HOT SPRINGS, GEYSERS, AND GEOTHERMAL ENERGY

by Donald L. Turcotte

Everyone knows that hot springs occur. Yellowstone National Park and other areas are famous for the geysering that is produced by a combination of boiling water and dissolved gases. But although hot springs and geysers are familiar natural phenomena, very little is known about their origin. Geochemical studies have shown that the water involved is circulating ground water. But what are the sources of heat?

Before the energy crisis, this question was primarily of academic interest. Today it is a major focus of the government's energy research program. The reason is geothermal energy.

The only producing geothermal field in the United States today is The Geysers, an area north of San Francisco. Here dry steam at an average temperature of 250°C is tapped from wells about fifteen hundred feet deep, and used directly to run turbines. This is a viable commercial operation with an installed capacity of six hundred megawatts, equivalent to half the power used by the city of San Francisco. But what is the potential for other fields? What are the criteria for finding them? And how can the heat be extracted?

EXTRACTING HEAT FROM THE EARTH'S INTERIOR

All geothermal energy is derived from the earth's hot interior where heat is produced by the decay of radioactive elements (^{235}U, ^{238}U, ^{232}Th, and ^{40}K). There are basically two sources of the heat for geothermal energy: the natural geothermal gradient, and cooling bodies of magma (liquid rock). The main types of systems that might be tapped for energy are hot dry rocks, hydrothermal systems producing hot water or steam or both, and geopressured systems producing hot water (and natural gas).

Processes suggested to extract heat from hot rocks are based on the idea of circulating water at depths where it would heat sufficiently to be usable for the production of electricity. Heat conduction causes a near-surface temperature gradient of about 20°C per kilometer, and assuming that an economically competitive geothermal energy plant would require a hot-rock temperature of 200°C, sufficient heat could be reached at a depth of about ten kilometers. In fact, in areas of relatively high heat flow, it is possible to drill into rock at this temperature at much shallower depths. Extraction of the heat is a more difficult matter, however. The Energy Research and Development Agency (ERDA) has proposed to circulate water between two wells in order to extract heat. But the problems associated with injecting and withdrawing the water while circulating it through fresh hot rock are severe, if not insurmountable.

An alternative way of extracting geothermal energy is by tapping natural reservoirs of hot water. These may reach the surface through convection as hot springs or geysers, or they may lie underground where they must be located and reached by drilling.

HOT SPRINGS AND THEIR SOURCES OF ENERGY

The hot springs of the eastern United States are generally attributed to the deep circulation of ground water in a near-normal geothermal gradient. The principal eastern hot springs are near the Virginia-West Virginia border and in Georgia. At Hot Springs, Virginia, the water reaches a temperature of 106°F, and at Warm Springs, Georgia, it reaches 87°F. In these

Figure 1

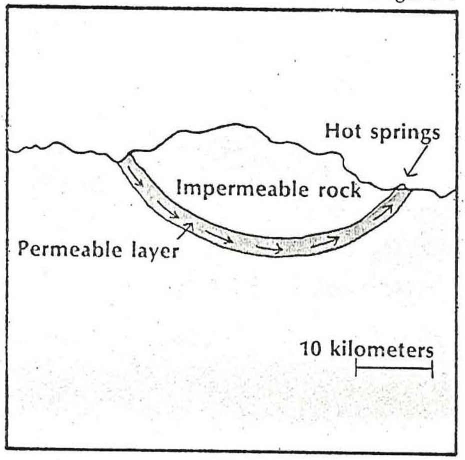


Figure 2

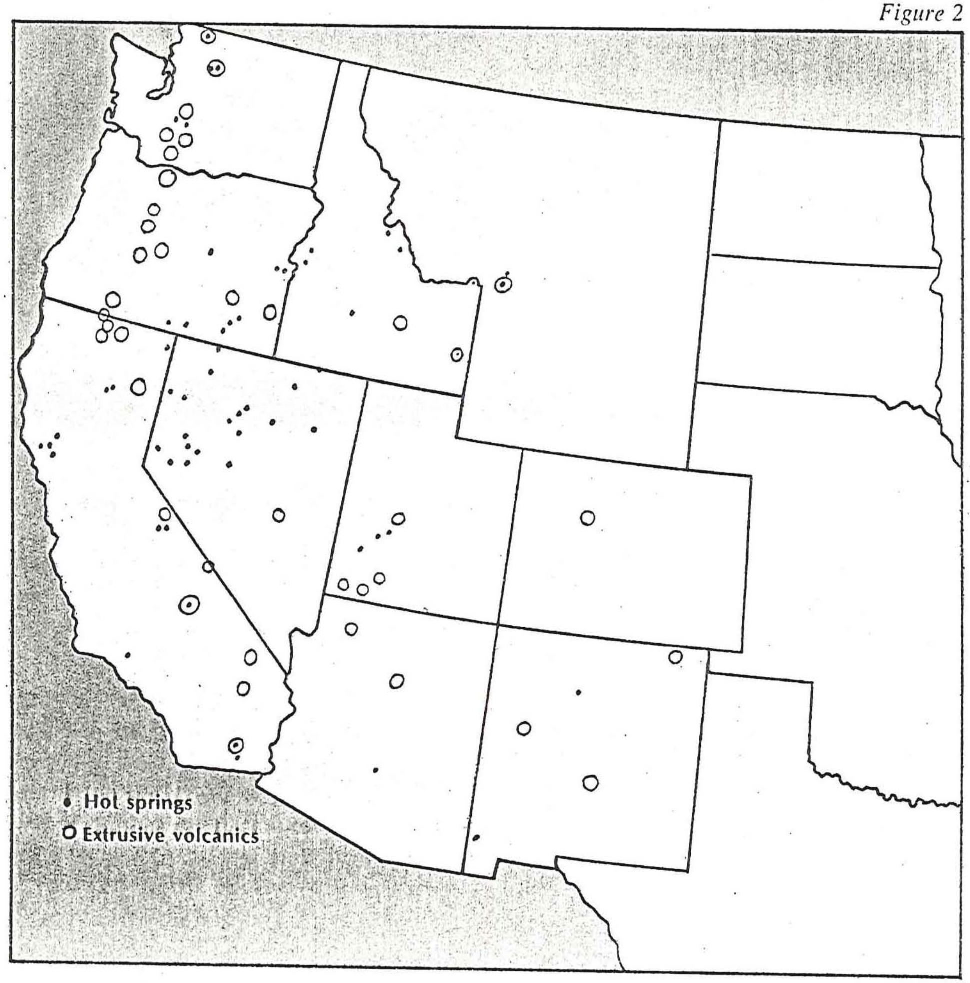


Figure 1. The deep circulation of ground water believed to occur near hot springs in the eastern United States. These springs are generally not hot enough to be used for the production of electricity.

Figure 2. The association of recent volcanic activity and hot springs in the western United States. The dots indicate the locations of hot springs with geothermal power potential; the circles represent extrusive volcanics with an age of less than ten thousand years. Although many of the hot springs appear to be related to recent extrusive volcanism, some must be generated by other thermal sources such as intrusive volcanic activity.

"But what are the sources of heat? Today (this question) is a major focus of the government's research program. The reason is geothermal energy."

cases, water is believed to circulate in an arched layer of permeable rock, as illustrated in Figure 1; but although this picture may be correct qualitatively, its validity has not been established. An extensive drilling program would be required to establish the presence and role of the permeable layer. And no model calculations have been carried out to establish whether water convecting in a permeable layer *can* extract heat from the surrounding low-permeability rocks over an extended period of time. In any case, it is very doubtful that geothermal energy could be extracted from the eastern hot springs, at least for the purpose of producing electricity; the temperatures are simply too low.

Water at high temperature is found in the extensive hot springs of the western United States, many of which reach or approach the boiling point of water, and may have associated geyser activity. Most investigators associate these hot springs with volcanic activity, of which there are two types, extrusive and intrusive. In extrusive volcanic activity, magma reaches the surface; and since surface rocks can be dated, areas in which there has been extrusive volcanic activity can be identified.

The areas of the United States where there has been volcanic activity in the last ten thousand years are shown in Figure 2. It is estimated that at depth, volcanic rocks of this age may still be cooling. Also shown in Figure 2 are the locations of hot springs with water temperatures, at depth, greater than 150°C. (The water temperature at depth can be deduced from the chemistry of the surface water.) It is clear from the locations of these two kinds of features that recent volcanism does generate hot springs, but that there are also many hot springs not associated with extrusive volcanics. An important question is whether these are also associated with volcanism.

GENERATION OF HOT SPRINGS FROM COOLING MAGMA

It is known from studies of eroded mountains that a large fraction of the volcanic rocks never reach the surface. These are the intrusive volcanics. The magma solidifies at depth and there may be no surface evidence of its presence. At the present time there is no way of identifying cooling magma bodies at depth, although attempts to locate them by seismic studies are being pursued actively. (The seismic reflection profiling techniques discussed by Sidney Kaufman elsewhere in this issue are potentially applicable to this kind of search.) It is probably reasonable to assume that the large, high-temperature hot-spring and geyser areas are associated

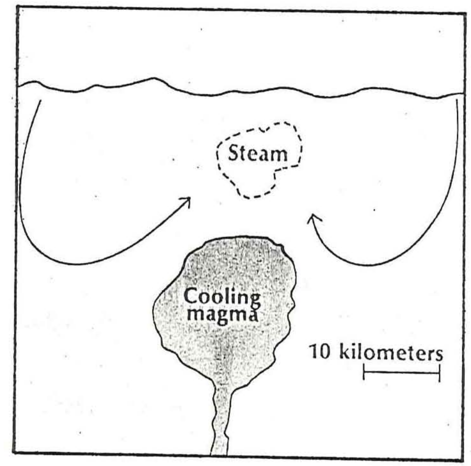
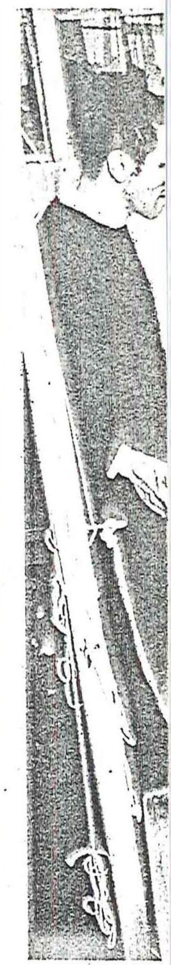


Figure 3. The mechanism thought to account for the generation of hot springs by cooling magma. Ground water circulating near the hot magma chamber is heated by conduction and then rises because of its decreased density.



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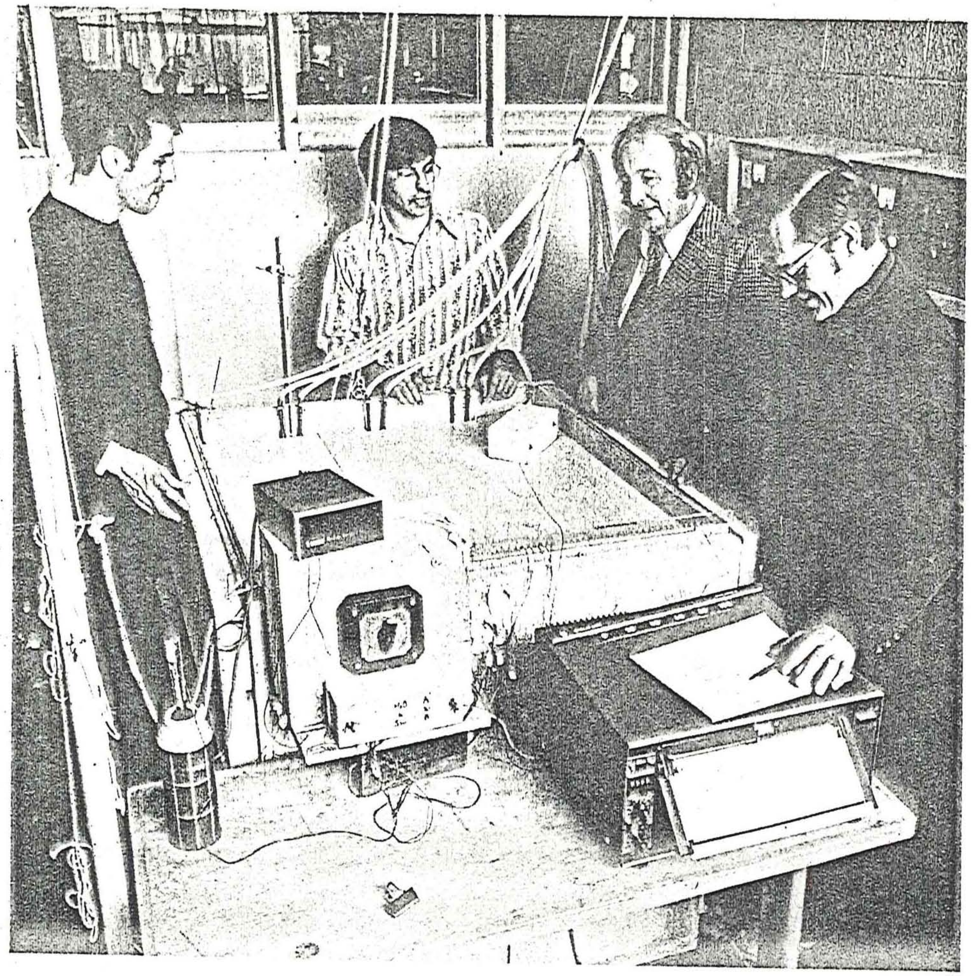

The Cornell research group studying two-phase convection in a porous medium includes (left to right) graduate students Bob Ribondo and Carl Sondergeld and professors Donald L. Turcotte and Kenneth E. Torrance. The "sand box," filled with glass beads and water, is used to simulate geothermal reservoir circulations; in this experiment, grids of thermocouples are being used to study temperature distributions. Near Torrance is a 24-channel multipoint recorder, and at the left is a thermally insulated switch that feeds data from 48 thermocouples into a digital panel meter.

with cooling magma at depth, but whether all hot springs of the West are associated with magma bodies is simply not known.

A cooling magma chamber is thought to generate hot springs through thermal convection in a mechanism illustrated in Figure 3. Cold ground water flows downward, probably through cracks and faults. As the water approaches the magma chamber, it is heated by conduction. As the temperature of the water increases, its density decreases; it becomes buoyant and rises to the surface, through cracks and faults, as hot springs. As the water rises, its pressure drops, and if the water is sufficiently hot, the reduction in pressure may cause it to convert or "flash" to steam. The reason that steam is produced in some cases and hot water in others is not known. The difference may be due to the availability of ground water, or the permeability of the rock (dependent on the number and size of cracks), or both.

CIRCULATION SYSTEMS: AN AREA FOR RESEARCH

Relatively little data are available on the behavior of the circulation systems at depth. Information on The Geysers area in the western United States is unavailable because it is proprietary. The most extensive studies have been carried out on the Wairakei area in New Zealand. We do know that when steam in the ground is tapped by a well, its behavior appears to be similar to that of a supply of natural gas at a wellhead: the steam does not appear to be replenished by natural processes during a withdrawal time of ten to twenty years.

Very little research has been carried out on the circulation systems associated with hot-water, two-phase, or dry-steam geothermal systems. It is possible that by drilling into a hot-water system and removing the water sufficiently rapidly, the system could be changed into a two-phase or a dry-steam system. It might also be possible to affect a hot-water system by reducing the availability of ground water, by changing drainage patterns, or in other ways.

Unfortunately, drilling is very expensive. Virtually all drilling today is being carried out by oil companies that are searching for dry-steam systems in the same way they would search for oil or gas fields. A research drilling program is being carried out on a modest scale in geothermal areas by the United States Geological Survey, but so far it has produced relatively little information of value.

THE CORNELL PROJECT ON GEOTHERMAL ENERGY

Because of the scarcity of information on geothermal systems involving hot water or steam, a Geothermal Energy Project has been organized at Cornell to carry out analytical, numerical, and laboratory studies of these systems.

The project got under way in the spring of 1974, when funds for two geothermal energy traineeships were received from the National Science Foundation. These were awarded to Robert Ribondo, a graduate student in mechanical engineering, and Carl Sondergeld, a graduate student in geological sciences. The research of these students is also supported by a grant from the Engineering Division of the National Science Foundation.

Bob Ribondo is carrying out a series of numerical calculations of thermal convection in a porous medium under the supervision of Professor Kenneth E. Torrance of the Sibley School of Mechanical and Aerospace Engineering. Initially he carried out studies of single-phase flows of water in a porous layer heated from below, and subsequently he performed numerical calculations of thermal convection in a porous layer in which the water is allowed to enter and leave through the upper boundary. These results have been applied in studies of the oceanic crust, where the circulation of salt water may be important in the formation of mineral deposits.

Ribondo has also considered thermal convection in a porous media when the fluid and the matrix have different temperatures. The purpose of this study is to understand hot springs, and the results have been applied to the Steamboat Springs system just south of Reno in Nevada. Ribondo is also extending his studies to two-phase thermal convection.

Carl Sondergeld has built a simulation facility for two-phase thermal convection under my supervision. The facility (see the photograph) is known as a "sand box," but in this case is filled with small glass beads and distilled water. The box is heated from below with radiation heaters until the boiling temperature is reached, and cooled from above with a cooling coil; the temperature distribution is monitored with thermocouples. Without the porous matrix, simple boiling would take place. The porous matrix stabilizes the flow and steady thermal convection occurs. The upper part of the convecting layer is water below the boiling temperature and the lower part is a mixture of steam and water at the boiling temperature. Steam is produced at the lower boundary of the layer and condenses at the interface between the two-phase and water zones. The density difference between the water and water-steam mixture drives the convection. These studies have already led to new insights into the basic processes involved in two-phase thermal convection. They are a first step towards an understanding of the far more complex processes that are occurring in geothermal areas.

Donald L. Turcotte, a specialist in geomechanics and geophysical fluid dynamics, joined the Cornell Department of Geological Sciences in 1973 after fourteen years as a member of the aerospace engineering faculty. His interest in geological aspects of fluid dynamics began during a 1965–66 sabbatic leave at the University of Oxford, where he began a continuing collaboration with E. Ronald Oxburgh, a lecturer in geology. Turcotte has conducted research, including laboratory experiments, numerical modeling, and theoretical calculations, on thermal and fluid convection in the moon as well as in the earth's mantle. At the present time his research primarily concerns the state of stress and the thermal convection of fluids in the earth's crust.

Turcotte earned an undergraduate degree in mechanical engineering in 1954 and a doctorate in aerospace engineering in 1958 at the California Institute of Technology. He also received the Master of Engineering (Aerospace) degree from Cornell in 1955. Before joining the Cornell faculty, he served for a year as an assistant professor at the United States Naval Postgraduate School.

He is the author of Space Propulsion, *published by Blaisdell in 1965, and coauthor of* Statistical Thermodynamics, *published by Addison-Wesley in 1963, and has contributed many articles to professional journals. He is a fellow of the Geological Society of America and a member of the American Physical Society, the American Geophysical Union, and the Seismological Society of America.*

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