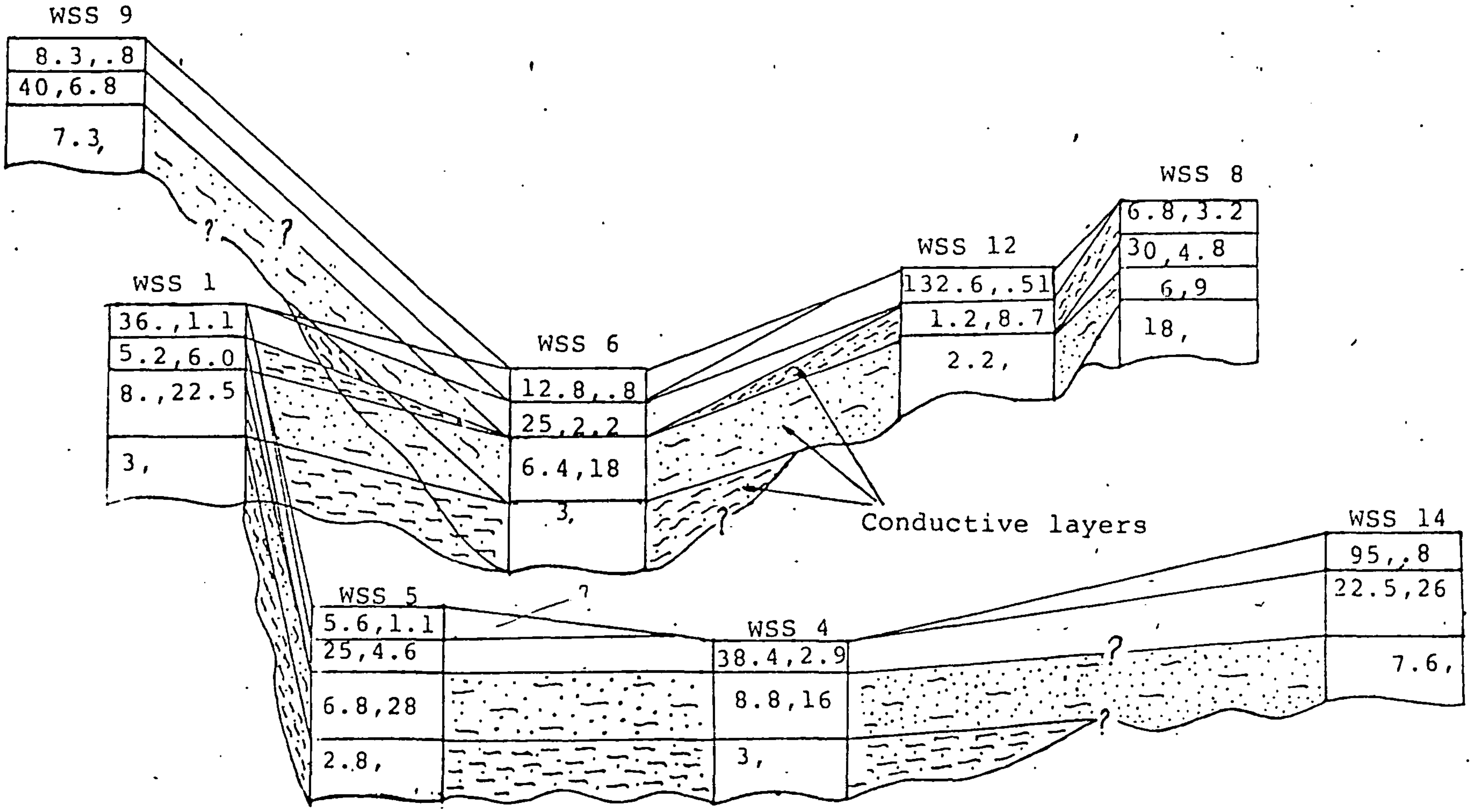


Figure 27. Schematic Diagram of Geoelectric Sections Around The Conductive Zone.

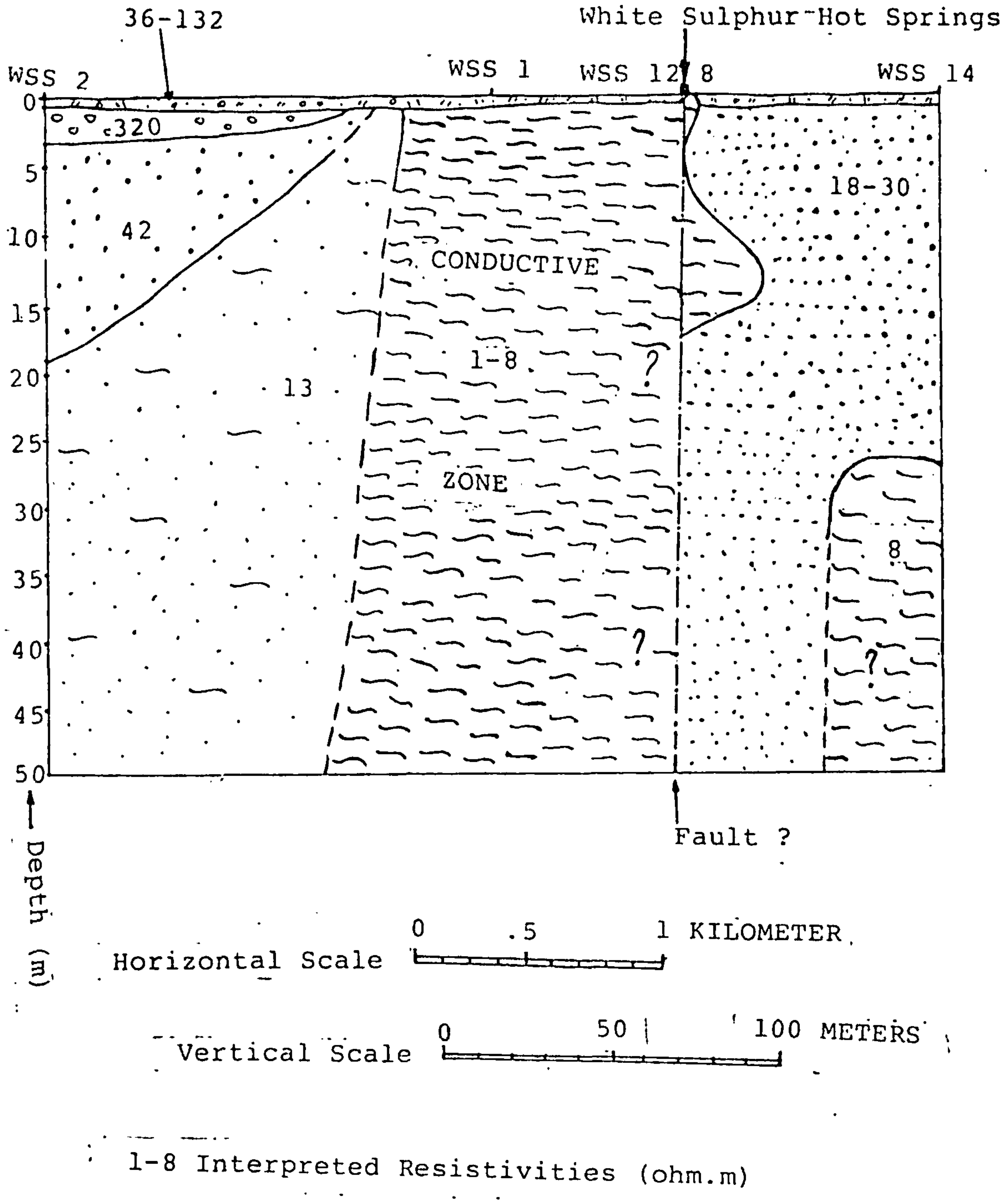


Figure 28. Geoelectric Section Across Stations 2, 1, 12, 8 and 14.

V. CONCLUSIONS

A. BOZEMAN HOT SPRINGS

(1) Sounding curves BOZ 5, BOZ 6, BOZ 8 and BOZ 9 map a conductive zone at depths of approximately 20 m below the surface near the hot springs.

(2) Resistivities similar to those expected for ground water saturated valley fill material have been shown by soundings BOZ 1, BOZ 4 and BOZ 7 at depths of approximately 20 m below the surface and away from the hot springs.

(3) Sounding BOZ 2 shows a conductive zone at a depth of approximately 24 m, which may be northwestern extension of conductive zone mapped near the hot springs.

(4) The conductive zone may be associated with waters of the geothermal system existing close to the hot springs, while the relatively nonconductive zone may be associated with normal ground water saturated basin fill sediments.

B. WHITE SULPHUR SPRINGS

(1) conductive zones are mapped by soundings WSS 12 and WSS 8 at the hot springs, by soundings WSS 1, WSS 4, WSS 5 and WSS 6 southwest of the hot springs, and by soundings WSS 3, WSS 9 and WSS 14, away from the hot springs.

(2) If the conductive zones are a result of geothermal waters, then the geothermal system at stations WSS 3 and WSS 9 may be southwestern and northwestern extensions of the system near the hot springs, while that at station WSS 14 may be a separate one.

(3) Lack of apparent correlation between soundings WSS 8 and WSS 12, closest to the hot springs site, suggests that soundings WSS 12 and WSS 8 were surveyed in geologically different environments. Sounding WSS 12 possibly was surveyed in intensely geothermally altered basin fill sediments, while WSS 8 was surveyed in slightly less intensely geothermally altered basin fill sediments.

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~~D. R. Cole~~

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Duplicate

Reversible control of aqueous aluminum and silica during the irreversible evolution of natural waters

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Abstract—Primary aluminosilicates are transformed at low temperature into a sequence of metastable and thermodynamically stable secondary minerals by an irreversible process. The aqueous concentrations in the associated solution may continuously change during the process or they may be maintained constant through hydrodynamic or chemical steady-state mechanisms or through chemical equilibrium with a reversible metastable solid.

Disequilibrium indices calculated for 152 natural waters and experimental solutions show that the solutions are unsaturated with amorphous aluminum hydroxide, microcrystalline gibbsite, amorphous silica and amorphous aluminosilicate, and they are supersaturated with gibbsite and kaolinite. The disequilibrium index for halloysite varies widely from unsaturation to supersaturation.

Only the index for the reversible metastable cryptocrystalline aluminosilicate whose composition is pH dependent is very close to zero indicating saturation. The index varies in a narrow range. This, supported by electron micrographs and the results of X-ray fluorescence spectroscopy presented by other authors, suggests that this metastable solid, and not the secondary aluminosilicate minerals, controls the concentrations of alumina and silica in natural waters.

INTRODUCTION

IT HAS BEEN PROPOSED that the concentrations of dissolved alumina and silica in natural waters are controlled by partial equilibria between solution and clay minerals and/or gibbsite (e.g. HELGESON, 1968; HELGESON *et al.*, 1969; FRITZ and TARDY, 1974, 1976; FRITZ, 1975; MICHARD and FOUILLAC, 1974; FOUILLAC *et al.*, 1977) or by equilibrium between solution and halloysite and/or microcrystalline gibbsite (HEM *et al.*, 1973). However, when the compositions of cold natural waters are compared with their calculated equilibrium compositions with respect to the minerals, significant departures from the equilibria are apparent (PAČES, 1970, 1972, 1973). Another possible controlling mechanism may be the adsorption of dissolved silica and aluminum on silica or silicate surfaces (BECKWITH and REEVE, 1963; MCKEAGUE and CLINE, 1963; STÖBER, 1967; ILER, 1973). However, the adsorption of aluminum is probably not very effective in controlling the aqueous concentration because of the high affinity of hydroxyl ions towards Al^{3+} ion and a rapid polymerization to form hydroxocomplexes (SMITH and HEM, 1972). While both the equilibrium with respect to well defined minerals and adsorption operate in Al_2O_3–SiO_2–H_2O system under favorable conditions, it is proposed here, that a reversible equilibrium between solution and a metastable cryptocrystalline aluminosilicate of varied composition explains best the observed concentration of alumina and silica in natural waters at low temperatures (0–25°C). This reversible mechanism operates during the irreversible dissolution of primary minerals and the irreversible formation of thermodynamically stable secondary minerals. The secondary minerals may have reached different stages of crystallinity (PETROVIC 1976, Fig. 1) and morphology (HENMI and WADA, 1976). The experimental studies of the effect of adsorbed aluminum on the solubility of amorphous silica in water (ILER, 1973) supports the hypothesis that silica and aluminum in solution combine to form a metastable aluminosilicate that is less soluble than either oxide alone. This solid behaves reversibly. Part of the aluminum and silicon are removed from solution irreversibility, because they are fixed in newly formed minerals.

THEORY

An example of a typical irreversible process at low temperatures, such as rock weathering, is illustrated in Fig. 1. During this process a primary mineral whose mass in moles is M_p dissolves and M_r moles of a reversible metastable mineraloid, M_{ir} moles of an irreversible metastable secondary mineral and M_s moles of a thermodynamically stable secondary mineral are produced. The portions of the chemical components remaining in the water are m_i, $m_j \ldots m_n$. The total irreversible process consists of a sequence of reactions whose rate constants are $k_1 \ldots k_6$. In general, the molarities in solution change during the irreversible process in which $dM_p/dt < 0$ and $dM_s/dt > 0$. However, concentrations of some components can be maintained constant due to a hydrodynamic steady state, chemical steady state and chemical thermodynamic equilibrium.

Let us consider a general sequence of reactions in Fig. 1. The rates of the reactions are controlled by

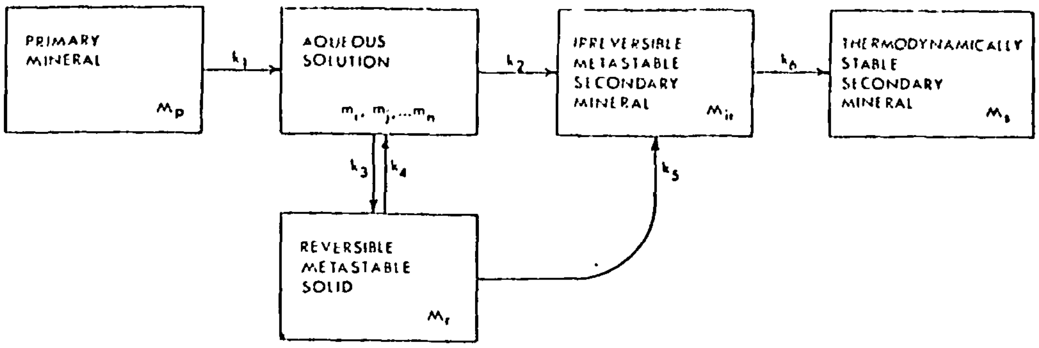

Fig. 1. Irreversible transformation of a primary mineral into secondary minerals and the position of a reversible metastable solid in a natural water system. M_p, M_r, M_{ir}, M_s are the extensive masses of the primary mineral and the reversible, irreversible metastable and thermodynamically stable secondary phases respectively. m_i, m_j, m_n are molarities of participating chemical components in aqueous solution.

the concentrations in solution. Their kinetic orders with respect to a dissolved species i are $\alpha_{1,i} \ldots \alpha_{4,i}$.

The general rate law of reaction r with respect to the aqueous species i is

$$R_{r,i} = \left(\frac{\mathrm{d}m_i}{\mathrm{d}t}\right)_r = k_r \prod_{j=1,i}^{n} m_j^{\alpha_{r,j}} \qquad (1)$$

where $j = 1, 2 \ldots i \ldots n$ includes all the aqueous species participating in the reaction r.

The hydrodynamic steady state is defined by the condition

$$\frac{\partial m_i}{\partial t} = 0 = R_{1,i} + R_{4,i} - R_{2,i} - R_{3,i} - \nabla v m_i. \qquad (2)$$

The hydrodynamic dispersion and diffusion are neglected in eq. (2), v is the mean linear velocity of water in the x, y and z directions and ∇ is space-gradient operator

$$\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}.$$

The chemical steady state is maintained under the following conditions

$$v = 0 \qquad (3)$$

$$\frac{\mathrm{d}m_i}{\mathrm{d}t} = 0 = R_{1,i} - R_{2,i} \qquad (4)$$

and

$$R_{4,i} > R_{3,i} \qquad (5)$$

or

$$R_{4,i} < R_{3,i} \text{ and } R_{5,i} > R_{3,i} - R_{4,i} \qquad (6)$$

so that

$$M_r = 0. \qquad (7)$$

The equilibrium concentration of a component i in solution is maintained under the following conditions

$$R_{1,i} \ll R_{4,i} \quad \text{and} \quad R_{2,i} \ll R_{3,i} \qquad (8)$$

$$\frac{\mathrm{d}m_i}{\mathrm{d}t} = 0 = R_{4,i} - R_{3,i}; \qquad (9)$$

for a reversible process

$$\frac{R_{3,i}}{R_{4,i}} = 1 \qquad (10)$$

and after substituting eq. (1) into eq. (10)

$$\prod_{j=1,i}^{n} m_j^{(\alpha_3-\alpha_4)_j} = \frac{k_4}{k_3} = K, \qquad (11)$$

here $(\alpha_3 - \alpha_4)_j$ is the stoichiometric coefficient of the component j in the reaction between the solution and the reversible metastable solid; K is the equilibrium molarity product identical to the equilibrium constant for ideal behavior.

The equilibrium control by the reversible metastable phase during an irreversible process permits changes in the molar quantities of the solid phases as follows:

$$\frac{\mathrm{d}M_p}{\mathrm{d}t} = -\nu_{1,i}R_{1,i} \qquad (12)$$

$$\frac{\mathrm{d}M_r}{\mathrm{d}t} = \nu_{1,i}R_{1,i} - \nu_{2,i}R_{2,i} - \nu_{5,i}R_{5,i} \qquad (13)$$

$$\frac{\mathrm{d}M_{ir}}{\mathrm{d}t} = \nu_{2,i}R_{2,i} + \nu_{5,i}R_{5,i} - \nu_{6,i}R_{6,i} \qquad (14)$$

$$\frac{\mathrm{d}M_s}{\mathrm{d}t} = \nu_{6,i}R_{6,i} \qquad (15)$$

where $\nu_{r,i}$ are the stoichiometric coefficients of a component i in the rth reaction.

The natural system can reach a steady state in which the irreversible process continues while both the aqueous concentrations and the molar quantities of the metastable phases are maintained constant.

In a closed system this steady-state condition is expressed by means of eq. (13) and (14)

$$\nu_{1,i}\, R_{1,i} - \nu_{2,i}\, R_{2,i} - \nu_{5,i}\, R_{5,i} = 0 \qquad (16)$$

$$\nu_{2,i}\, R_{2,i} + \nu_{5,i}\, R_{5,i} - \nu_{6,i}\, R_{6,i} = 0 \qquad (17)$$

from which

$$\nu_{1,i}\, R_{1,i} - \nu_{6,i}\, R_{6,i} = 0 \qquad (18)$$

or

$$\frac{\mathrm{d}M_s}{\mathrm{d}t} = -\frac{\mathrm{d}M_p}{\mathrm{d}t} = \nu_{6,i}R_{6,i} = \nu_{1,i}R_{1,i}. \qquad (19)$$

The steady state in an open system is expressed by means of eq. (2)

$$R_{1,i} + R_{4,i} - R_{2,i} - R_{3,i} - \nabla v m_i = 0 \qquad (20)$$

in combination with eqs. (16) and (17)

$$R_{1,i}(1 - \nu_{1,i}) - R_{2,i} + \nu_{6,i} R_{6,i} + R_{4,i} - R_{3,i} - \nabla v m_i = 0. \quad (21)$$

Since $R_{3,i} = R_{4,i}$ for the reversible process and $R_{2,i} = R_{1,i}$, providing that the steady-state composition has been reached, eq. (21) has the form

$$\nu_{6,i} R_{6,i} - \nu_{1,i} R_{1,i} - \nabla v m_i = 0. \quad (22)$$

After substitution of eqs. (12) and (15) into eq. (22)

$$\frac{dM_s}{dt} = \nabla v m_i - \frac{dM_p}{dt} = \nabla v m_i + \nu_{1,i} R_{1,i} \quad (23)$$

and

$$\frac{dM_p}{dt} = \nabla v m_i - \frac{dM_s}{dt} = \nabla v m_i - \nu_{6,i} R_{6,i}. \quad (24)$$

This formal treatment of the irreversible process leads to several conclusions. First, the formation of a thermodynamically stable phase does not necessarily control the concentration of a dissolved component in natural water through a chemical equilibrium. The controlling mechanisms may be the hydrodynamic steady state (eq. 2), the chemical steady-state (eq. 4) and a chemical equilibrium with a reversible metastable solid (eqs. 8, 9, 10, 11). Second, the control of the solution composition by a reversible reaction with a metastable phase does not preclude the formation and existence of irreversible metastable or stable mineral phases in the system. Third, the formation of the secondary solids can proceed independently of the equilibrium composition of the solution. Consequently, it cannot be assumed a priori that the evolution of the chemical composition of a natural solution can be calculated from the data on primary and secondary solids using the stoichiometry of reactions and their equilibrium constants (HELGESON 1968; FRITZ, 1975) unless it is proved that all the secondary solids behave reversibly and the rates of the irreversible dissolution are proportional to the masses of the primary solids. The evolution of the system is time dependent and the composition of the solution depends on the percolation velocity of water and the rate constants of the irreversible reactions as well as on the equilibrium constants of the reversible reactions.

The reliable data required to make the model represented by Fig. 1 quantitative are scarce. This paper is a partial contribution to the quantitative problem and deals with the reversible metastable solid which apparently controls the concentrations of aluminum and silica in natural waters during their irreversible evolution.

NATURE OF THE METASTABLE ALUMINOSILICATE

Early experiments by MATTSON (1928) and further elaboration by PARKS (1967) showed that the X-ray amorphous aluminosilicates which precipitate from aqueous solutions containing aluminum and silica have a neutral surface at given pH of the solution. This pH is called the point of zero charge (PZC). The PZC of pure hydrous alumina is at pH 9.2 and the PZC of pure silica is at pH 1.8 (PARKS, 1967). The compositions of the aluminosilicate which precipitated at various pH in the Mattson's experiments varied roughly linearly between pure silica at pH 1.8 and pure hydrous alumina at pH 9.2. This led PAČES (1973) to an assumption, that the reaction which controls the concentration of silica and alumina in cold waters is

$$[Al(OH)_3]_{(1-x)}[SiO_2]_x + (3 - 3x)H^+ \underset{k_3}{\overset{k_4}{\rightleftharpoons}} (1 - x)Al^{3+} + xH_4SiO_4 + (3 - 5x)H_2O. \quad (25)$$

The straight line in a plot x vs pH between the end points (x, pH) = (0, 9.2) and (1, 1.8) correlates reasonably well with Mattson's experimental points (PARKS, 1967, Fig. 10), hence

$$x = 1.24 - 0.135\,\text{pH}. \quad (26)$$

The activity quotient of the reaction (25) is

$$Q_{as} = \frac{a_{Al^{3+}}^{(1-x)} a_{H_4SiO_4}^{x}}{a_{H^+}^{(3-3x)}}; \quad (27)$$

assuming that a reversible equilibrium is maintained between the solution and the aluminosilicate, $Q_{as} = K_{as}$, where K_{as} is the equilibrium constant of reaction (25).

Table 1. Regression lines and correlation coefficients between pH of solutions and logarithms of the activity quotient of reaction (25): log $Q_{as} = a + b$ pH

Data set	n	r	a	b	log Q_{as}	
					pH=1.8	pH=9.2
Synthetic solutions[1]	56	0.997	-6.251	1.671	-3.24	9.13
Natural waters from granitic rocks[2]	37	0.957	-3.268	1.203	-1.10	7.80
Natural waters from granites[3]	23	0.946	-9.117	2.058	-5.41	9.82
Natural waters from gneisses[4]	23	0.936	-4.070	1.343	-1.65	8.29
Solutions of feldspars[5]	13	0.880	-10.400	2.473	-5.95	12.35
All samples	152	0.984	-5.891	1.588	-3.03	8.72
Linear plot between the solubility products of amorphous alumina and silica			-5.7	1.68	-2.7	9.7

[1] HEM *et al.*, 1973; [2] FETH *et al.*, 1964; [3] FOUILLAC *et al.*, 1976; [4] PAČES *et al.* in prep.; [5] BUSENBERG and CLEMENCY, 1976; BUSENBERG, written communication.

EQUILIBRIUM CONSTANT OF THE DISSOLUTION OF THE METASTABLE ALUMINOSILICATE

If the amorphous aluminosilicate were an ideal solid solution of amorphous silica and alumina, the equilibrium constant would be a combination of solubility products of silica ($K_s = a_{H_4SiO_4} = 10^{-2.7}$, KRAUSKOPF, 1956) and alumina ($K_a = a_{Al^{3+}} \cdot a^3_{H^+} = 10^{9.7}$, SILLÉN, 1964) with the solubility product of the aluminosilicate [eq. (27)]. At equilibrium

$$Q_{as} = K_{aas} = \frac{a^{(1-x)}_{Al^{3+}} a^x_{H_4SiO_4}}{a^{(3-3x)}_{H^+}}$$

$$= K^x_s K^{(1-x)}_a = 10^{9.7-12.4x}. \qquad (28)$$

Substituting eq. (26) into eq. (28)

$$K_{aas} = 10^{-5.7+1.68\,pH}. \qquad (29)$$

Six sets of experimental laboratory and field data on total aqueous aluminum, silica, pH, ionic strength and temperature were selected to calculate the values of Q_{as} given by eq. (27). They include 36 acid and 20 basic synthetic solutions of silica and aluminum aged from a few months to longer than four years (HEM *et al.*, 1973, Tables 3, 4), 37 filtered natural waters from granitic rocks in the Sierra Nevada, USA (FETH *et al.*, 1964, Table 1), 23 filtered natural waters from the granitic rocks in the Truyera River Basin, France (FOUILLAC *et al.*, 1976), 23 filtered natural waters from gneisses in the Trnávka River Basin, Czechoslovakia (PAČES *et al.*, in prep.) and 13 final solutions resulting from the dissolution of 9 feldspars in various initial solutions (BUSENBERG and CLEMENCY, 1976; BUSENBERG, 1976, written communication). The data are tabulated and entered into the files of NAPS*. All the samples were filtered through 0.1 μm membrane (FETH *et al.* (1964) used a 0.45 μm filter] prior to aluminum analysis and the pH of the natural waters was measured in the field. The activity of silica was assumed to be equal to its molarity. The activity of Al^{3+} was calculated using the equations in the Appendix. The calculated activities of Al^{3+} are included in the NAPS Document.

The base 10 logarithms of the activity quotients, log Q_{as}, calculated for all the data are plotted against the pH of the solutions in Fig. 2. The regression lines and correlation coefficients for the individual data sets and for all data are given in Table 1. The values of log Q_{as} for the PZC of the end members i.e. for pH 1.8 and 9.2 are included in Table 1. These values should correspond to the activity products of silica and alumina respectively under the conditions of the individual sets of data.

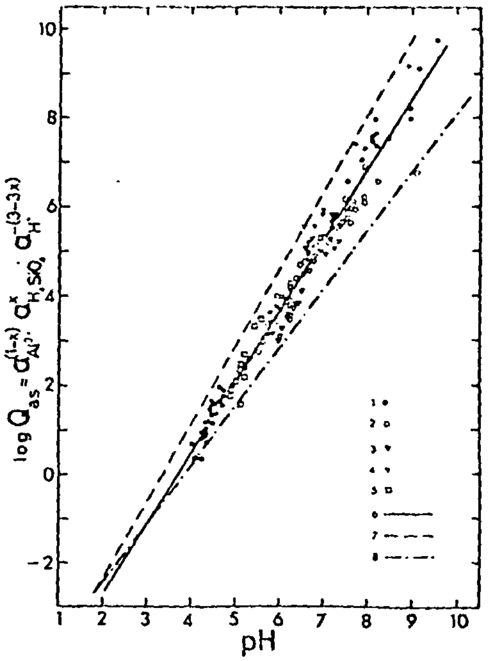

Fig. 2. The linear correlation between pH and logarithm of activity product $a^{(1-x)}_{Al^{3+}} \cdot a^x_{H_4SiO_4}/a^{(3-3x)}_{H^+}$ in experimental solutions and natural water samples. 1, Aged synthetic solutions of alumina and silica (HEM *et al.*, 1973); 2, subsurface water from granitic rocks in Sierra Nevada, U.S.A. (FETH *et al.*, 1964); 3, surface and subsurface water from gneisses in the Bohemian Massif, Czechoslovakia (PAČES *et al.*, in prep.); 4, subsurface and surface waters from granitic rocks of the Margaride Massif, France (FOUILLAC *et al.*, 1976); 5, final solutions resulting from the experimental dissolution of feldspars (BUSENBERG and CLEMENCY, 1976; BUSENBERG, written communication); 6, regression line for all the data points; 7, linear plot between the solubility products of amorphous alumina and silica at the pH values of their points of zero charge; 8, linear plot between the solubility products of microcristalline gibbsite and amorphous silica at the pH values of their points of zero charge (PZC of microcristalline gibbsite is at pH 11, SMITH, 1969).

The log Q_{as}-pH lines for the sets of experimental and field data deviate from the line connecting the solubility product of amorphous silica ($10^{-2.7}$) and alumina ($10^{9.7}$). This deviation may be explained by a hypothesis that the aluminum atoms after random precipitation assume coordinated positions during aging while silicon atoms maintain their random distribution (PAČES, 1973). Therefore, the solubility of the alumina end member in the aluminosilicate can vary while the solubility of the silica end member should remain similar to those of amorphous silica. The present results indicate that the solubility product of alumina decreases from theoretical $10^{9.7}$ down to $10^{9.13}$ in aged synthetic solutions, $10^{8.29}$ and $10^{7.80}$ in natural waters but increases in the solutions resulting from the feldspars. The decrease may be caused by the incomplete octahedral and/or tetrahedral arrangements of aluminum observed with X-ray fluorescence spectroscopy by HENMI and WADA (1976) in natural allophane and by HEM *et al.* (1973) in electron micrographs of aged laboratory precipitates.

The solubility product of the silica end member increases in two data sets from the theoretical value $10^{-2.7}$ up to $10^{-1.1}$ and decreases in three data sets

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[*] See NAPS document No. 03295 for pages of supplementary material. Order from ASIS/NAPS c/o Microfiche Publications, P.O. Box 3513, Grand Central Station New York, NY 10017, remitting \$3.00 for microfiche or \$5.00 for photocopies. Cheques to be made payable to "Microfiche Publications".

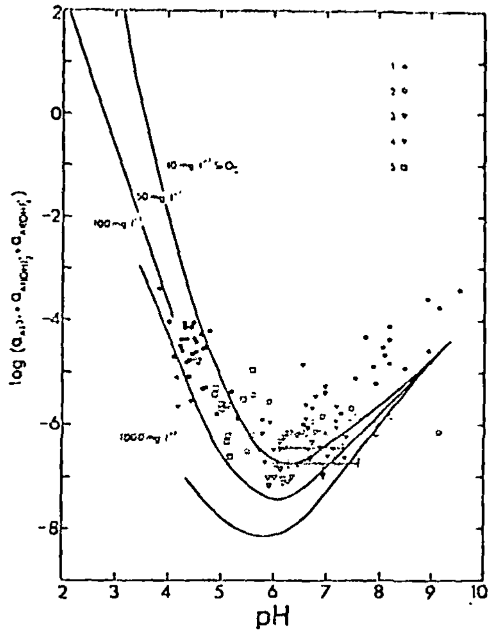

Fig. 3. The equilibrium sum of the activities of aluminum aqueous species with respect to the reversible aluminosilicate whose composition is determined by eq. (26) and its solubility product by eq. (30). The symbols are the same as given in Fig. 2. ⊢┬⊣ Represents mean pH and standard deviation for samples with aluminum concentrations below analytical sensitivity. The theoretical equilibrium curves for silica concentrations of 10, 50, 100 and 1000 mg.l⁻¹ are calculated using eqs. (31) and (32).

down to $10^{-5.95}$. The increase in the product is difficult to explain but is probably caused by the scatter of the data which affect the regression lines. The decrease may be due to both the nonideal behavior of the solid and to substitution of iron for silica McKYES *et al.*, 1974). In spite of all these uncertainties, the experimental and field data indicate that the concentration of silica and aluminum in natural waters may be controlled by a chemical equilibrium with a nonideal solid solution called here reversible aluminosilicate. Its mean solubility product given by the regression line for all the samples is

$$K_{ras} = 10^{-5.89+1.59\,\mathrm{pH}}. \qquad (30)$$

This solubility product, however, should be expected to change during aging and by the content of impurities.

A solubility diagram of the reversible aluminosilicate in terms of the total active aluminum ($a_{Al(Total)} = a_{Al^{3+}} + a_{Al(OH)_2^+} + a_{Al(OH)_4^-}$) vs pH is presented in Fig. 3 for 10, 50, 100 and 1000 mg.l⁻¹ of dissolved SiO₂. The solubility curves were calculated employing eqs. (26), 27) and (30) for the equilibrium condition $Q_{ras} = K_{ras}$. This yields

$$\log a_{Al^{3+}} = \frac{2.308 - \dfrac{5.891}{\mathrm{pH}} - 0.41\,\mathrm{pH} - \dfrac{1.24}{\mathrm{pH}} - 0.138\log a_{H_4SiO_4}}{0.135 - \dfrac{0.24}{\mathrm{pH}}}. \qquad (31)$$

The total active aluminum is calculated using the constants in the Appendix

$$a_{Al(Total)} = a_{Al^{3+}}\left(1 + \frac{10^{-9.76}}{a_{H^+}^2} + \frac{10^{-22.07}}{a_{H^+}^4}\right). \qquad (32)$$

The experimental and field data on total dissolved aluminum were recalculated in the form of the total active aluminum and are plotted in Fig. 3. The major feature of the model is the minimum solubility which shifts slightly with the increasing concentrations of silica from pH 6.35 at 10 mg.l⁻¹ SiO₂ to pH 6.1 at 100 mg.l⁻¹ SiO₂. The experimental and field data are in majority higher than predicted by the model. This is caused by the independent assumption on the composition of the reversible aluminosilicate expressed by eq. (26). If the PZC of the alumina in the solid solution is higher than 9.2 the solubility curves will shift to lower total active aluminum. The higher PZC (~ 11 pH) was measured on microcrystalline gibbsite (Smith, 1969).

DEPARTURES FROM EQUILIBRIA WITH VARIOUS Al, Si MINERALS AND SOLIDS

If the suggested reversible aluminosilicate controls the concentrations of aluminum and silica in natural waters then the waters should be in chemical equilibrium with the solid. However, they may depart from equilibrium with other solids or minerals. This can be tested by comparing the disequilibrium indices

$$I_p = \log \frac{Q_p}{K_p}$$

for the solubility products of various solid phases p. An aqueous solution is supersaturated with p if $I_p > 0$, it is unsaturated if $I_p < 0$ and it is in chemical equilibrium if $I_p = 0$.

The solids which may control the aluminum and silica concentrations in natural waters, the expressions for their activity quotients and their equilibrium constants are given in table 2.

The arithmetic means of the disequilibrium indices for all the data sets are summarized in Table 3. The variation of the indices is expressed by their standard deviations in Table 4.

By studying Tables 3 and 4 it is obvious that all or the majority of the solutions are unsaturated with amorphous Al(OH)₃, microcrystalline gibbsite, amorphous SiO₂ and amorphous aluminosilicate $[Al(OH)_3]_{(1-x)}\,[SiO_2]_{(x)}$. The solutions are supersaturated with gibbsite and kaolinite so that their precipitation is probable and will be irreversible. Some solutions are supersaturated and others are saturated or unsaturated with halloysite which was identified by HEM *et al.* (1973) in the secondary product during the aging of their synthetic solutions. The disequilibrium indices for the postulated reversible aluminosilicate. I_{ras} are close to zero in majority of data sets.

Table 2. Activity quotients, Q_p, and equilibrium constants, K_p, for 25 C for minerals and solids which may control the concentrations of Al and Si in natural waters

Solid	Symbol for p	Activity quotient Q_p	Equilibrium constant K_p /25°C/	Source
Amorphous $Al/OH/_3$	aa	$\frac{a_{Al^{3+}}}{a^3_{H^+}}$	$10^{9.7}$	Sillén, 1964
Microcrystalline gibbsite	mg	ditto	$10^{9.36}$	Hem and Roberson, 1967
Gibbsite	g	ditto	$10^{8.22}$	Smith, 1971
Amorphous silica	s	$a_{H_4SiO_4}$	$10^{2.7}$	Krauskopf, 1956
Halloysite	h	$\frac{a^2_{Al^{3+}}\, a^2_{H_4SiO_4}}{a^6_{H^+}}$	$10^{11.28}$	Hem et al., 1973
Kaolinite	k	ditto	$10^{6.74}$	Robie and Waldbaum, 1968
Amorphous /ideal/ alumosilicate $Al/OH/_3$ $/1-x/$ SiO_2 $/x/$ x	aas	$\frac{a^{/1-x/}_{Al^{3+}}\, a^x_{H_4SiO_4}}{a^{/3-3x/}_{H^+}}$ $x = 1.24-0.135pH$	$10^{-5.7+1.68pH}$	Pačes, 1973
Reversible /nonideal/ alumosilicate $Al/OH/_3$ $/1-x/$ SiO_2 $/x/$	ras	ditto	$10^{-5.89+1.59pH}$	this paper

Table 3. Mean values of the disequilibrium indices with respect to the solids in Table 2

Data set	number of samples	I_{aa} amorphous alumina	I_{mg} microcrystalline gibbsite	I_g gibbsite	I_s amorphous silica	I_h halloysite	I_k kaolinite	I_{aas} amorphous aluminosilicate	I_{ras} reversible aluminosilicate
Acid synthetic solutions[1]	36	-0.98	-0.62	0.50	-0.42	-0.06	4.48	-0.59	0.01
Basic synthetic solutions[1]	20	-0.51	-0.17	0.97	-0.89	0.04	4.58	-0.61	0.32
Waters from Sierra Nevada[2]	37	-0.91	-0.57	0.57	-0.76	-0.61	3.93	-0.95	-0.10
Waters from Truyere River Basin[3]	23	-0.92	-0.58	0.56	-1.21	-1.52	3.02	-1.04	-0.27
Waters from Trnávka River Basin[4]	23	-0.58	-0.24	0.90	-0.77	0.01	4.55	-0.68	0.13
Solutions of feldspars[5]	13	-0.58	-0.24	0.90	-0.67	0.23	4.77	-0.63	0.03

[1] HEM *et al.*, 1973; [2] FETH *et al.*, 1973; [3] FOUILLAC *et al.*, 1976; [4] PAČES *et al.*, in prep.; [5] BUSENBERG and CLEMENCY, 1976.

The near zero values of I_{ras} are not an independent proof of the existence of the solid because they are predetermined by the fact that the equilibrium solubility product is pH dependent and was fitted to the selected data. On the other hand, the smallest scatter of I_{ras} together with its near-zero values is a more significant support for the reversible control. A direct indication that an amorphous solid precipitates very fast in such systems are the high resolution micrographs presented by JONES and VEHARA (1973). The micrographs show that such a solid exhibits a coat-of-paint effect on the crystalline aluminosilicate surfaces. BUSENBERG (written communication, 1977) found experimental evidence that the reversible aluminosilicate controls aluminum and silica at higher concentrations of silica while halloysite and microcrystalline gibbsite control aluminum concentration at low to moderate concentration of silica.

CONCLUSION

This paper does not offer a definitive proof that the aluminosilicate of variable composition does exist. Nevertheless, the hypothetical solid which interacts with water according to reaction (27), whose composition is pH dependent according to eq. (26) and whose activity product is given by eq. (30) has the best predictive power for the behavior of silica and alumina in natural waters within the framework of the model

Table 4. Standard deviations of the disequilibrium indices from the mean values in Table 3

Data set	I_{aa}, I_{mg}, I_g	I_s	I_h, I_k	I_{aas}	I_{ras}
Acid synthetic solutions	0.50	0.32	0.98	0.13	0.13
Basic synthetic solutions	0.43	0.33	1.10	0.37	0.37
Waters from Sierra Nevada	0.62	0.16	1.19	0.49	0.43
Waters from Treyere River Basin	0.31	0.12	0.60	0.19	0.20
Waters from Trnávka River Basin	0.64	0.10	1.38	0.45	0.44
Solutions of feldspars	0.39	0.49	1.18	0.31	0.32

in Fig. 1 considering the common alumino-silicate minerals.

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APPENDIX

The equations for the solubility calculation:

$$m_{Al(Total)} = \frac{a_{Al^{3+}}}{\gamma_3} + \frac{a_{AlOH^{2+}}}{\gamma_2} + \frac{a_{Al(OH)_2^+}}{\gamma_1} + \frac{a_{Al(OH)_4^-}}{\gamma_1}$$

$$\frac{a_{Al^{3+}}}{a_{AlOH^{2+}} \cdot a_{H^+}^2} = 10^{5.00} \qquad \text{Hem } et\ al. \text{ (1973)}$$

$$\frac{a_{Al^{3+}}}{a_{Al(OH)_2^+}\, a_{H^+}^2} = 10^{9.76} \qquad \text{Hem } et\ al. \text{ (1973)}$$

$$\frac{a_{Al^{3+}}}{a_{Al(OH)_4^-}\, a_{H^+}^2} = 10^{22.07} \qquad \text{Hem } et\ al. \text{ (1973)}$$

$$\log \gamma_z = -Az^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\,I\right)$$

where a_i is activity of species i, $m_{Al(Total)}$ is total molarity of aluminum in solution, γ_z is the activity coefficient, z is the absolute value of the ionic charge, I is ionic strength, $A = 0.4883 + 7.38 \times 10^{-4} t + 2.723 \times 10^{-6} t^2$ where t is temperature in C.

ATTITUDES OF THE REAGAN ADMINISTRATION TOWARD GEOTHERMAL DEVELOPMENT

by

David C. Russell
Deputy Assistant Secretary
Land and Water Resources
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It's a pleasure to be here today and discuss with members of the Geothermal Resources Council attitudes of the Reagan Administration toward the leasing and development of geothermal resources in the United States.

Geothermal resources in the United States are located almost entirely in the Western States. The highest potential areas include The Geysers (80 miles north of San Francisco), the Imperial Valley (southern California), the Cascade Range (Washington, Oregon and Northern California), and central Utah; although Idaho, Nevada and New Mexico also have substantial potential.

The United States Geological Survey evaluates the Nation's geothermal resources in two classification categories. The first are known geothermal resources areas (KGRA) which have high potential for commercial production of either electrical or thermal energy. The second are prospective geothermal resources which have lesser potential but still may contain comercially valuable resources.

Presented by David C. Russell at the Geothermal Resources Council's Conference in Newport Beach, California, December 1, 1981.

The quantity of geothermal resources in Federal lands is, however, largely unknown although most authorities are in agreement that the potential for localized energy applications is substantial. The Department of Energy previously estimated, based on its own and USGS information, that geothermal energy production from all lands could exceed 125,000 megawatts by 2020. That would be the equivalent to approximately five million barrels of oil per day. The 1990 and 2000 projections are 10,000 and 38,000 megawatts respectively.

More than one-half of our geothermal resource potential occurs in Federal lands. Therefore, to the extent that lands are made available to exploration and development, Federal lands could contribute substantially to the future of geothermal energy in the United States.

The Bureau's geothermal leasing program began in 1974 -- four years after passage of the Geothermal Steam Act of 1970. In accordance with regulations appearing at 43 CFR 3200, lands within a known geothermal resources area (KGRA) are leased through competitive bidding. Lands not within a KGRA are leased to the first qualified applicant. Rentals for competitive leases are $2/acre/year noncompetitive leases are assessed $1/acre/year. All leases include specific diligent expenditure requirements which, if not met, subject the lease to termination.

As an incentive to exceed the minimum required expenditure, lessees are entitled to a refund of a special escalating rental, provided sufficient exploration has occurred. All leases are for 10 years, with five year extensions possible for drilling on the expiration date. Leases can be renewed for longer terms if there is production. Royalties are initially fixed at 10 percent of the value of production, but can be increased to 22-1/2 percent.

As of November 30, 1981, approximately 3.6 million acres (2000 leases) had been leased noncompetitively, and 700,000 acres (400 leases) had been leased competitively. Sales of competitive leases have earned the public almost $50 million, while annual rentals received are presently $3.5 million per year. In addition, a number of Federal leases are already providing steam for powerplants sited on private lands in California, and a major (110 MW) powerplant is nearing completion on public lands at the Geysers.

Royalties on production were only about $.5 million in FY 80, but increased to almost $2 million in FY 81 and they are expected to increase dramatically throughout the next two decades. In particular, some 25 leases in Nevada, Utah and Southern California have already been found to be producible and are awaiting construction of powerplants or other types of utilization facilities. Development plans to date have involved primarily electrical generation, but interest is growing in crop drying, greenhousing, and gasohol production.

The Bureau of Land Management has internally established a goal of leasing at least 20 million acres for geothermal development by 1990. This would include approximately 3.8 million acres already leased. The remaining 1.5 million KGRA acres that have not yet been offered (some will not be available for leasing), the 4.5 million acres currently under noncompetitive lease application (to be processed entirely by mid-1983), and approximately 1.5 million noncompetitive each year after 1983. This latter figure represents the Bureau's projection of anticipated industry interest in Federal lands.

Annual revenues from rentals and royalties are expected to increase from the $3.5 million received in FY 80 to a range of $46 to 70 million in 1990. In addition, competitive lease sales may earn the public between $40 - 120 million in bonus bids. Energy production by 1990 could approach 2000 megawatts, the equivalent of over 25 million barrels of oil per year.

All of these projections reflect the Administration's understanding of what the future of geothermal energy in this country can be.

This Administration, through Secretary James Watt, is committed to fostering the development of this clean, virtually renewable alternate energy resource. The Secretary has ordered a major overhaul of the Department's geothermal leasing and permitting program. Initiatives undertaken are:

Regulatory Reform

As part of a government wide program to reduce regulation of the private sector, the geothermal regulations appearing at 43 CFR 3200 (BLM leasing rules) have been reviewed to identify those provisions that are unnecessary, burdensome or counterproductive. Proposed regulation as they will soon appear in the Federal Register include:

1. Deleting the requirement for exhaustive prelease environmental reviews. This will allow the Bureau to use both "phased environmental reviews" and the "categorical exclusion" option, thereby greatly reducing the time needed to process lease applications.

2. Eliminating the requirement for an annual report from lessees demonstrating compliance with lease terms.

3. Allowing joint bonding for oil and gas and geothermal operations.

4. Deleting the requirement for a prelease plan of exploration or development.

5. Revising escalating rental provisions to allow for a waiver of these rentals rather than a refund.

6. Deleting the provisions that required lease applications, filed in excess of the lease acreage limitation, to be rejected.

7. Amending the powerplant licensing provisions to include licensing of nonelectrical utilization facilities.

A separate rulemaking pending since November 1979 is being made final and will soon appear in the Federal Register. That regulation will provide procedures under which the BLM will conduct a simultaneous geothermal leasing program similar to that used in the oil and gas program. Over 600 former leases involving over one million acres of land can now be reoffered. These simultaneous parcel offerings will be held in each BLM State office and will commence in April.

Administrative Actions

Secretary Watt, on September 9, 1981, ordered immediate acceleration of the Department's geothermal program. Noting that extensive backlogs existed, Secretary Watt Directed BLM and GS to process all pending lease applications within 90 days of receipt. In addition, all unleased KGRA acreage will be offered at competitive lease sales by the end of FY 82. Parcels receiving no bids will be reviewed for reclassification out of KGRA status on a priority basis.

Accordingly, BLM and GS streamlining includes efforts to:

1. Develop a Memorandum of Understanding (MOU) between BLM, GS and the Forest Service. This MOU will include specific agency response times for all government actions necessary to issue leases and approve exploration and developemnt of projects. The response times apply equally to BLM and FS field offices.

2. Revise Environmental Review Procedures. This involves adoption of phased environmental review and categorical exclusion by both BLM and FS offices.

3. Reduce the Use of Special Stipulations. A separate BLM/FS/GS MOU will be issued which should dramatically reduce the number of special stipulations being attached to leases.

4. Establish a Schedule for Leasing. Previous leasing schedules have been established, but never met. A new schedule is being originated jointly by BLM and FS field offices and revised as necessary by respective Washington Offices to assure elimination of backlogs. Under the Secretary's new Management by Objectives System, all BLM State Directors are being held accountable for meeting the leasing goals contained in the schedule.

Support Legislation

The Department is on record for not only supporting the goals of current House and Senate bills to amend the Geothermal Steam Act of 1970, but for urging enactment. Of particular importance in pending legislation is a proposed increase in the acreage limitation from 20,480 acres per State to 51,200 acres with a second increase possible to 115,200 acres in 1985. The Department has spent considerable time working with House and Senate staff to resolve other issues in the various bills to enable to encourage acreage limitation increases to go forward. We are especially concerned that if the limitation is not increased soon, lessees will be unable to absorb all of the leases that will be offered this year.

I hope that these comments have provided some insight as to the attitude of this Administration to geothermal energy. In closing, I wish to express my personal commitment to assisting the geothermal industry in developing geothermal energy in this country to its full potential.

Thank you.

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RECOMMENDATIONS

The geothermal community recognizes only one member of the Department of Defense (DOD) as being seriously interested in geothermal energy, the United States Navy. This is due to the work completed during the investigation of the Coso Springs geothermal area of California. The development of this area has been much slower than originally planned because of several factors concerning resource quality and quantity as well as managerial problems.

It is an appropriate time for the United States Air Force to take the lead in geothermal research and development within DOD. The large variety of and the potential for geothermal resources available for USAF utilization is the greatest for any of the United States military agencies. The following recommendations will assist the USAF in the goal of investigating, developing and utilizing geothermal resources.

1. Develop funding for geothermal research and development. This can be accomplished by (a) continuing to use the Engineering Assistance Program of DOE as has been accomplished for initial investigations of Hill and Williams AFB's; (b) contacting state agencies for assistance such as has been done with the State of Arizona; (3) use academicians through the Air Force Office of Scientific Research (AFOSR) to research topics of use to the Air Force and the development of geothermal energy; (d) front-end load funds into the geothermal resource program so money is available for the infrastructure building phase of geothermal development. This will assist private contractors in the early stages of development and help them gain the necessary expertise for future Air Force needs; (e) protect geothermal money in the Air Force budgeting process. Whenever a decision to cut either hardware or energy money occurs, energy loses. Normally this is the proper decision but one fact must be considered seriously . . . without energy the hardware will not be useable and as energy shortages become more common, the likelihood of national security problems

being created and mission capability crippled becomes more possible.

2. Make the geothermal community aware of the Air Force's interest in geothermal resource utilization. This can be accomplished by (a) joining the Interagency Geothermal Coordinating Council (IGCC) of the Federal government. Not only will this make the other members of the IGCC (National Science Foundation, Dept. of Agriculture, Environmental Protection Agency, Dept. of the Treasury, Dept. of the Interior, and the Dept. of Energy) aware of USAF's interest but the likelihood of increased geothermal knowledge and expertise being made available to the Air Force increases; (b) further visibility can occur by joining the Geothermal Resources Council composed of members from the academic world, private industry, government and research organizations; (c) the Air Force should also increase the manpower committed to geothermal energy. Full-time personnel is necessary if an on-going, serious geothermal program is to develop. The personnel involved would plan, implement, and coordinate the program and stay in contact and keep an active dialogue with individuals and groups involved in geothermal energy outside the Air Force, especially in private industry and with the Department of Energy. Such personnel could be assigned to AFESC/DEB at Tyndall AFB, Florida.

3. Make the United States public aware of the Air Force's interest in geothermal energy. In recruitment advertising show the need for energy awareness and the possibility of learning about energy and the career possibilities in energy fields.

4. Use the information presented in this report to develop a specific timetable for a geothermal energy program. The author of this report is applying for further funding to complete Phase II of the development plan illustrated in Table 6. After Phase II is completed the development of geothermal installations should occur on a regular basis.

5. New legislation dealing with geothermal energy in the Congress should be followed carefully and comments made to the appropriate members to enhance the Air Force's geothermal program.

6. Air Force/DOD should plan for eventual tie-in to existing power grids in order to wheel power from an Air Force/DOD geothermal-electric plant to other installations. The assumption is made that one or more DOD installations will eventually be producing geothermal-electric power excess to local base facility energy needs. To provide the most economical use of the excess capacity, arrangements could be made for feeding power into existing power grids for wheeling to other DOD installations.

7. Development and construction of the geothermal resources at Williams AFB should occur as soon as possible. The definite capability for cooling and the strong possibility of electrical production should be utilized as quickly as budgetary problems can be overcome. Each month that passes by makes the project more expensive and is a waste of money.

Type of Utilization		Possible Location	Exploration & Facility Cost ($ x 10^6
Electrical Power Plants			
10MW$_e$		Williams AFB	18- 22
15MW$_e$		Luke AFB or Saylor Creek	25- 30
25MW$_e$		Saylor Creek or Luke AFB	40- 45
	Subtotal		83- 97
Cooling Plants			
		Williams AFB	7- 9
		Luke AFB	9- 11
		Charleston AFB	11- 13
	Subtotal		27- 33
Heating Plants			
		Mountain Home AFB	2- 4
		Hill AFB	3- 5
		Ellsworth AFB	4- 6
		Kirtland AFB	5- 7
		Offutt AFB or Langley AFB	5- 7
	Subtotal		19- 29
	Total		129-159

Costs are approximate and may vary by as much as +50 percent to -20 percent. There are just too many unknowns at this time for a more exact cost estimate. The length of time to payback the cost will vary with each project but will average between eight and fifteen years. A more exact cost analysis will be completed after Phase II is finished (Table 7).

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GTHM
RGPM

REGIONAL GEOTHERMAL PROGRESS MONITOR

ACTIVITIES REPORT

JUNE 1982

HIGHLIGHTS

6.1 First Geothermal Exploration Holes Ever Drilled on Wyoming Federal Land are Completed: The University of Wyoming has completed drilling three shallow temperature gradient holes near Thermopolis. This is part of the continuing effort to locate a low temperature resource to be used for space heating in the city. The data are being analyzed.

6.2 Raft River Binary Plant Shut Down: The Raft River Binary Plant was shut down June 15 after a series of successful tests. The facility is being prepared for disposal through the General Services Administration.

6.3 Joint Hot Dry Rock Project Planned for Roosevelt Hot Springs: A joint hot dry rock project will be conducted by Phillips Geothermal and Los Alamos at Roosevelt Hot Springs in Utah.

GENERAL

6.4 DOE Geothermal Program Emphasizes Long Term R&D: The DOE geothermal program is switching emphasis from power on-line and in consonant with the President's proposed legislation to abolish DOE, is re-defining it toward long-term R&D that industry wouldn't take on, according to John E. "Ted" Mock, DOE geothermal division chief, addressing the EPRI annual geothermal conference in Snowbird, Utah on July 1.

Mock also showed DOE geothermal spendings declining from $55 million in the current year to $9.8 million in FY-83 to take on "high-risk R&D that industry is not expected to undertake alone" in table of all Federal agency geothermal spendings adding-up to $26.7 million in FY-83.

With switch away from electrical generation, Mock took a pledge to maintain the relevant program: "Through EPRI, the GRC, and our many other contacts, we will continue to do our best to interpret industry's interests and policies to make sure that our program remains relevant." He said demonstration programs would be phased-out as accent now goes to high risk R&D, but he didn't square this with the recent DOE decision to continue San Diego Gas and Electric's Heber 50 MW binary demonstration plant with $23 million re-programmed from DOE FY-82 appropriations. Nor did up-front Heber spendings show in tables's FY-83 columns. (Geothermal Report, July 1, 1982)

6.5 Ten PON Projects Discussed at IDHA Annual Conference: A presentation covering ten PON projects was given June 14 at the International District Heating Association's Annual Conference near Quebec City, Quebec, Canada. Frank Childs, EG&G Idaho, Inc. and George Budney, Rockwell's Energy Technology Engineering Center, each presented five projects; the former under DOE-ID's administration and the latter under DOE/SAN's administration.

6.6 Reservoir Engineering Handbook Published: The "Low-to-Moderate-Temperature Hydrothermal Reservoir Engineering Handbook," has been published. This document, a major milestone produced as a joint-project report by LBL and INEL, presents guidelines for developers and greater detail for consultants on testing, conceptual modeling, instrumentation and theory of low-to-moderate hydrothermal resources. The two-volume set will be distributed as IDO-10099.

6.7 GRC Holds Small Scale Geothermal Power Plants Workshop: The Geothermal Resources Council completed its scheduled June 14-16 workshop on "Small Scale Geothermal Power Plants" in Long Beach, California. This function was well attended (over 130) and well received by the geothermal community. The most important observations that were made during the course of the workshop are listed below:

1. Interest is extremely high in the development of small-power plants (1-10 MW) by operators, utilities, and financial firms.

2. There is a real need to demonstrate the reliability of the binary units. Although there are six or seven of these units available, none have been operated on a sustained basis. Some are only in the design stage and funds are being sought to develop them (see enclosed list).

3. The Sperry Research unit "Gravity Head-Heat Exchanger and Binary Power Plant" has tremendous potential. A test of this unit has been funded, and the test well should be drilled on the Magma lease of the East Mesa sometime in late 1982 or early 1983.

4. The Rogers Engineering EFP-System test was completed after a 30-day run at Desert Peak, Nevada. The results were positive and conclusive. The system will eliminate calcite scaling in the casing of production wells. This test has great significance for Northern Nevada and other numerous areas where calcite deposition is a problem.

5. Several financial firms (the Bank of America and the First Interstate Bank of California, to mention two) are extremely active in their efforts to underwrite small power-plant projects.

6. The geothermal community has finally realized the economic advantage of constructing small power plants at least for the first stages of development in a field. At present it is considered the best way to go as cash flow can be developed rapidly while the reservoir can be tested without making a large investment.

7. Development in the Cascades (northern California, Oregon, and Washington) will probably not be significant until the late 1980s because costly exploration techniques for the Cascades must be developed, and the energy need projections for the northwestern U.S. for the next ten years are very low.

The GRC expects that the largest initial effort in the installation of small power plants will take place in northern Nevada and other adjacent areas in the Basin and Range Province. At present, a flash plant is being constructed at Roosevelt Hot Springs in Utah; a 10 MW binary unit will soon be installed at Beowawe, Nevada; a 10 MW flash and a 10 MW binary unit are being considered for Dixie Valley, Nevada; a 10 MW binary unit will probably be constructed at Desert Peak, Nevada; a wood waste-geothermal plant will be constructed near Susanville, California; and two 3.5 MW units have been contracted for Casa Diablo Hot Spring near Mammoth Lakes, California. In addition, a major unnamed operator is considering the in-house construction of small-power plants.

6.8 <u>PON Projects Presented at ASHRAE Meeting</u>: PON projects at Pagosa Springs Colorado, Utah Roses, Utah, and Haakon School, South Dakota, were the complete agenda for the symposium section "Geothermal Heating System Operating Experiences." The symposium was held June 27 at the annual ASHRAE meeting that was held in Torono, Canada.

REGION VI

No geothermal development activities were reported for Nebraska, Arkansas, Louisiana, Oklahoma and Texas.

NEW MEXICO

Commercial Activities

None reported.

State and DOE Activities

6.9 Contracts Signed for all Eight State Grants: All eight geothermal demonstration project contracts have been signed. Negotiations are now underway to finalize the packages.

6.10 Geothermal Use Seminar Held: A seminar on geothermal heat as a resource for business and industry was held June 1 at New Mexico State University.

6.11 State Bibliography Completed: A comprehensive low temperature geothermal resource assessment bibliography for New Mexico was prepared, and is available from the NMERDI information center at the University of New Mexico.

6.12 Republic of China Representatives Visit NMSU: Visiting scientists from the Republic of China toured the New Mexico State University campus geothermal heating project.

6.13 Presentations Made by State Commercialization Teams: The state commercialization team made presentations at the "Forging New Mexico's Future Conference" in Albuquerque, and at the New Mexico Oil and Gas Association summer course for teachers at the University of New Mexico.

REGION VII

COLORADO

Commercial Activities

6.14 BLM Offering Four Colorado Tracts at July 12 Geothermal Lease Sale: A total of four leasing units containing 6662.91 acres in three federal Known Geothermal Resource Areas will be offered by the Colorado state office of the Bureau of Land Management at a sealed bid geothermal lease sale Monday, July 12 in Denver. The offering consists of two leasing units covering 3845.17 acres in the Mineral Hot Springs KGRA in south-central Colorado's Saguache County, and just to the east in the same county, one unit totaling 1636.42 acres within the Valley View KGRA, and one unit covering 1181.32 acres in the Poncha KGRA in Chaffee County, an offering area about 22 miles north-northwest of the other two mentioned KGRA's.

The Valley View-Mineral Hot Springs area of the northern San Luis Valley has attracted considerable exploration interest, according to the Colorado Geological Survey. The lands in the Mineral Hot Springs KGRA are just north of surface hot springs where temperatures range from 140 to 160 degrees Fahrenheit. The acreage offered in the Poncha thermal area is in the southeast portion of the KGRA, east of springs where temperatures over 392°F have been recorded. Temperatures to 99°F have been recorded at springs in the Valley View KGRA. (National Geothermal Service 6-25-82)

6.15 Routt Hot Springs Sold to Developer: Routt Hot Springs has been sold to a private developer. Plans are to expand the recreational aspects of the springs.

6.16 Splashland Resort Sold: The Splashland resort and thermal well at Alamosa has been sold. No information is available at this time regarding future plans for the resort.

6.17 Ouray to Display Geothermal Data: The city of Ouray is displaying geothermal information during the summer tourist season.

State and DOE Activities

6.18 Pagosa Springs Town Board is Pursuing Production Permit: The Pagosa Springs Town Board is going to prepare a proposal to acquire the senior water rights needed to obtain a production permit from the state. The permit must be obtained in order to complete the town's geothermal project.

6.19 City of Alamosa Well Results Disappointing: After numerous attempts to clean out the well, the final official airlift test was performed on June 7 to determine whether further testing was necessary to determine the cost share. The results were extremely disappointing as the well airlifted at a rate of 75-100 gpm with rapid drawdown. A temperature log run after the airlift indicated maximum bottomhole temperatures of approximately 180°F. However, a bridge still exists at about 6300 feet. DOE-ID plans no further activity on this well and will negotiate the cost share and closeout the project in the next few weeks.

MONTANA

Commercial Activities

None reported.

State and DOE Activities

6.20 Warm Springs State Hospital Construction Contract Signed: The construction contract for the Warm Springs State Hospital geothermal project was signed by 4-G Plumbing and Heating. Construction will start as soon as all materials are on site, which is expected to be in the first part of August.

NORTH DAKOTA

Commercial Activity

6.21 North Dakota Oil Well Has 276°F at 8000 ft: An oil well that was drilled about 1976 near the town of Bowman in the southwest corner of the state encountered a fault at about 8000 ft with a temperature of 276°F. The well was plugged and abandoned. The State Energy Office has been contacted for information and potential uses.

State and DOE Activities

None reported.

SOUTH DAKOTA

Commercial Activities

None reported.

State and DOE Activities

6.22 Dickinson Geothermal Study Completed: EG&G Idaho, Inc. has completed printing and distribution of "Final Report - Dickinson Geothermal Study," report No. EGG-2151, by G. O. Fossum et al, University of North Dakota Experimental Station, June 1982.

6.23 Well Data Being Gathered for the State: The State Office of Energy Policy is performing preliminary resource assessment by gathering appropriate data on existing wells throughout the state. (The state does not have a DOE resource assessment program.) The USGS has been contacted for information.

6.24 Geothermal Handbook to be Published: A Geothermal Handbook for the State is being prepared by the South Dakota Office of Energy Policy. The handbook scheduled to be completed September 1, will discuss direct-use applications, fan coils, radiation, and heat pump technologies.

UTAH

Commercial Activities

6.25 Another Roosevelt Hot Springs Well Completed as a Producer: Phillips Petroleum completed 35-3 Roosevelt Hot Springs on June 17. Total depth is 2607 ft for the reported potential geothermal producer.

6.26 Utah State Prison Well Flow Testing Proceeding: An extended flow test of well USPTH-1, the proposed production well for the Utah State Prison geothermal space heating project, was begun on June 17. The well was initially allowed to flow under artesian pressure at a rate of 300 gpm. Pressure drawdown in the production well, the Utah State Forestry Well, and the Utah Roses production well, has been closely monitored. The original intent was to run the test at constant flow for thirty days. However, preliminary results indicate that the effect of the 300 gpm flow on the other wells is only slight. In order to place more stress on the system and generate more representative data, the current plans are to increase the flow to 600 gpm.

6.27 Joint Hot Dry Rock Project Planned for Roosevelt Hot Springs: A joint hot dry rock project at Roosevelt Hot Springs will be conducted by staff from Phillips Geothermal and Los Alamos. A geohydrology and geochemistry investigation of shallow aquifers west fo the Opal Mound (Dome) fault will be made. Field work got underway this spring.

Dr. Francois-David Vuataz, a Swiss National, will be a member of the team making this study. Dr. Vuataz has been working in the Los Alamos Geothermal Energy Program since September 1981 on a fellowship provided by the Swiss National Fund for Scientific Research on a one-year appointment. He was recently appointed a laboratory-funded Post-doctoral Fellow to continue his work here for a second year.

WYOMING

Commercial Activities

None reported.

State and DOE Activiteis

6.28 Hot Springs County Wyoming Temperature Gradient Holes Drilled: The University of Wyoming, Laramie, has reported the completion of three shallow temperature gradient holes in northwestern Wyoming as part of a continuing attempt to target a thermal anomoly for the purpose of using low temperature geothermal energy for space heating in the town of Thermopolis. The wells were drilled to total depths of 354, 656 and 228 ft, all on the Thermopolis anticline from less than a mile north of the town of Thermopolis to five and a half to eight miles northwest of the town. An evaluation is currently being made of thermal log and hydrologic data. The wells are located along the crest of the asymmetrical anticline which has exposed Paleozoic limestones, sulphur and travertine deposits, all of which are abundant in the area. The wells were drilled in Hot Springs County and completed in the Paleozoic Tensleep sandstone, a regional aquifer and oil producing unit, according to Henry Heasler, geothermal specialist for the Department of Geology and Geophysics, University of Wyoming.

The drillsites are in an area most commonly known as the Big Horn Basin area...the Owl Creek Mountain area being another designation. C&N Drilling, Lovell, Wyoming, drilled all three wells. The program began May 25 and was completed June 4. Two wells, the UWT-1, ne sw 18-43n-95w, and the UWT-2, sw ne 2-43n-95w, are the first geothermal exploration holes ever drilled on federal land in Wyoming. The UWT-3, se sw 25-43n-95w, was drilled on city-county joint held land.

The project is financed by a $60,300 grant to the town of Thermopolis from the Wyoming Water Department Commission to explore geothermal resources identified in university research over the past three years. The wells were reportedly tested at the rate of 100 gallons of hot water per minute, and temperatures approaching 160 degrees Fahrenheit are anticipated. The long-term project, which could result in commercial development of Wyoming's geothermal resources, was initiated last year in cooperation with the U.S. Department of Housing and Urban Development (HUD). The university assessment team is responsible mainly for collecting data on the state's natural hot springs regions to determine the development potential area.

The cost of a town-wide heating system for Thermopolis is estimated at $14 million. The university will present its report, along with an engineering report from Coury and Associates, within a month to the town of Thermpolis regarding the feasibility of a district heating system. (National Geothermal Service 6-25-82).

REGION IX

ARIZONA

Commercial Activities

6.29 No Bids Received on Two Arizona Tracts in June 17 Geothermal Lease Sale: No bids were received for geothermal leases at the June 17 sale of Arizona federal lands held by the Bureau of Land Management in Phoenix. The geothermal leases offered consisted of two parcels covering a total of 2920 acres in the Gillard Hot Springs Known Geothermal resource Area, Grenlee County, southeastern Arizona. (National Geothermal Service 6-18-82).

State and DOE Activities

None reported.

NEVADA

Commercial Activities

6.30 Amax Drilling Second Geothermal Wildcat in Western Nevada: Amax Exploration has commenced drilling operations at 42-7 (N-84-21), se ne nw 7-1s-363, a geothermal wildcat projected to 8000 ft on the company's federal lease unit in western Nevada's Esmeralda County. The wildcat is about 22 miles west-north-west of the Silver Peak Known Geothermal Area. The leasing unit consists of lands held by Amax and Magma Energy.

Denver-based Amax, the unit operator, has suspended operations after drilling to 465 ft at its initial wildcat, the 81-14 Federal (N-31-993), ne ne 14-1s-353, in the northern Fish Lake Valley area. It is projected to 1500 ft. Amax has scheduled a total of seven wildcats thus far on the unit. (National Geothermal Services 6-11-82).

State and DOE Activities

6.31 State Completes Five Temperature Gradient Wells in Humboldt County: The University of Nevada has completed drilling five temperature gradient wells located in sections 26, 31, 32 and 33-35n-41e of Humboldt county. The wells were spudded in April and completed May 1, and ranged in depth from 220 to 480 ft.

6.32 Elko Well Rework Completed Satisfactorily: The Elko Heat Company well repair was successfully completed June 30. Billings Drilling cleaned out the bridged hole and deepened the well from 852 to 878 ft. It is estimated that the well production rate has increased between 100 and 200 gpm.

IDAHO

Commercial Activities

None reported.

State and DOE Activities

6.33 Raft River Binary Pilot Plant Shut Down: The Raft River Pilot Plant was shut down on June 15, 1982. The Engineering Test Phase extended from April 15 through June 15. The plant was on-line in either a thermal loop or electrical generation mode for approximately 1000 hours out of an available 1400 hours, and approximately 1500 MW hours were generated during the testing period. The test phase concluded with a 12 day power run. All major test objectives were achieved and the data gathered will be published in a final project report. Work is now proceeding on placing the plant in a cold shutdown condition in preparation for sale of the facility through the General Services Administration.

6.34 Boise Distribution System Installation to Start July 7: Owyhee Construction Company was given notice to proceed with the construction of the Boise city distribution system. Work will begin July 7 at both ends of the pipeline. Final inspection was completed satisfactorily for the mainline construction.

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REGIONAL GEOTHERMAL PROGRESS MONITOR

ACTIVITIES REPORT

JULY 1983

GENERAL

7.1 Initial Test Started for Heat Cycle Research Program: The Mobile Heat Cycle Research Facility, primarily composed of the 60kW binary experiment system relocated from the Raft River, Idaho DOE research project, began initial testing July 28 at East Mesa, California.

7.2 GRC/DOE-ID Reservoir Engineering Class Cancelled: The Reservoir Engineering class, jointly sponsored by the DOE-ID and the Geothermal Resources Council, was cancelled on July 12 with the concurrence of the class sponsors. As of July 12, only seven registrations had been received. Since nearly 40 people were required to break even, it was decided the small class was too costly and limited to be an effective application of technology transfer resources.

7.3 Raft River Binary Plant Bid Opening Delayed: The General Services Administration has delayed bid opening for the 5MW binary plant, wells and supporting items until August 11.

7.4 Renewable Energy Symposium to be Held end of August: The Renewable Energy Technologies Symposium and International Exposition will be held August 29 through September 1 in Anaheim, California. The event is sponsored by the Renewable Energy Institute, Dept. A, 2010 Mass. Ave., N.W. Washington, D.C., 20036, (telephone 202/822-9157).

7.5 Injection Research Program Underway at East Mesa: The Injection Research Program injection testing has been initiated at the Republic Geothermal, Inc. East Mesa geothermal field. Two wells are being tested by injecting cooled fluids with tracers and then monitoring the return of tracers during well backflow. Information is being collected on fluid mixing, heat transfer from the formation, chemical reactions with the formation and the effect of cold water injection on downhole pressure response. The data are complimentary to similar data collected at the Raft River geothermal field during 1982. Ultimately it is hoped the improved understanding of injected fluid interactions with the native reservoir will result in techniques which permit improved planning of reservoir development and management.

7.6 NCPA Geothermal Power Plant Dedicated, Development Accelerated by DOE Loan Guarantee Program: A unique $100 million geothermal project, the first to be financed with a combination of a Federal Loan guaranty and public offerings, was dedicated July 29 at the Geysers, a natural steam field 90 miles north of San Francisco.

Construction of the geothermal venture, NCPA Geothermal Project No. 2, was financed by a $45 million loan guaranteed by the U.S. Department of Energy and a $55 million bond issue. The geothermal plant, built and operated by the Northern California Power Agency (NCPA), has a capability of producting 110 megawatts of power.

NCPA is a California Joint Power Agency formed by nine Northern California municipalities and one electric cooperative (Alameda, Biggs, Gridley, Healdsburg, Lodi, Lompoc, Roseville, Santa Clara, Ukiah, and Plumas-Sierra Rural Electric Cooperative).

More information is available from:

Ed Dickinson
San Francisco Operations Office
1333 Broadway
Oakland, CA 94612
(415) 273-6563

7.7 OIT Receives DOE Grant to Continue Geothermal Technical Support: The Oregon Institute of Technology has received a grant to provide technology transfer and information dissemination services for geothermal energy development. OIT has provided these services for DOE since August 1978, and will continue to provide referral services between users and developers, conduct talks for lay and technical audiences, issue the Geo-Heat Center bulletin and other technical information, maintain the Geo-Heat Center library, and perform other limited services in the northwest and nearby states. The grant will be administered by DOE's Idaho Operations Office.

7.8 GRC Cascades Drilling Program Well Received: The Pacific Northwest Section of the GRC conducted a "Drilling in the Cascades" program July 7-8 in North Vancouver, B.C. About 50 persons attended the session that received a good representative of interested Canadians.

REGION VI

No geothermal development activities were reported for Arkansas, Louisiana, and Oklahoma.

NEW MEXICO

Commercial Activities

None reported.

State and DOE Activities

7.9 Presentation Made to Economic Development Board: The state geothermal team made a presentation to the Greater Las Cruces Economic Development Board concerning the status of geothermal development in Dona Ana County.

7.10 Israeli Firm Interested in State's Resources: Aquaculture Production Technology, Ltd., an Israeli company, was briefed by the State geothermal team regarding the state's geothermal potential for aquaculture applications.

7.11 NMSU to Drill New Well: New Mexico State University will drill a new well, PG-4, on campus property because no responsive bids were received for a proposed well-deepening program. Bids are due about mid-August. Concurrently, a new seismic profile will be run to verify sub-surface geology data developed as part of a geologic cross-section report. The seismic data should be available within 30 days, so as to validate the well location.

TEXAS

Commercial Activities

None reported.

State and DOE Activities

7.12 Bureau of Economic Geology Continues Statewide Integration of Geothermal Data: The last remaining bottomhole temperature/depth data have been compiled from electric logs in the Inner Gulf Coast Basin. These data have been numerically reduced and await photocopy reduction for contouring. The geothermal gradient data in the Tertiary Gulf Coast Basin have been compiled from the AAPG/USGS 1:1,000,000 depiction and will be presented on the map in progress as a contoured depiction of moving averages.

Along the Balcones/Ouachita Trend, compilation and refinement of lithic data continued into North-Central Texas. Data compilation were completed during July for Grayson, Cooke, Fannin, Dallas, Tarrant, Johnson, Hill, and McLennan Counties. Contouring of lithic data (top of Ellenburger and base of Buda) is underway in South-Central Texas. In this area, the purpose is to tie together geothermal anomalies, lithic discontinuities, and lineament trends.

REGION VIII

No geothermal activities were reported for Colorado, Montana and North Dakota.

SOUTH DAKOTA

Commercial Activities

None reported.

State and DOE Activities

7.13 Capitol Lake Complex Heating Project Continues: The preliminary report on the existing Capitol Lake well has been completed, and the project is going into Phase II. This phase involves preliminary design of the system that will provide space heating to the state's Department of Transportation building, and/or the Health Laboratory, and/or the Maintenance Building.

7.14 Heat Pump Workshops Held in Mitchell and Aberdeen: The state geothermal team conducted groundwater heat pump workshops for plumbing contractors in Mitchell and Aberdeen. Interest continues to run high and numerous requests for heat pump uses are being responded to.

7.15 Dupree School District Seeking Funding for Geothermal Heating: The Dupree School district is seeking funding to develop a geothermal heating system for their school located on the Cheyenne River Sioux Indian Reservation. The city of Dupree would turn over their existing 138°F well for use by the school district. A source of potential block grant funding is HUD's Office of Indian Programs in Denver, Colorado.

UTAH

Commercial Activities

7.16 <u>Groundbreaking for Utah State Prison Project Held July 12</u>: The groundbreaking for the construction of the Utah State Prison's geothermal space and domestic water heating system was held on July 12. Utah Governor Scott M. Matheson, Dr. Duncan Foley of UURI/ESL and Dr. Richard E. Wood of DOE-ID spoke at the groundbreaking. About 40 people attended, and the event was covered by three Salt Lake TV stations. The development of the geothermal system coincides with a general upgrading of the prison facilities and should receive more public exposure than usual.

REGION IX

No geothermal development activities were reported for Arizona.

NEVADA

Commercial Activities

None reported.

State and DOE Activities

7.17 Review of 1982 Mining Industry Published: A special publication describing exploration and mining and activities in Nevada during 1982 is now available from the Nevada Bureau of Mines and Geology. "The Nevada Mineral Industry 1982" is the fourth report in an annual series. It discusses 1982 activities in Nevada's mining industry, including mineral exploration and development programs, discovery of orebodies, new mines opened, expansions and closings at existing mines, oil and gas drilling and production, and geothermal drilling and utilization. A directory of operating mines in Nevada is included; it lists the location and type of mine, the primary mineral commodity produced, the average number of workers, and owner information. A section on the economic impact of the mining industry on Nevada's economy has been added this year.

Nevada Bureau of Mines and Geology Special Publication MI-1982--"The Nevada Mineral Industry 1982"--may be purchased for $5.00 at the sales office (room 310 in Scrugham Engineering-Mines Building on the university campus in Reno) or by mail (please add 10% postage and handling; Nevada Bureau of Mines and Geology, University of Nevada Reno, Reno, NV 89557-0088). For further information contact Arlene Kramer: (702) 784-6691.

REGION X

No geothermal activities were reported for Alaska and Idaho.

OREGON

Commercial Activities

7.18 Klamath Falls Aquifer Tests Started: A four-week geothermal aquifer test started July 5 in Klamath Falls. Ed Sammel, hydrologist with the U.S. Geological Survey in Menlo Park, California and coordinator of the three-phase geothermal test program in Klamath Falls, said water will be pumped from the well and injected into the A Canal at Main Street and the Alameda Bypass during the initial phase of the test. After about two weeks, water will be reinjected into the well at the Klamath County Museum.

Sammel estimated that water level drawdowns could be slightly more than 3 feet during the test. Such a drawdown would be much less than the drop in water levels during the winter heating season, he said. The winter drawdowns measure as much as 10 feet.

"The drawdowns will differ in different wells," he said, "They will differ in different directions."

Th test is meant to give scientists information about pumping of the reservoir.

"The objective is to learn something more than we do now," he said. The pumping test is being conducted by Sally Benson of Lawrence Berkeley Laboratories udner Sammel's supervision. After the test results are collected, they will be analyzed by LBL.

Anyone with questions or concerns may reach the test crew by telephoning George Wardell of Citizens for Responsible Geothermal Development, 884-1807; Klamath County Chamber of Commerce, 884-5193; or Dennis Long or Susan Swanson, Energyman Inc., 882-7203.

7.19 SeaTac Geothermal applies for Central Cascade Drilling: SeaTac Geothermal has applied for permits to drill two 300 ft holes in the central Cascades. Drilling activity is expected to start in September.

7.20 CEC Conducts Tour of Their Crater Lake Leases: California Energy Company, developers at COSO in California, conducted an informational tour of their lease holdings in the Crater Lake area. About sixty persons attended and were briefed on possible environmental effects, and given plant siting and other information to encourage a positive attitude about geothermal development in the area.

7.21 Burns Development Interest Continues: One developer is inspecting different properties for potential fish pond development, and another is considering greenhousing south of Burns using 90°F water in a newly devised floor heating system. The state geothermal team provided technical support to both developers.

State and DOE Activities

7.22 Wellhead Generator Computer Program Developed: The Oregon Institute of Technology has developed a computer program in TI-59 and Apple language that can be used to obtain the optimum size of a wellhead generator system and its net saleable power. The program is being finalized and should be available in September from Dave Brown, Oregon Department of Energy, Labor & Industries Building, Salem, OR 97310 (telephone 503/378-2788). Resource, data, well temperature, pumping and other data are factored in to determine what the optimum plant size should be.

WASHINGTON

Commercial Activities

7.23 GRC Cascades Drilling Program Well Received: On July 7-8, the Pacific Northwest Section of the GRC held the "Drilling in the Cascades" program in North Vancouver, British Columbia. A one-day field trip to the Meager Creek geothermal area concluded the program. The meeting was attended by 52 people.

7.24 District Heating Studies: During July, two communities in Washington were selected for evaluation by the Local Government Technical Assistance Program in the geothermal area. A feasibility study of district heating will be performed for North Bonneville and West Richland from funding supplied by BPA.

7.25 Economics of District Heating: Under contract to the State of Washington, Eliot Allen & Associates, Inc. is developing a computer program to study the economics of district heating. The methodology employed will be to evaluate heat load density as a criteria for evaluation.

7.26 Pacific Northwest Utility Conference Committee: On August 19, a meeting of the geothermal subcommittee of the Pacific Northwest Utility Conference Committee will be held to discuss the geothermal potential in the region and acquaint the subcommittee with the latest in drilling and conversion technology.

State and DOE Activities

7.27 Senate Bill 1237: During July, Mr. Gordon Bloomquist provided testimony in Washington, D.C. on Senate Bill 1237, the "Geothermal Tax Credits" bill sponsored by Senator Symms of Idaho.

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REGIONAL GEOTHERMAL PROGRESS MONITOR

ACTIVITIES REPORT

FEBRUARY 1984

GENERAL

2.1 Injection Test Program Field Work Completed: Republic Geothermal, Inc. initiated backflow of well 56-19 on Monday, February 13. They flowed the well through Friday, February 17 in an attempt to obtain a return of the injected tracers. No tracers were detected indicating a substantial flow within the reservoir. Well 56-30 was flowed for two hours to determine if the phenomenon of high initial tracer concentration was repeated. Visual inspection of samples indicates it was repeated again. The test program at the Geothermal Test Facility, East Mesa, CA is now concluded and data analysis is underway.

2.2 Indian Valley, CA Hospital Project Completed: A geothermal space and hot water heating system was recently completed for the Indian Valley Hospital in Greenville, California. The system is based on a well drilled to 560 ft on the hospital grounds. Resource temperature is 116°F and the well flows at 30 gpm artesian. The heating system, which also includes a nearby out-patient medical clinic and a separate office building requires about 50 gpm average flow to heat all three buildings and incorporates a variable speed motor controller on the well pump to automatically match fluid flow with load demand. Surface discharge has been allowed by the regional water quality control board.

The geothermal heating system which became operational in early January will result in a net savings to the Hospital District of about 275,000 kWh annually which has been provided by PG&E. The well was drilled and the heating system engineered by the firm of Gertsch, Juncal & Associates, Ltd., of Idaho Falls, Idaho and Milford, California.

2.3 Binary-Cycle Analysis Available: Geothermal power plant R&D, An Analysis of Cost-Performance Tradeoffs and the Heber Binary-Cycle Demonstration Project, is now available for distribution. The report, compiled by Thomas A. V. Cassel, Chris B. Amundsen and Peter D. Blair of Technecon Analytic Research may be obtained by writing the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161. (Petroleum Information 2/17/84).

2.4 Pumping of Geothermal Brine Conference Set for March 21-23: The Geothermal Resources Council will offer a course on the "Pumping of Geothermal Brine" March 21-23 in Los Angeles at the Biltmore Hotel, 515 South Olive Street. The program includes a basic introduction to downhole and surface pumps, followed by technical sessions on downhole pumps, downhole pump designs, surface pumps, and a four-hour session on corrosion including specific material applications. The GRC has made arrangements for special hotel rates and airfares, as well as rental car rates. Phone reservations to GRC Convention Center at (800) 525-3587 weekdays between 9:00 A.M. and 8:00 P.M. to assure special rates or write GRC Convention Center, 2323 South Troy, Suite 1058, Aurora, Colorado 80014 (Petroleum Information 2/17/84).

2.5 INEL Technology Transfer Activities Summarized: Data were compiled for FY-83 and FY-84 summarizing INEL related technology transfer activities. The summary includes input from state resource and geothermal teams, OIT, UURI-ESL and EG&G Idaho. About 183 technical and non-technical reports and publications were issued to approximately 181,000 recipients. Meetings and workshops totalling about 216 reached 51,600 persons. The profile of those involved include the geothermal technical community, state and local governments, developers and other interested persons.

REGION VI

No geothermal activities were reported for the region.

REGION VIII

No geothermal activities were reported for Colorado, Montana, the Dakotas and Wyoming.

UTAH

Commercial Activities

2.6 PSC Asked to Clarify Several Issues Holding up Small Power Producers: Last fall, Wayne Portanova's company, Mother Earth Industries, found near Cove Fort, in Millard County, what turned out to be only the fourth pure geothermal steam field in the world.

Most geothermal fields produce both water and steam, and they are more costly to develop than are pure steam fields.

Portanova told the Public Service Commission Tuesday he doesn't know yet how big his field is or how long it will produce, but it looks as if the steam could be used to generate 200 megawatts or more of electricity--possibly even 1,000. (A typical coal-fired generating unit may produce 400 megawatts.)

He wants to install turbines and produce power and sell it to the city of Provo. But he said he needs Utah Power and Light Company to transport his electricity to Provo, and UP&L won't do it.

Portanova testified during PSC hearings on the potential for small power production in Utah, the rates small power producers should get from utilities that buy their surplus, and the conditions under which such sales should take place.

He said the power transportation, or wheeling, issue is a key one to many potential producers.

Back in the early 1960s when the federal government was building power transmission lines in most states, he said UP&L was able to keep the federal system out of it by saying it could take care of the transmission needs of the state.

Now he said, if UP&L refuses to wheel, "you have a monopoly that prevents independent buyers and independent producers from getting together."

UP&L attorney Thomas W. Forsgren told the Deseret News that Portanova's description of the state of affairs was not correct.

"We haven't decided that we won't wheel for him," Forsgren said. But the company wants to handle each wheeling proposal individually, rather than through general PSC rules or standard agreements, he said, "because we believe they're site-specific situations."

Asked whether UP&L could be required to wheel someone else's power against the utility's wishes, Forsgren said that can be required under certain circumstances, but those circumstances again would have to be individually determined. He said UP&L intends to do what is legally required, as that may be decided in each individual instance.

Moving from the wheeling issue, Portanova also urged the commission to set UP&L's power buy-back rate at a reasonable level. He said the present rates of 2.2 to 2.6 cents per kilowatt-hour are ridiculously low, and little if any of the potential for small power projects will be developed if the producers can't get a higher rate for their power.

Portanova agreed with UP&L and the commission that the rate should equal UP&L's avoided cost--the amount UP&L would have to pay to buy power or build additional generating facilities if it weren't buying from the small power producers.

He said a rate that is higher than avoided cost would result in UP&L's ratepayers subsidizing the small power producers, and he doesn't want a subsidy. (Deseret News 3/1/84)

2.7 Unidyne to Participate in Roosevelt H.S. Development: Unidyne Corp. agreed to acquire all the assets of Steam Reserve Corp., the geothermal division of Amax Exploration, Inc. Consideration will be a majority of Unidyne common stock and private placement by Unidyne of $6 million in equity, with the assistance of Amax, to develop acquired properties, including Roosevelt Hot Springs geothermal field. Sale of geothermal resources from the field to Utah Power & Light Co. are to begin in April. (Oil & Gas Journal 2/27/84)

State and DOE Activities

2.8 Utah State Prison Work Completed: Construction of the Utah State Prison geothermal space and domestic water heating project has been completed. Final checkout of the system for the minimum security building is being performed.

REGION IX

No geothermal activities were reported for Arizona.

NEVADA

Commercial Activities

2.9 Dixie Valley Exploratory Well Spudded: On February 18 Monterey Energy Company spudded the 76-28 Dixie Federal, 28-25n-37e, a geothermal well on a 6,400-acre lease block about 18 miles northeast of the town of Dixie Valley in southeastern Pershing County, Nevada, within the Dixie Valley Known Geothermal Resource Area. The projected 9500-ft test is drilling below 2500 ft. VECO Drilling, Inc., Grand Junction, Colorado has the contract.

According to Monterey, the test will seek superheated water and steam reservoirs in interbedded volcanic and sedimentary rocks. In section 27, Monterey has locations staked for the 26-27 Dixie Federal and the 45-27 Dixie Federal, both in Churchill County. Drilling has not yet commenced at either of those sites.

Elsewhere in Churchill County, Transpacific Geothermal, Oakland, California will drill three new development wells within the Dixie Valley KGRA. They are the 54-33 in 33-25n-37e; the 75-33 in 33-25n-37e; and the 22-34 in 34-25n-37e. Last August, Transpacific completed the Dixie Belle, 33-25n-37e, Churchill County, as a potential geothermal producer. The company's 2 Dixie Belle, also in 33-25n-37e, has been drilled to an unreported depth. No other details have been released.

The Dixie Valley area is being developed to produce geothermal energy which will be converted into electricity to supply California and other western states. (P.I.-NGS 2/24/84)

2.10 Beowawe Geothermal Project Planned: Chevron Resources Company is targeting a year end 1985 start-up for the first phase of a Nevada geothermal project whose ultimate development could yield the energy equivalent of a giant oil field.

Chevron and partner O'Brien Resources Corp., Grass Valley, California, are trying to land a power sales agreement for a 5,000-10,000 kW demonstration power plant to exploit the geothermal resources at Chevron's 17,000 acre Beowawe Unit in northern Nevada.

Chevron and O'Brien, a 94% owned subsidiary of O'Brien Energy & Resources, Ltd., Toronto, last month signed a letter of intent allowing O'Brien to earn as much as a 50% interest in the unit under a noncash incentive farmout (OGJ, Jan. 30, p. 92).

Like geothermal project proposals elsewhere in the U.S., the Beowawe project has been held back by market conditions--lagging energy prices and an electrical power capacity surplus among utilities.

If a power sales contract could be worked out now, Chevron could launch detailed engineering on the project immediately and have a first phase plant on stream in less than 2 years.

The most likely candidate for power sales would be the Nevada utility, Sierra Pacific, but Nevada's Public Service Commission has applied federal guidelines for avoided cost pricing for power sales too stringently to offer enough incentive for a strong geothermal program in the state, says Chevron.

California's implementation of avoided cost guidelines offers more price incentive, Chevron notes, but that could involve a more costly transmission line to one of that state's major population centers.

California, however, has a strong commitment to develop electrical power capacity from alternative energy sources. Utah is another possibility. (O&G Journal 2/20/84)

State and DOE Activities

2.11 Nevada Legislation Allows Electricity Exporting: The 1983 session of the Nevada Legislature passed legislation allowing geothermal developers to export larger amounts of electrical energy from Nevada.

In the past, producers of electricity from geothermal resources were required to make:

--50 percent of their production capacity available to utilities located within the area and within the state; or

--Permit those Nevada utilities to recapture up to 50 percent of production from out-of-state utilities that had contracted to purchase the electricity from the geothermal producers.

Geothermal developers and the Nevada Mining Association members testified the restriction has discouraged investment towards the huge capital outlays needed to establish a geothermal-electrical utility in Nevada. They said Nevada-based utilities may not be able to purchase their half of the shares. Moreover, prospective out-of-state purchasers of geothermally generated electricity may find it uneconomical to contract for the energy if they are not guaranteed 100 percent of production.

The legislation, A.B. 592, now reads:

> "In case of geothermal projects, the construction permit (from the state) may be conditioned only on a prior offering of the capacity of the project to the public utility in this state which primarily serves retail customers in the service area nearest to the proposed project; and if the offer is declined, the applicant is free to export the capacity of the project without any obligation to re-offer that capacity to any public utility in this state."

The legislation was opposed by representatives of Nevada electrical utilities. (Geothermal Hot Line 12/83)

REGION X

No geothermal activities were reported for Alaska and Washington.

IDAHO

Commercial Activities

None reported.

State and DOE Activities

2.12 City of Boise Plans Geothermal Seminar March 23: A geothermal seminar will be conducted by the city of Boise on March 23 at the Red Lion Downtown in Boise. The day-long session will be held for small cities, large corporations, engineers, architects, etc. Topics of discussion will be the Boise city heating project, Idaho's geologic potential and permitting and legal status, and geothermal project financing. Contact Lee Post at 208/345-1265 for additional information.

2.13 Pacific Northwest Industry Group Meets: The Pacific Northwest Minerals Industry group met February 24 in Portland to discuss geothermal, oil and gas, and hardrock minerals. About 110 industry representatives, consultants, BLM and USFS officials and the Oregon Department of Energy participated in the informational meeting that was hosted by the Oregon Office of the BLM.

2.14 Klamath Falls to Start Operating District Heating System: The Klamath Falls City Council has agreed to a four month operational test of their district heating system, including 12 of 14 buildings already retrofitted and 120 residences. Operations are expected to start mid-March when temperatures and flow conditions will be monitored under actual heat load conditions.

REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT

MARCH 1984

GENERAL

3.1 <u>Geothermal Energy Addressed at 11th Energy Technology Conference</u>: To the theme of "Geothermal Energy and Electric Energy Generation," three stalwarts of the geothermal community addressed the 11th Energy Technology Conference in Washington, D.C. on March 19-20. John Mock, DOE geothermal division chief, Vasel W. Roberts, program manger of geothermal power systems at EPRI; and Ron DiPippo, professor of mechanical engineering at Southeastern Massachusetts University, were speakers at a well-attended geothermal session headed by Wilson Pritchett, National Rural Electric Cooperative Association.

Mock highlighted the vast contributions of DOE in supporting research needed by industry to make geothermal energy a more viable energy source in marketplace. Striking optimistic tone, he described positive attributes, e.g. large energy base, clean reliable resource and inexpensive power as plus factors in promoting geothermal utilization for electric power production.

Roberts, taking a more cautious tack, praised Mock and his DOE colleagues while recognizing uncertainties associated with size of resource base and reliability of supply of underground steam and hot water. He wound up his statement saying:

> "In closing, three thoughts should be iterated. First the long-term stability of objectives and attitudes of the (utility) industry have had a beneficial effect on deliberate and calculated progress. Secondly, the industry has maintained a level of support for geothermal development consistent with the best estimates of geothermal's capability to contribute to national energy needs.

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> They have frequently gone beyond this in their supportive encouragement to the exploration side of the activity. Finally, given any significant growth in power demand, the industry stands ready to continue the development of geothermal energy with the simple provisions that reserves be proven and that cost be competitive."

DiPippo, reviewing rapid growth of geothermal electric power generation worldwide, forecast global growth to 5800 MW within the next two years. DiPippo said that currently there are 139 separate plants generating total of just under 3400 MW. U.S. leads pack with the 1284 MW on line, followed by the Philippines with 781 MW and Italy with 457 MW. (Geotherma Report 4/2/84)

3.2 Bill Beneficial to Geothermal Out of Senate Committee: The Deficit Reduction Act of 1984 has passed out of the Senate Finance Committee, and includes features favorable to geothermal development. Tax credits would be allowed for geothermal energy that is used in a cogeneration mode with the credit base applying to the percentage of the system that is geothermal. It will also lower the tax applicable temperature required from 50 to 40°C.

3.3 Economics and Institutional Factors Workshop set for May 21-23: GRC and DOE are sponsoring a workshop on geothermal economics and related institutional factors that will be held May 21-23, 1984 in Palm Springs, CA. The intention of the session is to provide a strong background of economics yet include the critical features needed by geothermal developers. Information can be obtained from GRC-Convention Center, 2323 S. Troy, Suite 105B, Aurora, CO 80014, telephone 800-525-3587 (in Colorado 337-4809).

3.4 Heat Pump Technology Conference Issues Call for Papers: A call for papers has been made for the 7th Heat Pump Technology Conference to be held October 15-16, 1984 in Tulsa, OK. Abstracts or outlines are due June 1. Further information is available from Dr. Jerald Parker, Professor, School of Mechanical and Aerospace Engineering, 218 Engineering North, Oklahoma State University, Stillwater, OK 74078, telephone 405/624-5900.

3.5 UURI/ESL Has New Address: University of Utah Research Institute, Earth Science Laboratory has announced a change of address effective March 1, 1984. The new address is 391 Chipeta Way, Suite C, Salt Lake City, Utah 84108. The new telephone number is 801/524-3422.

3.6 GRC Announced Availability of Northern Basin and Range Publication: The Geothermal Resources Council has announced the availability of "The Role of Heat in the Development of Energy and Mineral Resources in the Northern Basin and Range Province." The 384-page publication is available by contacting the GRC at (916) 758-2360, or writing P.O. Box 1350, Davis, California 95617.

3.7 Sandia Issues Report on Deep-Hole Drilling: Sandia National Laboratories has released a report entitled "Research and Development of Improved Cavitating Jets for Deep-Hole Drilling," conducted under contract from the Department of Energy.

According to Sandia, improved cavitating nozzles have been developed as part of an on-going program to increase the rate of penetration of deep-hole drill bits. Based on incipient cavitation number, amplitude of pressure fluctuation, rock cutting and cleaning chips from the bottom of the hole, these new, self-resonating cavitating jets have outperformed both conventional drill bit nozzles and basic CAVIJET cavitating jets.

During the first phase of the study, Sandia reported that existing CAVIJET cavitating fluid jet nozzle designs were capable of operating under certain limited downhole conditions, and improved rates of penetration were observed with two-cone roller bits during both laboratory and field trials. However, the limits on their practical use motivated the study to determine whether principles of "self-resonance" could be developed for improving the performance of submerged cavitating jets. Sandia noted that this feasibility study demonstrated that self-resonating cavitating jet systems were capable of providing the required performance for use in deep drilling three-cone bits.

Among the specific conclusions from the study as identified by Sandia included was that several self-resonating nozzles types produce passive oscillations which cause the jet to structure into discrete ring vortices, and thus provide nozzle systems which have incipient cavitation numbers two to six times higher than obtained with either conventional CAVIJET nozzles or typical drill bit nozzles. In rock cutting trials, higher incipient cavitation numbers have been correlated with greater jet erosivity.

The report is available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161. (National Geothermal Service 3/30/83)

3.8 Gradient Measurements Made at 29 Palms, CA: The Division of Earth Science, University of Nevada, Reno, has completed a draft report of the gradient measurements made at 29 Palms, which has been submitted to the Navy. Results of the study will be available in several months through the NTIS.

REGION VI

NEW MEXICO

Commercial Activities

None reported.

State and DOE Activities

3.9 University of California Publishes Baca Well Paper: The University of California, Lawrence Berkeley Laboratory (Earth Science Division) has published "Hydrothermal Alteration in Well Baca 22, Baca Geothermal Area, Valles Caldera, New Mexico." The paper, written by Dennis James Fox for the Department of Geology and Geophysics, University of California at Berkeley, is available by writing National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

3.10 NMSU Designing Greenhouse Research Facility: A geothermally heated greenhouse research facility is being designed by the New Mexico State University Energy Institute in Las Cruces, NM. The 12,000 square foot greenhouse complex will demonstrate different geothermal heating systems and greenhouse designs. Principal greenhouse research activities will be in floriculture and aquaculture. The project is intended to trigger the establishment of a geothermally heated greenhouse industry in southern New Mexico. The greenhouse complex will be built on the university campus in Las Cruces, New Mexico.

The greenhouse facility will use the extensive geothermal resource from the Las Cruces East Mesa Geothermal Field. Water at temperatures of up to 146°F are produced from a depth of approximately 800 feet. Some 30 buildings on the NMSU campus are already being supplied with geothermal heat.

Even though $400,000 funding has been appropriated by the New Mexico Energy Research and Development Institute and New Mexico State University, release of the funds for actual construction of the facility is contingent on matching contributions from industry in the accumulative amount of $50,000. The Energy Institute is actively seeking these matching funds. Further information is available from Dr. Rudi Schoenmackers, Director, Energy Institute, Box 3EI, Las Cruces, NM 88003, Telephone (505) 646-1846.

REGION VIII

UTAH

Commercial Activities

3.11 No Bids Received on Utah Geothermal Leases at March 26 Sale: No bids were received for geothermal leases offered March 26 by the Utah Department of Natural Resources, Division of State Lands, in Salt Lake City. The sealed bid offering included nine geothermal tracts comprising 6,461.18 acres in Beaver and Millard counties.

Donald Prince, assistant director of the Division of State Lands, cited the location of the lands as the main reason for the lack of interest. Specifically, the lands consisted of two tracts covering 2,000 acres 12-16 miles south of the Crater Springs Known Geothermal Resources Area in Millard County; five tracts covering 3,200 acres 40-48 miles southwest of the Crater Springs KGRA in Millard County; one 640-acre Millard County tract eight miles northwest of the Cove Fort-Sulphurdale KGRA; and a single tract comprising 621.18 acres six miles east of the Roosevelt Hot Springs KGRA in Beaver County. (National Geothermal Service 3-30-83)

REGION IX

NEVADA

Commercial Activities

3.12 Sierra Pacific Requests Approval for Geothermal Contracts: Sierra Pacific Power Company, Reno, Nevada, is seeking approval from the Nevada Public Service Commission for three geothermal contracts which could result in the construction of the state's first commercial geothermal power plants within two years.

The contracts call for the utility to purchase up to 24 megawatts of geothermal power from three small pilot power plants. Before the projects can proceed, however, the company must receive PSC approval regarding the pricing mechanisms in each contract.

Under the first 10-year contract with Geothermal Development Associates, Reno, Sierra Pacific would purchase up to five megawatts of electricity from a plant to be built at Steamboat Springs, located nine miles south of Reno. The plant could be completed by June 1985.

Another 10-year contract calls for the company to purchase up to nine megawatts of geothermal power from Phillips Petroleum. The plant, which could be completed by the end of 1985, would be built at Desert Peak, 65 miles northeast of Reno.

The third contract with the partnership of National Energy Associates/ Sequoia Thermal, San Francisco and Big Smoky Valley, respectively, is for a 33 year period to supply the utility with as much as 10 megawatts of geothermal power produced at a plant to be constructed in the Big Smoky Valley of central Nevada. Work on that site would begin in the next few months, with power delivery to begin by late 1985 or early 1986.

According to Sierra Pacific, the utility won't have ownership in the plants, but will have access to all data relative to the quality of geothermal resources, the technological performance of the plants and their operating and maintenance costs. The company's goal is to have geothermal resources supply 25 percent of the energy needs of its customers by the year 2000. (National Geothermal Service 4-6-84)

REGION X

IDAHO

State and DOE Activities

3.13 Geothermal Energy Seminar Held in Boise: The city of Boise held a one-day seminar to highlight and further encourage the direct-use of geothermal energy in the state of Idaho. The seminar was held in Boise on March 23, and is part of a HUD contract with the city to summarize and encourage the direct-use of geothermal energy in the state of Idaho. About ten speakers at the seminar described the Boise project that is cost-shared by the U.S. DOE, the overall DOE Program Opportunity Notice field demonstration program, Idaho geology, project and user economics, project legal requirements, and project financing. Professionals from these fields, including engineers from the Geo-Heat Center at the Oregon Institute of Technology and the Idaho National Engineering Laboratory participated in the event that was attended by about 50 people. Some of the cities represented were: Idaho City, Caldwell, Nampa, Grangerville, Weiser and Payette.

OREGON

Commercial Activities

3.14 Agreement Signed for Binary Power Plant at Lakeview: Jack Woods & Associates, Inc. and Pacific Power and Light have signed an agreement whereby PP&L will purchase power produced from the Wood's binary generator located near Lakeview. Three Ormat units are at the site with a total capacity of 900 kW using the Hammersly Canyon well which produces about 1000 gpm of 221°F geothermal water. The agreement is for 7 cents/kWh for the first year and 1-1/2 cents beyond the first year.

3.15 Oregon BLM to Offer KGRA Lands for Geothermal Leasing: Ten leasing units comprising 18,379.83 acres within the Breitenbush Hot Springs, Carey Hot Springs and Vale Hot Springs Known Geothermal Resource Areas will be offered for geothermal leasing by the Bureau of Land Management. Bids will be opened and read at 2:00 P.M. on April 24 in the 15th floor conference room in accordance with CFR 3220.6(a). (National Geothermal Service 3-30-84)

WASHINGTON

State and DOE Activities

3.16 District Heating Feasibility Study Planned for Sunnyside: The community of Sunnyside has been added to the cities that are being evaluated for potential district heating through the state's local government Technical Assistance Program.

REGIONAL GEOTHERMAL PROGRESS MONITOR
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GENERAL

4.1 Geothermal Technology Transfer Grant Effective April 13 for the Oregon Institute of Technology: The Idaho Operations Office of U.S. DOE has awarded a $355,000 grant to the Oregon Institute of Technology Geo-Heat Center at Klamath Falls, OR. The Geo-Heat Center will work with potential users, consultants, industry organizations, engineers and state energy offices upon request to provide direct technical/economic feasibility analysis for those actively involved in geothermal development. This will include limited resource assessment, conceptual design options and life cycle cost analysis for geothermal projects involving direct and heat pump space heating, agriculture/aquaculture applications, industrial processes and low-temperature wellhead electric power generation. The center will also conduct training sessions as requested primarily for state energy offices' staff, conduct information talks for lay and technical audiences as requested, and direct tours and field trips. Technical information will continue to be disseminated through a quarterly bulletin, printing and distribution of literature, maintenance of their existing geothermal library, and performing progress monitoring activities.

EG&G Idaho will continue to provide technical direction for this activity that is similar to but of greater scope than another grant that was essentially completed April 13 by the Geo-Heat Center. The new grant will provide for the provision of technology transfer activities through June 1986.

4.2 PNW Chapter of GRC holds Meeting in Portland: The Pacific Northwest Chapter of the GRC held a six-hour meeting on April 12 at the Red Lion Jantzen Beach in Portland. Five speakers discussed geographical exploration tools and Cascade applications.

4.3 Coldwater Creek, CA Power Plant Project Proceeding:
California Energy Commission received application of certification from Central California Power Agency for its Cold Water Creek Project. CCPA is a joint power agency consisting of Sacramento Municipal District and Modesto Irrigation District and the City of Santa Clara. The first of two proposed 65 MW geothermal power plants will be owned by SMJD (75%) and MID (25%). The project site is located about 2 1/2 miles northwest of PG&G's Unit No. 1 power plant.

4.4 Sandia Releases Report on Detection of Fractures in Granite: Sandia National Laboratories has released a report entitled "Evaluation of Borehole Electromagnetic and Seismic Detection of Fractures," conducted under contract from the Department of Energy.

Experiments were conducted to establish the feasibility of downhole high-frequency techniques for location of fractures in the vicinity of boreholes. One method used involved an electromagnetic wave at 30 to 300 MHz, VHF frequencies. A transmitter consisting of a phased dual-dipole array to provide a signal toward the fracture was installed opposite the borehole. A receiver also was attached. In experiments using seismic waves at 4.5 to 6 KHz, the transmitter and receiver were located in separate boreholes.

According to Sandia, the conduction of hot fluids into geothermal wells is somewhat dependent upon the presence of natural or artificially induced fratures in the geothermally active rock matrix.

The tests performed using probe systems were developed by Southwest Research Institute for the U.S. Bureau of Mines and U.S. Army. The systems are basically geotechnical probes intended for use in shallow (1000 ft or less) vertical or horizontal boreholes. Electromagnetic and seismic probing techniques were evaluated as methods of detecting fractures in granite.

The report can be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. (Petroleum Information NGS 4-19-84)

4.5 Proceedings of Geothermal Review Meeting Available: Proceedings of the Geothermal Program Review II is now available for distribution through the National Technical Information Service, United States Department of Commerce, Springfield, Virginia 22161. The publication, sponsored by the United States Department of Energy Assistant Secretary, Conservation and Renewable Energy, Division of Geothermal & Hydropower Technologies, includes visuals and narratives presented at the Geothermal Review in October 1982 in Washington, D.C. (Petroleum Information NGS 4-19-84)

4.6 EPRI to Sponsor Workshop on Financing: Electric Power Research Institute will sponsor the eighth annual Geothermal Conference and Workshop June 25-29 at the Doubletree Plaza Hotel, 16500 Southcenter Parkway, in Seattle, Washington. The workshop theme is "Impacts of Third Party Financing on Geothermal Development." The program will consist of reports on major geothermal projects, utility projects, geothermal overview, research results and a discussion panel. (Petroleum Information NGS 5-11-84)

4.7 1985 GRC Conference to be Held August 26-30: The 1985 International Symposium on Geothermal Energy will be held August 26-30 at the Kona Surf Hotel, Kailua Kona Hawaii. There will be two days of single session invited presentations from various countries that have significant geothermal development, a day of optional field trips, and a final two days of triple session technical meetings. Information can be obtained from the Council, P. O. Box 350, Davis, CA 95617, telephone 916/758-2360.

SOUTH DAKOTA

State and DOE Activities

4.8 Heat Pumps Promoted at Home Builder Shows: The State geothermal team promoted the use of ground water heat pumps at home builder shows in Sioux Falls, April 5-8, and Rapid City, March 29 - April 1. About 1500 heat pump booklets were distributed. Sioux Falls activities were supported by the local ASHRAE Chapter.

UTAH

Industrial Activities

4.9 Second Production Well Completed at Cove Fort: Mother Earth Industries has completed a second production well, and are going into testing the two wells. These wells are located near the original abandoned well that experienced a blowout during drilling. Ormat generators are on site, but delivery of the turbines is pending steam characterization.

4.10 Turbine Purchased for Roosevelt H.S.: Utah Power & Light Co. let a contract to Biphase Energy Systems for installation of a 14,300 kw geothermal power unit at Roosevelt Hot Springs in Beaver County, Utah. The unit will use hot geothermal fluids and a mixture of steam and water under pressure to produce power in one step. Start-up is expected during first quarter 1986, and more units may be added as demand increases.

REGION IX

NEVADA

Industrial Activities

4.11 Geothermal Development Hearing Held in Reno: The status of geothermal development in Nevada attracted 23 state, federal and industry witnesses headed by NV Governor Richard Bryan at a one day hearing in Reno last month convened by Sen. Chic Hecht (R-NV) of the Senate Energy Committee (GR,2Apr,4). Long list of problems, roadblocks, hang-ups and what have you were paraded, some amendable to legislative solution, some not. Among them: increasing acreage limitation for leased Federal lands, increasing length of lease, extension of tax credits expiring next year and decreasing IRS temperature limitation on geothermal reservoirs from 50°C for tax deduction on cost of geothermal heating, etc.

Big hold-up in development of geothermal electricity in northern NV seemed to be Sierra Pacific Power's present maximum load requirement of 750 MW, against its current available capacity of 1000 MW, much of it inexpensive Bonneville power. Difficulty was seen in justifying development of probably higher cost geothermal, with built-in difficulty of new technology different from that at The Geysers. Some witnesses argued prudence of geothermal as new source of power, however, to ensure against future price hikes. Hearing also brought out fact Sierra Pacific has arrangements for three pilot geothermal projects with Phillips Petroleum, Geothermal Development Association's and National Energy Association's-Sequoia Thermal. Contracts for projects must be passed on by state PUC, however, and word is PUC will rule sometime this month (Geothermal Report 5-1-84).

4.12 Nevada BLM Requests Nominations for Geothermal lease Sale: The Bureau of Land Management, Nevada State Office, is requesting nominations of general areas of interest where competitive geothermal leases have been issued in the past for inclusion in an offering scheduled for late July or August. The leases should be either terminated or relinquished. Nominations could include a generalized list of Known Geothermal Resource Areas which contain the sections of interest. Nominations should be mailed to the Nevada State Director, BLM, 300 Booth Street, P.O. Box 12000, Reno, Nevada 89520, before May 30. For more information, contact Norm Melvin (702) 784-5133 (Petroleum Information NGS 5-4-84).

State and DOE Activities

4.13 1984 NV Bureau of Mines and Geology Publications List Available: The Nevada Bureau of Mines and Geology has published its 1984 Publications List. The catalog contains new material published by NBMG as well as a cumulative list of all NBMG publications on Nevada's geology and mineral resources, including reprints of previously unavailable items. Some of the earlier publications are available only as xeroxed or microfiche copies, but many libraries, including the Mackay School of Mines Library, have complete sets of the publications. The Bureau's publishing program includes bulletins, reports, maps, and special publications. The publications list also cited open-file maps and reports, and it features author and series indexes.

The new publications list is available free from the sales office (room 310 in Scrugham Engineering-Mines Building on the University of Nevada Reno, Reno, NV 89557-0088). For further information contact Arlene Kramer, telephone 702/784-6691.

4.14 New Maps Published by NBMF: The Nevada Bureau of Mines and Geology has published two new maps in its continuing Map Series, which is designed to provide information on Nevada's geology and mineral resources.

NBMG Map 77, "Geologic Map of the Yerington District, Nevada," by J. M. Proffett, Jr. and J. H. Dilles, is a geologic map of the Yerington district, including cross sections. The map depicts 53 geologic units and gives a geologic history of the district.

NBMG Map 79, "Quaternary Fault Map of Nevada--Reno Sheet," by John W. Bell, shows known Quaternary faults in the Reno 1x2° sheet. Faults are differentiated by age of most recent movement, illustrating the distribution of faulting related to moderate - to large-magnitude earthquakes.

Nevada Bureau of Mines and Geology Map 77 is available for $10.00; NBMG Map 79 is available for $5.00. The maps may be purchased at the sales office (room 310 in Scrugham Engineering-Mines Building on the University of Nevada campus) or by mail (Nevada Bureau of Mines and Geology, University of Nevada Reno, Reno, NV 89557-0088). For further information contact Arlene Kramer, telephone 702/784-6691.

4.15 Basin and Range Report Available: The Nevada Bureau of Mines and Geology has a new open-file report available to the public containing information compiled for the U.S. Geological Survey Task I Basin and Range Province Working Group.

NBMG Open-file Report 83-13, "Thirty-two Geologic Cross Sections, Clark, Esmeralda, Lincoln, and Nye Counties, Nevada, and Adjacent Areas in

California," by T. L. T. Grose, contains information on thirty-two geologic cross sections from eastern Nevada and southwestern Nevada and adjacent California. Cross section location maps are included, as well as a chart of lithologic units and a reference summary for each cross section--all of which show what rocks occur hidden below the Earth's surface.

NBMG Open-file Report 83-13 is available for public inspection in the Nevada Bureau of Mines and Geology unpublished-information office, located in Room 311 of the Scrugham Engineering-Mines Building on the University of Nevada Reno campus. For further information contact Becky Weimer-McMillion, 702/784-6691.

REGION X

IDAHO

Industrial Activities

4.16 Hydra-Co Enterprises Tasks Over Raft River Facility; Hydra-Co Enterprises, wholly-owned subsidiary of Niagra Mohawk and established by Syracuse, Ny utility to develop alternate energy sources, has been deeded Raft River 5 MW binary plant, wells and 560 acres of Federal land. After offering high bid of $750,000 for Raft River facility and real property near Malta, ID in General Services Administration disposal sale, physical possession by Hydra-Co had been held-up earlier this year pending completion of pro-forma Justice Dept. review to determine that no anti-trust problems were created as result of sale.

Charles J. Muoio, Hydra-Co vice president for cogeneration development, said it's still up in the air whether plant will be left at Raft River and its power sold locally, whether plant will be physically moved elsewhere, or sold to others, with heat from ID wells sold for direct use projects. These and other options are currently being examined. Idaho Power has filed suit against state PUC over avoided costs to be paid by utility to PURPA producers, and outcome of legal battle would affect decision of Hydra-Co to keep binary plant where it is for local sales. Muio said company expects to make up its mind on disposition of plant within 30 days (Geothermal Report 5-1-84).

State and DOE Activities

4.17 Boise Geothermal Work Continues: Work was completed on a $4,700 contract for a short pipeline extension on Short Street for the Boise districting heating project. Work on Idaho, Fulton and 9th Street received a low bid of $78,382, with part of the funding to come from the HUD Community Development Program. The second contract was awarded May 7, and work is scheduled to start in about a month.

4.18 Mountain Home Bostic 1A Well Data Available: Los Alamos National Laboratory has published "petrographic Analysis and Correlation of Volcanic Rocks in Bostic 1-A Well, near Mountain Home, Idaho." the publication, compiled by Barbara H. Arney, Jamie N. Gardner and Stephen G. Belluomini, contains a detailed analysis of the Bostic 1A well's geological samples. Copies may be obtained by writing the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

OREGON

Industrial Activities

4.19 Two Units Receive Bids at Oregon BLM Geothermal Lease Sale: Two units each received a single bid at the Bureau of Land Management's offering of Oregon lands for geothermal leasing held April 24 in Portland. Transpacific Geothermal Inc. submitted both bids for a total bonus of $41,895.63 on 4804.93 acres, an average of $8.72 per acre. The offering consisted of 10 leasing units comprising 18,379.83 acres within the Breitenbush Hot Springs, Carey Hot Springs and Vale Hot Springs known geothermal resources areas.

Transpacific acquired two of the five lease units offered in the Vale Hot Springs KGRA, including Tract #6, 2,243.53 acres, for $31,521.96; and Tract #7, 2,561.40 acres, for $10,373.67 (Petroleum Information NGS 4-27-84)

4.20 California Operator Planning Oregon Geothermal Exploratory Program: California Energy Co., Santa Rosa, California, has filed for permits to drill nine geothermal wildcats in an area approximately 50 to 64 miles northeast of Medford in the Winema National Forest in western Klamath County, Oregon. The wildcats, all targeted to 4000 ft., are the 3MZ Unit 1, 12-30s-6e; 4 MZ Unit 1,23-30s-6e; 6 MZ Unit 1,26-30s-6e; 9 MZ Unit 1, 11-31s-7 1/2e; 11 MZ Unit 1,15-31s-7 1/2e; 13 MZ Unit 1,27-31s7 1/2e; 1 MZ Unit II, 13-32s-6e 2 MZ Unit II, 14-32s-6e; and the 4 MZ Unit II, 23-32s-6e. The area is about eight to 12 miles southeast and northeast of Annie Spring, which has a temperature of 25 degrees Celsius, and 40 to 48 miles north-northwest of Klamath Falls Known Geothermal Resource area.

4.21 Publication of Klamath Falls Issued: The Oregon Department of Energy has issued "Geothermal Develpment in Klamath Falls, Oregon." The document, prepared by Lauren S. Forcella of the Oregon Department of Water Resources, describes both the cumulative scientific knowledge about the city's geothermal heating project, the conflicts and groups involved, and offers a comprehensive view of geothermal development in Klamath Falls.

WASHINGTON

Industrial Activities

4.22 Yakima County Jail Claims Big Energy Savings Using Geothermal: The Yakima County Jail recently went on-line with a geothermal heat pump system for heating and cooling the new $14 million facility designed by Paul R. Inman, Spokane, WA. The system operates from an 815 ft. production well and a 600 ft. injection well. The doublet is capable of pumping and disposing 700 g/pm of 76°F water. County jail administrator Doug Blair claims it costs about $4,000 per month to heat the 120,000 sq. ft. building compared to $24,000 per month before the geothermal system went on-line. Decision to go geothermal was based on a feasibility study performed by the OIT Geo Heat Center in 1979. Excess heat and cooled air will be piped underground to service other county buildings including the court house and a medical center. The Washington State Energy office has inlisted Paul R. Inman to investigate geothermal use of a similar system for the penitentiary at Walla Walla.

State and DOE Activities

4.23 Geothermal Heating for Fruit Processing Under Consideration: Yet another use of geothermal heating can be applied to WA's large fruit processing industry. According to Bloomquist, installation of such a system is being given serious consideration for plants in Grandview, about 35 miles southeast of Yakima on Yakima River. Warm water under there is in mid-70°F range, he said and is less expensive to heat than existing water sources at ground level which are much lower temperature.

Nobody knows exactly why, he said, but geothermally viable water can be found at relatively shallow depths in central Washington. To obtain water in mid-70 to low 80°F range, wells need only to be drilled to about 1500 ft. In most other parts of country, distance to water of similar temperature is double what it is here, Bloomquist said (Geothermal Report 4-2-84).

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GENERAL

5.1 Geothermal Economics Workshop Successful; The Geothermal Resources Council and the U.S. Department of Energy conducted a worshop on "Geothermal Economics and Related Institutional Factors" on May 21-23 at the Racquet Club, Palm Springs, CA. About 140 persons participated in the sessions that covered economic decision making, geothermal economics, sales contracts, avoided costs for small plants, management and financing.

5.2 Technology Transfer Session Held by USDOE: The U.S. Department of Energy held a workshop "A synthesis of Technology Transfer Methodologies" May 30-31 and June 1, 1984 at the L'Enfant Plaza Hotel, Washington, D.C. Representatives of USDOE, National Laboratories, National Science Foundation, NASA, National Acadamy of Science and Engineering, HUD, and the National Bureau of Standards participated in the meetings that emphasized the importance and need of transferring technology from the start through completion of research and development projects, especially with one-on-one contacts.

5.3 House Approves $30,087,000 Geothtermal Budget: The House of Representatives FY 1985 geothermal budget in thousands of dollars is as follows:

	FY-83 Approps.	Fy-84 Approps.	FY-85 Request	House Approvals
Hydrothermal Industrialization	$32,983	$2,000	$ 0	$ 0
Geopressured Resources	8,400	5,000	3,500	6,500
Geothermal Technology Dev.				
Hot Dry Rock Research	7,500	7,540	5,500	5,500
Hydrothermal Research	7,458	11,334	10,056	10,056
Hard Rock Penetration	0	2,640	4,600	4,600
Magna Energy Extraction	0	845	1,000	1,400
Technology Transfer	0	100	1,000	1,000
Salaries, administration	1,250	1,000	1,031	1,031
Total	$57,591	$30,459	$27,087	$30,087
Loan Guarantee Program	0	2,100	121	121

5.4 Economic Viability Seen in Smaller Geothermal Projects: For geothermal energy, small is beautifil. That, at least, is the opinion of L. Roy Mink, staff hydrologist, Morrison-Knudsen Company. Charged with the task of reviewing the status of geothermal energy in the United States, Dr. Mink told AAPG convention attendees in San Antonio last week that small projects are getting the industry back on track.

Regional Geothermal Progress Monitor (continued)

"The small, better-thought-out projects will provide an economic viability that will result in long, continuing use of geothermal energy," Mink said. Some promising projects are now occurring on a small enough scale to minimize risk, yet still show economic return, he reported.

This kind of approach appears much more productive than "the rapid failure of some of the larger systems we've seen in the past," he said.

While 50-megawatt plants were considered the minimum feasible size three years ago, now 20-megawatt plants are looked at as a maximum size, he said. The shift to five-to 20-megawatt power operations enables projects to come on line more quickly and help develop energy markets in stages, Mink noted.

The now-recognized complexity of geothermal reservoirs and the fluctuations of the energy market have changed the economics of geothermal energy considerably. Activity levels have dropped because much of the preliminary work in assessment has been completed. It has been government's philosophy to transfer actual power generation and heating project work to private industry, Mink said.

Formerly with the DOE and now based in Boise, Idaho, Mink listed California, Nevada and Utah as the main centers of interest for high temperature electric generation projects. Oregon, Idaho and Nevada were cited as key activity states for low temperature projects. (National Geothermal Service 6-1-84).

5.5 Western Status Mining Expo to be Held August 7-10: The Western States Mining Expo-84 will be held in Reno, NV August 7-10, 1984, where mining and rock mechanics will be discussed. Contact Dr. Yung Sam Kim, Nevada Institute of Technology, P.O. Box 8894, Campus Station, Reno, Nevada, telephone 702/827-0600 for details.

5.6 Hydrothermal Mineralogy Special Session Planned at GRC Annual Meeting: The Hydrothermal Mineralogy Group has tentatively scheduled an open meeting for the afternoon of Monday, 27 August 1984, as part of the 1984 GRC Annual Meeting in Reno, Nv. Anyone interested in research and the application of hydrothermal mineralogy in geothermal systems is invited to attend. For those interested in the hydrothermal session only, special one-day registration will be available. A generous portion of the session will be open to informal discussion of unresolved problems related to hydrothermal mineralogy, including active systems, epithermal mineral deposts, and low temperature secondary mineralization. All attendees will be encouraged to actively participate in the informal discussions.

The first meeting of the Hydrothermal Mineralogy Group was convened at the 1983 GRC Annual Meeting in Portland, OR to bring together representatives from universities, government agencies and laboratories, the metals industry, and the geothermal industry.

At this first meeting it was recognized that while hydrothermal mineralogy can be used as a guide for understanding the dynamics of geothermal systems, both active and fossil, only a small percentage of the geothermal industry in the U.S. is utilizing available information and techniques. Hydrothermal ore deposit research and exploration is providing extensive information about the dynamics and life of geothermal systems through analysis of fossil systems. Extensive studies of active geothermal systems are available for the Imperial Valley and Yellowstone National Park in the U.S., and for systems in Iceland, Japan, Mexico and New Zealand. Studies are also being conducted in the Cascades of the northwest U.S.

For more information, please contact Terry E. C. Keith, U.S. Geological Survey, MS 910, 345 Middlefield Road, Menlo Park, CA 94025, (415)323-8111 Ext. 4167, FTS 467-4167 or Al Waibel, Columbia Geoscience, 22495 NW Quatama Road, Hillsboro, OR 97124, (503)640-9877 (GRC Bulletin, May, 1984)

REGION VIII

North Dakota

State and DOE Activities

5.7 Heat Pump Seminar Planned for July 17: The North Dakota Energy Extension Service will hold a ground water heat pump seminar July 17 in Bismark. Speakers will include representatives from the State's Water Commission and Department of Health, University of North Dakota Energy and Experimental Station, private heating contractors, a utility, and the extension service.

South Dakota

Industrial Activities

5.8 Box Elder to Proceed with Geothermal System: The city of Box Elder is planning to proceed with a district heating system. Technical support was provided by the State Geothermal Team.

5.9 Watertown School to Install Heat Pump System: The Immaculate Conception School in Watertown will install a ground water heat pump system that will boost 50°F water to 160-180°F.

5.10 Heat Pump Workshop Set For Sioux Falls: A ground water heat pump workshop will be held July 10-11 in Sioux Falls. Contact Steve Wegman, Office of Energy Policy, Pierre, SD, Telephone (605)773-3603 for details.

REGION X

Idaho

Industrial Activities

5.11 Large Greenhouse Facility Under Construction at Bruneau: Leaf lettuce will be grown hydroponically in a one-acre greenhouse being constructed by Agri-Resources (Thurman Blake, Telephone (208)845-2070 in Bruneau). The lettuce is started in bottomless cups, transferred to styrofoam planks with the roots extending into the hydroponic fluid, and floated through long continuous tanks for harvesting at one end of the facility. The planks are replanted, returned to the other end of the tanks, and the process is repeated.

5.12 New Activity Scheduled for Idaho's Raft River KGRA

Geothermal Associated Products has scheduled location for six wells in the Cassia County portion of the Raft River Known Geothermal Resource area in southern Idaho. All of the ventures, comprising four development wells and two water injection wells, are in 15s-26e.

The development wells include the 1 Kristins Hope, in section 24, and the 2 J.W., 3 R.M. and 4 Lance, all in section 13. The two water injectors, the 1 and 2 GAPCO, are scheduled for sections 24 and 13, respectively. (National Geothermal Service 6-1-84).

5.13 Drilling Seminar Held in Boise: The Idaho State University Department of Engineering and Central Mine Equipment Co., St. Louis, MO sponsored a "Seminar on Drilling and Geotechnical Exploration" in Boise on May 1-3, 1984. The session focused on small diameter shallow (less that 500 ft) core drilling, including two afternoon drilling demonstrations. About 130 persons attended the event.

Oregon

Industrial Activities

5.14 Klamath Falls System Tryout Proceeding: A city ordinance that requires reinjection was challenged by the State, but was upheld by both circuit and appelate courts. The City of Klamath Falls subsequently amended the ordinance to permit temporary testing of the system that started in April and will end in June. Pending positive test results, the city could further amend the ordinance to permit permanent operation. An advisory group from a variety of agencies and public interest groups has been formed and will make recommendations on the system operation.

5.15 Belnap Hot Springs Heating System Operational: Heating system makeup for the Belnap Hot Springs Lodge from a nearby hot spring has been completed and is operating. Geoheat Center provided assistance for the design of the system.

Regional Geothermal Progress Monitor (continued)

State and DOE Activities

5.16 Oregon Trail Mushroom Co. Proceeding With Preconstruction Activities: A DOE loan guarantee has been finalized for a mushroom growing facility at Vale. CH2M Hill and Anderson and Kelly, both of Boise, ID, will perform engineering and geological consulting activities, respectively. The target project completion date is about January, 1985.

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JUNE 1984

GENERAL

6.1 Senate Appropriations Committee Restores State Resource Assessment Funds: Senator Pete Domenici (R-NM) felt hot dry rock effort at Fenton Hill, NM needed more money and persuaded the Senate Appropriation Committee last week to approve $2 million over the administration FY-85 request, upping total HDR funds to $7.5 million. The committee also restored to geothermal budget $2 million for State resource assessment program, increasing geothermal outlays by $4 million, to $31,087,000. The committee is shooting for senate action on DOE money bill next week.

The Senate's $4 million increase compares to House of Representatives' $3 million write-on for geopressured program. The Senate left geopressured drilling at the $3.5 million administration request. (Geothermal Report, 6-15-84).

Note: Final approval has $1 million for State resource assessment work.

6.2 Ocean Bottom Geothermal Development Being Investigated: Ocean bottom hydrothermal geothermal resources off the California and Oregon coasts and perhaps the Gulf of Mexico will be studied by EG&G Idaho to see if such applications as biomass conversion into oil and diesel-like transportation fuels appear economic.

The year-long technical-economic feasibility study has been requested by DOE's geothermal div., and Jack Ramsthaler of EG&G's geothermal group at Idaho Falls is managing the study. Geothermal div. sources said low level of funding will support an initial conceptual-type study.

Oceanographic research has found a number of underseas areas where geothermal hot water is released through what's thought to be fissures in earth's spreading crust, i.e. ocean spreading centers characterized by active volcanism. The Galopagos Islands are best known area of deep water geothermal-fed biosphere and recent discovery offshore from Ecuador at 8000 ft. found minerals from hot geothermal effluent deposited on ocean floor assayed at 10 per cent copper and 10 percent iron with smaller amounts of silver, zinc, cadmium, molybdenum and other valuable minerals of high assays.

MASSIVE ENERGY SOURCE. Ramsthaler says his generic type studies last year also began with review of oceanographic interest in geothermal minerals on ocean floor, but on finding USGS estimate that ocean geothermal energy approximated 2000 year supply "equal to entire world's energy," became convinced someone should study, "How do we use it?"

More precisely, Sandia report on magma energy roughly estimated that amount of energy in ocean spreading centers is 0.15 x 10^6 quads equivalent to 2,000 to 100,000 year U.S. energy supply at current annual total energy consumption rate of 75 quads.

Most recent discovery of about 300°C sources at 8000 ft. depth off CA and 6,000 ft. depth off OR will be considered by EG&G. If agreement can be arranged with Mexico, resources in Gulf belonging to that country and off Guaymas across from Baja California in Gulf of California may be included in investigations.

Idea is to develop geothermal heat in pipeline for process applications rather than generation of electricity due to difficulty of returning power to mainland involved in latter. One primary application to be concentrated on is possibility of using geothermal temperatures and high 3000 psi pressures as found off CA-OR shoreline in "reductive formulation" process, form of low temperature pyrolysis, which converts biomass into petroleum in short time, hours and days, instead of millions of years required by natural processes.

Use of kelp seaweed as biomass to be turned into oil was at first considered, but notion of gathering it along beaches has been discarded. This is because not only is gathering and transporting biomass in bulk to point of use non-economic, but also removal of kelp on appreciable scale along coast brings with it ecological drawbacks of erosion of beaches, loss of fish food and destruction of ecosystems. But Ramsthaler pointed out at ocean floor drilling site, kelp could be farmed and raised over it with nutrients transferred from lower waters on which kelp could feed.

Other biomass being looked at for suitability of conversion to petroleum are algae and coal, though latter almost certainly would entail disadvantage of transportation cost to geothermal site, plus its initial cost as source of energy.

OCEANWIDE DEVELOPMENT. Admitting to difficulty of deep ocean drilling, Ramsthaler points out Shell Oil has drilled in 6800 ft. of water to well depth of 7000 ft. with its dynamic positioning ship. Acoustic beacons located on sea bottom allow ship's computer to calculate its position and make appropriate corrections. Drill ships like Shell's now have capability to drill into ocean spreading centers of average 2.5 Km depth and to tap magma resource about 1 Km below surface. And to overcome antipathy felt by most to working on ocean bottom, Ramsthaler points out "world of robotics and remote handling are zipping ahead" and costs are coming down, spearheaded by Japanese technology. "Costs of remote handling are getting cheaper and cheaper," he said, and maybe with another 20 years progress geothermal development all over the oceans will be economic. (Geothermal Report 7/2/84).

6.3 Sandia Researching Electrically Conductive Fluids in Geothermal Wells: Researchers at Sandia National Laboratories in New Mexico think that injecting an electrically conductive fluid into the earth can increase the effectiveness of geothermal energy systems. The Sandia scientists also believe that the technique might enhance the success of hydraulic fracturing, used to free natural gas and oil trapped in underground rock formations.

The technique - called "surface electrical potential" or SEP - causes the areas where the fluid flows to have an electrical resistivity different from the surrounding rock. Measurements are taken as current travels through the borehole, into fractures, and into a current return well located several kilometers from the test site. Technicians can then produce a map showing the direction that the fluid has travelled, revealing information about discontinuities and fractures in the formations.

Sandia used the SEP system in conjunction with an acid stimulation of a Chevron well in the Beowawe geothermal field in Nevada, part of a Department of Energy program. Many geothermal systems must be stimulated because the minerals that occur in these environments clog fractures and reduce flow. An acid wash removes the clogs.

The Sandia researchers proclaimed SEP a success and are now planning to test it as a tool for determining the effectiveness of hydraulic fracturing; where fluid is pumped into an oil or gas formation at high pressure, cracking the rock. SEP might allow engineers to create a picture of the fracture to see how well the process is working. (Energy Daily 6/18/84)

6.4 Kenya to Drill 20 Wildcats: kenya received a $24.5 million loan from the World Bank's International Development Association affiliate to help pay for a $34.3 million geothermal exploration and fuels study project. Twenty wildcats and appraisal wells will be drilled in two areas of the Rift Valley, Olkaria, near a site where Kenya already taps geothermal steam for power generation, and Eburru. The project also calls for studies of the country's geothermal development program, potential for oil shale development, and natural gas market. (Oil and Gas Journal 6/18/84).

6.5 Geothermal Tax Credits not Extended: Geothermal tax credits, as part of renewable energy credits granted under National Energy Act of 1978 and other Federal laws since, weren't extended by conferees on tax bill to raise $50 billion in revenue over next three years. Huge bill containing armful of tax changes dropped provision to extend credit for both geothermal business and residential taxpayers beyond Dec. 31, 1985. Conferees' agreements were accepted by Senate and House of Representatives and bill passed last week.

Residential taxpayers now get 40 percent nonrefundable tax credit for geothermal investments for heating or cooling both new and existing residences up to $10,000 per year, yielding maximum tax credit of $4000. This credit now expires on December 31, 1985. Geothermal businesses receive special energy tax credit of 15 percent on their federal taxes for geothermal investments under 1978 Act, beyond 10 percent regular investment tax credit for business in general. This 15 percent incentive would be lost after 1985, under conferees' actions.

Further, conferees agreed to drop 25 percent credit for energy research-development provided under Economic Recovery Tax Act of 1981, which applied to R&D made after June 30, 1981 and before January 1, 1986.

Latest tax bill didn't affect such geothermal tax breaks as 22 percent depletion allowance sinking to 15 percent by this year and in future years, deduction of intangible drilling costs on same basis as oil and gas wells, accelerated depreciation deduction and federal tax exemption for interest on industrial development bonds used to finance certain alternative energy projects. (Geothermal Report 7/2/84).

REGION VI

NEW MEXICO

COMMERCIAL ACTIVITIES

6.6 Activity on Industrial Park Development Near Las Cruces Continues: Crown Geothermal Ltd, formerly Chaffee Geothermal, is targeting Agribusiness for its proposed geothermal industrial park that will be located near the New Mexico State University campus heating project. The resource has been defined, with wells producing 140-160°F waters flowing 1000 to 2500 gpm per well. The States Energy and Minerals Department is assisting in the search for financing the project that is in an excellent location.

6.7 Prawn Facility Under Investigation for Hidalgo County: Hidalgo Energy Enterprises, Inc. is looking at a possible joint venture with an Israeli firm to develop a prawn farm in Hidalgo County. The developers are also considering binary power generation to meet facility needs. The specific site has not been selected.

STATE AND DOE ACTIVITIES

6.8 Greenhouse Work Continues Near Animas: A geothermal greenhouse facility is developing near Animas in Hidalgo County for the production of roses. Tom Beal, the developer who relocated to the area from the State of Washington, has been assisted by the States' Energy and Mineral Department who provided matching funds ($75,000) through a 1982 appropriation for geothermal development. Major construction activity started in January of this year, resulting in the erection of one 24,000 square foot facility containing about 15,000 roses. Another similar sized unit is planned for the near future. One geothermal production well has been drilled and will be hooked into the system that is expected to be operational for the full heating season. Other unique features include fog nozzle watering and solar film glass applications.

6.9 Temperature Gradient Funding Still Available: The State Energy and Minerals Department has provided funding to New Mexico State University to support temperature gradient drilling in the State.

About one-half of the original $100,000 appropriation is available on a 100% cost shared basis. Most of the interest so far has been received for the southern part of the State. Jack Whittier, 505/646-1745, at NMSU is the contact for this program.

6.10 Chris Wentz Assumes Geothermal Lead in State Energy and Minerals Department: Chris Wentz has recently been assigned geothermal related responsiblities for the State of New Mexico Energy and Minerals Department, replacing George Scudella who has effectively filled the position since early in the State's geothermal program history. Chris may be reached at the NM Energy and Minerals Department, Resource and Development Division, 525 Camino De Los Marquez, Santa Fe, NM 87501, telephone 505/827-5994.

6.11 Hidalgo County Assessment is Proceeding: New Mexico State University is assessing the geothermal potential of Hidalgo County with funding provided the the State's Energy and Minerals Department. The work, focussing on reservoir characteristics, is expected to continue for about one year.

6.12 Four New Geothermal State Maps Available: The National Geophysical Data Center has published a set of four New Mexico state maps in the "Geothermal Resources of New Mexico: Scientific Map Series." Included in the set is one paper base map, "Late Tertiary and Quaternary Tectonics and Volcanism," and three clear-plastic overlays: "Bouguer Gravity Anomaly Map of New Mexico," "Composite Residual Total Intensity Aeromagnetic Map of New Mexico" and "Hydrology and Geochemistry." For further information, contact NGDC, NOAA, Code E/GC1, 325 Broadway, Boulder, Colorado 80303. Phone is 303/497-6125. (National Geothermal Service 7-6-84).

REGION VIII

COLORADO

STATE AND DOE ACTIVITIES

6.13 Pagosa Springs Heating Project Testing Proceeds: The Colorado Department of Water Resources has requested that a technical person monitor the end of season geothermal flow test at Pagosa Springs. A hydrologist from EG&G Idaho is checking out pre-test and early-test conditions to assure the satisfactory acquisition of data. The test is expected to start in the latter part of July.

MONTANA

STATE AND DOE ACTIVITIES

6.14 Montana Sites Toured as Part of Technical Support Work: Representatives of the OIT GeoHeat Center and the State geothermal office visited twelve sites in the state that had requested technical assistance through the OIT grant work. The visitations occurred during the last week in June. Space heating is being considered at a number of locations, and a district heating system is under review at White Sulphur Springs. Murphy Oil Company, Poplar, has resource capabilities of about 500 gpm at 205°F, and is looking at binary cycle power generation because of oil field electric costs of $18,000 to $21,000 each month. Information gathered from the trip is currently being evaluated at the GeoHeat Center.

SOUTH DAKOTA

STATE AND DOE ACTIVITIES

6.15 Field Use Computer programs Unveiled at Sioux Falls Workshop: The State geothermal team conducted a heat pump workshop in Sioux Falls where about 35 contractor and utility personnel were advised of the teams' developing computer programs for heat pump use. The programs, suitable for home computer use, are expected to be available about years' end. Contact Steve Wegman, 605/773-3603 for details.

UTAH

STATE AND DOE ACTIVITIES

6.16 Utah State Prison Final Construction Inspection Completed: The final construction inspection was held at the minimum Security Building marking final completion of the ninth successful low-temperature geothermal project administered by the Idaho National Engineering Lab (INEL) under the DOE Program Opportunity Notice Program. The project started in 1978 and provided for cost-sharing between the private sector and the federal government to develop geothermal resources. These projects serve as field experiments to demonstrate the technical and economic feasibility of moderate temperature geothermal energy systems. (Temperatures involved are less than 200°F). Nine of 13 projects could not be completed because of problems, such as inadequate flow or low water temperature. Capital investment in the 13 geothermal projects was $14.2 million. The nine operational projects can save about $2.15 million per year in avoided crude oil import costs.

REGION IX

CALIFORNIA

Commercial Activities

6.17 Susanville District Heating Development Continues: Use of the Susanville district heating system during the 1983-1984 heating season was limited to seven high school buildings because the injection well would only accept 150 gpm. Starting with the 1984-1985 heating season, discharge permits have been obtained to enable the connection of seventeen public buildings and 23 homes to the system. This summer, a 5000 ft. pipeline is being built to connect the residential loop to the system.

6.18 Calistoga Mini-District Heating System Underway: Ground was broken June 12, 1984 by initiating drilling of a geothermal well for the purpose of providing heat to the Calistoga city hall, police station and museum. Depending on a successful drilling, plans call for the use of a downhole heat exchanger system for the mini-district heating system.

STATE AND DOE ACTIVITIES

6.19 Heat Cycle Research Testing Continues: Thermal loop testing of the propane family of working fluid mixtures in the Heat Cycle Research Facility at East Mesa, CA was completed early in July by EG&G Idaho. Turbine repair and modification work is being performed by Barber-Nichols, and the assembly is expected to be delivered to the site before the end of July. Accelerometers will be used after startup to monitor the assembly vibration "signature" to watch for changes to detect problems before serious damage occurs.

6.20 Hybrid Plant Well Development Continues: GeoProducts has completed drilling of a second well for a hybrid geothermal-woodburning power plant to be built near Susanville. Testing of the second well indicates the geothermal fluid quantity to be an order of magnitude poorer than the first.

6.21 Success Story at Fort Bidwell, CA: In May 1979, Lucinda Lame Bull, Fort Bidwell Indian Reservation (west of Alturas), requested that GeoHeat Center personnel visit the reservation and speak to the tribal council about the possibility of using the geothermal resource within the Fort to relieve the unemployment problems. (The known resource, an abandoned artesian well, flows at 113°F.) GeoHeat Center provided a presentation of geothermal use, and discussed possible applications. Subsequently, a short report was provided on types of space heating systems, greenhouse sizes, and aquaculture applications that could be utilized with the then available and projected resource. Using this information, the tribe applied for and received grant funds from the State of California. One consulting firm provided preliminary design of space heating systems for the new apartment complex for the elderly, health clinic and several existing tribal community buildings; the other provided a geological and geophysical study. As a result of the geologic work, another well was successfully completed, providing more than enough water for the proposed space heating, and the original well flow was increased through refurbishing. Construction of the apartment complex and clinic were completed in 1983, and the tribal community building and a large old gymnasium were retrofitted for geothermal heat. Shortly after, a small greenhouse was constructed and is providing a few jobs and vegetables. The tribal council is receiving bids for the construction of catfish raceways, and an ex-employee of the GeoHeat Center, Bill Johnson, is teaching classes in aquaculture for tribal members in preparation of opening a small commercial aquaculture operation. Instrumental in the success of the tribes in their venture is a new administrator, Richard Della, who took office in 1981. Richard plans to construct additional greenhouse facilities, or attract a greenhouse operator to the area to expand the greenhouse operation and provide more jobs for tribal members.

NEVADA

COMMERCIAL ACTIVITIES

6.22 Magma Joins With Steam Reserve on Leaseholds at Fish Lake: At Fish Lake in Western Nevada about 40 miles from Bishop, CA, Magma has leaseholds and has joined with Steam Reserve, subsidiary of Amax Exploration, in unit on which 11 heat gradient wells have been drilled to 2000 ft. Aidlin was high on Fish Lake prospects where temperatures close to 400°F have been reported because, like Dixie Valley, NV, its location permits serving large population centers in CA on economic basis. (Geothermal Report 6/15/84).

6.23 Dixie Valley Not Part of Sun's Geothermal Disposal: Sun Oil's prime holdings at Dixie Valley, NV, 8,000 acres in middle of geothermal prospect plus acreage in outer reaches of Valley increasing total holdings to about 12,000 acres, aren't part of geothermal properties being disposed of by Sun. First official word of Sun's geothermal properties headed for auction block came from Robert McClements, Jr., Sun President and CEO, in Oil and Gas Journal issue of May 28th, stating company is discontinuing geothermal operations in drive to cut costs and streamline company.

To clarify McClements' remarks, Garland E. Robbins, head of Sun Geothermal in Dallas, said CEO was referring to disposal of geothermal exploration activities which actually had begun last Fall and closing out of Sunoco Energy Development office in Dallas, of which up until then geothermal exploration/development had been part. Robbins said apart from Dixie Valley, Sun has about 50,000 acres of leased geothermal lands in California, Oregon and New Mexico, including about 200 acres of producible, shut-in wells at The Geysers.

Robbins said company is now talking to interested parties at any number of these locations where sales are ongoing, but that he was unable to attach any total estimated value to properties.

Out of Sunedco, Sun Geothermal was established on January 1, 1984 primarily to manage Dixie Valley development. "We're going ahead there, securing permits and right of ways," Robbins said, for building 200 miles transmission line to Bishop, CA and working out sales contract with Southern California Edison. Few hundred acres of Dixie acreage are owned in fee by Sun, but rest is Federal land held on leases. Robbins said most of land for transmission line is held by BLM or counties and that he hopes to have all right of way permits in hand by first quarter of 1985. (Geothermal Report 7/2/84).

STATE AND DOE ACTIVITIES

6.24 1983 Mineral Industry Review Published

"The Nevada Mineral Industry 1983," a Nevada Bureau of Mines and Geology special publication, is now available. NBMG Special Publication MI-1983 is the fifth report in an annual series. Activities in Nevada during 1983 are detailed, including mineral exploration and development programs, oil and gas drilling and production, and geothermal exploration and development. A section on bulk-mineable, precious-metal deposits is included, as is a directory of operating mines in Nevada. The directory lists the location and type of mine, the primary mineral commodity produced, the average number of workers, and owner information.

The document may be purchased for $5.00 at the sales office (room 310 in the Scrugham Engineering-Mines Building on the university campus in Reno) or by mail (please add 10% postage and handling; Nevada Bureau of Mines and Geology, University of Nevada Reno, Reno, NV 89557-0088), or contact Arlene Kramer: 702/784-6691.

6.25 Grose Joins NBMG for Summer: T. L. T. Grose, Professor of Geology at the Colorado School of Mines, has joined the Nevada Bureau of Mines and Geology for the summer as a Research Associate. Grose and his students have been mapping areas in Western Nevada for many years.

Grose is mapping the geology of the Glenbrook and Marlette Lake quadrangles near Lake Tahoe. The maps will detail the geology of the two quadrangles and will serve as the basis for Earthquake Hazards Maps of the areas.

Grose is stationed at Zephyr Cove; mapping of the Glenbrook quadrangle is expected to be completed this summer, and Marlette Lake is scheduled for completion in the summer of 1985. For further information, contact John Schilling: 702/784-6691.

6.26 Beowawe Assessment Report Available: "Beowawe Geothermal Resource Assessment - Final Report, Shallow Hole Temperature Survey, Geophysics and Deep Test Hole Collins 76-17" is available at a cost of $3.00 (prepayment required). Contact Earth Science Laboratory, University of Utah Research Institute, 391 Chipeta Way, Suite C, Salt Lake City, UT 84108.

REGION X

IDAHO

COMMERCIAL ACTIVITIES

6.27 Intermountain GRC Group Tours Mackay Earthquake Area: The Intermountain Section of the Geothermal Resources Council, as part of a continuing annual visitation to areas of geothermal interest, toured the Mackay earthquake zone on June 23 to view the effects of the 7.3 magnitude October 29, 1983 earthquake.

Brent Russell, Manager of EG&G Idaho Geosciences, supported by Bill Downs and Jack Barraclaugh of that organization, provided an overview of the earthquake effects and the geology of the Snake River Plain, including Lost River hydrology and lineal features on the Idaho National Engineering Laboratory. The successful and informative bus tour outing was attended by 38 persons.

6.28 New Officers Elected for Intermountain GRC Chapter: Bill Domenico is the new Chapter President, Brent Russell is serving as Vice President, The Secretary post will be filled by Eldon Bray, and Tony Allen is the Treasurer. The Board is made up of Ron Hilker, Ben Lunis and Susan Prestwich. The officers are employed by EG&G Idaho (Idaho National Engineering Laboratory), or the Idaho Operations Office of DOE.

STATE AND DOE ACTIVITIES

6.29 Boise District Heating Work Continues: Boise city officials met with the Boise School Board on June 11. They plan to move ahead in parallel to simultaneous bid openings in August for a pipeline extension and school hookup. The Boise High School will be the largest district heating customer with 136,000 ft. and a peak geothermal fluid flow rate of about 250 gpm.

6.30 Magic Reservoir Area Geology Report Available: The Earthscience Laboratory, University of Utah Research Institute, 391 Chipeta Way, Suite C, Salt Lake City, Utah 84108, has "The Geology and Geothermal Setting of the Magic Reservoir Area, Blaine and Camas Counties, Idaho" available at no charge.

OREGON

COMMERCIAL ACTIVITIES

6.31 Geothermal Advisory Committee Organized for Klamath Falls: A committee has been created to advise appropriate governing bodies and developers on all matters concerning Geothermal resources in Klamath County. It will propose safeguards adequate to protect existing use, pose a gradual development plan for the unused resource potential, recommend priorities of use, oversee and maintain continued long term well monitoring and inventory, and provide a community resource information center. The committee is made up of a cross section of the community through representation by twelve organizations from local, state and federal sources. Each organization has two members with one vote each. Paul Lienau, OIT Geo Heat Center, was elected Chairman.

6.32 Lakeview Wellhead Generators Operated for Siting Council: The Lakeview binary system wellhead generators were operated for a few hours on June 28 for the Oregon Energy Facility Siting Council. Although the council is responsible for facilities over 25 MW, their interest in the technology of the 1 MW installation occasioned the plant operation. PUC approval, installation of a cooling tower, and a long term well test are needed to finalize the project.

6.33 Concerns Raised About Exploration Near Crater Lake: Representatives of three federal agencies will meet soon to try to satisfy concerns about geothermal exploration near Crater Lake National Park. The present plan is for California Energy, Inc. to drill four test holes to 4000 ft. depth near the park's last boundary and take temperature readings and core samples. Drill sites are about four miles from the lake on the Weinema National Forest. The Forest Service and Bureau of Land Management have approved the environmental assessment for the drilling. Park Service concerns, labeled primitive, potential, and unforseen long term impacts, deal with later exploration or development. California Energy, Inc. is working under contingent rights stipulation, a policy developed by the Interior Department that involves assessments of the individual stages of a project. The present document does not address impacts of full development. If the questions are not answered in EA actions, an environmental impact statement will be required. This approach will cancel drilling for this year, according to Art Du Fault, Weinema National Forest supervisor.

STATE AND DOE ACTIVITIES

6.34 Loan Guarantee Provided by DOE for Vale Mushroom Growing: DOE, acting through the Geothermal Loan Guaranty Program, has agreed to guarantee 95 percent of a $6 million construction loan from Idaho First National Bank, Boise, for installation of an $8 million semi-automated mushroom-growing facility in Vale, OR, which will use geothermal energy both for heating and cooling. Utilizing four existing 200-250°F wells 60-100 ft. deep, the plant will yield approximately 3.2 million lbs/yr of mushrooms. They will be marketed through a brokerage arrangement with Oppenheimer Co.'s, Boise-based international food sales organization. Startup will be no later than December 31, which will allow investors to take advantage of tax credit before year's end. Of total plant cost, $2.2 million will be for geothermal equipment, including pumps, piping and refrigeration. (Geothermal Report 6/15/84).

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UNIVERSITY OF UTAH
RESEARCH INSTITUTE
EARTH SCIENCE LAB.

REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
JULY 1984

7.1 DOE FY 1985 Budget Approved by Senate and House: The DOE FY-85 budget was approved by both the Senate and House of Representatives with $32 million included for conducting the geothermal R&D program.

Senate conferees got $7.5 million for hot dry rock research conducted by Los Alamos National Lab at Fenton Hill, NM, $2 million more than the House recommendation of $5.5 million. In return, House conferees got $5.5 million for geopressured well testing, which was $2 million more than the Senate had allowed. The Senate had restored $2 million to geothermal requests for State resource assessment programs, which the administration had zeroed, and the House hadn't seen fit to restore. Conferees split the difference and left the State program at $1 million.

The total geothermal budget request approved by Congress was $32,087,000, compared to the administration request of $27,087,000, or $5 million in add-ons by Congress. (Geothermal Report 7-16-84)

7.2 BLM Asks for Comments on Leasing: The Bureau of Land Management is considering offering smaller parcels in its simultaneous onshore leasing program and wants comments from the public by October 11.

Presently, parcels may not exceed 10,240 acres (except in Alaska). BLM is considering offering leases of 2,560 or 5,120 acres.

"This inquiry is in response to the concerns raised by the public that large lease tracts are undesirable and burdensome. Tract size for simultaneous oil and gas leases is established as a matter of policy and is not set by regulation," BLM explained. (OGJ Newsletter 7-23-84)

7.3 PBA Revises Load Forecast: The Bonneville Power Administration is updating its forecast of electricity requirements in the Pacific Northwest for the next 20 years. The new BPA forecast embraces three possiblities - 1, medium and high growth - and assumes average annual load growth of between 0.5 percent and 3.4 percent. The 20-year forecast is somewhat changed from last year's version: the high case is up slightly from what was forecast in 1983 while the medium and low cases are down:

- In the high case, BPA sees a need for 28,800 megawatts of capacity in the Pacific Northwest by 2003; the 1983 forecast was 28,100 megawatts.
- In the medium case, BPA forecasts demand of 22,200 megawatts in 2003; last year it was 22,700 megawatts.
- In the low case, demand is expected to be 17,400 megawatts, down markedly from last years projection of 19,600 megawatts.

Bonneville claims that its three new forecasts are "compatible" with the regional forecast contained in the Northwest Power Planning Council's plan, adopted in April '83. BPA's high and medium forecasts are roughly comparable to the regional council's high and medium-low projections; BPA's low case is somewhat lower than the council's low forecast. (Energy Daily 7-25-84)

7.4 United Nations Holds Geothermal Conference: The United Nations Economic Commission for Europe (not to be confused with the European Economic Community) sponsored a conference on Utilization of Geothermal Energy for Electric Power Production and Space Heating. This conference was held in Florence, Italy May 14-18, 1984, with about 100 attendees in all. Attendance from Iron Curtain countries was sparse while Italy had the largest representation.

Considerable emphasis was placed on electricity generation and the following statistics may be of interest. In 1960, the worldwide geothermal capacity was 375 MW. This increased to 2,800 MW by 1982 (940 in U.S. and 450 in Italy), and is projected to increase to 5,000 MW in 1986.

Considerable emphasis was placed on electricity generation and the following statistics may be of interest. In 1960, the worldwide geothermal capacity was 375 MW. This increased to 2,800 MW by 1982 (940 in U.S. and 450 in Italy), and is projected to increase to 5,000 MW in 1986. Nineteen percent of El Salvador's total energy use of 500 MW is geothermal, as is 12 percent of the Phillipines' nearly 5,000 MW, and 10 percent of Nicaragua's 1,370 MW. Worldwide, most turbine/generator units are 30 MW or less, but The Geysers claim the largest, 130 MW. (Geothermal Report 8-1-84)

7.5 Personnel Changes Occurring at DOE: Richard Benson, Director of Office of Renewable technology, is transferring the end of this week to a new job at the Los Alamos National Laboratory where he will head various environmental and, possibly, geothermal programs. No replacement in Washington has been named. Allen J. Jelacic is transferring to the nuclear waste program within DOE in Washington, after heading the Hot Dry Rock program since 1979, and more recently the geopressured program. No replacement has been announced, although James Rannels succeeded Jelacic as the HDR program manager previously having served in DOE solar programs.

Marshall J. Reed has also joined the DOE geothermal staff as an earth scientist within the technology development branch. He is responsible for reservoir definition, brine injection, and state resource assessment programs. Reed was previously with the U.S. Geological Survey, and has worked as liaison officer between DOE geothermal division and the Survey. Presently, the Survey's liaison position is held by Raymond H. Wallace. Dave Lombard, who has served as Benson's assistant for the past 7 months, says he expects to continue in the same capacity with the new director of renewables. (Geothermal Report 8-1-84)

7.6 Soviets Starting "Hot Rocks" Project: The Soviet Union has drilled the first well for its first experimental "hot rocks" geothermal electrical power plant in the western Ukraine near the Carpathian Mountains.

First stage of the project will produce only 10,000 kw-hr/year. Plans call for increasing the plant's capacity "by tens of times" if tests are successful.

The first drilled to dry, hot rocks is about 4,000 m (13,123 ft) deep. Bottom hole temperature is 200°C. A second well will be drilled shortly.

Cold water injected to the hot rocks will be obtained from a nearby river.

The Moscow newspaper Sotsialisticheskaya Industriya (Socialist Industry) says that despite sizable initial expense, hot rocks geothermal plants can produce electricity at a cost comparable to that for conventional thermal and nuclear power plants. In addition, the paper emphasized, hot rocks geothermal power stations are pollution free. (Oil & Gas Journal 7-23-84)

REGION VI

NEW MEXICO

Commercial Activities

7.7 Las Cruces Looking at District Heating Possibilities: The City of Las Cruces has enlisted the assistance of Jack Whittier, NMSU Energy Institute and CH_2M Hill to investigate the potential for the city to become involved in the district heating business. The New Mexico Energy and Minerals Department provided $35,000 for the study. (Jack Whittier, NMSU Energy Institute)

REGION VIII

UTAH

7.8 Commercial Activities

Provo to Buy Geothermal Electricity: The city of Provo, Utah, expects to begin receiving next fall power produced at two dry steam geothermal wells located about 130 miles away from the city.

Provo has contracted to purchase all of the power output of wells at a geothermal tract being developed by a Connecticut firm, Mother Earth Industries. Geologists have said the power output from the tract could reach 200 MW, according to Bud Bonnett, Provo utility director. The first two wells drilled by the company produced a high quality steam, Bonnett said. The company plans to drill additional wells this summer.

Provo is working on an agreement with Utah Power & Light Co. to have the geothermal power wheeled from the wells to the city.

The city will pay about six cents per kWh for the initial 2.8 MW of power. The rate is higher than the city's average cost of power, but Bonnett said the premium is paid "with the realization that we have to help them get off the ground." (Public Power Weekly 5-14-84)

7.9 UP&L Experiencing Pump Problems at Milford No. 1: UP&L's Milford No. 1 plant at Roosevelt Hot Springs has rolled its turbines, but problems with surface transmission pumps have prevented regular operations. The single flash plant of 20 MW that was scheduled to be in operation this spring, and the 14.3 MW Milford No. 2 Biphase unit scheduled to startup in early 1986, contribute to UP&L plans to have geothermal supply up to 5 percent of the company's future energy requirements. Experts have estimated that the Roosevelt reservoir could produce 200,000 to 400,000 KW for 35 years.

The first production at Roosevelt was from a 1500 KW Biphase unit which began November 10, 1981, and UP&L says all its units will continue to tap this reservoir. Milford No. 1 will be the "nation's first permanent, commercial geothermal electric-generating plant outside California," says UP&L. The No. 3 unit is planned for 1987, if the development cycle goes well at Roosevelt.

UP&L's existing steam plants, almost exclusively coal-fired, supplied 94 percent of the company's 1983 electrical generation, worth $855 million in revenues. The rest of the company's electricity came from hydro plants, and UP&L has no nuclear facilities. Its' latest, Hunter Plant No. 3, was completed in 1983 and cost $452 million, or $1130/KW. UP&L also mines its own coal, and with the Hunter Plant being located about 13 miles from the coal mines, i.e. no big haulage costs, coal provides a low cost target.

The Milford No. 2 geothermal plant costs were $748/KW, not including site civil work, piping, wiring, etc., or Phillips geothermal brine gathering costs. Milford No. 1, estimated at $23 million, or about $1150/KW, will be interesting to note, once finally added-up, and more interesting yet to compare with PG&E's 120,000 KW Unit No. 20 at The Geysers using dry steam and estimated to cost $216 million, or $1900/KW. (Geothermal Report 7-16-84)

WYOMING

Commercial Activities

7.10 Geothermal Study of Southeastern Wyoming Basins Available: Geothermal resources in the Laramie, Hanna and Shirley basins of southeastern Wyoming are discussed in a report recently published by the Geological Survey of Wyoming. The report is the first of six to result from a five year study through the University of Wyoming's Department of Geology and Geophysics. The study made use of oil well bottomhole temperatures, thermal logs of wells and heat flow data, all within the framework of geological and hydrological information, to determine the geothermal regimes in the basins and to predict where the states potential geothermal resources exist.

The 26-page report, "Geothermal Resources of the Laramie, Hanna, and Shirley Basins, Wyoming," includes four folded map sheets: A geological map, a thermal gradient contour map, a structure contour map on the top of the Cloverly formation and a ground-water temperature contour map of the Cloverly and Morrison formations. The report is available as Report of Investigations No. 26 from the Geological Survey of Wyoming, Box 3008, University Station, Laramie, Wyoming 82071. The survey phone number is (307)766-2286.

REGION IX

CALIFORNIA

Commercial Activities

7.11 Exploration at Medicine Lake KGRA Continues: A deep test well is being drilled by Phillips Petroleum near Medicine Lake volcano, located about 55 kilometers northeast of Mt. Shasta. Approximately 20 temperature gradient holes have been drilled in the Medicine Lake area over the past several seasons. Five holes are permitted between 2000 and 3000 ft. deep. Occidental, the operator at the site, is currently drilling a temperature gradient hole near the test well. Union Oil is also working in the area, with all companies continuing with geophysical work. (Paul Lienau, OIT)

7.12 Southern California Edison to Buy Geothermal Plant's Output: Republic Geothermal Inc. has a buyer for the 24,000 kilowatts of electricity to be produced by its East Mesa geothermal project in California's Imperial Valley. Republic has signed a 30-year power purchase contract with Southern California Edison for the power from the East Mesa project, scheduled to start operating early in 1986. Southern California Edison will also buy the output from another geothermal project in which Republic is involved. Together with Parsons Corp., Republic is also building a $135-million plant in Niland, Calif., that will produce 25,000 kilowatts at first, to be expanded later to 49,000 kilowatts. (The Energy Daily 7-30-84)

NEVADA

Commercial Activities

7.13 High-Efficiency Biphase Turbine to be Installed at Phillips Desert Peak Plant: Phillips Petroleum has bought a 10 MW Biphase rotary separator turbine for use at Desert Peak, which is about 50 miles northeast of Reno. Output from the plant will be sold to Sierra Pacific Power of Reno.

The Phillips-designed plant is scheduled for operation in the 3rd quarter of next year. Some site excavation already has begun in anticipation of the first equipment shipment late this year from Biphase Energy Systems Division of Transamerica Delaval. The Biphase rotary separator turbine uses the liquid portion of the geothermal fluids, as well as steam, and is calculated to deliver up to 30 percent more power than conventional systems from the same well flows. No costs for plant or equipment have been given by Phillips or Biphase.

At odds with any claim of the Phillips Desert Peak plant being the first geothermal unit in Nevada, Bob Bassett, Sierra Pacific's senior electrical engineer, pointed out the first such unit to operate in this state is a 600 KW Ormat unit which started operation three weeks ago at the Wabuska geothermal area. The unit owned by Tad's Enterprises of Orinda, California delivered power to the Sierra Pacific grid for a short time before shutting down to repair condenser leaks. (Geothermal Report 8-16-84)

7.14 NPSC Clears Way for Development of Nevada's Desert Peak Geothermal Field: The Nevada Public Service Commission has cleared the way for Phillips Petroleum to develop its Desert Peak Geothermal field that is located 60 miles northeast of Reno. The Nevada Commission gave its approval to a 10-year contract which will allow Sierra Pacific Power Co. to purchase the geothermal energy from a nine-megawatt demonstration power plant to be built by Phillips. Construction of the unit is slated to begin later this year, with completion scheduled for late 1985 or early 1986.

Phillips began exploration in the Desert Peak area in 1972 when it drilled six deep tests to determine the size and potential of the reservoir. New plant technology for converting geothermal fluids into electricity will be demonstrated at the Desert Peak location.

Earlier this year, Phillips entered its first commercial geothermal venture at Roosevelt Hot Springs in southwestern Utah, where it operates four producing wells. Steam from these wells is sold to Utah Power and Light Co. for its 20-megawatt power plant at the Roosevelt Hot Springs Geothermal site. (National Geothermal Services 7-27-84)

7.15 Commercial Well Completed at Fish Lake: Steam Reserve Corp., Golden, Colorado completed a commercial geothermal well on its Fish Lake Prospect in Esmeralda County, 45 miles from Tonopah, Nevada. The well was drilled to 8,149 ft in a fracture zone in a Paleozoic, Harkless formation. Temperatures of about 400°F were recorded. (O&G Journal 7-30-84)

REGION X

IDAHO

Commercial Activity

7.16 Marsing Greenhouse Produces First Crop: Express Farms have produced their first crop of tomatoes from their geothermally heated greenhouse at Gibbons Hot Springs near Marsing, southwest of the Caldwell/Nampa area. The 3600 sq. ft. facility is using 99°F water. The owners, Gary and Teresa Schwisow, have another 3600 sq. ft. unit under construction. (Leah Street, Idaho Department of Water Resources)

OREGON

Commercial Activity

7.17 Vale and Breitenbush Hot Springs Bids Received by BLM: BLM's Oregon office in Portland has accepted Trans Pacific Geothermal bids for Vale Hot Springs. Only two bids were received for 10 units offered at Breitenbush Hot Springs, Carey Hot Springs and Vale. Award of the leases would put the Oakland firm over the maximum 20,480 acres per state any one company or person is allowed under the Federal geothermal leasing program.

While Congress has failed to increase the acreage limitation for each of the last 3 years, Jackie Clark, adjudicator in the Portland office points out that the Geothermal Steam Leasing Act of 1970 will have reached its 15th anniversary on December 24, 1985, at which time the acreage may be increased to 51,200 acres in any one state by the Interior Secretary after public hearings. If no legislation is passed before then, and if Trans Pacific can hold on it might get its leases at that time. (Geothermal Report 7-16-84)

Washington

Commercial Activities

7.18 Geothermal Development Interest Shown by Sea-Tac: Sea-Tac Geothermal, a partnership in which John Hook, well known geologist, and C. Gerard Davidson of Portland, Oregon, an Assistant Secretary of Interior in the Truman administration, are showing interest in geothermal development in the Oregon/Washington Cascades. Working with the geothermal section of the Department of Energy, Sea-Tac has tried to promote exploration of prospects from Canada to California. Sea-Tac has a number of geothermal leases and lease applications, primarily in Washington and Oregon, and represents others who have leases.

Sea-Tac advocates drilling exploration wells in the Cultus Lake-Lookout Mountain area of Deschutes National Forest, with BLM looking on favorably, but some environmental objections being raised by others. After meeting attended by representatives of a number of geothermal companies and other interested parties, Sea-Tac thought it saw some interest displayed in drilling in the Mt. Baker area, particularily south of Mt. St. Helens, and the north part of Mt. Hood National Forest. Other areas of drilling interest are the southeastern portion of Mt. Hood National Forest, Blue Lake-Santiam Pass area, and around Crater Lake. (Geothermal Report 8-1-84)

REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
AUGUST 1984

GENERAL

8.1 Salton Sea Scientific Project Reviewed at Reno GRC Meeting: An informational meeting describing the status of the Salton Sea Scientific Drilling Project (SSFDP) was held August 29 at the MGM Grand Hotel in Reno, Nevada in conjunction with the 1984 annual meeting of the Geothermal Resources Council. The session was intended to provide a project update and to offer the opportunity to discuss technical aspects of the project with potential investigators.

Raymond Wallace, U.S. Geological Survey, discussed management plans for the project. Describing the plan to drill to approximately 10,000 ft. in the Salton Trough near the Salton Sea Geothermal Area as a test of hydrogeothermal potential, Wallace noted the program will "make available a wealth of opportunities to the scientific community for scientific research." Originally, the project was to entail deepening of a well in the Niland Area from 12,000 to 18,000 ft. for experimental purposes. At that depth, the proposed well would have been the world's deepest geothermal test. The Salton Trough well, for which a $5.0 million appropriation has been set aside, is expected to encounter temperatures in excess of 300° celsius at a depth of 4000 ft. A drilling contract for the well is to be let by mid-September with startup projected for early 1985, according to Wallace.

Energy Department representative John Crawford issued a call to industry for input in cooperative effort to expand the goal of the project. He appealed for a creative approach from geothermal scientists comparable to the efforts made in space research programs. Crawford noted that the research well will be open for 12 months for industry access, and that agreement for management of the project is being discussed with the Bechtel Group of San Francisco. (National Geothermal Service, 9-7-84)

8.2 Plans Requested for District Heating Systems: The Energy Department wants communities to submit applications for federal funding of district heating systems--the once prevalent technology for heating large numbers of buildings by connecting them to a central plant through an underground piping system. In a recent notice in the Federal Register, DOE says that it will weight applications on such criteria as whether a proposed system would improve energy delivery, substitute renewable resources for scarce fuels or boost the economy of a community. After examining applications, DOE hopes to fund initial design and--eventually--the construction of new district heating projects. (The Energy Daily, 9-7-84)

8.3 Modular Power Plant Workshop to be Conducted: The Pacific Northwest will conduct a one-day workshop for their November 14 section meeting. Presentations will be made by manufacturers, developers, and financiers. Decision making processes will also be discussed. Details are being developed, and Gordon Bloomquist, Telephone 206/754-0774, should be contacted for information. (Gordon Bloomquist, WSEO).

8.4 Positive Attitude Noted at Annual GRC Meeting: EG&G Idaho personnel, who participated in the annual Geothermal Resources Council meeting in Reno August 26-29, observed a more optimistic attitude in general. Attendance was up to about 610 persons. Interest is increasing in the potential and actual use of smaller electric generating units, especially binary systems. Papers presented at the meeting are available in Transactions Volume 8 from the Geothermal Resources Council, P.O. Box 1350, Davis, CA 95617.

8.5 DOW Chemical Introduces H_2S Removal System: Dow Chemical U.S.A. has introduced a new process, Gas/Spec RT-2 that removes H_2S from geothermal steam and water. Dow says the process, which involves simple chemistry that requires few control points and minimal hardware, converts H_2S to a soluble sulfur compound that's returned to the geothermal formation. (Oil & Gas Journal, 8-27-84)

8.6 Hydrothermal Mineralogy Workshop Set for October 8-10: The Pacific Northwest Chapter of the GRC and Portland State University are sponsoring a Hydrothermal Mineralogy Workshop to be held October 8-10, 1984 at Portland State University, Portland, Oregon. Topics to be discussed include hydrothermal alteration mineralogy and textures at Newberry Volcano, geothermal and epithermal deposits, light stable isotopes used in evaluation of geothermal systems, and applied hydrothermal mineralogy. Contact Hub Tour and Travel, Inc. at 800/547-7772 or 503/266-2711 (inside Oregon) for details.

8.7 Inovative Energy Financing in the Eighties Session Set for October 3-5: The second annual Innovative Energy Financing Workshop will be held October 3-5 in Livingston, MT. The meeting is patterned after the highly successful session held last year at the same location and promises an impressive array of experts in energy financing. Contact Cory Plantenberg or Jeff Birkby at the Montana Department of Natural Resources and Conservation in Helena, Telephone 406/444-6696.

8.8 Technology Assistance Service Implemented by DOE: The National appropriate Technology Assistance Service (NATAS) has been implemented by DOE. NATAS is an information and technical assistance source to answer questions about energy-related appropriate technologies, i.e., technologies that use the sun, wind and water resources, and energy conservation methods and devices. It is available to anyone in the United States, including utilities, homeowners, farmers, small businesses, entrepeneurs, State and local governments, non-profit organizations, and educational institutions. Contact USDOE, P.O. Box 2525, Butte, MT 59702-2525, telephone 800/428-2525 (800/428-1718 in Montana).

REGION VIII

SOUTH DAKOTA

State and DOE Activities

8.9 Japanese Representative Tours State's Direct-Use Projects: Dr. Feikoa of Japan's Defense Academy toured numerous direct-use projects in South Dakota with the State's geothermal team member. Dr. Feikoa plans to prepare a paper on the tour, and distribute it in Japan. (Steve Wegman, OEP)

8.10 Two South Dakota Projects Receive DOE Energy Awards: National recognition was given to two geothermal projects in the State. DOE energy awards were granted to the St. Joseph Indian School in Chamberlain, and to John Werzma for his private heat pump utilization project in Brookings. (Steve Wegman, OEP)

REGION X

IDAHO

State and DOE Activities

8.11 Boise High School Added to District Heating System: The Boise City Council awarded a contract on August 20 to install the pipeline for the Boise High School. The school will be the largest customer of the PON project system expansion.

OREGON

Commercial Activities

8.12 Development Plan for Deschutes County Under Discussion: Eliot Allen and Associates have prepared a development plan for the Deschutes County Planning Commission. Union Oil has voiced objection to the plan that it is considered to be "middle-of-the road" in its' approach. Action on the plan is pending for the environmentally concerned county that contains such prime geothermal areas as the Three Sisters, Newberry Crater, and Mt. Batchelor. (Gordon Bloomquist, WSEO)

9.13 Union Oil Co. of California Schedules Wells in Oregon: Activity in Oregon during the week included Union Oil Co. of California staking location for a pair of temperature gradient tests in Deschutes County. The wells, #24-15, 15-21s-13e, and #62-12, in 12-21s-12e, are both projected to 3000 ft. (National Geothermal Service, 8-10-84)

8.14 Deschutes County Gets Temperature Gradient Wildcat; Oxy Geothermal has staked location for a temperature gradient wildcat in Deschutes County, Oregon. The #1 Oxy-Newberry Crater, 28-21s-12e, is projected to 4000 ft. (National Geothermal Service, 8-10-84)

8.15 Breitenbush Expansion Being Pursued: The Oregon Department of Energy, DOGAMI, and Water Resources Department are gathering and assessing well and spring data from three land parcels in the Breitenbush Hot Springs area. Significant expansion of utilization of geothermal energy on two of the parcels is being considered, and the proposed development is before the County Planning Commission. (Alex Sifford, ODOE)

8.16 Newberry Crater Development Viewed by Siting Council: The Oregon Facility Siting Council, with jurisdiction over projects exceeding 25 MW, received an August 9 and 10 briefing by industry, Oregon Department of Energy, and the U.S. Forest Service on the status of development for the Newberry Crater area. Subsequent to the briefing, a formal motion was made and accepted to examine the suitability/unsuitability of the use designation of lands within the State. (Alex Sifford, ODOE)

REGIONAL GEOTHERMAL PROGRESS MONITOR

ACTIVITIES REPORT

September 1984

GENERAL

9.1 Ocean Hydrothermal Energy Evaluations Show Promise: EG&G Idaho has completed some prelimiinary evaluations regarding utilization of ocean hydrothermal energy. Three feed stocks considered for use in an ocean hydrothermal energy petroleum production facility were considered. Kelp and algae are not promising, but densified refuse derived fuel shows promise. It was found that the process is very similar to coal liqufication. Using this type of fuel from west coast cities with ocean access and a population exceeding 130,000, a simple payback of five years has been estimated for a complete production facility.

9.2 Stanford Reservoir Engineering Workshop to be held in January: The tenth annual Stanford University workshop on geothermal reservoir engineering will be held January 22-24, 1985. Contact Jon S. Gudmundsson, Stanford Petroleum Engineering Depament, Mitchell Building, Room 360, Stanford, CA 94305 for details.

9.3 GRC Idaho First Abstract Set: Special Report No. 14, Geothermal Energy Abstract Sets, was issued by the Geothermal Resources Council. The document contains the first three sets of abstracts that are part of a set of twelve being compiled by the GRC under a U.S. DOE grant. Selected abstracts on case histories, drilling, and reservoir engineering are in the first document. Contact the GRC at P.O. Box 1350, Davis, CA 95617, telephone 916/758-2360 for more information.

9.4 China to Expaned Yangbajain Geothermmal Station: China plans to more than triple electrical power generating capacity at its Yangabajain geothermal experimental station in Tibet Autonomous Region.

Present capacity of 7,000 kw plant will be expanded by installation of five additional 3,000 kw gnerators by 1990, Beijing Review reports. Yangbajain station, the largest in China, was built in 1977.

Another 3,000 kw geothermal power station is planned near Ali to supply power to Shiquanhe township.

Yangbajain station, in a geothermally active basin in the Himalayan Mountains, supplies power to the capital city of Lhasa 54 miles to the southeast. The city formerly used hydroelectric power, which wasn't available in winter.

The geothermal steam employed to run Yangbajain generators comes from a depth of about 656 ft. Chinese and French geologists estimate that a 932 degree F steam reservoir lies 3-3.5 miles deep and that 1,800 degrees F magma could be found at 8.5-21 miles.

Chinese geologists believe a geothermal belt in the southern Tibet Plateau extends 1,200 miles from the Ali area of western Tibet through Kashmir, Afghanistan, Iran, and Turkey, where it joins the Mediterranean geothermal belt. To the east, the belt extends to China's Yunnan Province, Burma, and Indonesia, Beijing Review says.

Width of the belt is from the northern slope of the Himalayas in the south to the Gangdise Mountains in the north, and north of the Nyainqentanglha Mountains.

The heat vented from the belt is estimated to be equal to that generated by burning 3 million tons/year of coal.

China's present use of geothermal resources saves about the same amount of coal, its largest hydrocarbon resource. (Oil & Gas Journal 9-10-84)

9.5 Energy Financing Workshop Successful: The second annual Innovative Energy Financing in the Eighties workshop held October 3-5 received positive commendations. The sessions, considered to be an evolution of last year's conference, went beyond conceptual discussions of shared savings, tax exempt leasing and other third-party financing options to actual case studies. About 80 persons attended the Livingston, MT event spearheaded again by Jeff Birkby of the Montana Department of Natural Resources and Conservation and the U.S. Department of Energy.

9.6 Small Scale Systems Guide is Available from CEC: The California Energy Commission has prepared and is offering a "Small-Scale Systems Using Geothermal Energy: A Guide to Development" at no cost for the first copy and $2.20 for additional copies. It provides a comprehensive overview of 100kw to 10mw electric systems using geothermal hot water. Contact CEC, Geothermal Office, MS-43, 1516 Ninth St., Sacramento, CA 95814.

REGION VI

New Mexico

State and DOE Activities

NMERDI Receives Grant for Exploration Work:

9.7 The New Mexico Energy Research and Development Institute is requesting proposals to explore for electrical-grade geothermal reservoirs, moderate to intermediate temperature reservoirs, and for programs based on temperature gradient drilling to locate sites for deeper drilling. The request is in response to a $90,000 grant to the state from the U.S. Department of Energy to explore for Geothermal sites in New Mexico. Proposals must be submitted to the department no later than November 5 to Dr. Larry Icerman, 12205 St. Francis Drive, Pinon Building Room 358, Santa Fe, New Mexico 887501. (National Geothermal Service, 9-28-84)

Region VIII

Montana

State and DOE Activities

9.8 Energy Financing Workshop Successful: Refer to the General section (9.5) for information.

Region IX

California

Industrialization Activities

9.9 Ft. Bidwell Indians Begin Commercial Fish Farm: A geothermal aquaculture facility consisting of two fiberglass raceways will be used to rear catfish. On October 22, 40,000 fingerlings will be introduced into raceways and will achieve a weight of about two pounds each in eight months. A dry fish food pellet will be used as feed, consisting of soybeans, fish meal, vitamins, and alfalfa. Live fish will be marketed in metropolitan areas, especially the San Francisco Chinese community. The fish are expected to retail at about $2 per pound and will gross about $15,000 per grow-out. An artesian well, flowing at 300 gpm of 92 degrees F water is mixed with about 100 gpm of cool water to provide the 82 degrees F flow through the raceways. Capacity of the well is 2000 gpm; therefore a total of ten raceways are expected to be eventually supplied from this well. (Paul Lienau, OIT)

State and DOE Activities

9.10 Mammoth Lakes Receives CEC Grant for District Heating Study:

Mammoth County has received a grant from the California Energy Commission for a district heating feasibility study. A consultant, to be selected, will investigate the use of geothermal water for space and water heating of commercial buildings, hospital, schools, condominiums, low cost housing projects, and possibly an industrial park. A snow-melt system will also be considered in the design. Three resource options will be considered; 1) use of reject water from the binary power plant at the top of Diablo, 3 to 5 miles distant, 2) union has offered free heat from a proposed power plant adjacent to the City. Delays in leasing have prevented the drilling of the production wells, and 3) the City would drill its'own wells. (Paul Lienau, OIT)

NEVADA

Industrialization Activities

9.11 **Fish Lake Well Successful:** Steam Reserve Corporation (SRC), a wholly-owned geothermal subsidiary of AMAX Exploration, Inc. reported completion of a commercial geothermal well on its Fish Lake Prospect in Esmeralda County, Nevada. The SRC well is located about 45 miles west of Tonopah, Nevada.

The well was bottomed at 8,149 feet in a fracture zone in the Palaeozoic Harkless formation. Well temperatures near 400 degrees F. have been reported.

The well has evidenced capability of supporting 3-4 megawatts of generating capacity under self-flow. Pumped flows will significantly enhance the capacity.

The majority of the funding for the well was provided under the terms of a joint venture between SRC and Geo-Energy Partners, 1983 Ltd., a Colorado limited partnership. (The Geyser, 9-84)

State and DOE Activities

9.12 Elko Project Receives Innovative Energy Award: The Elko Heat Company district heating project in Elko has been awarded a DOE Innovative Energy Award. Formal presentation of the award took place in Washington, D.C.

Region X

Alaska

State and DOE Activities

9.13 Unalaska Exploration Project Completed: State geothermal commercialization team activities were completed with the issuance of the final report of the Electric Power Generation Analysis for the Unalaska Geothermal Exploration Project. The study, prepared for the Alaska Power Authority, evaluates different geothermal power systems to generate electricity for the towns of Unalaska and Dutch Harbor. Because of uncertainties in electric load forecasting, it is recommended that development occur in phases timed to growth in demand. A binary cycle system was selected. The "reconnaissance study of Energy Requirements and Alternatives Appendix: Unalaska" recommends for the near term the use of diesel driven generators, especially when they are equipped with waste heat recovery systems.

Idaho

Industrialization activities:

9.14 Leaf Lettuce Comes Off Assembly Line at Bruneau Greenhouse: A hydroponic leaf lettuce geothermal heated greenhouse owned by Thurman Blake of Bruneau started to produce lettuce in September. The lettuce is started in bottomless cups, transferred to styrafoam planks with roots extending into hydroponic fluids and floated through long continuous tanks for harvesting at one end of the facility. It requires about eight weeks to produce a head of lettuce. After two weeks, 16,000 plants are transplanted at a time from the cups to the planks.after the planks reach the end of the tanks in six weeks, they are replanted and about 8000 heads per week go to market. The 25,000 sq. ft. facility is heated by six 3,000 Btu/hr air handling units producing 95 degrees F air from 110 degrees F geothermal water. An artesian well used for irrigation provides the water, which after heating the greenhouse, is returned to an irrigation ditch. (Paul Lineau, OIT)

State and DOE Activities

9.15 Kimberland Meadows Development Evaluated: The OIT Geo-heat Center completed a preliminary evaluation of the potential use of Zim's Hot Springs fluids for the Kimberland Meadows housing development at New Meadows, ID. The study indicates relatively high distribution costs and the need to reassess the approach that would use the 166 degrees F geothermal fluids.

Oregon

Industrialization Activities

9.16 Geothermal Advisory Committee Moves on Klamath Falls Development: The GAC recommended gradual development in stages for major systems using geothermal energy in Klamath Falls. The advisory committee, consisting of two members from twelve citizen, state, local governments and federal agencies recommended to the City that their system consisting of fourteen government buildings operate on a test basis for the 1984-85 heating season. Private wells in area will be monitored for pressure and temperature changes. Data will be analyzed by a Hydrologist who will report findings to the committee. Retrofit of the 120 homes on Michigan Street is to begin soon. However, connection to the heating system will depend on test results. It is recommended that the City proceed with the planning and conceptual design for the residential/commercial system for the Mills addition. Development of this system depends on a review by the GAC and test results. (Paul Lienau, OIT)

8.17 <u>Reports Available on Klamath Falls Acquifer Test</u>: Work on the Kamath Falls geothermal aquifer test by Stanford University, a pumping and reinjection test by LBL, temperature studies and collection of aquifer discharge use data by OIT Geo-Heat Center, and sampling for chemical analysis by the USGS has been completed. The following reports are available from USGS Open File Services Section, Western Distribution Branch, Box 25425, Federal Center, Denver, Co 80225.

1. Data from the Pumping and Injection Tests and Chemical Sampling of the Geothermal Acquifer at Klamath Falls, OR, open file report, 84-146.

2. Analysis and Interpretation of Data Obtained in the Tests of the Geothermal Acquifer at Klamath Falls, OR, Water Resources Investigation, 84-4216. (Paul Lienau, OIT)

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REGIONAL GEOTHERMAL PROGRESS MONITOR
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General

10.1 Bill extends Federal Geothermal Leases: Supporters of geothermal energy development have won congressional agreement on a two-year extension of leases that might lapse before the Geothermal Steam Act can be revised.

The conference committee on the fiscal 1985 continuing appropriations accepted a Senate proposal that extends through 1986 the primary term of leases in effect on July 27, 1984, if the Interior Department determines that a substantial development investment has been made and that a bona fide first sale has not been completed because of administrative delays by government agencies.

The provision was backed by Sen. Chic Hecht (R-NV), who sought to protect 270 geothermal leases in seven western states where primary lease terms have expired recently or will expire before the end of 1986. The extensions will have the largest impact in Nevada, where there are 100 leases representing more than $50 million in capital investment, according to Hecht.

A comprehensive revision of the Geothermal Steam Act has been in the works for more than four years. A new version is expected to allow for lease extensions in situations where external market conditions delay commercial production. The current extensions are intended to protect existing leases during the next session of congress.

The final version of the appropriations bill also includes a ban on geothermal leasing on 488,000 acres of federal land adjacent to Yellowstone National Park. Proposed by Sen. John Melcher (D-MT), the ban affects the Island Park Known Geothermal Resource Area in Idaho, Wyoming, and Montana. The boundary of Island Park is 13.5 miles from Old Faithful, and Melcher said that he wants to ensure that "no geothermal development will be pursued that jeopardizes the existence of the Yellowstone National Park geysers." (National Geothermal Service, 10-19-84)

10.2 Drilling to Assess Deep Geothermal Resource: The U.S. government and industry have launched a project to tap the deeper potential of California's big geothermal resource with what will be one of the hottest geothermal wells drilled in the U.S.

Department of Energy let a $5.3 million contract to Bechtel National Inc., a unit of Bechtel Engineers & Constructors, to spearhead a program to gather geological/geochemical data from and assess the resource potential of deep geothermal reservoirs near the Salton Sea in California's Imperial Valley.

Project drilling is expected to encounter high temperatures, pressures, and salinities in combinations never before dealt with, Bechtel says.

Geothermal experts have dubbed the Imperial Valley the "Saudi Arabia" of geothermal power potential. A number of projects have been launched in recent years to tap the huge geothermal potential in the valley (OGI, May 3, 1982, P. 91).

Deeper reservoir potential in the Imperial Valley could yield 25 million kw of geothermal electric power capacity during the next 50 years vs. current shallow reserves potential there of about 5-7 million kw, says Robert W. Rex, president and chief executive officer of Republic Geothermal Inc., Santa Fe Springs, California.

Moreover, DOE says the Bechtel contract may represent the first of a government sponsored series of U.S. research efforts under the joint DOE/U.S. Geological Survey/National Science Foundation continental scientific drilling program, which entails other exploration and study of the earth's crust. (Oil & Gas Journal, 10-29-84)

10.3 PNW-GRC Installs New Officers and Conducts Workshop in Portland:

The Pacific Northwest Section of the Geothermal Resources Council conducted a one-day workshop November 14 in Portland, OR that included the installation of new officers. The Section, now in its second year, boasts a membership near 155 persons. Dr. Gordon Bloomquist, Washington State Energy Office, was reelected President. Phil Essner, California Energy, is Vice President, Alex Sifford of the Oregon Department of Energy is Secretary/Treasurer, and Elliot Allen, Elliot Allen and Associates, and John Reader of Canadian Geothermal Energy Association are the Directors. Power plant engineering needs, plant financing methodologies, BPA geothermal plant cost studies, and small scale power plants were the topics of discussion at the meeting attended by about 40 persons.

10.4 Ronald Loose is Acting Director of DOE Office of Renewable Technology: Ronald R. Loose has been named the acting director of DOE Office of Renewable Technology replacing Richard Benson who left the job in August to join the Los Alamos National Laboratory staff. Loose, a long time DOE employee, will also continue as chief of the Research & Technology Integration staff directly under Robert San Martin, Dep. Assistant DOE Secretary for Renewable Energy. (Geothermal Report, 10-15-84)

10.5 Minnesota to Host District Heating Conference: Minnesota's Twin Cities of Minneapolis and St. Paul will be the hosts for the 76th Annual District Heating and Cooling Conference June 2-6, 1985. The conference site is the Hyatt Regency Minneapolis.

The conference will include technical programs, committee meetings, and discussions on operation, ownership, financial, and policy issues. New on the agenda are tours of the major district heating systems in the Minneapolis/St. Paul area and over 30,000 square feet of exhibit space.

For conference information, call the International District Heating Association: 1-202-223-2922. For tourist information, call 1-800-328-1461.

10.6 Third Annual DOE Geothermal Program Review Conducted: El Centro, CA was the site for the third annual DOE Geothermal Program Review that was held October 16-19. Dr. John "Ted" Mock, Director of DOE's Geothermal Hydropower Technologies Division chaired the session attended by about 200 persons. DOE geothermal program overviews were provided and Rep. Duncan (R-CA) gave an opening day speech. Technical presentations were given on binary and flash system, magma binary systems, injection studies, power well pump development, in-line instrumentation, advanced binary development, well stimulation and studies, and other related technical topics. Tours to nearby geothermal development sites were also included.

10.7 Texaco and Chevron Subsidiaries Plan Indonesia Geothermal Venture: Subsidiaries of Texaco, Inc. and Chevron Corp. have finalized a contract with Indonesia's Pertamina National Oil Company providing for the exploration and development of geothermal resources in the Darajat area of West Java.

Exploration expenditures could total as much as $16 million through the venture, with any produced steam sold for electrical generation to PLN, Indonesia's state-owned electricity agency.

Texaco said the Drajat Block comprises 42,970 acres approximately 100 miles southeast of Jakarta and some six miles from Petamina's Kamojang geothermal field. Steam production there is currently used to power 30 megawatts of electricity with an expansion program underway. (National Geothermal Service, 11-16-84)

REGION VIII

MONTANA

Industrialization activities

10.8 Montana Lumber Company to Use Geothermal for Heating: Madison Lumber Company of Ennis, Montana will be using a 95°F resource to provide heat for a new 4500 square foot building. A radiant floor system using 3/4" polybutylene lines on 7 1/4" centers, placed 2" below the concrete slab will heat the building at a -15°F outside temperature with a flow of only 28 gpm. Since this is a manufacturing type building, an inside temperature of only 55°F will be required. (Paul Lienau, OIT)

REGION IX

CALIFORNIA

Industrialization Activities

10.9 Drilling Planned at Boyes Hot Springs Village Project: The objective of drilling a 600 to 800 foot exploratory well at Boyes Hot Springs, California is to determine the characteristics of the geothermal resource at this site and establish important engineering parameters which will determine the final depth and scope of drilling required. The project includes 87 single family units to be housed in 20 structures. An outdoor swimming pool, spa and bath house are also included. The geothermal system would provide 2.8 million Btu/hour for space and domestic water heating and 500,000 Btu/hour for pool heating. Geothermal capital costs were projected to be $226,000 in comparison to

$136,000 for a conventional gas fired system. A life cycle cost analysis using equity financing gives a rate of return on the geothermal system of 27% and a simple payback in four years. (Paul Lienau, OIT)

NEVADA

Industrialization Activities

10.10 Binary Cycle Generator Producing Power at Wabuska: A 750 kW ORMAT binary cycle generator has been installed by Neal Townsend at Wabuska, located about 30 miles east of Reno. The geothermal well produces 740 gpm with a wellhead temperature of 228°F. Well depth is only 350 feet. A nearby pond is used for cooling water and the generator produces approximately 600 kW when the pond temperature is at 55 to 60°F. Output dropped during late summer months when the pond temperature increased to 90°F. Power is sold to Sierra Pacific at less than 6 cents per kWh. Future plans are to install an additional pair of 750 kW ORMAT generators, bringing the total capacity at the site to 2.25 MW. Cooling towers may be added to the system when the additional power goes on line. (Paul Lienau, OIT)

10.11 Trans-Pacific to Construct Geothermal Electrical Transmission Line: Trans-Pacific Geothermal, Oakland, and TGS Associates, have entered into a partnership to construct a 225 mile geothermal electrical transmission line from Nevada to California. TGS is operator of two geothermal wells in Dixie Valley, Nevada, where the line will emanate and extend to a Southern California Edison Substation power plant in Bishop, California. Construction is scheduled for completion in early 1987. The Dixie Valley Known Geothermal Resource Area is approximately 40 miles northeast of the town of Fallon. (National Geothermal Service, 11-16-84)

10.12 High Bids Total $119,373.26 at Nevada KGRA Sale: Only seven of the 48 geothermal leases offered drew bids at a KGRA sale held by the Bureau of Land Management in Nevada September 27. Total bonus at the sale was $119,373.26, an average of $8.82 per acre. Of the 98,076.43 acres offered, only 13,532 acres were leased. Munson Geothermal was the high bidder on five of the seven parcels sold. The tracts are in the Brady-Hazen, Dixie Valley, and Kyle Hot Springs KGRA. The last BLM auction of geothermal leases in a Nevada KGRA was at a 1982 sale which drew no bids.

10.13 Churchill County Site of Another Phillips Well: New geothermal activity during the week included a new location in Churchill County, Nevada. Phillips Geothermal at weeks end was moving in rotary tools at its 67-21 Desert Peak, 21-21in-27e, a projected 8000-ft test. The new location is in the Desert Peak Known Geothermal Resource Area. Peter Bawden #11 rig is on contract. (National Geothermal Service, 10-12-84)

10.14 State and DOE Activities - Nevada Proposes New Geothermal Regulations: A new department, the Nevada Department of Minerals, was set up by legislative action during 1983. The department has proposed new definitions and regulations that make very little if any distinction between electric power type resources and direct uses.

The department categorized wells as domestic, commercial or industrial. A domestic well would have a temperature of less than 212°F and less than 1800 gallons per day of flow. This definition would include all water wells including those under jurisdiction of the State Engineer. A commercial well was defined as one with a temperature less than 250°F. Industrial wells were defined as those greater than 250°F, primarily used to generate electric power. A conflict with these definitions exists at Wabuska, where binary cycle generators are producing power from a 228°F well.

Section 41 of the regulations requires any operator to collect water samples from all wells within a one mile radius of a producing well. This applies to all three categories and would be a prohibitive expense for a home owner using a well for heating purposes.

State Engineer, Pete Morros, said "I would see adoption of the regulations delayed until the legislature meets to clear up jurisdictional problems". (Paul Lienau, OIT)

10.15 Gravity Data of the Lund and Walker Lake 1 x 2° Sheets Now Available: The Nevada Bureau of Mines and Geology has published two maps on gravity data compiled from the Walker and Lund sheets in Nevada. The publications are two in a series of 12 gravity maps already published by the Bureau. Both maps, at a scale of 1:250,000, include 5 mgl gravity contours and generalized geology. The maps may be purchased for $4 each at the sales office (room 310 in the Scrugham Engineering - Mines Building on the University campus in Reno) or by mail (please add 10% postage and handling; Nevada Bureau of Mines and Geology, University of Nevada Reno, Reno, NV 89557-0088). For further information contact Arlene Kramer, telephone 702/784-6691.

REGION X

IDAHO

Industrialization Activities

10.16 College of Idaho Geothermal Potential: Based on an October 1984 Geo-Heat Center report, potential for geothermal conversion at the College of Idaho appears promising. The campus is located in southwestern Idaho in the town of Caldwell. Fifteen major structures are located on the campus with a total of approximately 350,000 square feet of area using natural gas to individual building boilers as the primary source of energy. There appears to be a good potential for a 160°F resource at the College of Idaho site. Both existing well data and recent geologic and hydrologic investigations suggest that such a temperature should be available at a depth of approximately 3500 feet. A geothermal system based on the above resource temperature would be capable of displacing about 78% of current natural gas consumption attributable to space and domestic hot water heating. Geothermal water would pass through heat exchangers in 12 of the 15 major buildings on campus, then be injected into a disposal well. The heat exchangers would deliver heat to the existing heating loops. Most buildings would still require a small amount of input from the existing boiler during the coldest periods of the year. Total system savings would amount to 315,053 therms/year and at a value of 44 cents/therm that results in a figure of $138,623 per year. Total capital cost was calculated to be $1,325,000; of this figure, the production and injection well make up is 59%, distribution system 13%, and building retrofits 22%. It is evident that a reduction in required depth of the injection well would have a noticeable effect upon overall system cost. Based on a 6% annual inflation rate and rates of approximately 2% for energy values, the simple payback would be 7.23 years. (Paul Lienau, OIT)

10.17 Idaho State School and Hospital Geothermal Potential Analyzed: The Idaho State School and Hospital is located at Nampa, Idaho, nineteen miles west of Boise. There are 17 major buildings that are currently heated from a central boiler plant fired by natural gas. The purpose of the investigation by Balzhiser/Hubbard & Associates was to determine the feasibility of converting this facility to geothermal energy. There appears to be a good potential for a 160°F resource, similar to that found in Boise, existing at a depth of 3000 feet at the hospital site. Two possible geothermal systems were analyzed. Scheme #1 considered circulating geothermal water to each building where heat exchangers would deliver heat to existing heating loops. Scheme #2 involved the installation of heat exchangers in the boiler room from which secondary heated water would be circulated to each building. Scheme #1 was recommended based on less construction cost and greater overall energy savings. Changing over to a geothermal hot water system will reduce natural gas consumption by 75%. Most of the remaining gas use (steam) would be in the laundry and kitchen. Total capital cost of the geothermal system would be $1,989,350 and would save $235,193 per year in energy costs for a simple payback of 8.46 years. (Paul Lienau, OIT)

REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
NOVEMBER 1984

GENERAL

11.1 Hawaii to Build Geothermal Research Facility: Development of a geothermal research facility in Hawaii was given the "green light" in mid 1984 when Hawaii's Governor George Ariyoshi approved Capital Improvement Project (CIP) funds of $325,000. The Puna High Technology Facility (PHTF) will be constructed at the site of the highly successful HGP-A well head generator which has operated almost continuously since 1982, proving the feasibility of producing electricity from Hawaii's geothermal energy resource.

The facility will perform research, development and demonstration of projects that will explore uses of geothermal energy and the by-products of geothermal energy production. The research program will be the responsibility of the Hawaii Natural Energy Institute in cooperation with the University of Hawaii at Hilo. PHTF is expected to lead to construction of an industrial park and programs in multipurpose dehydration and bioconversion, which will provide jobs and tax revenues to stimulate the Puna area economy.

The $325,000 in CIP funds will finance a small shell building and $115,000 in equipment. An additional $26,500 in cost sharing support has been contributed by the County of Hawaii under the leadership of Mayor Hebert Matayoshi, and efforts are being coordinated by Big Island Representative Andrew Levin to secure further supplementary financing for the project. PHTF will be constructed by the Research Corporation of the University of Hawaii under contract with the State Department of Planning and Economic Development. (GRC Bulletin, December 1984)

11.2 Cascades Exploration Proposals are Under Review: Proposals to drill three or four thermal gradient test holes in the Cascades region of California, Oregon and Washington are being reviewed by the Idaho Operations Office of DOE. About $700,000 of FY-1985 funding is being made available to drill test holes to depths of 2000 to 3500 ft. A maximum of $200,000 per site would be provided on the basis of not exceeding the total amount, not including any fees, contributed by the developer.

11.3 Chinese Professors to Study U.S. Geothermal Systems: Professors Wang and Shi from Tianjin University and Mr. Li from Tianjin Agriculture Research Academy will spend three months in a special training program at the OIT Geo-Heat Center, starting December 1, 1984.

Professor Wang is the Deputy in charge of district heating systems design for the city of Tianjin. Tianjin, a city of 7 million people, has a severe air pollution problem caused by coal heating. The Chinese government has established Tianjin as a model city to develop its geothermal resources as a solution to the environmental problem of air pollution. Geothermal water temperatures in the Tianjin area range from 50 to 96°C and contain four times (4000 mg/l) the amount of dissolved solids as compared to the Klamath Falls, OR resource. Professor Shi is involved with research on corrosion problems and how to control corrosion. Mr. Li is in charge of six geothermal greenhouses raising tomatoes, cucumbers, green peppers and watermelons.

The United Nations Department of Technical Cooperation for Development has provided fellowships for the Chinese to study at the Geo-Heat Center. The program will include field trips, geothermal course work and project feasibility analysis. (Paul Lienau, OIT)

REGION VIII

COLORADO

State and DOE Activities

11.4 Pagosa Springs adds First Noncommercial Customer: The first residential customer has been added to the Pagosa Springs district heating system, and others are expected to utilize the city system after final water rights hearings are concluded. The system continues to operate very satisfactorily without negative impact on neighboring geothermal wells.

UTAH

Industrialization Activities

11.5 Roosevelt Hot Springs Plant Renamed, Dedicated: Utah Power and Light has designated its' 20 MW facility at Roosevelt Hot Springs as Blundell I. The change is in honor of Harry Blundell, retiring UP&L chief executive officer. The plant, officially dedicated October 24, 1984 was known as Milford I. The single flash steam plant came on line July 31 after a two-year construction phase.

REGION IX

CALIFORNIA

Industrialization Activities

11.6 Long Valley Binary Plant Power Agreement Signed: A power purchase agreement has been signed between Southern California Edison and Wood and Associates of Auburn, CA. The agreement, based on Standard Offer No. 4, is for the purchase of 10 MW over a thirty year period from Wood's power plant in Long Valley, CA. Terms call for a guaranteed escalation rate of 7.5 cents per kWh during the first 10 years. After 1994, the price of energy will be consistent with the posted PURPA price.

Wood has taken delivery of three 600 kW ORMAT units. Installation of the first 3 MW will be completed by the end of 1984, with the balance of the units being delivered by the end of 1985. (Paul Lienau, OIT)

State Activities

11.7 CEC Offers Technical Assistance for Geothermal, Wind and Photovoltaic Projects in California: The California Energy Commission, in August, 1984, started to provide technical assistance to both public and private developers of geothermal, wind and photovoltaic projects. Such assistance may include engineering and economic feasibility analysis, and for geothermal projects, resource assessment of low to moderate temperature resources.

The Commission's objective in funding this program is to promote these alternative technologies by reducing a portion of the development risk. Applicants who are selected for this program will be provided technical assistance by Commission staff working with the following consultants: The Berkeley Group Inc. for geothermal resource assessment; The Oregon Institute of Technology Geo-Heat Center for geothermal feasibility and engineering analysis; San Diego State University for photovoltaics projects; and Science Applications Inc. for wind projects.

The Commission is especially interested in providing assistance to developers who, with minimal assistance , will be in a position to construct a project. Applicants who desire assistance with resource confirmation at a specific location, economic evaluation of a project, review of work previously conducted, or preliminary feasibility analysis of a proposed project will be given priority.

All public and private developers of geothermal, wind and photovoltaic projects are eligible for this program. The total number of applicants that can be provided technical assistance under this program is limited. If you are interested in applying for such assistance, contact: The California Energy Commission, Office of Small Power Producers, 1516 9th Street, Sacramento, CA 95814, telephone 916/324-3509. (Paul Lienau, OIT)

NEVADA

Industrialization Activities

11.8 Phillips Plans 9MW Plant at Desert Peak: Phillips Petroleum will construct a 9 MW plant at Desert Peak in Churchill County northeast of Fernley. Two producing wells have been completed that will provide power to a Biphase Turbine. Phillips has a contract with

Transamerica to produce electric power, which will be sold while long term tests on the reservoir are being conducted. (Paul Lienau, OIT)

11.9 Contract Signed With Navy for Development at Fallon Naval Air Station: General Intertech of San Diego has signed a contract with the Navy to deliver 25 MW in three years and 75 MW by the end of the 5th year at Fallon. The Navy's power requirement at Fallon is 2.5 to 3.0 MW and the agreement allows the excess to be wheeled to substations in the north or south. The Navy will buy the power at 3.9 cents per kWh. Several 500 foot temperature gradient holes and one 2000 foot exploratory well were drilled at the site which came in with a temperature of 200°F. Production drilling and testing will begin immediately at the site. (Paul Lienau OIT)

11.10 Work Underway at Amax Wildcat in Nevada Fish Lake Area: Amax Exploration at week's end was drilling below 2300 ft at a geothermal wildcat in the Fish Lake Area of Esmeralda County, Nevada. The 88 (17-12) 11, 11-1s-36e, spudded on November 17, is projected to 8000 ft. The new test is being drilled from the same surface location as the operator's 88-11. That well is currently being tested at 8149 ft. (National Geothermal service 17-7-84)

REGION X

IDAHO

State and DOE Activities

11.12 Boise District Heating Continues to Add Customers: The Boise geothermal district heating system continues to operate satisfactorily. Eighteen customers are now on line, another will be added in December, and four others are in various stages of retrofit. System capacity will accomodate significant utilization in excess of current demands, and the city is actively seeking new customers.

11.13 Mackay Geothermal Potential Document Available: A report summarizing the results of a preliminary investigation of the geothermal potential of the Mackay area has been issued by the Earth Science Laboratory, University of Utah Research Institute. Data obtained indicate a very low potential to locate a resource above 22°C. Contact Bruce Sibbett at 391 Chipeta Way, Suite C, Salt Lake City, Utah 84108, telephone 801/524-3422 for more information.

OREGON

Industrialization Activities

11.14 Drilling Near Crater Lake National Park Receives BLM Approval: The BLM and the USFS have ruled in favor of drilling 4 sites adjacent to Crater Lake National Park. Cal-Energy plans four exploratory holes up to 4000 ft. There are thirty days in which the decision can be appealed. (Paul Lienau, OIT)

11.15 Vale Mushroom Grower Uses Geothermal Heat: In early May of 1984, the Oregon Trail Mushroom Company of Vale, Oregon secured a $6.5 million loan, guaranteed by the U.S. Department of Energy, for construction of a semi-automated mushroom growing plant using geothermal fluid for heating and cooling.

The loan from the Idaho First National Bank of Boise, Idaho, and the loan guarantee were both executed on May 4, 1984. The loan is scheduled for repayment in approximately 18 years.

The plant will be built in a designated KGRA on a 10 acre plot just east of Vale, across the Malheur River from town. Production started in December 1984 and is expected to reach a capacity of greater than three million pounds per year by mid 1985. Oppenheimer Companies, Inc., based in Boise, Idaho, will market the mushrooms. (Paul Lienau, OIT)

State and DOE Activities

11.16 Model Standards Regulation of Small Scale Energy Facilities Being Developed for Oregon Counties: The Oregon Department of Energy currently is developing model standards for counties to use to evaluate siting of small (25 MW or less) geothermal power plants. The model standards are designed to be adapted to county zoning ordinances. Facilities over 25 MW are governed by the State Energy Facility Siting Council's one stop permitting process.

State agencies regulate some aspects of small geothermal facilities. The Department of Geology and Mineral Industries regulates high temperature geothermal wells and fluid disposal. The Water Resources Department regulates low temperature wells and fluid disposal. The Department of Environmental Quality (DEQ) covers the air and water effects of these facilities. However, local governments are not precluded from adopting more stringent air and water quality standards. The DEQ also regulates disposal of solid waste from small geothermal facilities.

While state agencies regulate wells and emissions, local land use plans and ordinances govern facility siting. County regulation of geothermal facilities has been influenced by state land use law. State law allows geothermal exploration in exclusive farm use districts (ORS 215.283(1)g.). Geothermal mining and processing and commercial energy facilities are allowed in these farm zones subject to standards (ORS 215.283(2)b. and f.).

Most counties allow geothermal exploration, mining and processing in one or more of their resources districts. However, few counties have adopted specific standards for evaluating geothermal development. In most cases, general standards and conditions that apply to a broad range of land uses will be applied to geothermal facilities.

The first draft model geothermal standards and background document were distributed for comment in October 1984. Two advisory groups assist the development of the standards. The final document will be published in the spring of 1985. (Paul Lienau, OIT)

11.17 Local Regulation of Geothermal Resource in Klamath Falls Upheld in Courts: The Supreme Court of Oregon has denied review of the Water Resources Department vs. Klamath Falls case and the Court of Appeals ruling is in effect. This means the case is over. It has been ruled that the Water Resources Department does not have exclusive authority to manage the appropriation of ground water and that a local government may have their own rules, regulations, permitting processes, etc. for ground water appropriation pending that their management plan is consistent with Water Resources Department policy.

The Klamath Falls citizen initiative was challenged by WRD in the Klamath County Circuit Court. Because the initiative virtually inhibits use of the geothermal resource except through downhole heat exchange (where there is no withdrawal of water), WRD claimed that the initiative, in essence, regulates the appropriation of ground water resources. WRD contended that such local regulation is an infringement of WRD's exclusive statutory authority to manage ground water. However, the initiative was upheld by Circuit Court on the basis that the State has not preempted local governments from adopting regulations and the local ordinance did not conflict with any existing state regulations pertaining to ground water resources.

In October, 1983, WRD took the case before the Oregon Court of Appeals. Seven months later, in May 1984, the Court of Appeals reached a decision favoring the City of Klamath Falls. The essence of their ruling is that local governments have the authority to adopt regulations consistent with the policy of the Ground water act as outlined in ORS 537.525. Although the statutes vest considerable authority in the WRD Director to execute a single water policy applicable to the entire state, they do not expressly prohibit local bodies from engaging in regulatory activities of their own. If specific state regulations are established, local plans that conflict with those regulations must fall under the paramount state law. However, until such time as the WRD Director establishes such regulations, the Court ruled that there is no reason to prohibit local plans that creatively foster water resource development and conservation consistent with existing state policy. The Oregon supreme Court declined to review the question and the case is closed.

When the case first went to court, WRD had not adopted rules regarding low temperature geothermal effluent disposal. However, in December, 1982, such rules were adopted as OAR Chapter 690, Division 65. These rules allow reinjection of effluent into the same or compatible aquifer via any well whose construction and location will not cause adverse impacts such as those described in OAR 690-65. Had these rules been before the court in the previous case, the judge would have had to determine if the local ordinance conflicted with state regulations covering the same subject. The decision would have been based on whether the ordinance prohibits an act which the state permits. When both a local ordinance and a state regulation are prohibitory, with the only difference being that the ordinance goes farther in its prohibition, the two may be able to coexist unless the intent to prohibit more restrictive local regulation appears in the state rules. (Paul Lienau, OIT)

WASHINGTON

State and DOE Activities

11.18 WSEO to Evaluate State's Legal and Institutional Factors: The Washington State Energy office has received a DOE grant to identify and evaluate the legal and institutional factors that presently impede geothermal exploration, development, and utilization in the State of Washington. The effort will result in publishing by the end of fiscal year 1985 a developers guide to leasing, permitting and licensing. Dr. Gordon Bloomquist, WSEO manager for the project, has initiated work on the task.

REGIONAL GEOTHERMAL PROGRESS MONITOR
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JANUARY 1985

GENERAL

1.1 Field Management of Geopressured Programs Transferred to DOE-ID: The Department of Energy has transferred field management responsibilities for the geopressured programs from their Nevada Operations Office to the Idaho Operations Office. This is part of the Departments' effort to consolidate geothermal programs into fewer offices in response to an order issued by the Secretary of the Department. The reassignment also includes management of a bilateral agreement with the Electric Power Research Institute for the design, fabrication and operation of the first geopressured resource electrical generating system. Idaho Operations Office responsibilities rest with Charles E. Gilmore (telephone 208/526-1808). Program technical support to DOE-ID is being provided through the Idaho National Engineering Laboratory with Jack Ramsthaler (telephone 208/526-9688) of EG&G Idaho serving as program manager.

1.2 Cascades Drilling RFP to be Reissued by DOE-ID: A Department of Energy-Idaho Operations Office solicitation to conduct cost-shared exploratory drilling for potential high temperature resources in the Cascades Mountain range will be reissued. Lack of adequate response to the initial request has necessitated a second solicitation that is expected to be sent out in the near future.

1.3 District Heating Meeting for Policy Makers Set for Mid March: The U.S. Conference of Mayors is scheduling a district heating meeting March 14 and 15 in Boise, Idaho at the Red Lion-Riverside. The session is scoped towards policy makers and will carry the participants through the entire development and implementation process. Additional details can be obtained from Dave Williams, Association of Idaho Cities, phone 208/344-8594.

REGION VI

NEW MEXICO

Industrialization Activities

1.4 Amax Continues Drilling in Hidalgo County: Amax is drilling below 1320 ft in its' 55-7 NM 34790 in 7-25s-19w well located in the Lightning Dock Known Geothermal Resource Area. The well was spudded on December 29, 1984 and is projected to 7000 ft. The operator has set 20-inch casing at 360 ft, and 13-3/8-inch casing at 1050 ft. Amax has staked location for three additional tests in the same area. The 48-6 NM 34790 in 6-25s-19w, 67-7 NM 34790 in 7-25s-9w and the 82-18 NM 34790 in 18-25s-19w (National Geothermal Service 1-25-85).

REGION VIII

UTAH

STATE AND DOE ACTIVITIES

1.5 Utah State Prison Well Loses Artesian Flow: The Utah State Prison Well is reported to have lost artesian flow from its' geothermal well. Warm water spring flow into the bottom of a nearby pond used for fish rearing, and two small surface ponds are also affected. Geothermal waters are being pumped from the same reservoir at the rate of about 480 gpm for heating the nearby Utah Roses greenhousing facility. The situation is currently under evaluation.

REGION IX

NEVADA

INDUSTRIALIZATION ACTIVITIES

1.6 Amax Continues Fish Lake Area Well Drilling: Amax Exploration was drilling at 8589 ft at the 88 (17-12) 11 in 11-1s-36e in Esmeralda County. The Fish Lake Area development well was spudded on November 17, 1984 with the test scheduled to 8000 ft. Also in 11-1s-36e, Amax has shut-in for evaluation its'

88-11. That well was spudded on April 11, 1984 and reached a total depth of 8149 ft. the operator has set 30-inch casing at 14 ft, 20-inch at 278 ft, 13-3/8-inch casing at 1051 ft, and 9-5/8-inch casing at 6803 ft. Seven-inch liner was set at 6553-8140 ft. Amax currently has four additional test locations staked, the 77-29 in 29-1n-38, 1/2e, the 82-13 (N-96-47) in 13-1s-35e, the 66-15 (N-31-991) in 15-1s-35e and the 51-24 (N-103-11) in 24-1s-35e. (National Geothermal Service 1-25-85).

1.7 Elko Junior High Well Successful: The new Elko Junior High School will have an ample source of geothermal heat, it was announced this week. The school district received a state energy grant to drill a geothermal well at the site of the new school, and preliminary drilling began last September by Paul Williams and Sons, an Idaho drilling firm.

The well drilling was hampered by several problems, and the lack of indications of water in the heat source encountered at lesser depths caused the final well to reach a depth of over 1975 feet before a sufficient pressure of water was tapped.

Superintendent of Schools, Chuck Knight, commented that the new water source, first tapped on Monday, forced pressurized water and steam out of the well, and sent steam out of storm drains in the vicinity of the new school.

Preliminary estimates indicate that the water temperature is over 190 degrees and maintains a pressure of over 150 gallons per minute.

Knight said that this will provide sufficient water to heat the junior high and the hospital, as well as Elko High School.

He explained that any excess heated water could be used for nearby municipal buildings, such as the swimming pool and the Convention Center.

The next stage for the well is testing and logging temperatures, and the school district will apply for a discharge permit from the state's Department of Environmental Protection for a consumptive use of the geothermally heated water. A consumptive use permit has already been granted by the State Engineer's Office, provided no noticeable damage occurs to the already existing geothermal well operated by Elko Heat Company.

Geothermal heat will not be used in the new school when it opens for students this spring, but is expected to be in use by next winter. (Elko Independent 2-6-85)

REGION X

WASHINGTON

Industrialization Activities

1.8 Yakima County Opts to Bring Suit Against System Designer: Commissioners of Yakima County have opted to bring suit against the architectural firm of Walker, McGough, Foltz and Lyerla, a Spokane-based company, which designed geothermal heating and cooling system for the county's new $14.5 million jail, which had been scheduled for opening last Spring. Improper design, the county contends, caused delay in receiving the first of 265 inmates until early January when the facility began operating with an electric boiler. According to jail administrator Doug Blair, the geothermal system will not be ready for another 3 to 4 months.

Blair said that just before the ultarmodern jail was to take on its first inmates last April, it was observed that pipes in the mechanical system were rusted and corroded because the heating and cooling system was improperly designed. He said it took five months and about $100,000 to fix the problem. Basically, what was required, he said, was to convert equipment from an open system, where water was being exposed to air, to a closed-loop system with heat exchanger and filters, in which the same water is run continuously through loops. the open system had caused sand infiltration from geothermal wells, he said, and the resulting system shutdown enabled discovery of corrosion which formed on mesh screens inside pipes.

Although Yakima County commissioners are satisfied that redesign will eliminate malfunctioning, they plan to "look to those responsible for our problem to reimburse us for the cost of reconstruction." Cost of salaries for 30 security guards hired last Spring to man facility may be included. (Geothermal Report 2-1-85)

circulate
Ann Celsray

REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
MARCH 1985

GENERAL

3.1 Special Technology Transfer Poster Session Planned for Annual GRC Meeting: The Geothermal Resources Council, in conjunction with the U. S. Department of Energy, will conduct a special "Technical Transfer Opportunities Poster Session" to be held August 25 at the International Symposium in Kona, HI. The purpose of the session is to disseminate research findings that have been developed by Department of Energy contractors and others. Contact the Council office, telephone 916/758-2360 for more information.

3.2 Research Foundation Provides Aquaculture Information: The Geothermal Aquaculture Research Foundation (GARF) was founded in 1979 as an educational extension service to help people establish commercial geothermal aquaculture projects. The foundation studies geothermal water chemistry and aquatic life suitable for aquaculture. Personnel of the Geothermal Aquaculture Research Foundation are, therefore, good sources of all types of information regarding successful approaches to aquaculture projects and will very gladly provide advise on this subject. Freshwater shrimp and fish such as tilapia are examples of animals found suitable for geothermal aquaculture. The stocking of ponds prior to determining the water chemistry is a practice which has proved fatal to thousands of fish. The foundation can offer many suggestions to avoid mistakes of this type.

Foundation membership is $75.00 a year for individuals and $200 a year for corporations. A monthly publication is distributed.

For further information, contact Leroy Headlee, Director, Geothermal Aquaculture Research Foundation, 1321 Warm Springs Avenue, Boise, Idaho, 83712, telephone 208/344-6163. (Geothermal Hotline, 12-84)

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Industrialization Activities

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REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
APRIL 1985

GENERAL

4.1 BPA is Preparing to Issue 10 MW RFP: BPA is preparing to issue a request for proposals to develop 10 MW of geothermal power as part of the agency's implementation of the Regional Power Plan. Scheduled for early summer, the RFP is expected to stipulate that the initial development of 10 MW in-plant capacity must be at the site with at least 100 MW potential, and that the project be environmentally acceptable. (GRC-PNS Newsletter 3-85).

4.2 Regional Council Updates Power Plan: The Northwest Power Planning Council has begun the biennial revision of the Regional Power Plan, an updating process that should be completed in late 1985. The treatment of geothermal resources in the Plan is not expected to change in terms of the 20-year supply projection, but Council staff are interested in receiving comments in changes to the two year action plan which would be more responsive to current geothermal circumstances. Information and schedules for the geothermal component of the update process can be obtained from Jeff King at the Power Council office in Portland, telephone (503)221-5161. (GRC-PNS Newsletter 3-85)

4.3 New Officers Elected to GRC-PNC: The annual election of Section officers was completed in November, 1984 with the following results: President, R. Gordon Bloomquist, Washington State Energy Office; Vice President, Phil Essner, California Energy Company; Secretary/Treasurer, Alex Sifford, Oregon Department of Energy; Directors at Large, Eliot Allen, Eliot Allen & Associates, Inc. and John Reader, Barchan Geological Services Ltd. (GRC-PNS Newsletter 3-85)

4.4 New Regional Geothermal Assessment Completed: The state energy offices of Idaho, Montana, Oregon, and Washington are completing an 19-month assessment of geothermal potentials in the Pacific Northwest for BPA. Coordinated by R. Gordon Bloomquist of the Washington State Energy Office, this regional assessment project has inventoried resource and end-use potentials at approximately 250 sites using a custom-designed computer model named Georank to rate resource feasibilities for BPA. Contact any of the state energy office geothermal specialists for more details. (GRC-PNC Newsletter 3-85)

4.5 Symposium on Operating Geothermal District Heating Systems and Short Course on Corrosion Engineering Presented: The purpose of the symposium, convened at Oregon Institute of Technology on the 23-25 April 1985, was to exchange information and operating experiences on district heating. Highlights included a presentation on the development status of systems throughout the United States by David Meeker, Chairman of the National Research Council Committee on District Heating and Cooling. Other presentations covered reservoir depletion problems of the Reykjavik, Iceland system in a country where over 80% of space heating requirements are met by geothermal, and curbing air pollution caused by burning coal in Tianjin, China. Speakers on seven U.S. Systems covered such topics as: 1) partnership drilling and marketing in Boise; 2) educating engineers and contractors to assist with marketing in San Bernardino; 3) private venture in Elko; 4) factors leading to successful projects at Pagosa Springs and others; 6) complications caused by Ra 226 and agreement to sell effluent to businesses by the Haakon School District; and 7) institutional problems of interference in private wells and hydrology study for Klamath Falls. Kinds of geothermal corrosion, guidelines to select material and corrosion control were presented in an intensive short course by Peter Ellis, Radian Corp. The final day included roundtable discussions on financing, economics, technical assistance, and component selection as well as tours of the OIT, Merle West Medical Center and City of Klamath Falls district heating systems. Forty-one persons attended the symposium and its success can be attributed to the fact that speakers drew from "real life" experiences.

4.6 GRC Intermountain Section Elects Officers: Brent Russell, EG&G Idaho, is the new Section President and the Vice-President is Dick Macatee, also of EG&G Idaho. Charles Gilmore will serve as treasurer, and Susan Prestwich is the new secretary - both are with DOE-ID. The Board is made up of Ben Lunis and Bill Domenico of EG&G Idaho, and Susan Prestwich.

REGION VI

NEW MEXICO

State Activities

4.7 New Mexico Foundation Aids Geothermal Project: Burlington Northern Foundation has granted $25,000 to the New Mexico State University Energy Institute for use in its geothermal energy program. The institute reports that the grant will help finance a 12,000-square foot geothermally heated greenhouse on a 30-acre site near the university's main campus in Albuquerque.

The project will document technical and economic performance of various heat delivery systems and show that geothermal energy is cost-competitive for commercial greenhouses. The total cost of the complex is estimated at $465,000.

The Burlington Northern Foundation represents the Burlington Northern Railroad Co., El Paso Exploration Co./Milestone Petroleum Inc., El Paso Hydrocarbons Co., El Paso Natural Gas Co., Glacier Park Co., Meridian Minerals Co., and Plum Creek Timber Co. (Renewable Energy News, April 1985).

REGION IX

CALIFORNIA

Industrialization Activities

4.8 Wellhead Generators to be on Line Soon at Wendel: Wineagle Developers, a California limited partnership, expects two 350 kW Barber Nichols Model 24 25 binary generators on line by May 15, 1985 at Wendel, California. A 1350 foot artesian well supplies geothermal water at 230°F. Power will be wheeled by DP National to PG&E under standard offer No. 4. Two additional units at 1.4 MW each are planned. Operation and maintenance will be handled by Barber Nichols and management by Lahonton, Inc.

4.9 Cedarville Schools to Use Geothermal: A pumping and distribution system from a 125°F well has been completed at Cedarville to two high school buildings, a greenhouse, shops, elementary school building and two modular buildings. The geothermal system is designed to meet the peak heat load of all buildings with only the building retrofits left to be completed.

NEVADA

Industrialization Activities

4.10 Elko School District Drills Geothermal Well: A new well at Elko, Nevada, completed in February 1985 was intended to heat only the new Junior High School. In a preliminary test the well produced 190°F artesian flow rate at 150 gpm. With this temperature and production potential, it has been estimated that both the Junior and Senior High Schools as well as nearby municipal buildings and facilities, e.g. the Convention center and swimming pool, could be heated. The well will be logged and flow tested over a period of time before the exact use is determined.

4.11 Turbine Purchase Proceeding for Beowawe Site: Chevron Resources Co. let a contract to Mistsubishi Corp. for supply of a turbine and a generator to be used in a 17,000 kw geothermal power plant. Mitsubishi Heavy Industries Ltd. will supply the turbine and related gear, and Mitsubishi Electric Corp. will supply the generator. The plant, to be built in modules and delivered to a Beowawe, Nevada, site in October, will start up by year end. (O&G Journal 5/6/85)

REGION X

OREGON

Industrialization Activities

4.12 Drilling to Proceed Near Crater Lake: With the geothermal capability of the 800 mile chain of the cascade Mountains a possible major energy source equal to more than 400,000 MW of electricity over a 30 year span, attention is being given announced plans of California Energy, Santa Rosa, California, for early drilling of exploratory wells in the vicinity of Oregon's Crater Lake in Klamath County.

Crater Lake, as its name indicates, lies in the crater of what was known as Mt. Mazama, an extinct volcano which blew itself out centuries ago.

California Energy is the holder of the greatest number of geothermal leases on federal lands in Oregon, 53 leases totaling 90,485 acres. The firm plans to drill this summer, not only near Crater Lake, but on the slopes of the Newberry Volcano in Deschutes County, according to spokesman Joe LaFleur. (O&G Journal 4-22-85)

State Activities

4.13 Oregon To Prepare Power Plant Siting Standards: On March 7, 1985 the Oregon Energy Facility siting council ordered its staff to begin developing siting standards for geothermal power plants over 25 MW. This will be a 6-12 month project, including public hearings to be announced in the near future. Contact Alex Sifford (503/378-2778) at ODOE for more information. (GRC-PNC Newsletter 3-85)

Permission to drill was given recently to the company by the Bureau of Land Management, which supervises such activity on U.S. held lands.

Authority to regulate geothermal activity was handed the BLM under the Geothermal Steam Act of 1970, and the first leases were granted in 1974. The total of present leases in Oregon and Washington is 342, aggregating 629,197 acres. In Washington only three firms hold leases, Vulcan (with three partners), Phillips Petroleum, and Union Oil. The three hold 21 leases in all, of which Vulcan has 18 for 33,273 acres.

4.14 Deschutes County Adopts Local Policies and Regulations: Deschutes County, Oregon recently completed a 15-month project to prepare and adopt geothermal policies and standards to guide development on private and state-owned lands in the County. These measures, contained in the County's Comprehensive Plan & Zoning Ordinance, will also be advisory to the Forest Service and BLM in their decisions on federal lands that make up a large share of the County. Presently over 200,000 acres of lands have been leased in the County, and industry interest is particularly directed at the Newberry volcano and eastern Cascade areas. (GRC-PNC Newsletter 3-85)

4.15 State Geologist Registration Needs May be Re-defined: The State of Oregon Board of Geologist Examiners is currently involved in what appears to be an attempt to re-define a portion of Oregon revised Statutes Chapter 672. The portion in question is 672.505, where terms used in the law controlling registration and practice of geology within the State of Oregon are legally defined. The specific point in question concerns who is legally qualified to practice geothermal exploration within the State of Oregon. If recommendations of two of the five Board members are followed, most geologists who have been involved in geothermal exploration in the past will no longer be allowed to continue without becoming re-registered.

The effects of changing the definition of who will legally be allowed to practice geothermal exploration within the State of Oregon will be two-fold. The first effect has to do with public safety. The group legally franchized to conduct geothermal exploration would be inexperienced and without the knowledge to ensure short term and long term safety of a geothermal development. The second effect has to do with professional ethics. An illusion of competence will be presented to the public by the Board. The Board will be presenting a group that currently is without geothermal expertise as the only legal geothermal experts.

The results of the above attempts will directly affect the GRC members. Developers and utilizers will be adversely affected by the loss of available technical expertise. Geologists will be affected by disenfranchisement. Members interested in following this activity are encouraged to contact the Board of Geologist Examiners, Department of Commerce, 403 Labor and Industries Building, Salem, OR 97310 (503/378-4458). Let your feelings on this matter be known, and please send copies of your comments to Alex Sifford at the Oregon Department of Energy, 102 Labor and Industries Building, Salem, OR 97310. Printed, abridged minutes of the Board meeting and notices of upcoming meetings are supplied upon request. Complete minutes of the Board meetings on cassette tapes are available for listening at the Salem office. (GRC-PNS Newsletter 4-9-85)

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REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
May 1985

GENERAL

5.1 Three Firms Selected for Cascades Deep Thermal Gradient Drilling Cooperative Agreement: Three West Coast firms were selected the week of June 2 to enter into negotiations for cooperative agreements to drill four geothermal gradient holes in the Cascades Volcanic Region of Oregon.

The three firms selected are Blue Lake Geothermal Company, Portland, Oregon; GEO Operator Corporation, Menlo Park, California; and Thermal Power Company, Santa Rosa, California.

The Cascades Region is known to contain considerable geothermal potential as shown by recent volcanism and other thermal activities. The drilling program will further define this potential through data collection such as well logs, rock samples, and fluid samples. The results will be transferred to the public for possible further development of hydrothermal resources.

The two-year program, estimated at approximately $1 million, will result in drilling of up to four deep thermal gradient holes. (Sue Prestwich, DOE-ID)

5.2 Monitoring Methods for Injection of Geothermal Wastewater Report Available: Lawrence Berkeley Laboratory has completed a computer simulation study that compared different dc resistivity techniques for monitoring the location of chemical and thermal fronts from injection of geothermal wastewater into geothermal wells. Wastewater injection is necessary in fields where environmental constraints prohibit surface disposal.

The study used a three-dimensional finite-difference computer program and an idealized representation of a reservoir to model the injections. The methods investigated included both surface and downhole techniques with variations in wastewater flow rate, salinity, and location of dc resistivity sensor. Projections of the chemical and thermal fronts were calcualted throughout the reservoir using the computer program for periods up to 3 years.

The findings of the study clearly indicated that downhole measurements can better detect the effects of injection than surface measurements. In addition, it was found that the best conditions for monitoring are when the wastewater has a much higher salinity than in-situ water, and relatively large amounts are injected. It was estimated that the change in apparent resistivity due to thermal effects is one-tenth that of the chemical effects. For further information, contact Norman E. Goldstein, Lawrence Berkeley Laboratory, Building 50A-11450, Berkeley, CA 94720, Telephone No. (415) 486-5961.

REGION VI

NEW MEXICO

Commercial Activities

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Franklin cited the quieting of environmental opposition to development with institution of new drilling practices. Five or six wells were drilled for the first time from a single pad, reducing environmental damage. Owing to precautions taken in the design and construction of collection, steam feed and stripping, and sulfur removal systems, he said, "a near-zero H_2S emission level has been achieved."

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DOE Activities

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REGION X

IDAHO

Commercial Activities

5.6 Idaho Cuts Rates for Cogenerated Power: Bowing to complaints from the Idaho Power Company that it is awash in unwanted cogenerated power, Idaho regulators have slashed by 35 percent the 6.78 cents a kilowatt-hour that the utility had previously been obliged to pay cogenerators and small power producers. Last week, the Idaho Public Utility Commission ordered Idaho Power to reduce its per kilowatt-hour rate to 4.42 cents. The new rate will be effective until the commission rules on a request by the company for a permanent reduction in the amount it has to pay cogenerators. The first round of hearings on this request ended last week and a decision by the commission is expected by the end of the summer.

Last week, the commission also granted Idaho Power a $12.1 million (or 4.1 percent) rate increase designed to cover the cost of cogeneration contracts the utility has signed over the last four years. Idaho Power had asked the commission for a $21 million rate increase. Idaho Power, which charges retail customers a little less than 4 cents a kilowatt-hour for electricity, complains that the high rate the Idaho commission has forced it to pay cogenerators has attracted small power producers from hundreds of miles around. To add insult to injury, a utility spokesman complained, many cogenerators have not supplied the power they contracted to provide. As a result, Idaho Power is involved in a number of collection proceedings — trying to get back the money it paid out to cogenerators in advance. (The Energy Daily, 5-14-85)

OREGON

Commercial Activities

5.7 Klamath Falls Geothermal Resource Management Act is Being Processed: An ordinance to provide comprehensive management of the geothermal resources and thermal groundwaters within and adjacent to the City of Klamath Falls, Oregon is going through hearings for enactment. Its main provisions are to conserve and protect the geothermal fluids while allowing individual utilization (including pumping) of thermal groundwater for residential, institutional, commercial, industrial and other beneficial purposes. A specific provision eliminates wasteful effects of thermal water discharge within five (5) years. This Act will amend the previous City Geothermal Ordinance which prohibited pumping and injection of thermal groundwater and will encourage proper development and use of the reservoir. (Paul Lienau, OIT)

State Activities

5.8 State Geothermal Law Provisions Extensions Granted to CEC: The Oregon Department of Geology and Mineral Industries Governing Board Acted on California Energy Company's request for suspension of provisions of State geothermal law for their development work near Newberry Crater. The board approved a temporary well permit extension from 180 days to one year and extended confidentiality of data from four years to eight years or the life of the lease. (Paul Lienau, OIT)

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REGIONAL GEOTHERMAL PROGRESS MONITOR
ACTIVITIES REPORT
MARCH 1985

GENERAL

3.1 Special Technology Transfer Poster Session Planned for Annual GRC Meeting: The Geothermal Resources Council, in conjunction with the U. S. Department of Energy, will conduct a special "Technical Transfer Opportunities Poster Session" to be held August 25 at the International Symposium in Kona, HI. The purpose of the session is to disseminate research findings that have been developed by Department of Energy contractors and others. Contact the Council office, telephone 916/758-2360 for more information.

3.2 Research Foundation Provides Aquaculture Information: The Geothermal Aquaculture Research Foundation (GARF) was founded in 1979 as an educational extension service to help people establish commercial geothermal aquaculture projects. The foundation studies geothermal water chemistry and aquatic life suitable for aquaculture. Personnel of the Geothermal Aquaculture Research Foundation are, therefore, good sources of all types of information regarding successful approaches to aquaculture projects and will very gladly provide advise on this subject. Freshwater shrimp and fish such as tilapia are examples of animals found suitable for geothermal aquaculture. The stocking of ponds prior to determining the water chemistry is a practice which has proved fatal to thousands of fish. The foundation can offer many suggestions to avoid mistakes of this type.

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IDAHO

Commercial Activities

5.6 Idaho Cuts Rates for Cogenerated Power: Bowing to complaints from the Idaho Power Company that it is awash in unwanted cogenerated power, Idaho regulators have slashed by 35 percent the 6.78 cents a kilowatt-hour that the utility had previously been obliged to pay cogenerators and small power producers. Last week, the Idaho Public Utility Commission ordered Idaho Power to reduce its per kilowatt-hour rate to 4.42 cents. The new rate will be effective until the commission rules on a request by the company for a permanent reduction in the amount it has to pay cogenerators. The first round of hearings on this request ended last week and a decision by the commission is expected by the end of the summer.

Last week, the commission also granted Idaho Power a $12.1 million (or 4.1 percent) rate increase designed to cover the cost of cogeneration contracts the utility has signed over the last four years. Idaho Power had asked the commission for a $21 million rate increase. Idaho Power, which charges retail customers a little less than 4 cents a kilowatt-hour for electricity, complains that the high rate the Idaho commission has forced it to pay cogenerators has attracted small power producers from hundreds of miles around. To add insult to injury, a utility spokesman complained, many cogenerators have not supplied the power they contracted to provide. As a result, Idaho Power is involved in a number of collection proceedings — trying to get back the money it paid out to cogenerators in advance. (The Energy Daily, 5-14-85)

OREGON

Commercial Activities

5.7 Klamath Falls Geothermal Resource Management Act is Being Processed: An ordinance to provide comprehensive management of the geothermal resources and thermal groundwaters within and adjacent to the City of Klamath Falls, Oregon is going through hearings for enactment. Its main provisions are to conserve and protect the geothermal fluids while allowing individual utilization (including pumping) of thermal groundwater for residential, institutional, commercial, industrial and other beneficial purposes. A specific provision eliminates wasteful effects of thermal water discharge within five (5) years. This Act will amend the previous City Geothermal Ordinance which prohibited pumping and injection of thermal groundwater and will encourage proper development and use of the reservoir. (Paul Lienau, OIT)

State Activities

5.8 State Geothermal Law Provisions Extensions Granted to CEC: The Oregon Department of Geology and Mineral Industries Governing Board Acted on California Energy Company's request for suspension of provisions of State geothermal law for their development work near Newberry Crater. The board approved a temporary well permit extension from 180 days to one year and extended confidentiality of data from four years to eight years or the life of the lease. (Paul Lienau, OIT)

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REGIONAL GEOTHERMAL PROGRESS MONITOR
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GENERAL

4.1 BPA is Preparing to Issue 10 MW RFP: BPA is preparing to issue a request for proposals to develop 10 MW of geothermal power as part of the agency's implementation of the Regional Power Plan. Scheduled for early summer, the RFP is expected to stipulate that the initial development of 10 MW in-plant capacity must be at the site with at least 100 MW potential, and that the project be environmentally acceptable. (GRC-PNS Newsletter 3-85).

4.2 Regional Council Updates Power Plan: The Northwest Power Planning Council has begun the biennial revision of the Regional Power Plan, an updating process that should be completed in late 1985. The treatment of geothermal resources in the Plan is not expected to change in terms of the 20-year supply projection, but Council staff are interested in receiving comments in changes to the two year action plan which would be more responsive to current geothermal circumstances. Information and schedules for the geothermal component of the update process can be obtained from Jeff King at the Power Council office in Portland, telephone (503)221-5161. (GRC-PNS Newsletter 3-85)

4.3 New Officers Elected to GRC-PNC: The annual election of Section officers was completed in November, 1984 with the following results: President, R. Gordon Bloomquist, Washington State Energy Office; Vice President, Phil Essner, California Energy Company; Secretary/Treasurer, Alex Sifford, Oregon Department of Energy; Directors at Large, Eliot Allen, Eliot Allen & Associates, Inc. and John Reader, Barchan Geological Services Ltd. (GRC-PNS Newsletter 3-85)

4.4 <u>New Regional Geothermal Assessment Completed</u>: The state energy offices of Idaho, Montana, Oregon, and Washington are completing an 19-month assessment of geothermal potentials in the Pacific Northwest for BPA. Coordinated by R. Gordon Bloomquist of the Washington State Energy Office, this regional assessment project has inventoried resource and end-use potentials at approximately 250 sites using a custom-designed computer model named Georank to rate resource feasibilities for BPA. Contact any of the state energy office geothermal specialists for more details. (GRC-PNC Newsletter 3-85)

4.5 <u>Symposium on Operating Geothermal District Heating Systems and Short Course on Corrosion Engineering Presented</u>: The purpose of the symposium, convened at Oregon Institute of Technology on the 23-25 April 1985, was to exchange information and operating experiences on district heating. Highlights included a presentation on the development status of systems throughout the United States by David Meeker, Chairman of the National Research Council Committee on District Heating and Cooling. Other presentations covered reservoir depletion problems of the Reykjavik, Iceland system in a country where over 80% of space heating requirements are met by geothermal, and curbing air pollution caused by burning coal in Tianjin, China. Speakers on seven U.S. Systems covered such topics as: 1) partnership drilling and marketing in Boise; 2) educating engineers and contractors to assist with marketing in San Bernardino; 3) private venture in Elko; 4) factors leading to successful projects at Pagosa Springs and others; 6) complications caused by Ra 226 and agreement to sell effluent to businesses by the Haakon School District; and 7) institutional problems of interference in private wells and hydrology study for Klamath Falls. Kinds of geothermal corrosion, guidelines to select material and corrosion control were presented in an intensive short course by Peter Ellis, Radian Corp. The final day included roundtable discussions on financing, economics, technical assistance, and component selection as well as tours of the OIT, Merle West Medical Center and City of Klamath Falls district heating systems. Forty-one persons attended the symposium and its success can be attributed to the fact that speakers drew from "real life" experiences.

4.6 GRC Intermountain Section Elects Officers: Brent Russell, EG&G Idaho, is the new Section President and the Vice-President is Dick Macatee, also of EG&G Idaho. Charles Gilmore will serve as treasurer, and Susan Prestwich is the new secretary - both are with DOE-ID. The Board is made up of Ben Lunis and Bill Domenico of EG&G Idaho, and Susan Prestwich.

REGION VI

NEW MEXICO

State Activities

4.7 New Mexico Foundation Aids Geothermal Project: Burlington Northern Foundation has granted $25,000 to the New Mexico State University Energy Institute for use in its geothermal energy program. The institute reports that the grant will help finance a 12,000-square foot geothermally heated greenhouse on a 30-acre site near the university's main campus in Albuquerque.

The project will document technical and economic performance of various heat delivery systems and show that geothermal energy is cost-competitive for commercial greenhouses. The total cost of the complex is estimated at $465,000.

The Burlington Northern Foundation represents the Burlington Northern Railroad Co., El Paso Exploration Co./Milestone Petroleum Inc., El Paso Hydrocarbons Co., El Paso Natural Gas Co., Glacier Park Co., Meridian Minerals Co., and Plum Creek Timber Co. (Renewable Energy News, April 1985).

REGION IX

CALIFORNIA

Industrialization Activities

4.8 Wellhead Generators to be on Line Soon at Wendel: Wineagle Developers, a California limited partnership, expects two 350 kW Barber Nichols Model 24 25 binary generators on line by May 15, 1985 at Wendel, California. A 1350 foot artesian well supplies geothermal water at 230°F. Power will be wheeled by DP National to PG&E under standard offer No. 4. Two additional units at 1.4 MW each are planned. Operation and maintenance will be handled by Barber Nichols and management by Lahonton, Inc.

4.9 Cedarville Schools to Use Geothermal: A pumping and distribution system from a 125°F well has been completed at Cedarville to two high school buildings, a greenhouse, shops, elementary school building and two modular buildings. The geothermal system is designed to meet the peak heat load of all buildings with only the building retrofits left to be completed.

NEVADA

Industrialization Activities

4.10 Elko School District Drills Geothermal Well: A new well at Elko, Nevada, completed in February 1985 was intended to heat only the new Junior High School. In a preliminary test the well produced 190°F artesian flow rate at 150 gpm. With this temperature and production potential, it has been estimated that both the Junior and Senior High Schools as well as nearby municipal buildings and facilities, e.g. the Convention center and swimming pool, could be heated. The well will be logged and flow tested over a period of time before the exact use is determined.

4.11 Turbine Purchase Proceeding for Beowawe Site: Chevron Resources Co. let a contract to Mistsubishi Corp. for supply of a turbine and a generator to be used in a 17,000 kw geothermal power plant. Mitsubishi Heavy Industries Ltd. will supply the turbine and related gear, and Mitsubishi Electric Corp. will supply the generator. The plant, to be built in modules and delivered to a Beowawe, Nevada, site in October, will start up by year end. (O&G Journal 5/6/85)

REGION X

OREGON

Industrialization Activities

4.12 Drilling to Proceed Near Crater Lake: With the geothermal capability of the 800 mile chain of the cascade Mountains a possible major energy source equal to more than 400,000 MW of electricity over a 30 year span, attention is being given announced plans of California Energy, Santa Rosa, California, for early drilling of exploratory wells in the vicinity of Oregon's Crater Lake in Klamath County.

Crater Lake, as its name indicates, lies in the crater of what was known as Mt. Mazama, an extinct volcano which blew itself out centuries ago.

California Energy is the holder of the greatest number of geothermal leases on federal lands in Oregon, 53 leases totaling 90,485 acres. The firm plans to drill this summer, not only near Crater Lake, but on the slopes of the Newberry Volcano in Deschutes County, according to spokesman Joe LaFleur. (O&G Journal 4-22-85)

State Activities

4.13 Oregon To Prepare Power Plant Siting Standards: On March 7, 1985 the Oregon Energy Facility siting council ordered its staff to begin developing siting standards for geothermal power plants over 25 MW. This will be a 6-12 month project, including public hearings to be announced in the near future. Contact Alex Sifford (503/378-2778) at ODOE for more information. (GRC-PNC Newsletter 3-85)

Permission to drill was given recently to the company by the Bureau of Land Management, which supervises such activity on U.S. held lands.

Authority to regulate geothermal activity was handed the BLM under the Geothermal Steam Act of 1970, and the first leases were granted in 1974. The total of present leases in Oregon and Washington is 342, aggregating 629,197 acres. In Washington only three firms hold leases, Vulcan (with three partners), Phillips Petroleum, and Union Oil. The three hold 21 leases in all, of which Vulcan has 18 for 33,273 acres.

4.14 Deschutes County Adopts Local Policies and Regulations: Deschutes County, Oregon recently completed a 15-month project to prepare and adopt geothermal policies and standards to guide development on private and state-owned lands in the County. These measures, contained in the County's Comprehensive Plan & Zoning Ordinance, will also be advisory to the Forest Service and BLM in their decisions on federal lands that make up a large share of the County. Presently over 200,000 acres of lands have been leased in the County, and industry interest is particularly directed at the Newberry volcano and eastern Cascade areas. (GRC-PNC Newsletter 3-85)

4.15 State Geologist Registration Needs May be Re-defined: The State of Oregon Board of Geologist Examiners is currently involved in what appears to be an attempt to re-define a portion of Oregon revised Statutes Chapter 672. The portion in question is 672.505, where terms used in the law controlling registration and practice of geology within the State of Oregon are legally defined. The specific point in question concerns who is legally qualified to practice geothermal exploration within the State of Oregon. If recommendations of two of the five Board members are followed, most geologists who have been involved in geothermal exploration in the past will no longer be allowed to continue without becoming re-registered.

The effects of changing the definition of who will legally be allowed to practice geothermal exploration within the State of Oregon will be two-fold. The first effect has to do with public safety. The group legally franchized to conduct geothermal exploration would be inexperienced and without the knowledge to ensure short term and long term safety of a geothermal development. The second effect has to do with professional ethics. An illusion of competence will be presented to the public by the Board. The Board will be presenting a group that currently is without geothermal expertise as the only legal geothermal experts.

The results of the above attempts will directly affect the GRC members. Developers and utilizers will be adversely affected by the loss of available technical expertise. Geologists will be affected by disenfranchisement. Members interested in following this activity are encouraged to contact the Board of Geologist Examiners, Department of Commerce, 403 Labor and Industries Building, Salem, OR 97310 (503/378-4458). Let your feelings on this matter be known, and please send copies of your comments to Alex Sifford at the Oregon Department of Energy, 102 Labor and Industries Building, Salem, OR 97310. Printed, abridged minutes of the Board meeting and notices of upcoming meetings are supplied upon request. Complete minutes of the Board meetings on cassette tapes are available for listening at the Salem office. (GRC-PNS Newsletter 4-9-85)

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NV Summary

REGIONAL GEOTHERMAL PROGRESS MONITOR
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GENERAL

8.1 Fifteen-year Extension of Geothermal Leases Sought by U.S. Senator: Democratic Senator Chic Hecht of Nevada is lobbying during the off-session of Congress just ending for passage of a bill he is sponsoring to extend for 15 years, if needed, geothermal leases on property having proven power resources that cannot now be developed for economic reasons. Seeking co-sponsors and planning to request Congressional hearing this fall, Hecht said that "the combination of large front-end development costs, risky power plant technology and uncertainty over future world energy prices has led to the cancellation or delay of many promising geothermal power projects."

"These problems," he said, "are now being compounded by certain inflexible provisions of the Steam Act (of 1970) which prohibit the extension of leases where diligent field development has occurred, but actual power plant construction has been delayed by market forces. Section 319 of last years continuing resolution gave geothermal lease holders a temporary respite by allowing the conditional two-year extension of original 1-year leases issued under the Steam Act." But this isn't sufficient, he contends.

Hecht's bill would establish a permanent mechanism for granting up to three successive five-year extensions. Firms seeking more time would have to prove with each five-year request that they had made substantial investments in exploration without being able to produce geothermal energy in commercial quantities. As company plans are reviewed, bill would require the Department of Interior to consider terminating leases "not reasonably necessary to the economic viability of a unit or cooperative plan."

Regarding attempts by environmentalists to establish "buffer zones" against geothermal development around Yellowstone National Park in Wyoming and about 20 other national Parks and monuments in country containing geothermal features, Hecht indicated that, although there's no intention to permit intrusion in these preserves, the de facto propaganda campaign instituted by park protection advocates has "dealt a serious blow to the entire geothermal industry because of their opposition to development in a few specific areas of the country."

If Hecht's amendment is adopted, every lease issued in accordance with geothermal Steam Act and, in effect, on or after July 27, 1984, would be eligible for extension if applied for either within 180 days after adoption of amendment or 60 days before lease's primary term expires, depending on which is later. (Geothermal Report 9-2-85)

8.2 St. Mary's Hospital Project Report is Available: "Geothermal Heating Project at St. Mary's Hospital, Pierre, South Dakota" final report, No. DOE/ET/28441-7 (DE85008336) is available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, telephone 703/487-4600

St. Mary's Hospital, Pierre, S.D., with the assistance of the U.S. Department of Energy, drilled a 2,176' well into the Madison Aquifer to secure 108°F artesian flow water at 385 gpm (475 psig shut-in pressure). The objective was to provide heat for domestic hot water and to space heat 163,768 sq. ft. Cost savings for the first three years were significant and, with the exception of a shutdown to replace some corroded pipe, the system has operated reliably and continuously for the last four years.

8.3 <u>East Mesa Pump Test Facility Report Issued</u>: The "East Mesa Geothermal Pump Test Facility (EMPTF)" Final Report, No. DOE/SF/11556-T1 (DE85003521) is available from the NTIS, address noted above.

Barber-Nichols was awarded a contract in September, 1981 for design and fabrication of a Geothermal Pump Test Facility at East Mesa (EMPFT) by the U.S. Department of Energy. The test facility provides the pump industry with a tool for in-the-well testing at typical operating conditions for submersible pumps while eliminating the risk of actual downwell geothermal field testing. The aim of this project was to produce a test facility for use by pump manufacturers to encourage research and development of electric submersible geothermal pumps.

8.4 <u>Sugar Refining Report Released</u>: The NTIS has released "Use of Geothermal Heat For Sugar Refining in Imperial County" Pilot Plant Implementation Report, No. DOE/SF/10814-T1 (DE85003673).

A program aimed at replacing fossil fuels with geothermal energy for the processing of sugar beets was conducted under a Department of Energy (DOE) Program Opportunity Notice (PON). The program was to be carried out in three phases: this report documents activities during the second phase.

The first phase was performed by TRW Energy Systems Group with the Holly Sugar Corporation as industrial participant. That phase involved the preliminary evaluation of the design and potential benefits of a geothermal industrial process heat system at Holly's plant in Brawley, California.

The second phase of the program, to which this report is addressed is entitled "Pilot Plan Implementation". During this phase, Holly Sugar Corporation acted as lead organization with

TRW Energy Systems Group as integration contractor. The objective of the phase was to develop a successful geothermal resource and use it in conjunction with a geothermal process heat pilot plant to demonstrate the adequacy of a system which could provide technically sound, economical, and environmentally acceptable process heat.

The third phase of the program was planned to carry the pilot plant design to full scale and replace fossil fuel use in accordance with the design projections of the first phase.

During the second phase drilling of an exploratory production well was carried out. The well reached a total depth of about 10,000 feet. Static bottom hole temperatures as high as 393 degrees F were calculated. However, the well did not produce a free flow of more than 2-3 barrels of brine per hour. Attempts were made to stimulate the well by gas lift and circulation. These procedures were unsuccessful in promoting flow, and the well was shut in. At that point the DOE decided to terminate the project.

8.5 <u>DOE and Industry Unite to Boost Geothermal</u>: Government and industry have formed a group to help finance and develop geothermal energy technologies. The Department of Energy and 18 private organizations have founded the Geothermal Drilling Organization (GDO), a screening committee that will share development costs for promising technologies. DOE's Sandia National Laboratories of Albuquerque, N.M., is the manager of the program. Chairman of the new group is Del Pyle, manager of drilling operations for Union Oil Co. of California.

A GDO advisory committee, made up of four officers and two scientists appointed by the chairman, will review proposals for fabrication of hardware or field work. GDO members interested in funding a specific proposal will then form an ad hoc group to negotiate an agreement and to select a project contractor. DOE will contribute 50 percent of the funding and GDO members will meet the other half of the costs.

According to the guidelines of the new organization, all contracts must insure that patents resulting from the funded work be issued in the names of the contractors that commercialize the technology, according to a DOE spokesman. In addition, DOE and GDO members that fund projects will be entitled to royalty-free licenses for any patented equipment.

GDO members are: DOE; Union Geothermal; Geothermal Resources International; Republic Geothermal; Phillips Geothermal; Chevron Geothermal; California Energy Co.; MCR Geothermal; Steam Reserve Corp.; Mono Power Co.; Anadarko Production Co.; Foamair Products; Eastman Whipstock; NL Industries; Dresser Industries; Smith International; Dailey Directional Services; H&H Tool, and Pajarito Enterprises.

The group has already funded its first venture: Squire-Whitehouse Inc. of San Diego, Calif., received a 20-month, $950,000 award. According to the contract, Squire-Whitehouse, a logging tool manufacturer, will build two acoustic borehole televiewers that will operate at temperatures of up to 275 degrees Centigrade and will conduct laboratory tests to confirm their effectiveness. Flo-Log Inc. of Long Beach, Calif., will then use the tools for a year to conduct any geothermal well-logging operations that are requested by interested energy companies. Union Geothermal and Geothermal Resources International are the GDO members that are helping fund the work.

The U.S. Geological Survey predicts that 100,000 megawatts of electricity and process heat could be produced from geothermal energy. Presently, geothermal yields about 1,200 megawatts. Some 80 wells have been drilled this year.

"Although this country's geothermal drilling effort is tiny when compared with the oil and gas drilling business, the geothermal resources in the western United States with proper nurturing, could become a significant contributor to the nation's electrical energy mix," says James Kelsey, GDO secretary and supervisor of Sandia's geothermal technology division.

GDO, he adds, is considering funding other ventures, including the development of an aqueous foam that can be used for well clean-out, development of drill string components that use high-temperature elastomers, and development of an open-hole bridge plug. (The Energy Daily, 8-27-85)

REGION IX

CALIFORNIA

INDUSTRIALIZATION ACTIVITIES

8.6 Spa in a Bar Developed: Larry Durkin of Santa Rosa, California has developed an evaporation process to recover minerals from hot springs. Spa in a Bar consists of minerals from 26 gallons of hot spring water, powdered milk and dehydrated lemon to produce a bar that when used in a bath gives the same effect as soaking in a thermal pool.

8.7 California Energy Commission (CEC) Announces Grant and Loan Program: The California Energy Commission is beginning the sixth funding cycle for the Geothermal Grant and Loan Program for Local Jurisdictions. Through this program the CEC distributes funds received by the state from federal geothermal leases to local jurisdictions for projects relating to geothermal development. The CEC has approximately $2.5 million available for: 1) planning projects for large and small scale power plants and direct use development; 2) projects to assess and develop geothermal resources; and 3) projects to monitor or mitigate impacts of existing geothermal development. Questions regarding this program should be directed to Michael Smith,California Energy commission, 1516 9th St, MS 43 Sacramento, CA 95814.

NEVADA

Industrialization Activities

8.8 One Operating, Four More Power Plants to Go on Line This Year: No less than four geothermal power plants are scheduled to go on line by the end of this year and one little project - Wabuska Hot Springs north of Yerington - has been supplying geothermally produced electricity to Sierra Pacific Power Company for more than a year.

While the plants are small compared to a Valmy coal-fired plant, they already are starting to add up. Geothermal projects planned or under construction in Nevada over the next three years total 121 megawatts - bigger than any of the units at Sierra Pacific's old oil and gas-fired power plants at Tracy or Fort Churchill.

That's enough electricity to supply a city the size of Reno. About a third of that - just under 40 megawatts - is scheduled to go on line by the end of this year at plants already under construction at Beowawe, southeast of Battle Mountain; Desert Peak and Brady's Hot Springs, between Fallon and Lovelock, and Steamboat, south of Reno.

Plants are nearing construction in Big Smoky Valley, south of Austin, Fish Lake Valley, between Tonopah and Bishop; and Dixie Valley, east of Fallon. And that's just scratching the surface, geothermal experts say.

A conservative estimate of Nevada's geothermal resources - 4,000 megawatts - is double the entire generating capacity of conventional power plants in the state today, said Dan Shockett, vice president and general manager of ORMAT Systems, a new

Reno-based company selling complete, packaged geothermal generating plants. Over the years, that could create a $4 billion energy exporting industry in Nevada, said Shockett. In fact, ORMAT moved its company headquarters from Boston to Reno last year to be closer to the action.

Beowawe has been one of the most thoroughly drilled geothermal areas in the state, which may account for the disappearance of several of its natural geysers, according to geologist Larry Garside of the Nevada Bureau of Mines and Geology. It and Brady's Hot Springs have the hottest geothermal steam wells in the state, Garside found in a 1979 survey of Nevada's geothermal resources.

Development of Beowawe finally got under way last year when Chevron Geothermal Co., a subsidiary of the big oil company, and the Crescent Valley Geothermal Co., a subsidiary of Southern California Edison Co., teamed up to start the largest geothermal power plant under construction in the state. They hope to start testing their 15.2-megawatt plant as early as mid-September and have it operating by the December 31 tax credit deadline.

Chevron will invest about $5 million to bring in several deep production wells, while the Southern California Edison subsidiary will spend $15 to $20 million for the power plant, said Mark Murray of Crecent Valley Energy. They are buying the plant from Mitsubishi Heavy Industries, so Japanese engineers are at the site, along with John McGregor, a Scottish project engineer for Associated Southern Engineering, which is installing the plant, and people from the Dravo Corp., the construction subcontractor. They are slant drilling to a depth of 8,000 feet in the main well where they encounter temperatures in excess of 400 degrees.

The Chevron-Edison partnership is negotiating to send the power to Southern California over Sierra Pacific's lines. Since those lines may only have a capacity for 10 or 11 megawatts, the rest will have to be sold to utilities north of Nevada or Sierra Pacific, Murray said.

While it isn't the biggest, Tad's Enterprises of Wabuska is the first geothermal plant in Nevada. Last July, the Wabuska facility began sending 650 kilowatts into Sierra Pacific lines, giving northern Nevada its first truly home-grown power.

Tad's Enterprises is the investment firm of two Bay area brothers, Neal and Don Townsend, who have been experimenting with their geothermal hot springs, 15 miles north of Yerrington, since the late '70s. First they put in a gasohol plant, using the hot water to distill corn, only to watch the oil shortage turn into an oil glut. Then they started an algae farm, growing the protein-rich plants in geothermal pools for health food outlets. They transferred that operation last year to a hot springs they own at Klamath Falls, Oregon. Now they have put another $1 million into buying a small power plant from ORMAT. "It's experimental to some degree," Neal Townsend said. "We intend to make money out of it, but we had a lot of adjustments we had to do."

A lot of geothermal experts were skeptical that Wabuska's 220-degree water could be used to generate electricity. That's considered a pretty low temperature for power generation. But the freon-based generator from ORMAT was just upgraded to 800,000 kilowatts and the Townsends plan to buy a second, 1.20-megawatt unit next year. If that proves successful and the PSC approves a favorable long-term contract with Sierra Pacific, they will add a 5-megawatt plant in 1987 or 88, he said.

Sierra Pacific, the Department of Energy and the University of Oregon have started extensive tests to monitor its efficiency of converting a low-temperature geothermal resource into electricity.

Geothermal Development Associates has been building its 5-megawatt plant at Steamboat "in a goldfish bowl," said company president Martin Booth. Its location at the busy intersection of U.S. Highway 395 and the Mount Rose Highway gives it something most Nevada geothermal projects don't have to contend with: people.

Some Steamboat Springs residents - notably Dorthy Towne, who has extensive geothermal holdings herself, as owner of the old Steamboat spa - has objected about the possibility of noise and odors from the new plant. But there are ways to get rid of the hydrogen sulfide odors that sometimes accompany gothermal water, Booth said, and the project's special use permit from Washoe County requires the plant to be 10 percent quieter than a typical residential neighborhood. The plant is being built as if it were surrounded by houses, said Booth, although the nearest, other than Towne's, is still pretty far up the Mount Rose Highway. "We want to be very good neighbors because this resource can be used by northern Nevada people. We are putting this together in a gold fish bowl because everyone can see us, so we go well beyond what we are required to do." And GDA wants a good reputation in case the project proves to be expandable, he added.

Other partners include power systems engineer Dave Mendive, Greenhouse Garden Center owner Bob Ruf of Carson City and Reno mining attorney Richard Harris. They have raised $10 million in private financing to build the plant on 30 acres owned by Sierra Pacific. PSC officials found that particularly attractive, since it can save money by hooking into a big electrical substation already on site.

GDA also is buying its generators from ORMAT, whose freon-based system will allow it to extract electricity from a "moderate" temperature of 300 to 350 degrees. At 500 to 2,000 feet deep, the three production wells are shallow compared to most geothermal projects, Booth said.

A mile or two to the south, Phillips Geothermal Group is hitting temperatures of 440 degrees in much deeper wells. Phillips also has plans for a 5 to 10 megawatt geothermal power plant at Steamboat. Officials of both companies insist their operations won't affect each other, especially since Phillips is going so much deeper. The oil company subsidiary is boring its third deep well at Steamboat in partnership with Yankee Petroleum Company. Each production well has cost about $1 million. Their latest drill rig is towering above Pleasant Valley. The companies have no projected date for their Steamboat plant, said Tom Turner, geothermal development director for Phillips.

Pieces of Phillips' 9-megawatt power plant began arriving at Desert Peak last week, where 70 workers will assemble it this fall. Turner said the $15 million project is ahead of schedule so it should have no problem beating the December 31 tax credit deadline. Desert Peak is the only "blind" geothermal reservoir in the country, Turner said - that is, there were no hot springs, geysers or steam vents to indicate the presence of super-hot water underground. Phillips geologists began poking and drilling the little mountain in 1973. Since then, according to the Nevada PSC, the company has spent $7 million in exploration alone . . . that's before spending a dollar on the power plant.

Phillips is using an experimental "biphase turbine" built in Trenton, N.J. by TransAmerica Corporation that will simultaneously generate electricity from steam and super hot water from two 9,000-foot wells which hit 410-degree water.

PSC officials said Phillips originally estimated Desert Peak has a potential for 300 or 400 megawatts, but the company has put future expansion on the back burner. It used so much of its capital to stave off a take-over bid by "corporate raider" T. Boone Pickens that it has little available for exploration, Turner explained. It has put its geothermal properties up for sale to recoup much-needed cash. That could slow geothermal development in Nevada; Phillips is one of the most active companies in the field with more than 50,000 acres under geothermal leases in Washoe, Churchill and Pershing Counties. Its Desert Peak leases take in 36 square miles of "checkerboard" lands with sections alternating between the BLM and Southern Pacific Railroad's real estate company.

Steve Munson plans to generate 9.9 megawatts of electricity there (Brady Hot Springs) by the end of the year. Like the geothermal people at Steamboat, Munson said his wells won't hurt the food processing plant, about a mile away, and the Phillips wells at Desert Peak won't hurt his operation, seven miles distant. "Our properties are on substantially different resources than Phillips' and Brady Hot Springs" he said. Munson's wells are shallower than Phillips and, at 300 to 320 degrees, not as hot. He will use two different types of generators - one from ORMAT for about 3.9 megawatts and another from a pilot project in Idaho. It is a dual turbine that splits the geothermal fluid into a high and low-pressure streams and extract electricity simultaneously from both. He has signed a contract to sell his output to Sierra Pacific Power Co. and applied for PSC approval only two weeks ago. Munson has been testing the hot waters at Brady's for five years.

Nevada Geothermal Associates is drilling test wells along a 15-mile line running roughly between two well-known hot springs in Big Smoky Valley - McCloud and Darrough, where Locals often soak away their cares in a geothermal pool. Its planned 10-megawatt power plant was one of the three Sierra Pacific Power Company contracts approved by the PSC last year.

The group is still working on financing, said Jack Tjeersdma of Mill Valley, one of the investors. Other principals include land and leaseholders in the Nye County area, about 60 miles south of Austin. Tjeersdma said they expect to pay close to a rule of thumb that geothermal power costs about $2,000 per kilowatt to develop, counting exploration drilling, construction and financing. If so, their investment will total about $20 million.

Steam Reserve Corporation is negotiating with Southern California Edison to sell 15 megawatts it intends to generate in Fish Lake Valley, about 60 miles southwest of Tonopah. The company intends to install its first 5-megawatt generator next year and add the other 10 megawatts by 1988, said Dean Pilkington, chief geologist. It is a subsidiary of Amax Exploration Co., which is a subsidiary of AMAX, which operates the biggest molybdenum mine at Climax, Colorado. The power plant will feed into the facilities of Valley Electric Association, a small rural cooperative serving the Esmeralda County area, which will relay the electricity to Oasis, California, east of Bishop for distribution in California. To do that, Steam Reserve will have to build its own seven-mile power line through the remote valley. Exploration started in 1981 and the company has reached water up to 383 degrees in deep wells. "We'll operate the plant and pay for the power line," Pilkington said.

Although Dixie Valley is one of the most promising geothermal areas in the West - Hoops (BLM) thinks it could generate at least 500 megawatts of power - its developers are in a tough spot. They have to build their own power line - 220 miles from the remote Churchill County valley across Mineral county to Bishop. And the U.S. Navy which just abandoned its own geothermal project in Fallon, is balking at the high towers and drilling rigs that would be around its bombing and test ranges at Dixie Valley, Hoops said, even though the route is outside the military withdrawal. The BLM is due to release an environmental assessment of the 230-kilovolt line soon.

Oxbow Geothermal plans to build a 50 megawatt plant that would serve Southern California Edison, said Doug Powell, the company's Reno representative. That makes it the biggest geothermal project on the drawing boards in Nevada. About 20 people would be needed to operate it. If the power line is approved, construction could begin next year with power production as early as mid-1987, Powell said. For the power line and plant, he said Oxbow is prepared to spend about $100 million. (Excerpts from Reno Gazette-Journal Article, Pages 1F and 2F, August 18, 1985).

8.9 Development for Navy at Fallon Halted: The Helioscience General joint venture has thrown in the towel on developing up to 75 MW of geothermal energy at the Navy's Fallon, Nevada facility. The Joint venture decision between Helioscience and General Ener-Tech to terminate its contract with the Navy, without penalty, thus writes the finish to a project which began in April, 1983. The joint venture participants cited a sharp decline in the contract selling price of electricity as the cause for ending the contract, and said spending of $700,000 would be written off by Helioscience in 1985.

OREGON

INDUSTRIALIZATION ACTIVITIES

8.10 District Heating Considered for Goldmohr Terrace in Lakeview: Goldmohr Terrace, consisting of 25 to 30 homes in Lakeview, is seriously considering a residential district heating system. System and development costs are being investigated.

8.11 Greenhouses in Lakeview to Undergo Modifications: The "Greenhouse", formerly Oregon Desert Farms, is in the process of modifying its heating system for more efficient operation. Bare pipe mounted under benches and changes in the downhole heat exchanger in the well are expected to reduce flow requirements by 60%. The "Greenhouse" is operated by Andy Parker and the primary crop is flowers.