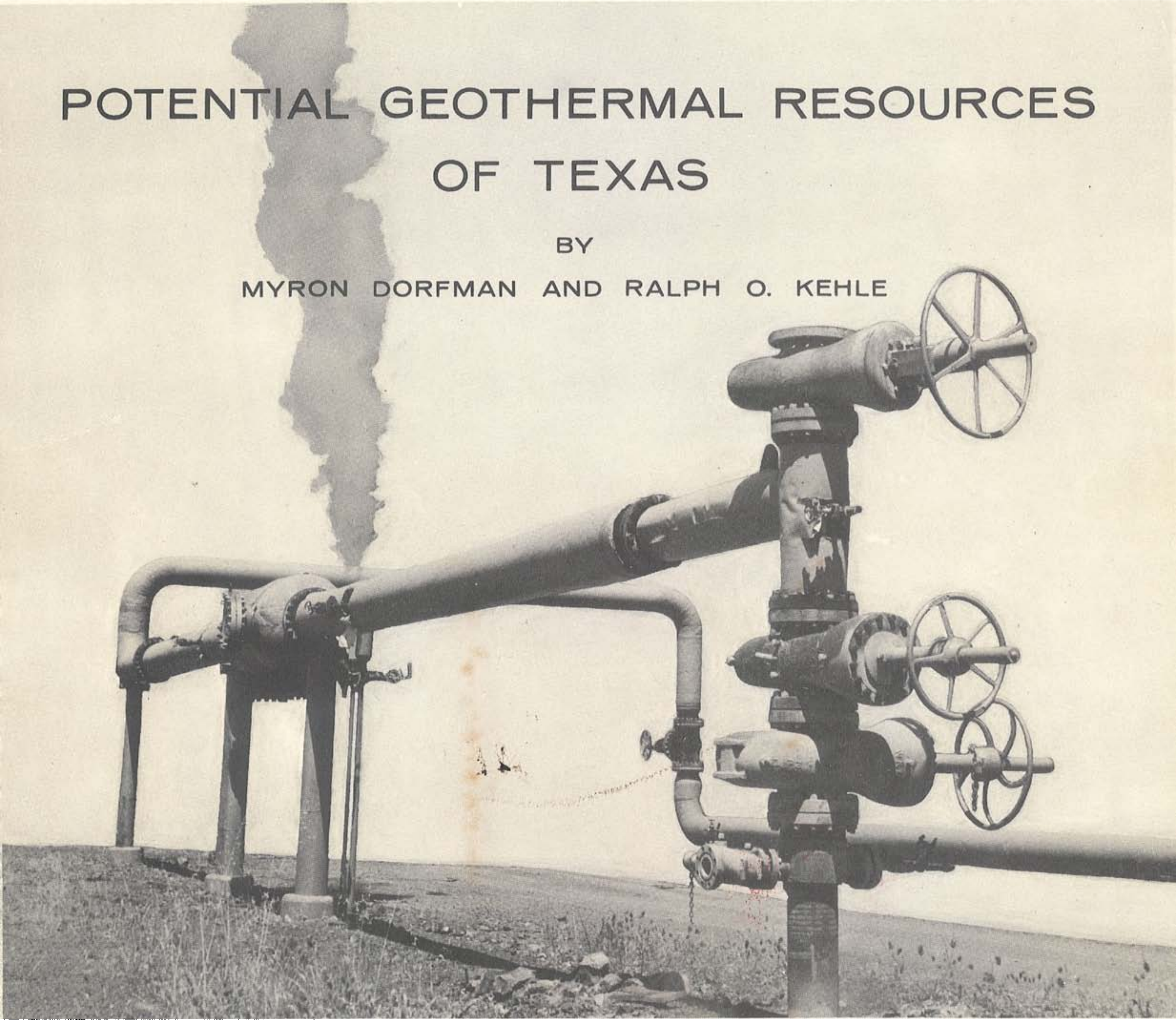
GEOLOGICAL CIRCULAR 74-4

POTENTIAL GEOTHERMAL RESOURCES OF TEXAS

BY

MYRON DORFMAN AND RALPH O. KEHLE



BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
W. L. FISHER, DIRECTOR
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POTENTIAL GEOTHERMAL RESOURCES OF TEXAS

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Myron Dorfman[1] and Ralph O. Kehle[2]

INTRODUCTION

Geothermal energy is rapidly becoming recognized, both in the United States and abroad, as a viable source of energy which can supplement fossil fuels for electric power generation. Exploration and development of geothermal reservoirs is intensifying in the western United States and Mexico, and will continue to expand as petroleum supplies diminish and costs increase. Although geothermal energy is commonly perceived as a new and exotic energy source, it is neither. Steam has been used for electric power generation since 1904 in Larderello, Italy, and geothermal waters have been used for space heating and agricultural purposes in other parts of the world since 1890 (fig. 1). Geothermal power generation began in the United States in 1960 at the Geysers, California, and new fields are under development in the Salton trough of southern California.

Herein we will attempt to answer some of the basic questions about geothermal energy: what it is, how deposits are formed, and where these deposits are located. Special emphasis is placed on the potential geothermal resources of the Texas Gulf Coast and Trans-Pecos Texas. This discussion should provide the reader with an appreciation for both the problems and advantages of this unfamiliar form of energy as well as the potential it holds for supplying Texas with a portion of its future energy needs.

GEOTHERMAL ENERGY—THE EARTH'S HEAT

What is geothermal energy? Basically, it is the energy that can be extracted from the natural heat of the Earth. The fact that the Earth is a vast storehouse of heat is evidenced by widespread occurrences of volcanoes, fumeroles, and hot springs. Boreholes drilled into the Earth show progressively higher temperatures with depth. Scientists estimate that temperatures at the center of the Earth lie within the range of 6000°F to 8000°F (3500°C to 4500°C). However, most of this heat is beyond the range of our most sophisticated technology, and will remain so for centuries. At this time we can only drill for and economically utilize the heat located within about the upper 25,000 feet (7½ km) of the Earth's crust. Although this thin outer shell represents only a tiny fraction of the total volume of the Earth, White (1973) calculates that more than 3×10^{26} cal of heat is stored in this surficial layer—this is more than 2,000 times the heat stored in all the known coal deposits in the world. The energy supply is so great that it could potentially supply a large percentage of our power needs for centuries to come.

Although the Earth's heat is vast, current technology does not enable us to randomly drill wells in order to obtain sufficient quantities for efficient utilization. Like other sources of fuel, we must locate concentrations of geothermal heat at relatively shallow depths in order to provide an economically feasible supply of power. These concentrations of heat are primarily located in specific areas that possess very high heat flow at shallow to moderate depths.

Many of these high heat flow areas coincide with the boundaries of huge plates that make up the crust of the Earth (fig. 1). These plates are in constant motion relative to one another. Along some plate boundaries, the motion is convergent and the Earth's crust is crushed together with such force that mountain ranges are uplifted and solid rocks melted into magmas (fig. 2). Along other boundaries, the plates separate from one another creating fissures through which molten material from the interior of the Earth ascends into the

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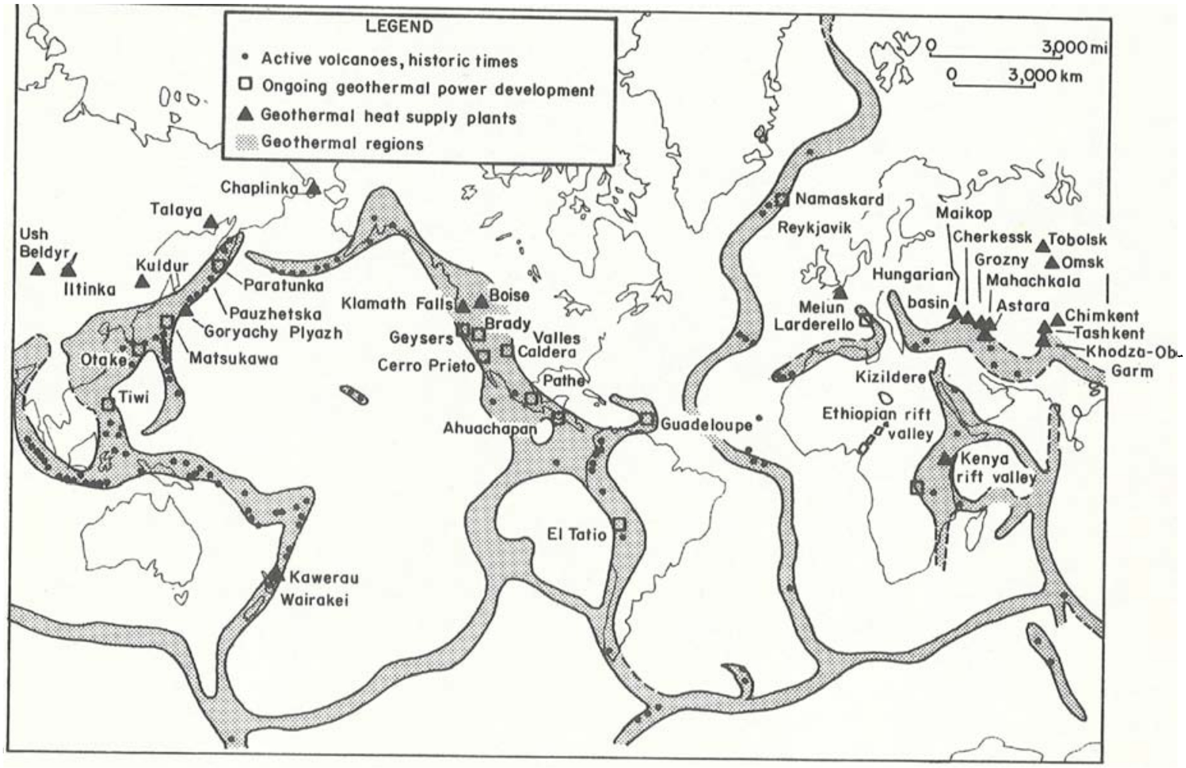


Figure 1. Geothermal regions of the world. After Meidav, 1974.

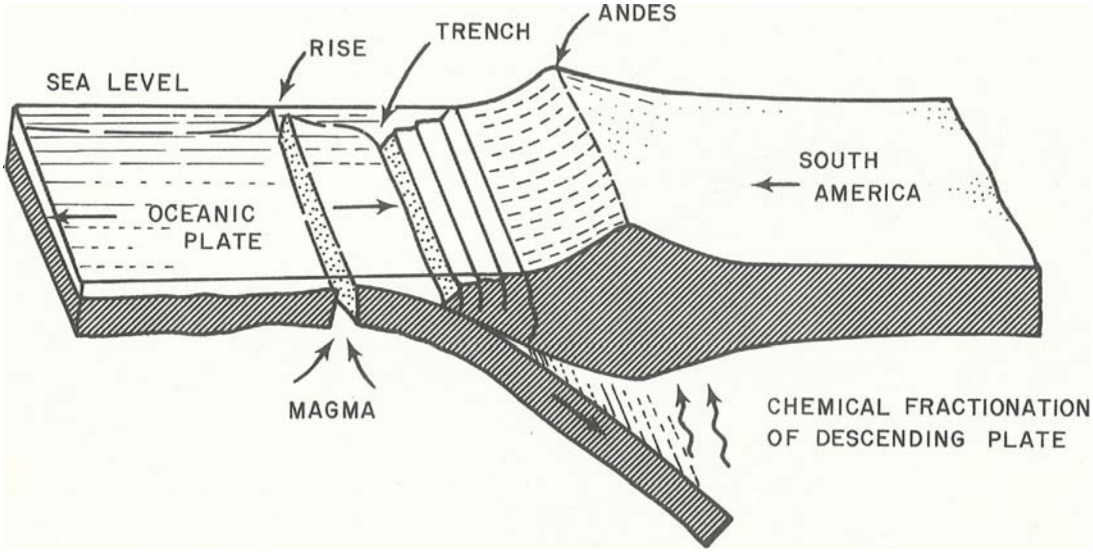
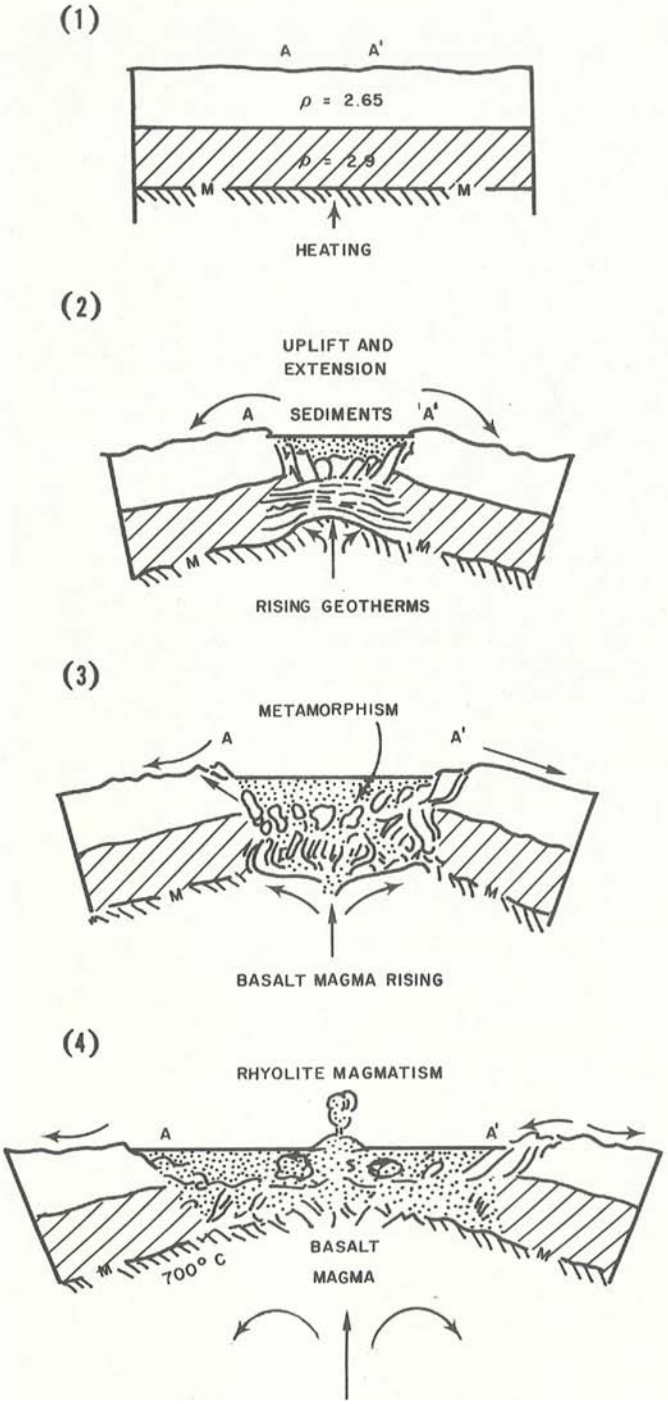


Figure 2. Schematic section of subduction along the western edge of South America. Modified from Dorfman, 1973a.

MODEL OF CRUSTAL RIFTING
MAGMA GENERATION



1. Continental crust prior to rifting.
2. Initial uplift and extension. Trough is partly filled with sediments and sediments are invaded by oceanic water.
3. Intrusive magma causes metamorphism of sediments. Fluid is heated and entrapped in fractures.
4. Extrusion of rhyolitic magma, in the form of volcanoes. Circulating hot brines cause greenschist metamorphism at shallow depth.

Figure 3. Model of crustal rifting and magma generation. Modified from Lehner, 1969.

shallow crust (fig. 3). In either setting, some of the magmas (masses of molten rock) reach the surface and discharge as lavas or pyroclastics from volcanoes or large fissures. Other magma bodies are trapped in the crust before reaching the surface. The trapped bodies slowly crystallize as they cool, emitting enormous quantities of heat in the process. These bodies of cooling magma supply a relatively small volume of the Earth's crust with the large amount of heat it needs to form two important types of geothermal deposits—(1) convective hot water or vapor-dominated deposits, and (2) hot-dry rock deposits.

Other geothermal energy accumulations are located in areas of normal heat flow. Sufficient concentrations of energy for power production only occur where heat is trapped beneath layers of rock with high insulating characteristics. High concentrations of immobile interstitial water, which occur principally in thick deposits of mud and sand, retain heat flow and establish an insulating blanket. The most important geothermal resources of this type are associated with major ancient river systems. When they debouch into oceans, these rivers deposit great volumes of mud, as well as porous and permeable sands, as deltas. Where buried to depths of 10,000 feet or more and heated from beneath the thin oceanic crust, the temperature of the sands and the water contained within them commonly exceeds 300°F (150°C), sufficient for power production using newly developed binary generating systems.

Geothermal deposits of lower quality, generally suited only to space heating, are found in most sedimentary basins throughout the Earth. These basins cover roughly 80 percent of the Earth's surface.

USING GEOTHERMAL ENERGY

Geothermal energy is being exploited in many parts of the world today. In Iceland, individual homes and entire communities are heated with hot geothermal water while vegetables and flowers are grown in hothouses fueled by geothermal springs. Shallow deposits of hot water are tapped for home heating in Klamath Falls, Oregon, and Boise, Idaho. Using geothermal steam, modest amounts of electricity are being generated in the United States, Italy, Japan, Mexico, New Zealand, and other locales (fig. 1).

Today the technology exists for a much greater use of geothermal energy for power production. New processes under development are likely to lead to significant expansion of this power source. The total potential impact of these developments is estimated (Rex and Howell, 1973) as having the ability, ultimately, to meet half of the electric power generating needs of the United States.

The manner in which geothermal heat is used to produce power depends in part on the manner in which heat is stored in the deposit. In some regions, geothermal deposits contain dry steam with little or no associated water. This characterizes the Geyser deposit in Sonoma County, California (figs. 4, 5) and the deposit in Larderello, Italy. In these deposits, heat is extracted as steam through boreholes drilled into the deposit and equipped in much the same way as natural gas wells. The produced steam is fed directly into turbines, which in turn generate electricity.

In other areas, such as Wairakei, New Zealand, and Cerro Prieto, Mexico, the deposits contain very hot water produced from boreholes equipped similarly to high volume oil or water wells (fig. 6). At the surface, the hot water is passed through a flash separator which, by reducing the pressure on the water, causes a high percentage of the water to flash into steam. The steam in turn is passed through turbines which generate electricity. The residual water at Wairakei, New Zealand, contains a modest amount of dissolved solids (12,000 ppm) and disposal presents no problem; in fact, many such deposits may serve as sources of relatively fresh water in arid regions. Other deposits, including the one at Cerro Prieto, contain far too many dissolved solids to be suitable for domestic or agricultural uses. Here, careful disposal or desalination of the waste water is necessary. The desalination process is now being carried out at the Mesa geothermal anomaly of the Imperial Valley of California. In other cases, such as the Buttes deposit also in the Imperial Valley, California, the dissolved solids content of the water is so high that minerals extracted from the water may be profitable by-products of power generation.

In many deposits, water temperatures are too low for efficient flash separation. A new and quite different geothermal power process, the

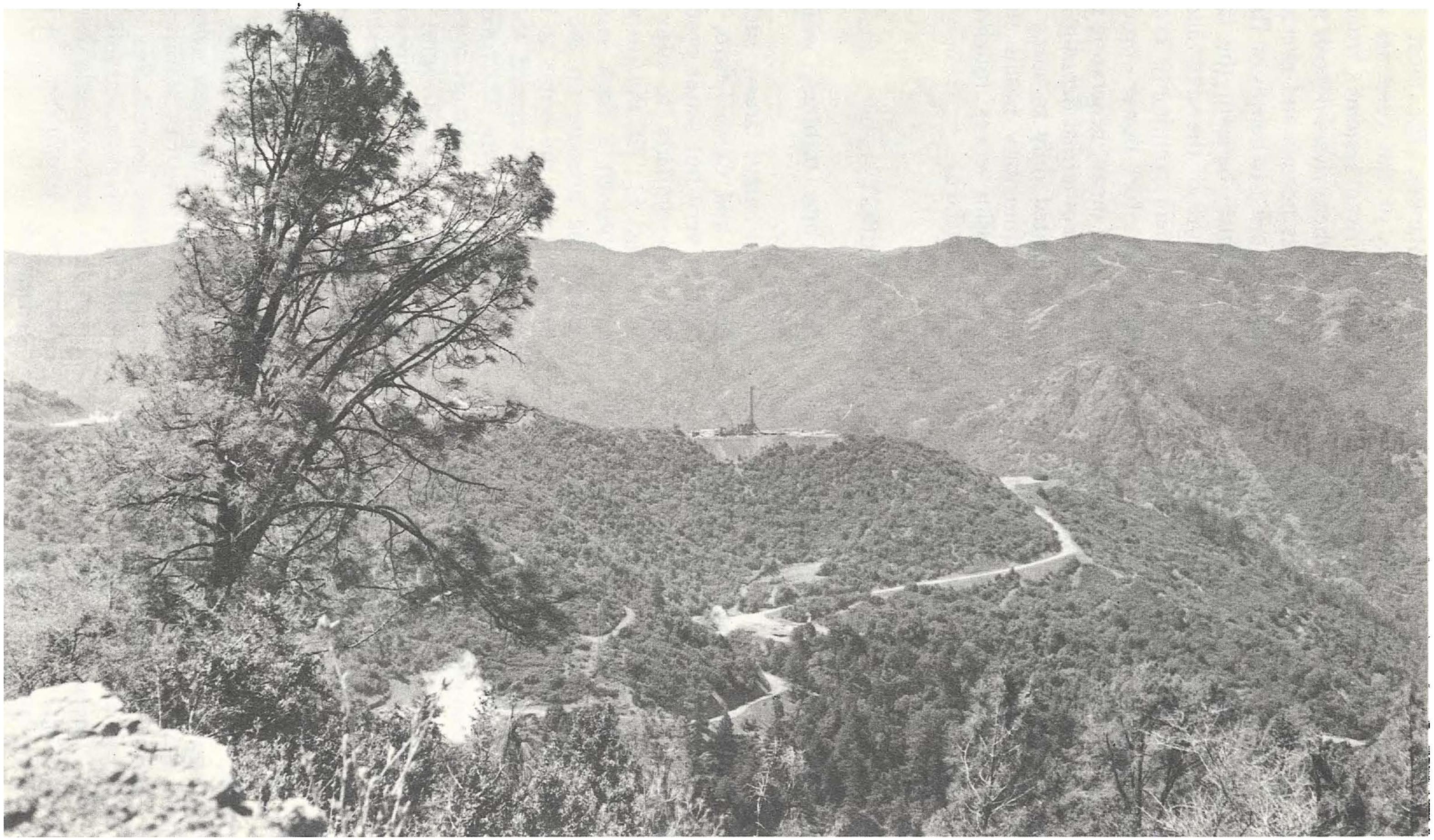


Figure 4. Drill site and producing wells, the Geysers, California.

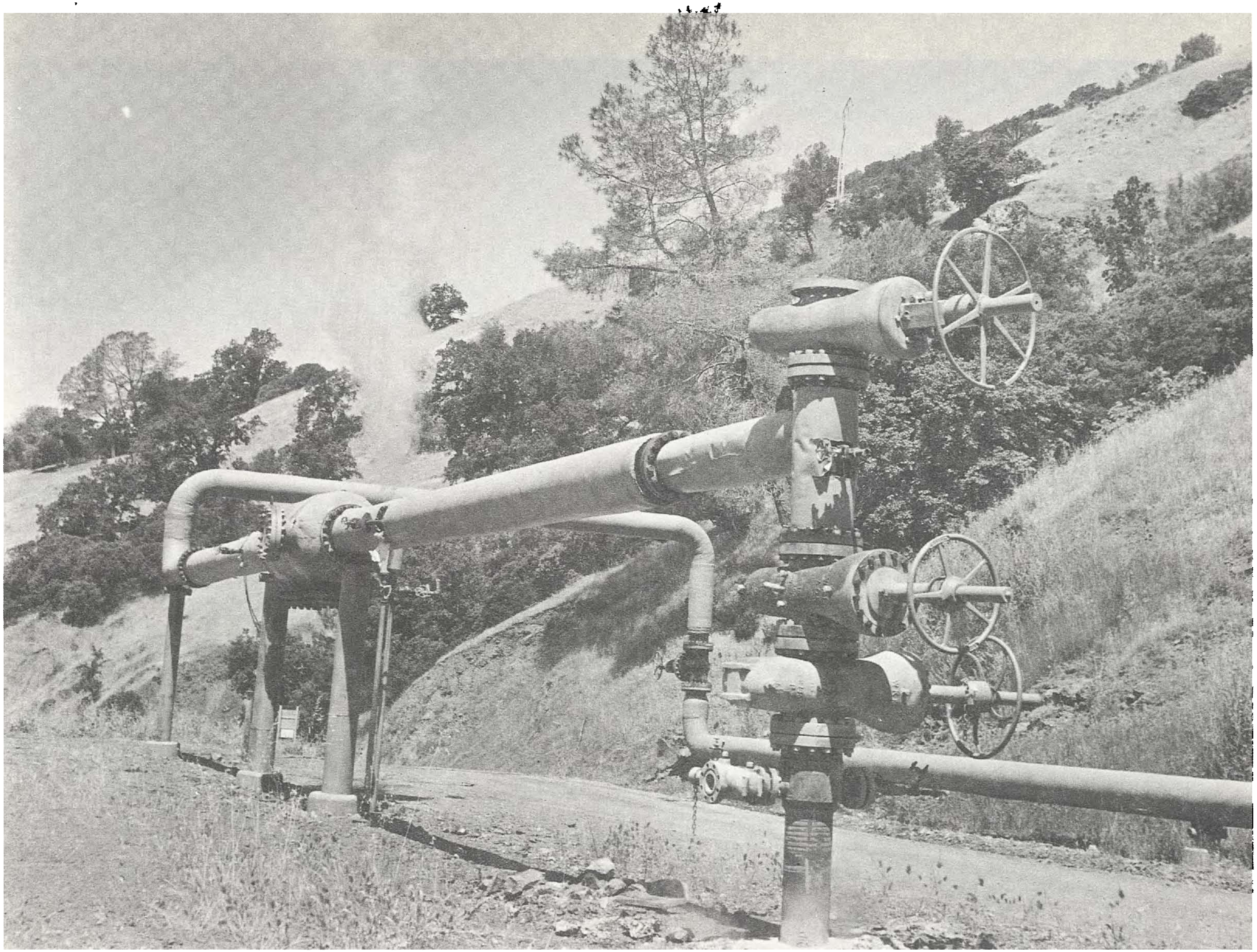


Figure 5. Typical well head and insulated flowline, the Geysers, California.

Figure 6. Steam and brine discharge, Cerro Prieto geothermal field, Mexico; Cerro Prieto volcano in background.

vapor-turbine or "binary system," has been developed for these conditions. In this process hot water brought to the surface is passed through a heat exchanger where it gives up heat in order to boil and superheat a high-density vapor. The vapor then expands through a turbine to produce power and is recycled to the heat exchanger. Practical and economic advantages of this process may be great enough to turn vast, potential areas of geothermal energy into commercially productive areas.

The binary system is shown in simple form in figure 7. First, hot water is brought to the surface; to insure that no steam is produced and no dissolved gases escape from the water, the water is kept above saturation pressure throughout the process. The water gives up its heat in a heat exchanger to heat the second fluid, boil it, and superheat it. The cooled water is then reinjected into the reservoir through another well, carrying all dissolved gases and most of the solids in solution with it. The injected water maintains reservoir pressure, and continuous cycling provides a means of transporting heat from the rocks to the surface.

Various fluids can be used in the power cycle. Isobutane is believed to show the most favorable economics for developing power from water having temperatures near 325°F, however Freon is used in at least one power plant in the U.S.S.R.

Binary generating systems of this type may be employed in the extraction of energy from abnormally pressured hot water deposits, such as those occurring along the Texas Gulf Coast.

In most areas, subsurface water at depths less than 25,000 feet is too cool for power production, even using binary generating systems. These waters occur in more than 70 percent of the land area of the United States which is underlain by sedimentary rock strata. However, in many locales this water is hot enough to use for space heating. The water can be produced through ordinary wells, cycled through radiators or heat exchangers, and pumped back into the underground reservoir. Such systems could provide low-cost heat to local communities for long periods of time.

Finally, some potential geothermal deposits, the so-called hot-dry rock deposits, contain no water or steam at all. In order to extract the stored heat, water must first be pumped into the rock, then heated to sufficient temperature. The technology for accomplishing this extraction process is under development at the Atomic Energy Commission's Los Alamos Scientific Laboratories in New Mexico. The method envisions creating a fracture of approximately 1 km^2 between two wells located within the deposit. Water pumped into the fracture at the bottom of one well is vaporized upon contact with the rock (fig. 8). The steam rises in the fracture and is extracted through another well at a shallower depth. The steam is then passed through a turbine into a condenser and finally back into the first borehole where it is heated again.

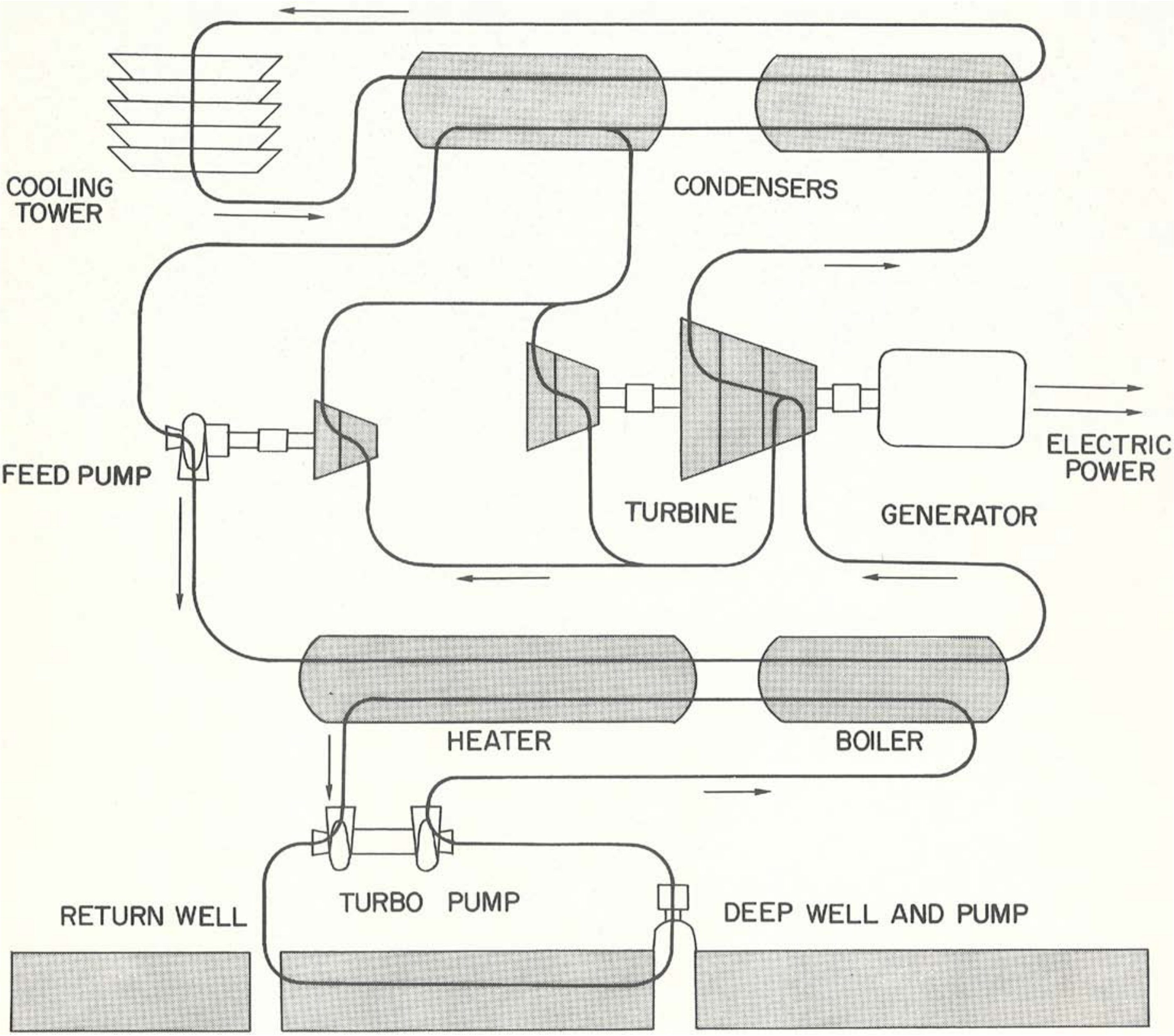


Figure 7. Model of the binary system geothermal power process. From Barnea, 1972.

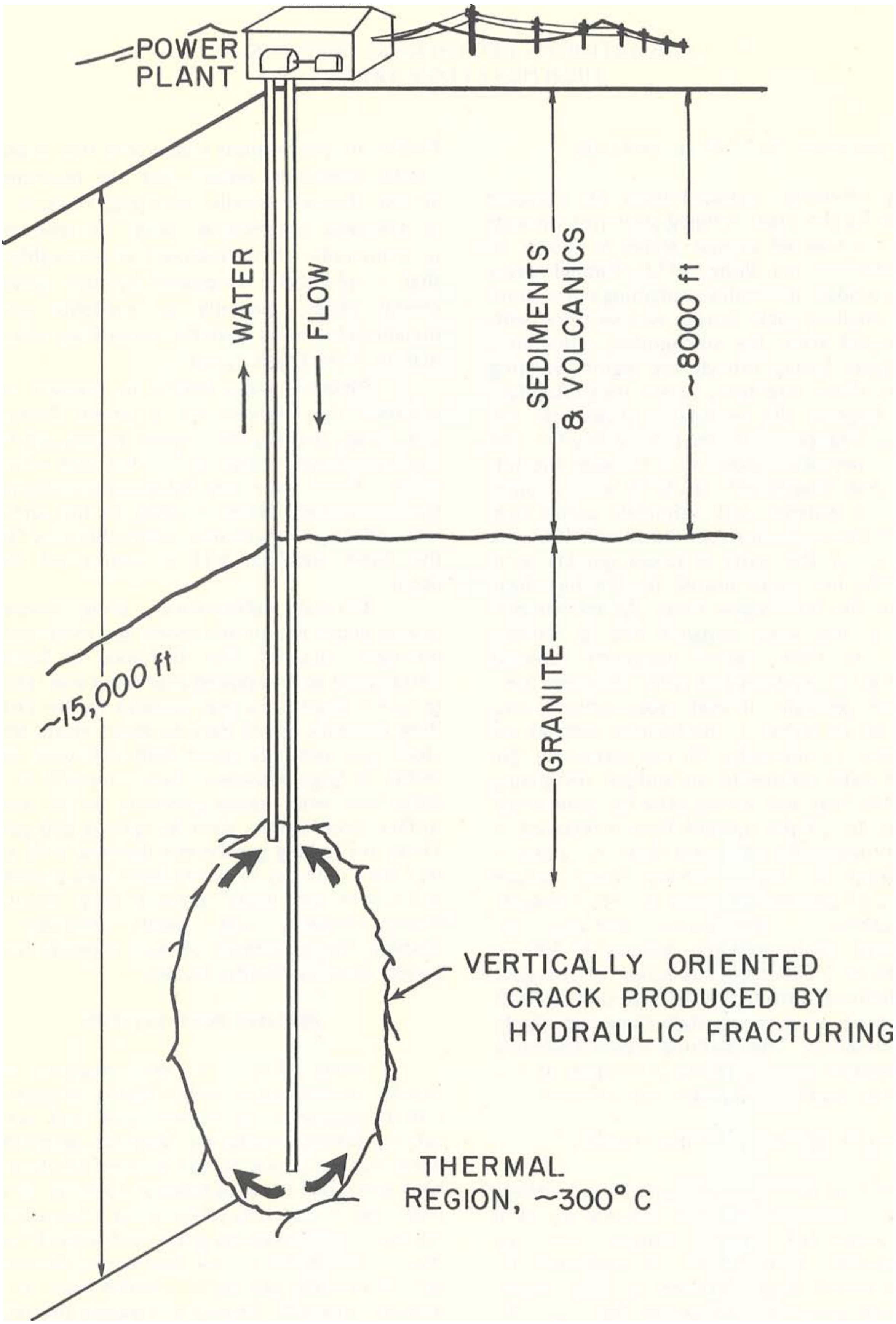


Figure 8. Typical dry rock geothermal energy system produced by drilling and hydraulic fracturing. From Brown and others, 1973.

FORMATION OF GEOTHERMAL DEPOSITS—HIGH HEAT FLOW AREAS

AREAS OF CRUSTAL SEPARATION

A schematic representation of a region where the Earth's crust is being stretched through divergent motion of crustal plates is shown in figure 9 (Muffler and White, 1972). Parallel ranges of fault-bounded mountains containing older, commonly crystalline rocks border valleys filled with debris eroded from the surrounding mountains. Local magma bodies intrude the region, yielding large heat flows into the country rock. Rainfall, typically large in the mountains, flows into the valleys and disappears into the loose valley fill. The cool water percolates downward through the fill, descends past impermeable strata by way of faults and fracture systems, and ultimately ponds near the top of the crystalline rock basement. Here the temperature of the water is raised quickly as it contacts the hot rocks heated by the high heat flow from the hot magma body. As the temperature rises, the water expands and its density decreases. It then moves buoyantly upward through fracture systems and valley fill in the form of a plume, generally of small cross-sectional area (1 to 20 square miles). If the fracture systems are too pervasive or the valley fill too permeable, the rising hot water escapes to the surface, dissipating much of the heat and leaving little for commercial extraction. But if the upward flow is retarded or completely halted by impermeable strata, a potentially commercial deposit occurs. Some surface dissipation of geothermal fluids is not necessarily disadvantageous. In the Geysers, surficial vents have lowered the bottom-hole pressure to 500 psi at a depth of 7,000 feet, but influx of meteoric water, combined with high heat flow and lowered vapor pressure, serve to maintain the steam supply from the reservoir. The resulting vapor-dominated system provides electric power generation at low cost, since extraction of liquids is not required.

AREAS OF CRUSTAL COMPRESSION

Much of the Pacific margin of the Americas constitutes a boundary between converging crustal plates. Complicated terrain is formed where the plates converge. Such regions are commonly intruded by recent magma bodies and may possess large, active composite volcanoes (fig. 10). The mechanics by which a geothermal deposit is formed in these regions is similar to that in areas of crustal stretching except that the reservoirs are almost always intensely developed fracture zones in otherwise impermeable rocks. The reservoir seal is commonly an unfractured impermeable rock that is physically emplaced by the converging crustal plates, generally an ophiolite suite of metamorphic rocks from the ocean floor and upper mantle of the Earth's crust.

Meteoric water enters the fracture system wherever the reservoir seal is absent. Being cool and dense, it descends to great depths and travels along the fracture systems to a hot spot where it is heated. From there, the hot water ascends up the fracture system, either escaping to the surface or accumulating beneath an impermeable seal. Only in the latter situation will a commercial deposit occur.

Crustal deformation along converging crustal plates is typically severe and most rocks are intensely fractured. The likelihood of having an unfractured seal emplaced over otherwise fractured terrain is small. This may account for the rarity of these deposits. Where they do occur, steam temperatures are typically quite high and well deliverability is large. However, steam deposits in these areas have been found primarily on the basis of surface occurrences, such as springs and geysers. These are leaking geothermal deposits with imperfect seals. The use of newly developed exploration techniques will likely uncover many heretofore hidden deposits with totally effective seals. Possibly the occurrence of such deposits is much greater than is presently known.

HOT-DRY ROCK SYSTEMS

Along all types of plate margins, and in certain circumstances within plates, magmas may intrude sequences of impermeable rock without causing intense fracturing. Without permeability, water has no access to the molten intrusion. The heat is trapped for long times in both the intrusion itself and in the rocks surrounding it because rocks are poor conductors and good insulators of heat. In many ways, hot-dry rock geothermal deposits are similar to many ore deposits which occur in halos around intrusions. Instead of valuable metals, heat is stored in the rocks surrounding the magma body.

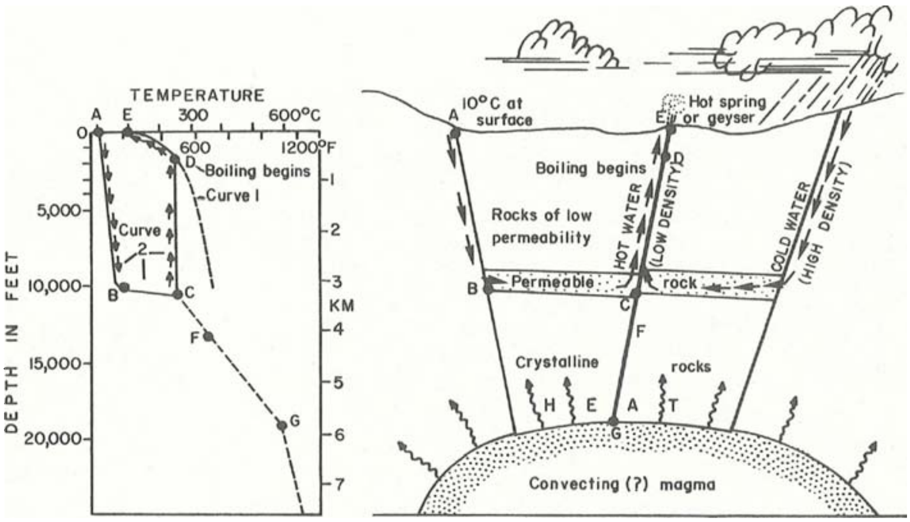


Figure 9. Schematic model of a hot water geothermal system. From Muffler and White, 1972. Curve 1 shows the boiling point of pure water under pressure exerted by a column of liquid water everywhere at boiling, assuming water level at ground surface. Dissolved salts shift the curve to the right; dissolved gases shift the curve to the left. Curve 2 shows the ground temperature profile of a typical hot water system.

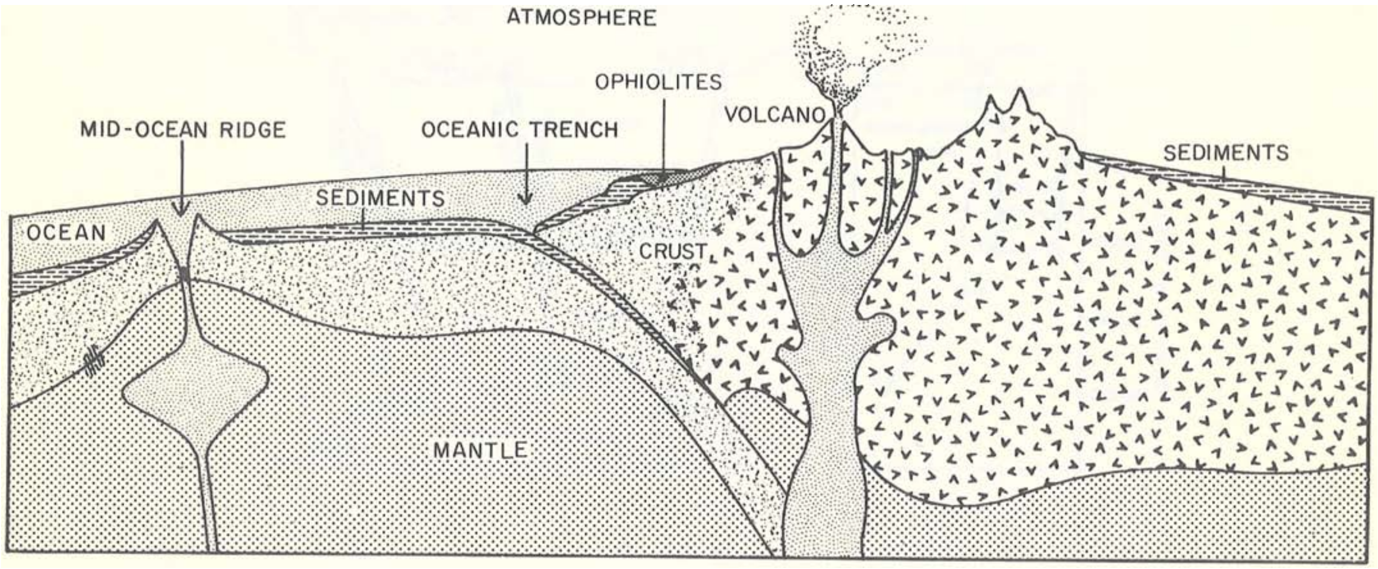


Figure 10. Cross-sectional representation of the outer shell of the Earth showing geophysical processes by which the crust, atmosphere, and oceans are brought in contact with one another. From Sevier, 1974.

Temperatures near the edges of the magma body may be very high, exceeding 900° F (500°C) for recently intruded masses. As the magma cools and the heat front moves outward away from boundaries of the intrusion, the volume of heated rock increases. But in the process, the average temperature in the heated zone diminishes. Ultimately, all the heat is lost from the system.

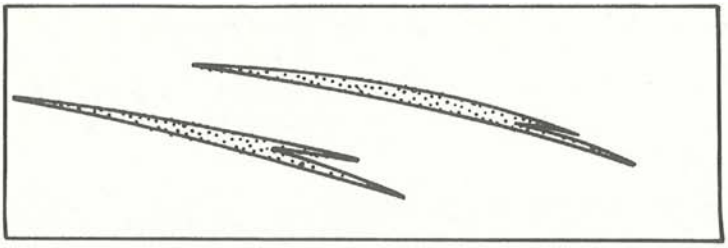
If an intrusion is relatively young geologically (less than 5 million years old), chances are good that a large volume of rock around the interior is hot enough for commercial heat extraction. As mentioned previously, this is accomplished by injecting water into the rock through deep wells and then extracting the produced steam.

GEOTHERMAL DEPOSITS IN SEDIMENTARY BASINS

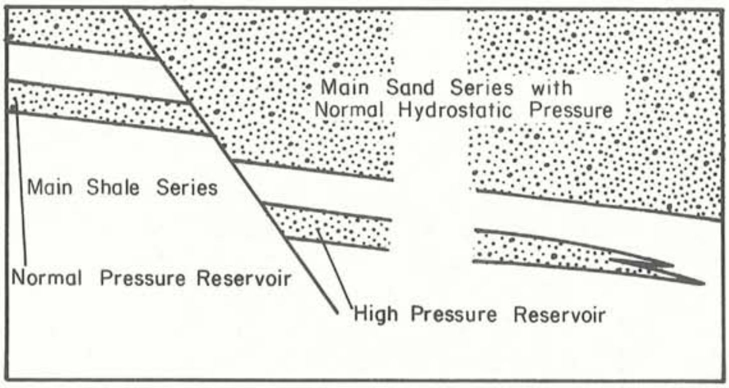
Normal pressure.—Moderate to thick sequences of layered rock strata cover much of the Earth's surface. Many of these strata are porous and permeable, containing water and sometimes oil and gas in the pore spaces. Over much of the United States, temperatures of 150° F (66°C) occur at depths of 5,000 feet or shallower. These temperatures are hot enough for space heating. Water may be cycled through the reservoir almost indefinitely without significantly lowering its temperature. Hot water can be extracted from most of these strata for use in geothermal heating projects.

Abnormal pressure.—Abnormally high fluid pressures result when interstitial formation waters are trapped during burial and subsequent basin subsidence. Figure 11 (from Dickey, 1968) shows various sections of abnormally pressured sands. Rapid accumulation of mud and sand occurs along the fronts of prograding delta systems. If the contained water cannot be squeezed out because of restricted fluid movement, compaction of the sediment grains will not occur and pore water will begin to carry a part of the overburden load. When this occurs, formation fluid pressure greater than hydrostatic develops; such regions are said to be geopressured. In sedimentary basins underlain by thin oceanic crust, upward flow of heat from the mantle causes rocks and fluids within these geopressured zones to develop abnormally high temperatures, often exceeding 500° F. However, the undercompacted zones act as heat insulators, and normally pressured zones overlying these intervals have normal temperature gradients (Jones, 1969; Lewis and Rose, 1969).

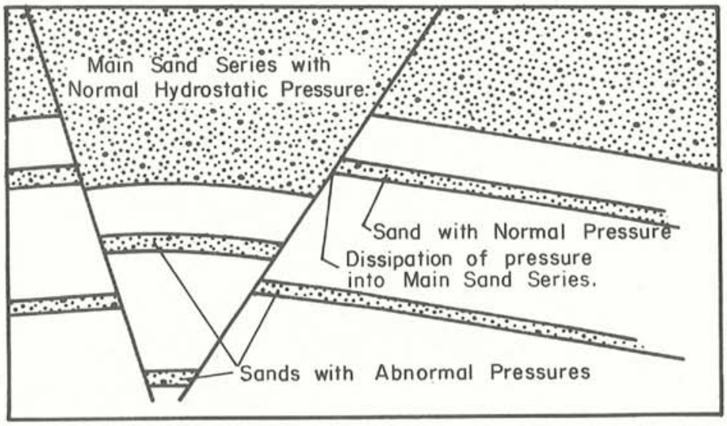
Abnormally pressured zones are found throughout the world, beginning at depths between 5,000 and 15,000 feet. Some of the basins which contain these zones are the North Sea, South China Sea, and numerous Indochinese basins. Perhaps the best documented basin containing geopressured zones is the Gulf Coast basin of the United States and Mexico.



SMALL RESERVOIR SEALED BY PINCHOUT
(A)



LARGE RESERVOIR SEALED UPDIP BY FAULTING DOWN AGAINST THICK SHALE SERIES, SEALED DOWNDIP BY REGIONAL FACIES CHANGE.
(B)



RELATIVE POSITION OF FAULT SEALS IN UPTHROWN AND DOWNTHROWN BLOCKS.
(C)

Figure 11. Types of reservoir seals necessary to preserve abnormal pressure. From Dickey, 1968.

LOCATION OF POTENTIAL GEOTHERMAL AREAS IN TEXAS

Texas has an abundance of energy resources. Its enormous resources of oil and gas are known worldwide. Not so well known is the fact that Texas also has large reserves of lignite, a form of coal. It appears that the State may also house major reserves of geothermal energy, both in the Trans-Pecos region of West Texas and along the Gulf Coast. In the arid valleys of the far western part of the State, both hot water convective systems and hot-dry rock deposits are likely to occur, and the industrialized Gulf Coast overlies the best documented, deep, abnormally pressured deposits of hot water in the world.

Not to be overlooked, however, is the potential for geothermal space heating that exists in much of the rest of the State. Almost everywhere, porous and permeable beds containing hot water underlie the surface at depths of 4,000 feet or more. The possibility of developing this less exciting source of energy is also discussed in this paper.

RIO GRANDE RIFT SYSTEM, TRANS-PECOS TEXAS

The Rio Grande rift system is part of the Basin and Range province of the western United States. It shares its geologic origin, history, and characteristics with many of the western states. Not surprisingly, it also shares much of the same geothermal potential. This is a region of diverging crustal plates. Here the Earth's crust is being stretched and faulted into parallel mountain ranges and deep elongate intermountain valleys. The valleys are filled with debris eroded from the surrounding mountains. They are known as bolsons.

The valley of the Rio Grande near El Paso is known as the Rio Grande trough, one of two main fault-bounded bolsons in the region with geothermal energy possibilities (fig. 12). It extends from south-central New Mexico into Texas near El Paso and continues southwest along the course of the river for approximately 50 miles (80 km). The second valley of importance is the Presidio bolson, which occupies the region between Candelaria and Presidio, a distance of about 55 miles (85 km). Both bolsons are surrounded by mountains known as the Rim Rock Ranges whose origins are related to Middle Tertiary volcanic activity and block faulting.

It is likely that more recent volcanic activity of interest to geothermal prospecting has occurred, but the evidence is not so well documented.

The Presidio and Rio Grande bolsons developed after volcanism in the area. Considerable geologic evidence points to their continuing development today (Clabaugh, personal communication, 1973). Commonly, formation of this type of valley is preceded and accompanied by both intrusion and extrusion of igneous rocks. This occurs in geologically similar settings such as the Imperial Valley of California and the rift valleys of Africa (Barker, personal communication, 1973). Little direct evidence exists for current igneous activity in West Texas, except for existence of several cinder cones (small volcanoes) 15 miles from El Paso and for continuing seismic activity. Indirectly, there is considerable evidence for the existence of recent intrusions of magma into the crust beneath the Rio Grande and Presidio bolsons. The same evidence suggests the existence of potentially commercial geothermal deposits of the hot water convective type. In particular, the portion of the Rio Grande trough in New Mexico exhibits high heat flow at many studied locations. This area is included in the U. S. Department of Interior report of potential geothermal areas, and is considered a major potential geothermal area by Summers (1972). Thirty-seven anomalies are reported in this basin, and numerous hot springs are present with recorded surface temperatures in excess of 104°F (40°C). Temperatures in excess of 30°F above ambient temperature are considered potential indicators of geothermal reservoirs.

In Texas, numerous hot springs occur along the sides of the bolsons at the surface juncture of bounding faults. Groat (1972) has noted at least 15 of these springs along the periphery of the Presidio bolson (fig. 13). The temperatures reported for hot springs in this area (Waring, 1965) are over 100°F. Hot springs almost always indicate leaking hot water convective plumes rising from hot rocks recently intruded by magma. It seems probable that closed convective systems will occur in the same areas as leaking systems and thus the two bolsons are likely geothermal areas.

Unpublished geophysical studies by the U. S. Geological Survey (Gates, personal communication, 1973) indicate a thickness of approximately 3,000 meters of sedimentary fill in the Rio Grande trough near El Paso, and 1,300 meters of sediments in the northern portion of the Presidio bolson. This is analogous to the Salton

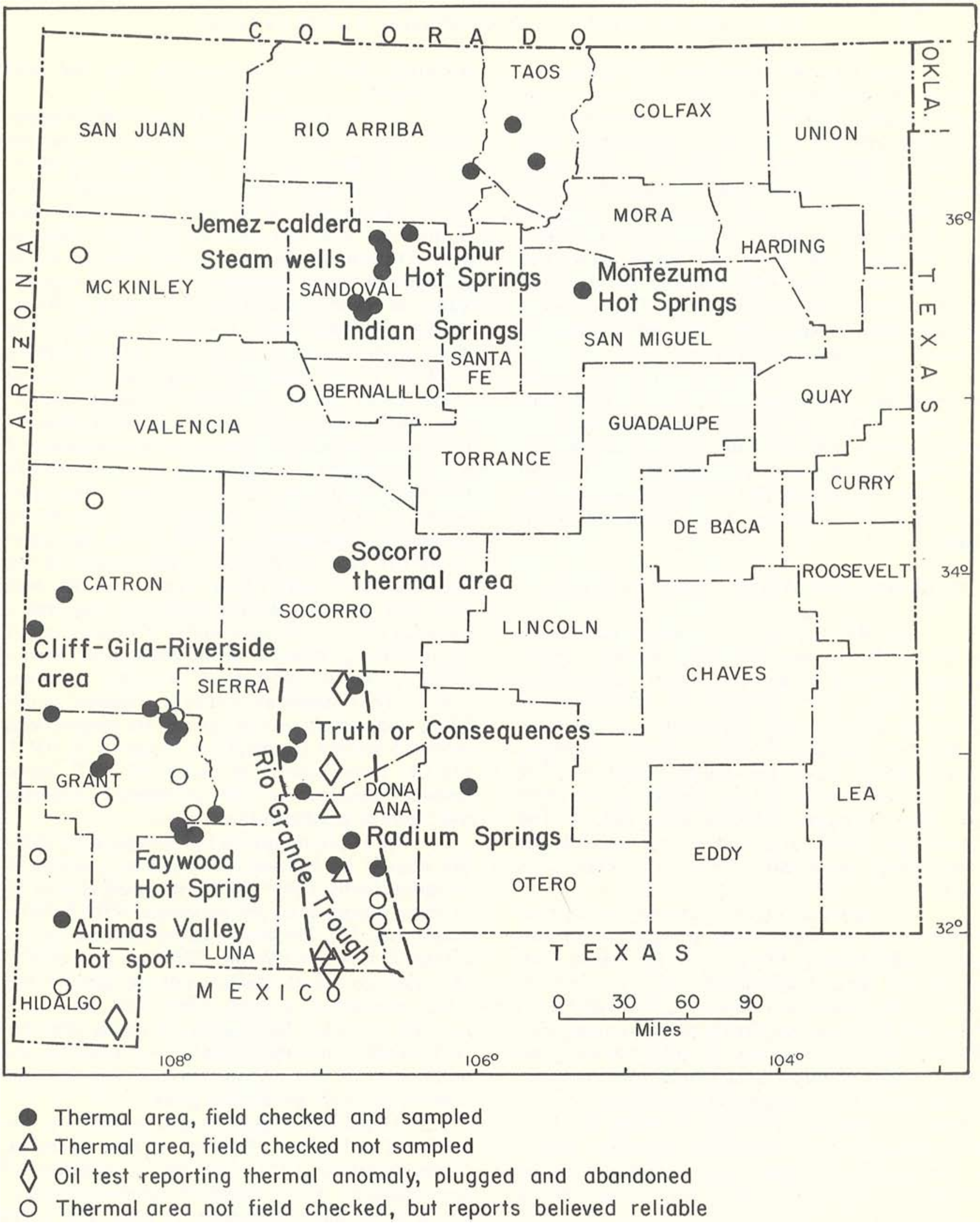


Figure 12. Thermal areas of New Mexico showing Rio Grande trough.

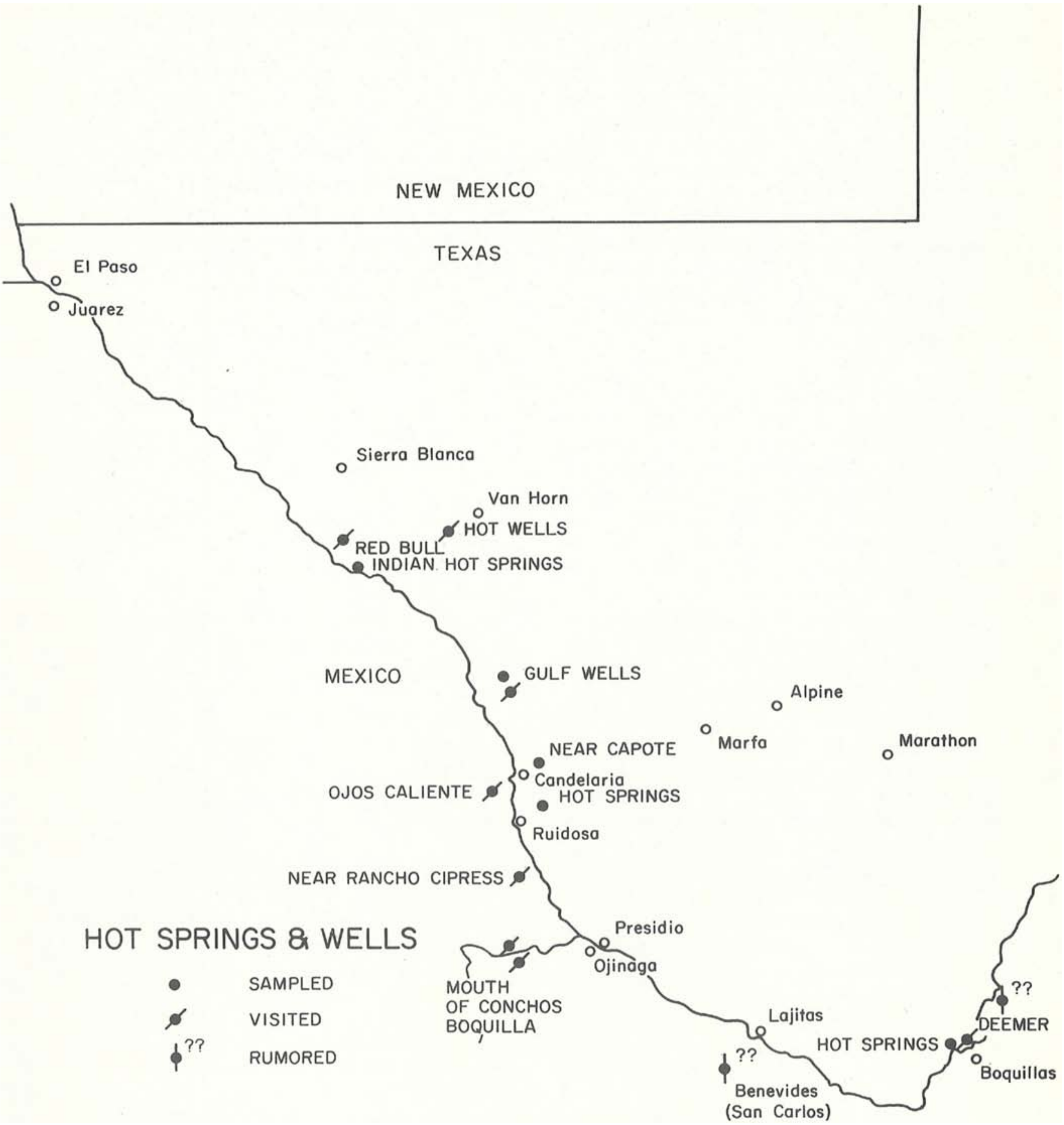


Figure 13. Hot springs and wells along periphery of Presidio bolson. From Groat, 1972.

trough which contains an average fill of 2,800 meters of sediments with numerous geothermal anomalies.

Shallow wells drilled for oil and gas within the bolsons have been unsuccessful. In geothermal areas formed as a result of rifting, temperature gradients are commonly so high that a thermal barrier prevents accumulations of petroleum (Price, 1973). Although data are sparse, it is known that two wells which were unsuccessfully drilled for petroleum in the Presidio bolson contain hot water at shallow depth. These well waters have temperatures over 140°F (60°C) at Hot Springs resort, north of the Chinati Mountains, and at Indian Hot Springs, south of the Quitman Mountains (Groat, 1972).

Surface investigations of the bolsons evidence continuation of basinal downfaulting into recent time (Clabaugh, personal communication, 1973). Continuation of rifting may therefore be postulated; although surficial expressions of recent activity have not been established in Texas, such evidence occurs in New Mexico 15 miles northwest of El Paso and typically accompanies this type of faulting elsewhere in the world.

Recently acquired infrared photographs, taken by the Earth Resources Technology Satellite (ERTS), indicate areas of possibly high heat flow both within the bolsons and along bounding faults.

This evidence, in sum, seems to support the premise that a relatively small but possibly important geothermal area is located along the extreme western margin of the State of Texas. The area encompassed by this system covers approximately 4,150 km^2. By comparison, the Salton trough covers an area of 23,300 km^2. Studies by Rex and Howell (1973) indicate that the Salton trough may contain potential geothermal reserves of as much as 30,000 MW centuries of power. (The term megawatt century refers to the number of megawatts which can be produced effectively for 100 years.) If the Rio Grande rift system is the structural equivalent of the Salton trough, as many geophysicists believe today, its potential reserves would equal about 5,000 MW centuries. Since current consumption is about 1 kw of power per person in the United States, the geothermal potential of the Rio Grande may be sufficient to supply the power needs of 5 million people for 100 years. In addition, hot water convective systems of this type often contain highly mineralized waters, which affords the opportunity for the development of a new industry—the extraction of important minerals from brines. In the Salton trough, the geothermal waters contain lithium, borates, and potash. If economic factors are favorable, the technology exists for mineral extraction from these brines.

Another important consideration in the Rio Grande area is potable water. It has been found that important new technological breakthroughs have recently provided means of desalinating brines using the temperature of the water itself for multistage distillation-type desalination. The U. S. Department of Reclamation at the Mesa anomaly, California, has installed a new plant that uses water from a geothermal reservoir to provide irrigation water for the prolific crop-growing area of the Imperial Valley. If geothermal reservoirs exist in the Rio Grande rift, their waters could play an important role in future development of the area.

TRANS-PECOS IGNEOUS ROCKS

If the hot-dry rock system for geothermal power generation proves to be commercially feasible, a large area of western Texas may have potential for this type of development. The area east of the Hueco and Presidio bolsons and north of the Big Bend National Park is an area of extensive outcrops of extrusive and intrusive Cenozoic igneous rocks. These rocks have their greatest areal extent near Sierra Blanca and in the northern part of the Quitman Mountains. The occurrences in the Quitman Mountains are rhyolitic and trachytic volcanic flows and diorite and quartz diorite plutons. Dikes and sills of rhyolite porphyry are also reported. In the Finlay Mountains, dikes and sills of andesite porphyry and latite porphyry are abundant. In the Sierra Blanca peaks, five rhyolitic laccoliths are known and sills occur on the Diablo Plateau (Albritton and Smith, 1965). Dating of rocks in this remote area is not extensive, but various studies indicate that intermittent extrusion of lavas and ignimbrites began during the Oligocene from 40 to 30 million years ago. Later, two generations of dikes and sills were emplaced, the first about 22 million years ago and the second about 19 to 18 million years ago (Albritton and Smith, 1965). Although younger volcanics have not been reported in West Texas, Quaternary volcanics and intrusives are present to the west of the Rio Grande trough in Mexico, and 30 km north of El Paso in New Mexico (F. Bullard, personal communication, 1973). The volcanics in New Mexico record high heat flow values of 2.24 heat flow units (Summers, 1972).

There are indications, primarily from ERTS imagery, that younger intrusives in West Texas may be present and may have potential for the hot-dry rock type of geothermal electric power generation.

If this system works, additional research will be required to determine the extent of the resource in Texas. Since the extent of usable rocks is unknown, the following calculation (table 1) will serve to indicate the enormity of the usable heat that may be contained in only one pluton having a diameter of 10 km.

Table 1.–Calculation of potential energy from an intrusive pluton.

Volume of rock: PiR^2 x 1 km (thickness) = 78.5 km^3
Density of pluton: 2.75 g/cm^3
Mass of hot pluton: 216 x 10^{15} g
Assuming an average temperature of 290°C and a cutoff temperature of 100°C,
useful dT = 190°C
Heat capacity of pluton: 0.2 cal/C/g
Useful dH = 38 cal/g
Total available enthalpy = 8.2 x 10^{18} g-cal
Assuming a 14% conversion efficiency, useful available enthalpy for electric
power generation = 11.5 x 10^{17} g-cal
This is multiplied by 1.162 x 10^{-9} MWh/g-cal = 1.34 x 10^9 MWh,
or, 1550 MW centuries
A century of electric power for over 1 million people in West Texas may be derived from only one intrusive mass.

TEXAS COASTAL PLAIN

When the Rocky Mountains formed in the western United States during Cretaceous and early Tertiary time (over 50 million years ago), major river systems also were born on the newly elevated continent. The largest of these made their way to the Gulf of Mexico via Texas, and deposited enormous volumes of mud and sand along the Texas Coast. At that time, the shoreline was between 100 and 150 miles inland of its present location and deep ocean water occurred everywhere beneath what is now the Texas Coastal Plain. Slowly, the rivers transported debris into the ocean, filling the void and causing the shoreline to advance to its present location. The great weight of the sediment pile downwarped the Earth's crust along the Coastal Zone, allowing sediments to accumulate to thicknesses in excess of 50,000 feet (fig. 14). The lower half of the sedimentary wedge is mud, overlain by interbedded sand and mud (fig. 15). As the deltas prograded out into the ocean over their own prodelta muds (the low-density, high-pressure shales of figure 15), wedges of sand and shale sank into the underlying mud, isolating the sands from continuous-permeability channels to the surface by enveloping them in mud.

As growth faulting continues because of successive deposition, the downthrown wall of the fault is subjected to an ever-increasing overburden. At depths of between 2 and 4.5 km, depending upon the local geothermal gradient, a second stage of dehydration of prodelta muds begins. This dehydration occurs between temperatures of 80°C and 120°C and results in an endothermic reaction in which montmorillonite, the primary component of the mud, is converted to illite. This process results in the expulsion of an additional 15 percent of the water contained in the muds into the overlying sand (Burst, 1969). The additional free water which is forced into the saturated contained-sand aquifers along the growth faults has two immediate effects; it forces the water to support a portion of the overburden which results in a sudden pressure increase, and it decreases the salinity of the water in the lower section of the aquifer, since the water which is expelled from the muds is essentially fresh.

Studies by Jones and Wallace (1974) show that in Cenozoic sediments in the Gulf Coast basin, the 120°C isotherm ranges from 2.5 to 5 km below sea level and conforms generally to the top of the geopressured zone. In addition, water salinity begins decreasing in both the Frio and Wilcox at the depth of the 120°C isotherm. Dissolved solids reach a low level of 5,000 mg/l at deeper levels in these formations. As the upward flow of water from muds to sands is impeded, the geopressured zones become overheated but the heat appears to be confined to the level of the aquifer. Lewis and Rose (1969) contend that the geopressured zone constitutes a thermal barrier because it is under-

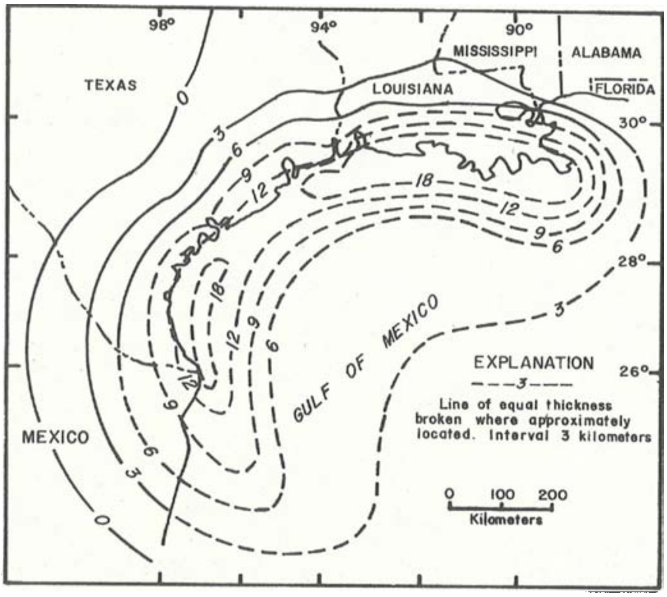


Figure 14. Thickness of Cenozoic deposits in the Gulf Coast geosyncline. From Jones, 1969.

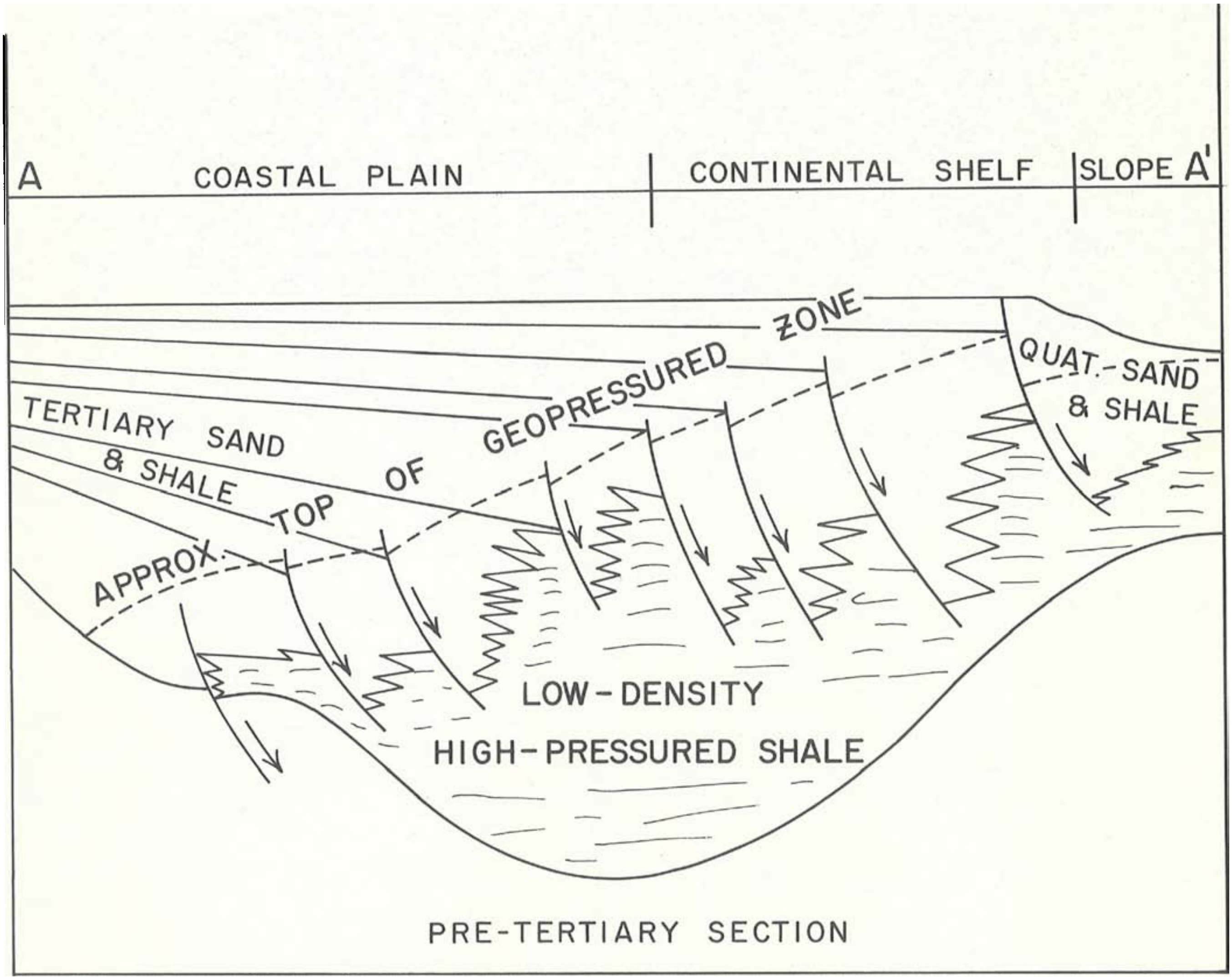


Figure 15. Cross section of Coastal Plain illustrating deposits of sand that form geothermal reservoirs. Adapted from Bruce, 1973.

compacted—the greater the water content, the greater the insulation value of the zone. Thus, the movement of water resulting from thermal alteration of clays appears to be a major factor in heat flow within the sedimentary basin. It is these abnormally pressured waters that serve as principal geothermal energy reservoirs of the Gulf Coast.

Figure 15 shows a cross section of the entire coastal region and illustrates the multiple deposits of sand that form the geothermal reservoirs. Each is of a different geologic age, ranging from earliest Eocene to middle Miocene. Each has a significant geothermal energy potential and will be discussed separately in the following sections.

Eocene Series

The Eocene Wilcox Group is the oldest zone in the coastal area with major geothermal potential. Facies studies by Fisher and McGowen (1967) indicate a linear development of sands covering an area some 950 miles (1,460 km) in length and 60 miles (100 km) in width, subparallel to the coast. The area extends from the Mexico border north of Laredo, Texas, to the Louisiana border north of Beaumont, Texas (fig. 16). Wilcox sediments were deposited by high-constructive deltas in the eastern half of the State, while in the southwestern portion of the State, sediments were carried westward by longshore drift and subsequently deposited as barrier bars. Regional growth faulting is common in this formation, and structural and stratigraphic traps at relatively shallow depths provide important petroleum reservoirs in the State. Numerous wells have encountered geopressured zones at depths of 10,000 feet (3,000 m), and temperatures in excess of 325° F (180°C) have been reported at depths of 13,500 feet (4,000 m). Jones and Wallace (1974) find that the top of the geopressured zone occurs generally at a depth of 10,000 feet (3,000 m) where temperatures average 250° F (120°C). Overall sediment thickness ranges from 2,400 feet (700 m) to 5,500 feet (1,700 m) within this interval. Few wells have been drilled below 16,500 feet and the total thickness is unknown. The downdip limits for sand occurrence likewise are not established.

The following calculation (table 2), is an indication of the potential for power generation which may be contained in the long, linear, high-volume aquifers which comprise the major geopressured sections of the Wilcox Formation.

Table 2.—Calculation of geothermal potential in Wilcox Sand.

Length of Wilcox sand trend: 1,460 km
Width of known geopressured zone: 40 km
Areal extent of Wilcox geopressured zone: 58,400 km^2
Average zone thickness in geopressured interval: 1,200 m
Assuming 20% of interval is sand, average sand thickness: 240 m
  Estimated volume of geopressured sand: 14,000 km^3
Assuming average porosity of sand is 15%, Vol. of water: 2,100 km^3
  Density of water: l g/cc
  Mass of water: 2 x 10^{18} g
  BHT: 175°C
  Useful dT: 75°C
  Heat capacity: 1.0 cal/°C/g
  Useful dH: 75 cal/g
  Total enthalpy: 1,575 x 10^{18} g-cal
Assuming a 14% efficiency in conversion to power,
  Total useful enthalpy: 22.05 x 10^{18} g-cal x 1.16 x 10^{-9} g-cal/MWh =
  25.62 x 10^{9} MWh, or 2.96 x 10^{4} MW centuries.
  Power potential = 7,400 MW centuries based on 25% reservoir depletion.

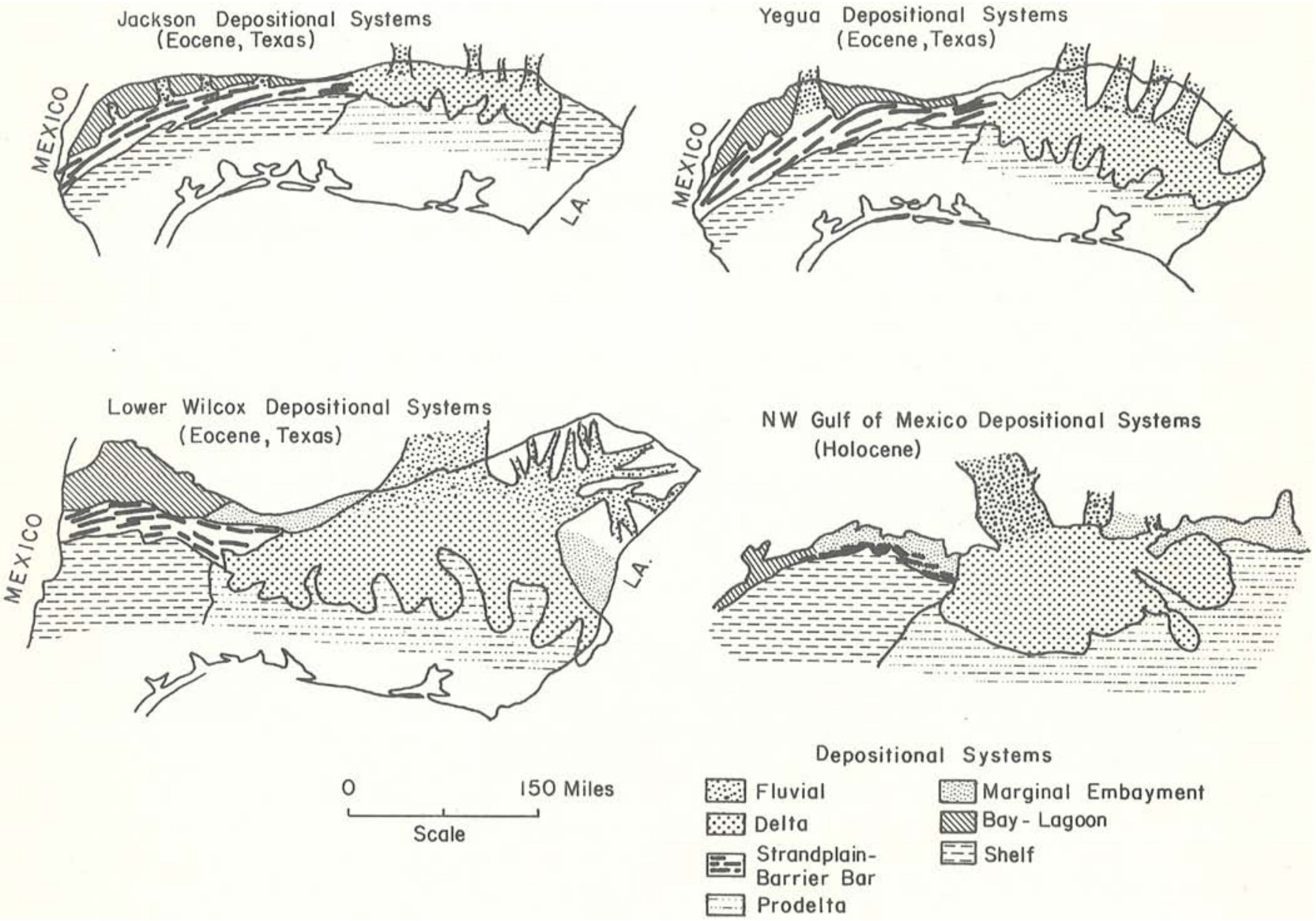


Figure 16. Distribution of principal depositional systems, contrasting Eocene Lower Wilcox, Yegua, and Jackson of Texas, and Holocene of northwestern Gulf of Mexico. Modified from Fisher, 1969, and Fisher and McGowen, 1967.

Deeper drilling will doubtlessly encounter higher temperatures, and small increases in useful heat will greatly increase the enthalpy available for power generation. The calculation of potential geothermal resources is based upon 25 percent reservoir depletion, and this figure is tentative. Known reservoir drives in geopressured zones include: (1) expansion of fluid, (2) solution gas drive, (3) compaction of sediment, and (4) influx of interstitial waters from adjacent shales.

Of these four potential drives, the big unknown is the degree of water influx from adjacent shales. Wallace (1969) has noted that such influx has been a major factor in maintaining high reservoir pressure in certain gas reservoirs in the top of geopressured zones in South Louisiana. Our assumption is based upon the use of major aquifers associated with growth faulting, with underlying undercompacted shales of sufficient magnitude to provide major reservoir energy.

The two other Eocene-age rock systems are the Yegua and Jackson. Studies by Fisher (1969) and Fisher and others (1970) show these units to be similar in character to the Wilcox, except that the Yegua and Jackson deltas did not prograde as far basinward as the Wilcox (fig. 16).

Consequently, growth faults active during Yegua and Jackson time are principally Wilcox faults. Displacement along these faults during Yegua and Jackson time was generally inadequate to isolate the sands. Extensive areas of all abnormally pressured sediments simply failed to develop. For this reason, it is unlikely that Yegua and Jackson sands will contribute large amounts of geothermal energy, although detailed facies studies may uncover isolated aquifers of sufficient magnitude to provide commercial electric power generation.

Oligocene-Miocene Sediments

Huge volumes of sediments continued to be transported from the Rocky Mountains region to the Texas Gulf Coast throughout Oligocene and early Miocene time. The deposits of interest are the Frio and Fleming Formations of Oligocene and Miocene age respectively. Both are very important oil and gas producers and both have considerable geothermal potential.

Although these formations are well developed along the entire Coastal Plain, adequate thicknesses of abnormally pressured sediment occur only south of Houston and are best developed south of Refugio (fig. 17). As with the Wilcox, each of these units represents a major influx of mud and sand which resulted in seaward advancement of the coast. Large growth faults developed again as the heavier sands sank into underlying prodelta muds, setting the stage for development of abnormal fluid pressure (fig. 15).

More than 20,000 square miles (50,000 km^2) of the Texas Coastal Plain is underlain by abnormally pressured Frio sediments. Sand thickness and reservoir properties are similar to the Wilcox, which leads to an estimate of the total potential geothermal reserve of 30,000 MW centuries with perhaps 25 percent of this amount exploitable. Estimate for the Fleming is not easily made because most of the abnormally pressured sediments occur offshore where data are sparse. Indications that the total extent of the Fleming sediments will be smaller than the Frio sediments suggest that half of the total Frio reserve is obtainable.

Thus, the total energy available for electric power generation from Gulf Coast geothermal sands appears to be approximately 20,000 MW centuries, which may be a conservative estimate.

Additional Benefits of Gulf Coast Geothermal Sands

In addition to the production of electricity, the use of the geopressured water in the Gulf Coast offers other benefits. This water is basically fresh water expelled from shales due to thermal diagenesis of clay minerals. Well log studies indicate that salinities in the geothermal reservoirs commonly are less than 5,000 ppm. Thus, upon exposure to atmospheric conditions, the waters will be comparatively fresh and can be used for consumption or irrigation in South Texas with minimal desalination efforts. They can also be used for secondary recovery operations in adjacent petroleum reservoirs, which are commonly located at shallow depths along the same regional growth faults as the geothermal reservoirs.

Another often overlooked potential benefit is the production of natural gas from geothermal waters. Laboratory studies (Culberson and McKetta, 1952) indicate that approximately 40 ft^3 of natural gas, primarily methane, may be dissolved in each barrel of water under reservoir conditions. At the high producing rates required for generation of electricity, production of over 1 MM ft^3/well/day of natural gas is not an unreasonable assumption. Assuming that 20 wells are required to produce 100 MW of electricity at a producing rate of 25,000 bbl/well, the field may

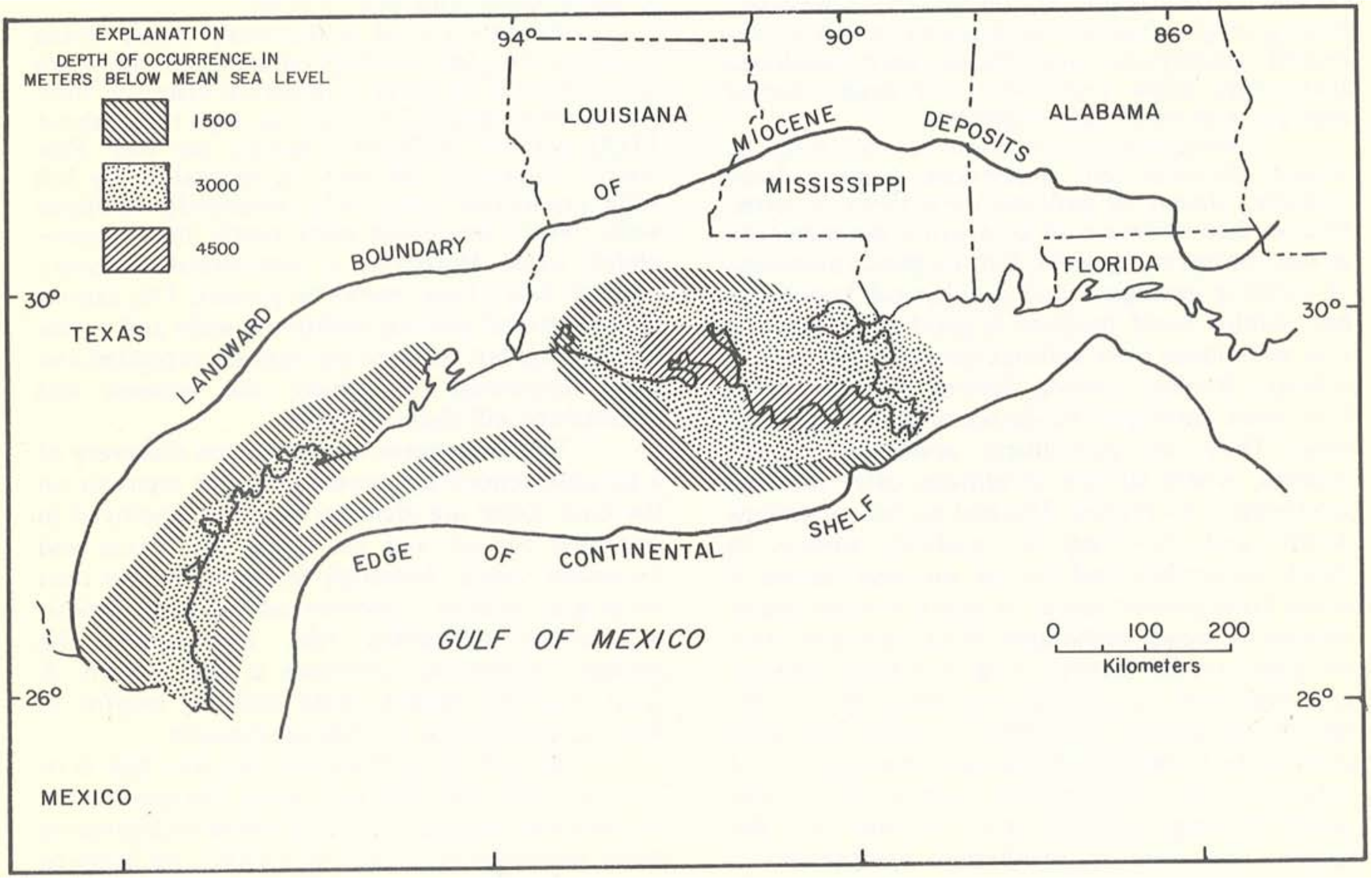


Figure 17. Location and depth of occurrence of the geopressured zone in the northern Gulf of Mexico basin. From Jones, 1969.

also produce 20 MM ft^3 of gas. This approximately doubles the energy recovered from these wells, substantially reducing cost of geothermal energy. In fact, full development of this resource may serve to significantly increase the State's reserves of natural gas.

TECHNOLOGY OF EXPLORATION

At the turn of the century, petroleum exploration involved the search for seeps of oil and gas, tar sands, and paraffin ground. Most exploratory holes were drilled near such surface manifestations of petroleum. As the industry developed, both geologic theories and procedures and sophisticated geophysical instruments were developed that today allow exploration for deeply buried deposits with no surface expression.

Geothermal exploration is following an almost identical, but accelerated history. Until recently, almost all exploratory activity occurred near surface evidences of geothermal deposits such as hot springs and geysers, but the great storehouse of existing geological and geophysical knowledge has enabled rapid progress in geothermal exploration techniques even without intensive commercial activity. Remote sensing devices of many types have been developed to detect areas of high heat flow. They are particularly applicable in rift systems, where surface conditions offer minimal interference to probes. Thermal probes at shallow depths and dipole-dipole resistivity surveys in which current is passed through successive layers of strata have proven useful in many thermal areas. Among the newer techniques which have been used are ground-noise surveys, magnetotelluric surveys, and high-level infrared photography. Where hot springs are present, geochemical studies have been used to help locate and estimate temperatures of deep reservoirs. Several new techniques are now under investigation and offer promise for the future. The state of geothermal exploration in areas of high heat flow must be considered rudimentary at this time, but methods are improving rapidly. Most of the methods mentioned are less costly than geophysical exploration techniques used in the search for petroleum.

Once evidence of a possible deposit is uncovered by geophysical, geological, or geochemical means, a well must be drilled. Like a properly researched oil or gas prospect, the drilling of a geothermal test involves risk of failure; the risk is less than for a randomly drilled hole, but it is a risk nevertheless. In addition to high discovery risk, there is a substantial mechanical risk arising from the severe drilling conditions, especially at the temperatures one hopes to encounter. For this reason, costs are great in shallow areas with high heat flow, typically much greater than in oil wells drilled to comparable depths. Drilling costs in areas of high heat flow have been discussed in detail in an earlier work (Dorfman, 1973a).

Recognition of a discovery poses severe problems also, because high temperatures alone are not sufficient to prove commercial viability. Individual wells need to produce at high rates, about 1,000 gal/min or 34,000 barrels per day. Productive capability can only be ascertained by full scale production tests with completely equipped wells, which are much more costly than uncompleted wells. Moreover, a commercial discovery requires that a large reserve be present. This cannot be determined without additional wells and extensive testing, but as more deposits are exploited and more knowledge is gained, the expense and uncertainty will likely diminish.

The procedures leading to the discovery of a suitable abnormally pressured water reservoir on the Gulf Coast are identical to those employed in searching for oil and gas along the Texas and Louisiana coasts. Although far easier to find than oil or gas, locating a commercial hot water deposit will entail substantial risk. Fortunately, the geology of the Gulf province is well known. A great deal of existing data will be helpful in locating commercial geothermal deposits.

As with oil exploration, the first task is to delineate the most favorable areas. For geothermal exploration, we need to know where high-pressure water reservoirs occur and where they are likely to be the hottest. Jones and Wallace (1974) have made extensive studies of abnormal pressure along the Texas Coast and their methods can be extended to unsurveyed areas. The second question is best answered through the construction of a regional geothermal gradient map or depth to isotherm map. The A.A.P.G. Geothermal Survey of North America is preparing such a map for North America. Publication is anticipated in 1975 (Kehle and others, in press). Having once identified the most favorable areas, subsurface geology is combined with seismic profiles to establish individual prospects. After delineating the prospect and acquiring the necessary acreage, a wildcat must be drilled to confirm the deposit.

COST OF GEOTHERMAL POWER

Although risks are involved in geothermal exploration and drilling due to the high temperature and physical characteristics of the rocks, costs of development and operation are attractive when compared to other sources aside from petroleum.. Table 3 shows the cost of geothermal electricity production in many fields. Most generate electricity at costs of between 4 and 7 mills/kwhr. The Los Alamos Scientific Laboratories of the AEC estimates that the cost of power generation in the hot-dry rock system will be approximately 6.3 mills/kwhr. These costs are considerably less than those of either coal or nuclear generation and, with the cost of petroleum continuing to rise, appear competitive with oil as well.

Plant and well costs in geothermal fields are, similarly, below those of other petroleum alternatives or substitutes. Both Cerro Prieto and the Geysers list total costs of wells and plants between $100 and $150/kw. The hot-dry rock system will cost an estimated $245/kw (Brown and others, 1973), compared with estimates of $250/kw for coal-fired steam and $350/kw for nuclear generation. Currently, we can only make rough approximations of the cost of geothermal energy in the Gulf Coast geopressured sands. If we assume, however, that each well has the capability of producing 5 MW, the following costs appear applicable:

Table 3.—Cost of geothermal electricity production.

	Millions of $ (1973)
100-MW generating plant, cooling tower, and auxiliary equipment:	**$10**
20 producing wells @ $0.5 million each:	**10**
Reinjection or additional contingency items:	**5**
	$25

This total cost of $25 million for a 100-MW power generation facility means a cost factor of $250/kw, which is also competitive with coal-fired steam, assuming that the cost of coal would remain at today's levels.

ENVIRONMENTAL EFFECTS

Though sometimes heralded as a completely pollution-free source of energy, the production of geothermal power involves a number of environmental effects. The more important are judged to be waste-water disposal, subsidence, and air pollution. Huge volumes of waters will accompany the production of geothermal power from either the hot water convective systems of West Texas or the abnormally pressured reservoirs along the Gulf Coast. These waters need to be disposed of or, in some cases, desalinated. Subsurface injection of the waste water is a possible solution. Fortunately, more than 300,000 producing oil wells are located in the Texas Gulf Coast basin, and most have been completed in subsurface reservoirs far below the fresh-water table. As oil production diminishes, these wells can be converted into brine-disposal wells at low cost. Already a large brine-disposal industry is developing along the Coastal Zone. Thus, considerable practical experience can be brought to bear on this problem.

The principal difference between oil field brine disposal and geothermal saline-water disposal is the magnitude of the water to be handled. For a small 100-MW plant, water is produced at a rate of 8 to 16 million gallons per day, equal to between 200,000 and 400,000 barrels. The water output from only 10 of these small plants will approximate Texas' daily oil production of 3 million barrels per day. To indicate the large scale of this endeavor, we note that the East Texas Field Salt Water Disposal facility, the largest such operation in this State, currently injects approximately 540,000 barrels per day into subsurface formations. The average per well injection rate is 6,000 barrels per day. If comparable injectivity prevails along the coast, each 100-MW plant will require between 35 and 70 disposal wells, although the greater sand thicknesses that prevail on the coast may allow a substantial reduction in the number of wells. The problem may in part be solved by desalinization. Most current plant designs call for conversion of about 80 percent of the feedwater into usable water, thus reducing the volume requiring disposal to one-fifth of the total produced water. But, the cost of desalinization may limit its applicability.

A completely different light is cast on the subject of waste-water handling by the fact that some engineers believe that disposal of waste water by subsurface injection may be a requirement for longevity of certain geothermal deposits. Without reinjection, reservoir energy in abnormally pressured deposits might be depleted after only a small percentage of the formation water is extracted if replenishment of reservoir fluids from adjacent undercompacted shales does not occur. Hot water convective systems are also depletable, with the heat in the initial charge of water representing only a minor fraction of the systems' total heat content. If a large percentage of the extracted water is reinjected into either type of reservoir, a much larger fraction of the systems' heat becomes extractable. Such a procedure is comparable to secondary recovery processes for oil extraction. And, of course, in hot-dry rock systems, it is essential that the injected fluid equals or exceeds the volume of extracted steam.

A problem directly associated with waste-water handling is that of land subsidence. An earlier analysis by Kehle (1972)[3] shows that if abnormally pressured reservoirs are produced by depletion rather than cycling, they are economical only if between 6 and 16 percent of the total produced water is derived from the dewatering of interbedded and interstitial clays. The expulsion of these waters is accompanied by an equal amount of compaction of the contributing clays. Shale dewatering in the Houston area has resulted in a subsidence bowl that extends entirely over Harris County and into adjacent counties. The maximum depression is over 6 feet. Because much of the land is near sea level, subsidence of this magnitude can cause serious problems with surface drainage, seawater invasion of aquifers, and flooding.

The depth of the abnormally pressured reservoirs in the Texas Gulf basin may cause the cone of subsidence to be very large, and thus the effect on the immediate area might not be serious. Subsidence would be mitigated if waste brines were reinjected into the producing formations, which would also solve the disposal problem. On the other hand, subsidence in either the Rio Grande trough or the Presidio bolson should not pose a problem except if it involved existing urban areas. In fact, studies of the Salton trough deposits suggest that no subsidence will occur there, which may mean that no problems will exist for the West Texas deposits. Even if large subsidence occurs, new communities could be designed for the expected subsidence at no real cost.

Land use will cause some minor problems. Blowoff pits, evaporation ponds, and the like are generally unsightly, but with proper procedures, these can be handled once an operation is underway. A more important consideration is the production of noxious gases. In addition to steam and methane, produced brines contain various amounts of carbon dioxide, hydrogen, ammonia, and hydrogen sulfide. If flash separation methods are used to extract steam, they will also extract all of the undesirable noncondensable gases, but these will not be separated from the methane. The current acute shortages of methane suggest that there is a ready market for the gas, and the natural gas industry is capable of handling the extraneous gases. The price for methane will reflect a diminished gas quality and needs no additional consideration here. If binary cycle generators are used and reinjection becomes practical, the noxious gases will be returned to the reservoir from where they came, thus solving the problem.

Additional environmental effects could include activation of preexisting faults, heat rejection, and physical hazards of well blowouts, but it is not believed that these will prove to be significant factors in the development of the geothermal resources of Texas.

Notwithstanding the potential environmental problems, it is important to bear in mind that the environmental impact must be considered on the basis of the entire fuel cycle and its effect upon man and nature. A typical fuel cycle begins with mining, processing, and transporting fuel to the generating site. After utilization of fuel, it involves disposal of spent wastes. When considered in this light, the environmental impact of geothermal generation compares favorably with either coal or nuclear generation. All environmental effects are limited to the generating site and its immediate environs. The succession of problems involved in normal mining operations for coal or uranium are absent, and transportation to the generating site requires flow lines of less than 1 mile in length. Disposal of spent wastes, the major problem in geothermal operations, is not as severe as the problem posed by either slag or ash from coal or radioactive wastes from nuclear operations.

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[3] Prepared as a presentation for a conference, United States Energy, sponsored by the U. S. Department of Interior. Summary in Hickel, W. J., 1972, Geothermal energy, a special report: University of Alaska.

NEW TECHNOLOGY REQUIREMENTS

Very little new technology is needed to develop either the hot water convective system of West Texas or the abnormally pressured geothermal reservoirs of the northern Gulf basin. The petroleum industry's experience in drilling deep holes and the electrical industry's experience in generating power from geothermal steam seem to apply directly to the exploitation of these geothermal resources. Because many of the elements of the envisioned systems are in the early stages of development, it is expected that technological improvements may increase production efficiency as more plants are brought on line. But such improvements are not necessary to make the exploitation of these resources commercially attractive.

The principal uncertainty regards the reservoir performance of deep, abnormally pressured sands and the longevity of hot water convective fields. In the last decade, petroleum engineers have developed techniques capable of predicting actual reservoir performance with precision by using mathematical models matched to the early producing life of a reservoir. But reasonably accurate predictions cannot be made a priori. Each prediction depends on obtaining detailed engineering data from the first year or two of the producing life of a reservoir.

Because we are unable to predict reservoir performance in advance, it is clear that the true potential of the geothermal resources of Texas cannot be reasonably estimated until at least one pilot operation is on stream in both West Texas and the Texas Coast. Thus, if there is to be geothermal power production in Texas prior to 1980, it is essential that we immediately begin an evaluation of "typical" geopressured and hot water convective reservoirs by actually producing the reservoirs at rates comparable to those needed for power production.

At a minimum, it would appear appropriate to complete a producing well in a thick, abnormally pressured sand sequence using conventional oil field technology and to produce this well under varying conditions of high deliverability for a period of a year or more. In order to fully evaluate the performance of such a well, it would also be desirable to have at least two observation wells completed in the same reservoir. Information regarding the drainage efficiency of the producing well is obtained from these supplemental wells. After two to three years of testing, a reasonable appraisal of the various assumptions made in this analysis would be forthcoming, at least for one reservoir.

The testing is a very expensive undertaking. To avoid risks associated with exploring for a suitable reservoir, it is suggested that a survey of existing, abnormally pressured, producing hydrocarbon reservoirs be made and that one be selected for testing. Nearly depleted or abandoned wells could be converted into observation and producing wells, significantly reducing the initial investment. A continuing program of very detailed production and reservoir-pressure monitoring, and produced-fluids analysis is essential. This information is used to construct a high-confidence mathematical model of the reservoir, which will allow an accurate assessment of the resource potential.

In summary, a proposed research program involves (1) delineating abnormally pressured reservoirs to select a site, (2) enlisting cooperation of the owner of this reservoir, (3) acquiring or drilling suitable production and observation wells, and (4) evaluating the reservoir performance under actual operating conditions.

CONCLUSIONS

1. Worldwide distribution of geothermal resources may be classified within the framework of plate tectonics. High-enthalpy water or steam reservoirs are found in areas of plate convergence known as subduction zones; high-enthalpy brines are found in areas of plate divergence known as crustal rift systems. Low-enthalpy fluids are found at moderate to great depths in geopressured sands in subsiding sedimentary basins. Cenozoic intrusives which retain high heat flow comprise a fourth potential reservoir category, but this system is unproven at the present time. Reservoirs contained within the first three categories are presently being utilized for production of geothermal energy in various areas around the world.

2. The State of Texas contains three geographic areas where geothermal resources may be located:
   a. The Rio Grande trough, located along the western edge of the State, has the configuration of a crustal rift system. Its extension into New Mexico is a known area of high heat flow, but heat flow has yet to be investigated in the Texas portion of the system.
   b. The Trans-Pecos igneous rocks, located north of the Big Bend National Park, consists of large areas of Cenozoic intrusives, but high heat flow in these rocks has not yet been established.
   c. The Texas Coastal Plain consists of great volumes of Tertiary geopressured sands with known widespread distribution.

3. If the Texas portion of the Rio Grande trough is found to have high heat flow, it should contain a minimal geothermal reserve of 5,000 MW centuries of electric power. Based upon the characteristics of other rift systems, the brines contained within this system may also contain valuable minerals which may be extracted from the water. Brines can be desalinated to provide potable water for consumption and irrigation.

4. Assuming that the Trans-Pecos igneous rocks have high heat values, and that a viable system is developed for utilization of this heat, these rocks appear to represent a major potential reserve of energy for development of electric power.

5. Large reserves of potential geothermal energy are present in the Gulf Coast geothermal sands. Rough calculations based partially on studies of Tertiary depositional systems indicate a reserve of at least 20,000 MW centuries of power. Natural gas in solution may be extracted to greatly increase the reserve of this valuable fuel, and potable water could be a valuable by-product of power generation in arid regions.

6. With the rapid depletion of our petroleum reserves, alternative sources of energy are required to alleviate dependence on foreign fuel. Geothermal energy represents a viable energy source which, with rapid development, may partially fulfill our energy requirements. Present technology is sufficiently advanced to explore for, drill, and produce geothermal wells. Costs are usually less than those encountered for power generation using other petroleum substitutes or alternatives. Environmental effects are also less troublesome than those reported using alternative power sources. Texas contains areas of known and suspected major reserves of geothermal energy. Intensive research and development can lead to rapid utilization of this resource.

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