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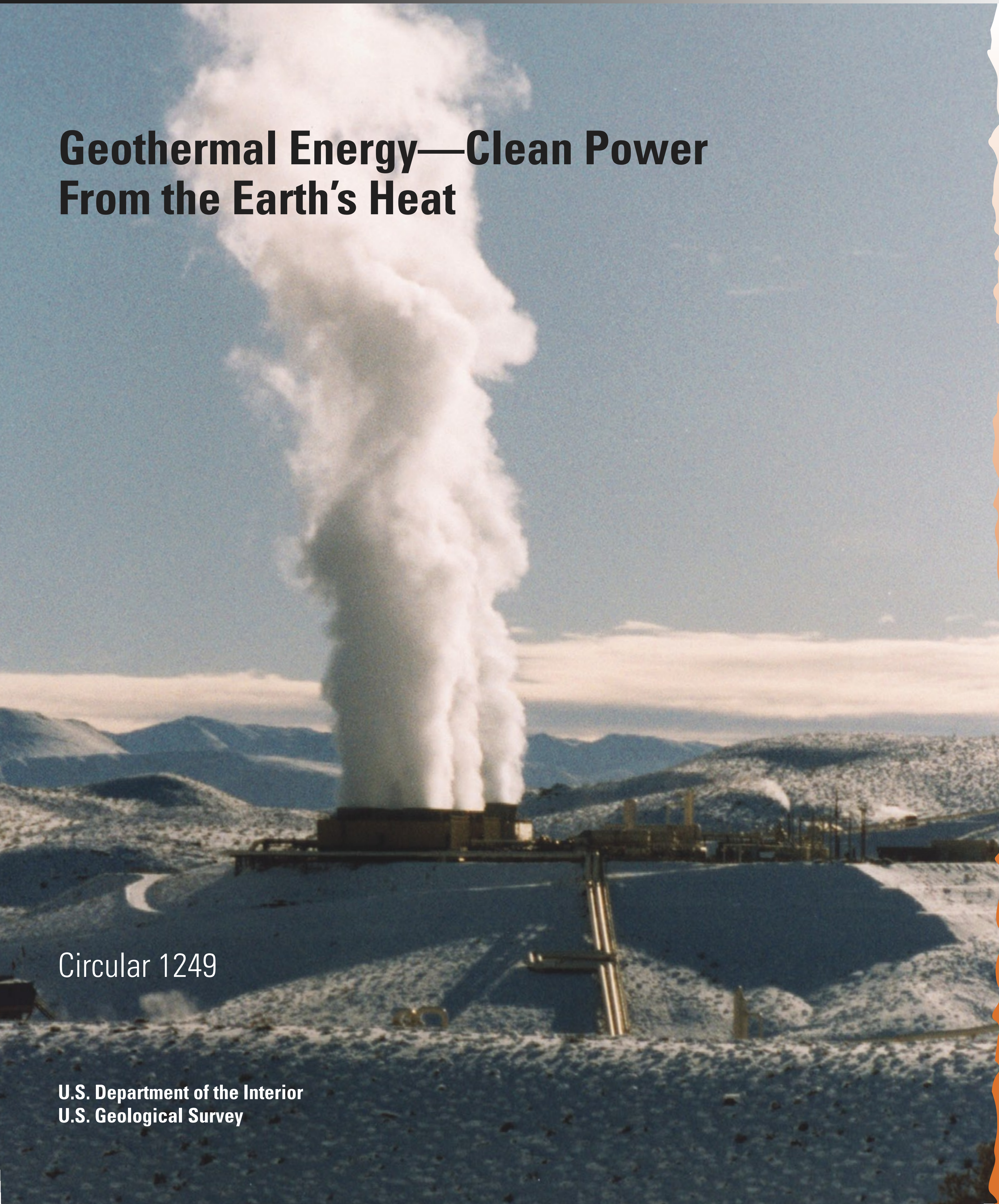
Geothermal Energy—Clean Power From the Earth's Heat



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U.S. Department of the Interior
U.S. Geological Survey

Geothermal Energy—Clean Power From the Earth's Heat

By Wendell A. Duffield and John H. Sass

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Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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Cover—Coso geothermal plant, Navy One, at Naval Air Weapons Station China Lake in southern California (U.S. Navy photograph).

Foreword

One of the greatest challenges of the 21st century is the production of sufficient energy to power the economies of both the developed and developing world. Fossil fuels—coal, oil, and natural gas—will continue to supply most energy through at least the first half of the century. However, declining reserves of fossil fuels, increased demand, and environmental constraints will challenge human ingenuity in providing alternative sources of energy. Alternative technologies that employ the Sun's energy (solar-electric and wind power) are advancing rapidly and provide electrical power at costs that are approaching those of conventional technologies.

Direct use of the Earth's heat for agricultural, recreational, and industrial purposes dates back to earliest human history. Modern technology has increased the use of geothermally heated fluids dramatically, resulting in the worldwide production of more than 10,000 megawatts annually of geothermal energy. Geothermal heating and cooling of both commercial and residential buildings is already widespread throughout the world. There is great potential for increasing the direct use of the Earth's heat, thereby reducing dependence on fossil fuels.

Geothermal energy currently supplies less than 1 percent of the energy consumed in the United States. If the presently known geothermal resources are fully developed in conjunction with continuing technological advances, this clean, renewable energy source could contribute several times that amount. The purpose of this report is to describe the distribution and nature of geothermal energy, review geothermal systems, consider potential resources, and summarize the role of earth-science information in assessing geothermal resources worldwide.

Energy decisions for the Nation should be based on good science. The USGS supports the Nation by providing the best information possible on energy resources to enable sound decisions for public health and prosperity.

Charles G. Groat
Director, U.S. Geological Survey

Conversion Factors

For readers who wish to convert measurements from the metric system of units to the inch-pound system, the conversion factors are listed below.

Multiply	By	To obtain
hectacre	2.47	acre
square meter	10.76	square foot
kilometer	.6214	mile
metric ton	1.102	short ton (2,000 pounds)
metric ton	.9842	long ton (2,240 pounds)
cubic kilometer	.2399	cubic mile
liter per second	15.85	gallon per minute
kilogram per second	27.273	pound per minute

To convert from degrees Celsius (°C) To degrees Fahrenheit (°F), multiply the °C value by 1.8 and add 32 to the resulting value.

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Special Topics

Index map of Western United States showing locations of some places discussed in the text.

Some of the names used for geothermal features in this report are not officially recognized or approved by the U.S. Board on Geographic Names.

Geothermal Energy—Clean Power From the Earth's Heat

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Introduction

Societies in the 21st century require enormous amounts of energy to drive the machines of commerce and to sustain the lifestyles that many people have come to expect. Today, most of this energy is derived from oil, natural gas, and coal, supplemented by nuclear power.

Local exceptions exist, but oil is by far the most common source of energy worldwide. Oil resources, however, are nonrenewable and concentrated in only a few places around the globe, creating uncertainty in long-term supply for many nations.

At the time of the Middle East oil embargo of the 1970s, about a third of the United States oil supply was imported, mostly from that region. An interruption in the flow of this import disrupted nearly every citizen's daily life, as well as the Nation's economy. In response, the Federal Government launched substantial programs to accelerate development of means to increasingly harness "alternative energies"—primarily biomass, geothermal, solar, and wind. The new emphasis on simultaneously pursuing development of several sources of energy recognized the timeless wisdom found in the proverb of "not putting all eggs in one basket." This book helps explain the role that geothermal resources can play in helping promote such diversity and in satisfying our Nation's vast energy needs as we enter a new millennium.

For centuries, people have enjoyed the benefits of geothermal energy available at hot springs, but it is only through technological advances made during the 20th century that we can tap this energy source in the subsurface and use it in a variety of ways, including the generation of electricity. Geothermal resources are simply exploitable concentrations of the Earth's natural heat (thermal energy). The Earth is a bountiful source of thermal energy, continuously producing heat at depth, primarily by the decay of naturally occurring radioactive isotopes—principally of uranium, thorium, and potassium—that occur in small amounts in all rocks. This heat then rises to and through the Earth's surface, where it escapes into the atmosphere. The amount of heat that flows annually from the Earth into the atmosphere is enormous–equivalent to ten times the annual energy consumption of the United States and more than that needed to power all nations of the world, if it could be fully harnessed.

Even if only 1 percent of the thermal energy contained within the uppermost 10 kilometers of our planet could be tapped, this amount would be 500 times that contained in all oil and gas resources of the world. How might we benefit from this vast amount of thermal energy beneath our feet? Where, by what means, and how much of the Earth's natural heat can be usefully harnessed? These are especially important questions to contemplate, because global population is expected to soon exceed seven billion and many scientists believe that the world's fossil-fuel resources may be substantially depleted within this century. Faced with such prospects, both the public and private sectors are working toward more fully utilizing the Earth's abundant thermal energy and other alternative energy resources.

A skeptic might question the wisdom of devoting much national effort to geothermal energy development, especially because many experts think that geothermal heat can contribute at most about 10 percent to the Nation's energy supply using current technologies. However, ongoing advances in exploration and heat-extraction technologies are improving our ability to use the resource and may substantially increase the geothermal contribution to the Nation's energy supply.

In an attempt to help national planners and average citizens alike understand the nature and energy potential of geothermal resources, this book (1) describes the distribution and nature of geothermal energy, (2) reviews the common types of geothermal systems that provide useful energy with current technology, (3) considers potential geothermal resources that might someday be tapped with developing technologies, and (4) summarizes the role of earth-science information in assessing and harnessing geothermal resources wherever they occur worldwide.

The predecessor to this book (*Tapping the Earth's Natural Heat*, U.S. Geological Survey Circular 1125, published in 1994) summarized the situation in the early 1990s. In an effort to support national energy planners, this new circular incorporates more recent advances in geothermal science and technology.

Acknowledgments

We thank Suzanne Weedman and the Energy Resources Program for providing financial support for publication of this Circular. We would also like to thank the Department of Energy, U.S. Navy, and the Geothermal Resources Council for additional funds provided for printing. Bob Tilling and Frances Pierce provided valuable reviews of the draft document. We thank Gudmundur Omar Fridliefsson, Iceland National Energy Authority, for reviewing and suggesting updates to the Iceland segment. We used several illustrations from the files of the Geothermal Education Office. Jacques Varet supplied updated information on the geothermal usage in France. Susan Priest, Tracey Felger, and Robert Fournier supplied illustrations. We thank Sara Boore, Susan Mayfield, James Hendley, and Peter Stauffer for their creative input.

Geothermal Then—Geothermal Now

Scene from a Japanese spa shows one of the early uses of geothermal energy. Artwork was originally published in a guidebook called "Seven Hot Springs of Hakone" written and painted anonymously in 1811 by a writer whose pen name was Bunsou and an artist whose pen name was Rouka. (Courtesy of Hakone Museum of Folk Culture in Hakone City, Japan.)

Geothermal in Ancient Times

Long before recorded history, some ancient peoples must have been aware of geothermal features such as hissing steam vents, erupting geysers, boiling mud pots, and bubbling hot springs. One can only speculate on their reactions to such impressive natural phenomena, but some combination of fear, awe, and appreciation seems likely. By the time of recorded history, hot springs and other geothermal features were being used by people for food preparation and for bathing. The geothermally heated spas of the ancient Greeks, Romans, and Japanese have been imitated throughout history, and today their modern counterparts attract many visitors for recreational and medical reasons.

Prehistoric and early historical uses of geothermal features were effectively limited to those found at the Earth's surface. With rare exception, such features produce water or steam with temperatures of less than 100°C (the boiling point of water at sea level); their relatively low temperatures restrict the variety of possible uses. Lack of knowledge and technical limitations prohibited any attempt to develop deeper, hotter geothermal energy. Still, many early civilizations benefited from the geothermal resources with which they were provided by nature.

Geothermal Now

With modern technology, drills can penetrate thousands of meters into the Earth in search of geothermal resources. Such drilling has resulted in the discovery of geothermal fluid as hot as 500°C, which can provide a resource of high-pressure steam to drive turbine generators at the Earth's surface. The traditional, ancient uses of geothermal water continue to have considerable scenic and recreational value, but the present-day capability to produce high-temperature fluid through drilled wells opens the door to diverse utilization of geothermal energy over a broad range of temperatures. Information gathered from measurements made during flow testing of geothermal wells can indicate how much power they can provide. A "typical" commercial geothermal well can power between 5 and 8 megawatts of electrical generation capacity (1 megawatt = 1,000 kilowatts = 1 million watts).

Research and development have shown that the size and vigor of geothermal surface features are not necessarily representative of the entire subsurface system. For example, at The Geysers in northern California, where the surface geothermal features are relatively weak, drilling revealed the world's largest known reservoir of steam. Electricity generated from The Geysers geothermal field, which is fed into the regional power grid, is nearly enough to meet the energy demands of the nearby city of San Francisco. Similarly, in the Imperial Valley of southern California, rare and feeble hot springs belie the presence of many large subterranean reservoirs of hot water now partly harnessed to produce about 475 megawatts of electrical power. A major challenge for future exploration is to develop improved techniques that can help identify geothermal resources that have no surface expression whatsoever.

Swimmers enjoying a hot water pond near Grindavík, Iceland, formed by salty waste-water from a geothermal powerplant (in background) dumped onto the ground. This pond—called the "Blue Lagoon" by Icelanders—is believed to have healing powers. (Photograph by Robert Fournier.)

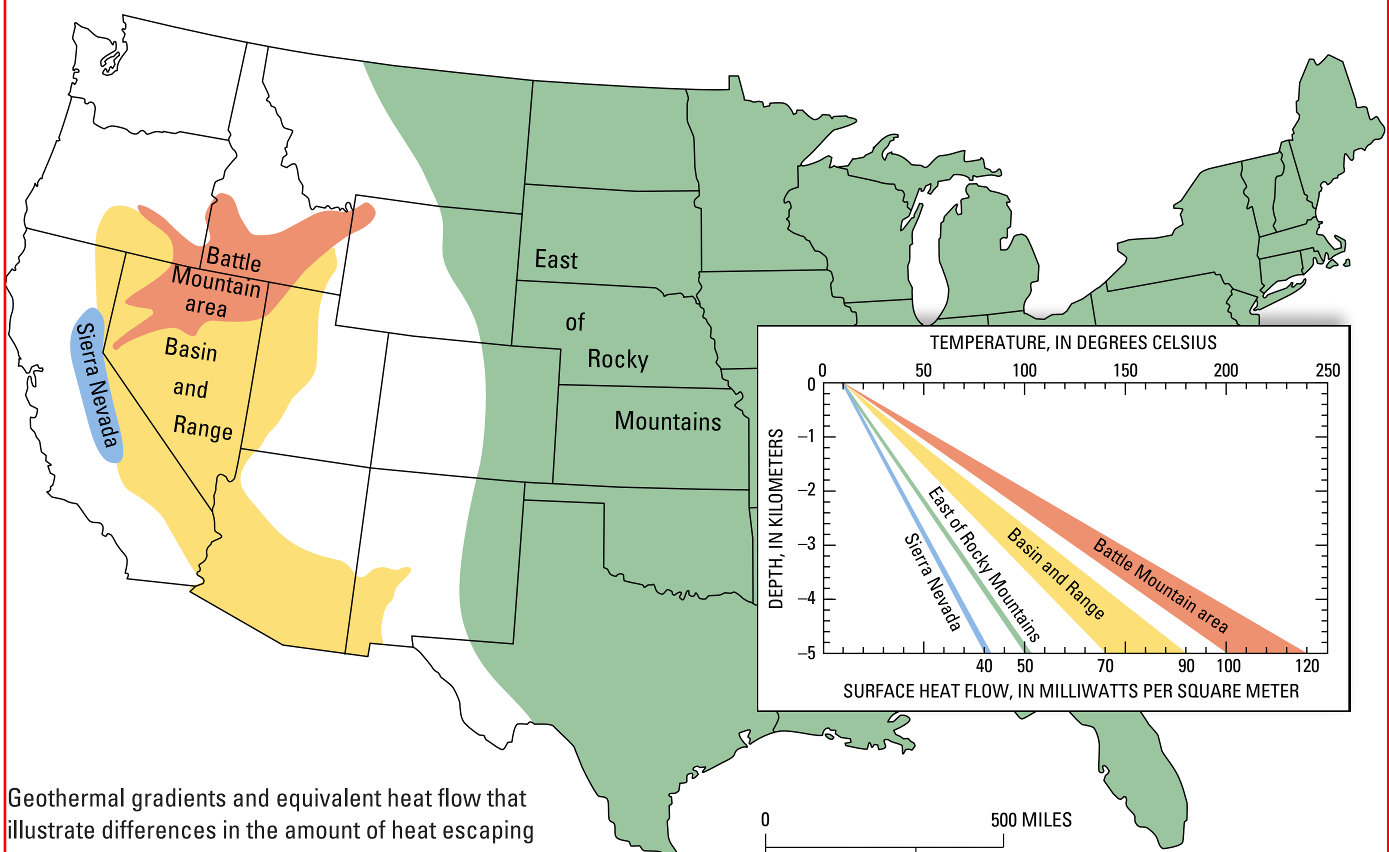
Geothermal Energy as a Natural Resource

Geothermal energy is present everywhere beneath the Earth's surface, although the highest temperature, and thus the most desirable, resources are concentrated in regions of active or geologically young volcanoes. Though the resource is thermal energy rather than a physical substance such as gold or coal, many aspects of geothermal energy are analogous to characteristics of mineral and fossil-fuel resources. Geothermal energy also has some unique, desirable attributes.

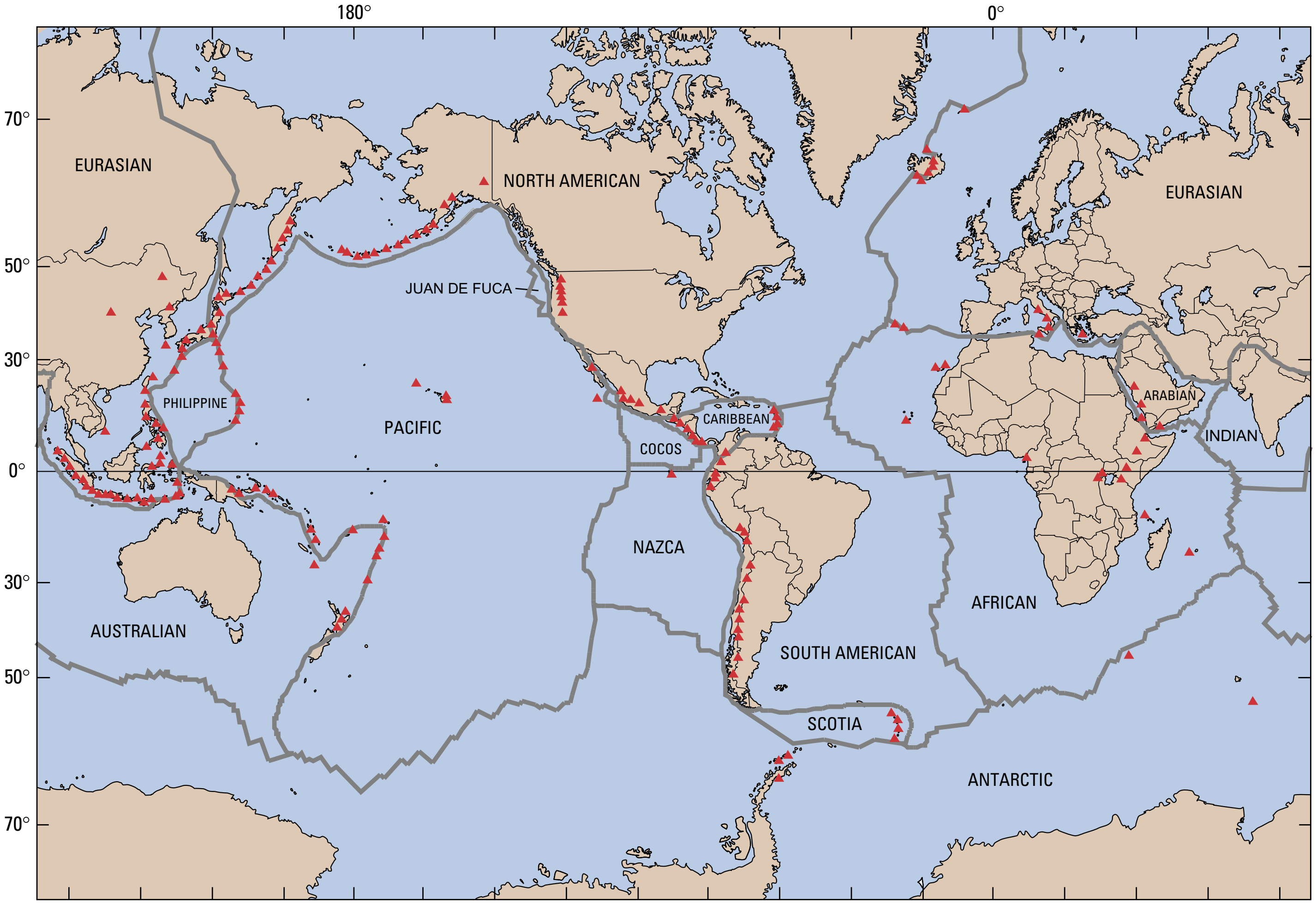
Global Distribution

Measurements made in drill holes, mines, and other excavations demonstrate that temperature increases downward within the Earth. The rate at which the temperature increases (temperature gradient or geothermal gradient) is proportional to the rate at which heat is escaping to the surface through the Earth's crust (heat flow). Thus, zones of higher-than-average heat flow are the most likely places for encountering high temperatures at shallow depth, perhaps shallow enough to favor exploitation of geothermal energy. The average rate at which heat escapes through the Earth's crust accounts for a prodigious amount each year, but local heat flow can vary widely from region to region.

Large quantities of heat that are economically extractable tend to be concentrated in places where hot or even molten rock (magma) exists at relatively shallow depths in the Earth's outermost layer (the crust). Such "hot" zones generally are near the boundaries of the dozen or so slabs of rigid rock (called plates) that form the Earth's lithosphere, which is composed of the Earth's crust and the uppermost, solid part of the underlying denser, hotter layer (the mantle). According to the now widely accepted theory of plate tectonics, these large, rigid lithospheric plates move relative to one another, at average rates of several centimeters per year, above hotter, mobile mantle material (the asthenosphere). High heat flow also is associated with the Earth's "hot spots" (also called melting anomalies or thermal plumes), whose origins are somehow related to the narrowly focused upward



Geothermal gradients and equivalent heat flow that illustrate differences in the amount of heat escaping from the Earth for broad regions and smaller areas of the United States (Sierra Nevada, Basin and Range physiographic province, Battle Mountain area of Nevada and nearby states, and east of the Rocky Mountains). The heat flow shown for the area east of the Rocky Mountains is equivalent to the average heat flow for continental crust worldwide.



Map showing Earth's main lithospheric plates and some of the world's active volcanoes (triangles).

flow of extremely hot mantle material from very deep within the Earth. Hot spots can occur at plate boundaries (for example, beneath Iceland) or in plate interiors thousands of kilometers from the nearest boundary (for example, the Hawaiian hot spot in the middle of the Pacific Plate). Regions of stretched and fault-broken rocks (rift valleys) within plates, like those in East Africa and along the Rio Grande River in Colorado and New Mexico, also are favorable target areas for high concentrations of the Earth's heat at relatively shallow depths.

Zones of high heat flow near plate boundaries are also where most volcanic eruptions and earthquakes occur. The magma that feeds volcanoes originates in the mantle, and considerable heat accompanies the rising magma as it intrudes into volcanoes. Much of this intruding magma remains in the crust, beneath volcanoes, and constitutes an intense, high-temperature geothermal heat source for periods of thousands to millions of years, depending on the depth, volume, and frequency of intrusion. In addition, frequent earthquakes—produced as the tectonic plates grind against each other—fracture rocks, thus allowing water to circulate at depth and to transport heat toward the Earth's surface. Together, the rise of magma from depth and the circulation of hot water (hydrothermal convection) maintain the high heat flow that is prevalent along plate boundaries.

Accordingly, the plate-boundary zones and hot spot regions are prime target areas for the discovery and development of high-temperature hydrothermal-convection systems capable of producing steam that can drive turbines to generate electricity. Even though such zones constitute less than 10 percent of the Earth's surface, their potential to affect the world energy mix and related political and socioeconomic consequences is substantial, mainly because these zones include many developing nations. An excellent example is the boundary zone rimming the Pacific Plate—called the "Ring of Fire" because of its abundance of active volcanoes—that contains many high-temperature hydrothermal-convection systems. For the developing countries within this zone, the occurrence of an indigenous energy source, such as geothermal, could substantially bolster their national economies by reducing or eliminating the need to import hydrocarbon fuels for energy. The Philippines, Indonesia, and several countries in Central America already benefit greatly from geothermally generated electricity; additional projects are underway and planned. Of course, the use of geothermal energy already contributes to the economies of industrialized

Magma, Volcanoes, and Geothermal Energy

Geologists have long known that molten rock (magma) in the Earth's crust provides the heat needed to create most high-temperature geothermal resources that have potential for electricity generation. The clearest evidence for this conclusion is the common occurrence of young, sometimes active, volcanoes within areas of proven high-temperature geothermal resources. Because of this link between magma and high-temperature geothermal resources, geologists of the U.S. Geological Survey (USGS) developed a method to determine the approximate size and temperature of a body of magma in the crust today from the age and volume of volcanic rocks erupted most recently from that body. A key point in this method is that for each volume of magma erupted, about ten times that volume remains in the Earth's crust. This 1:10 relationship is based on studies of volcanic rocks and their subsurface magmatic-rock roots at many locations worldwide.

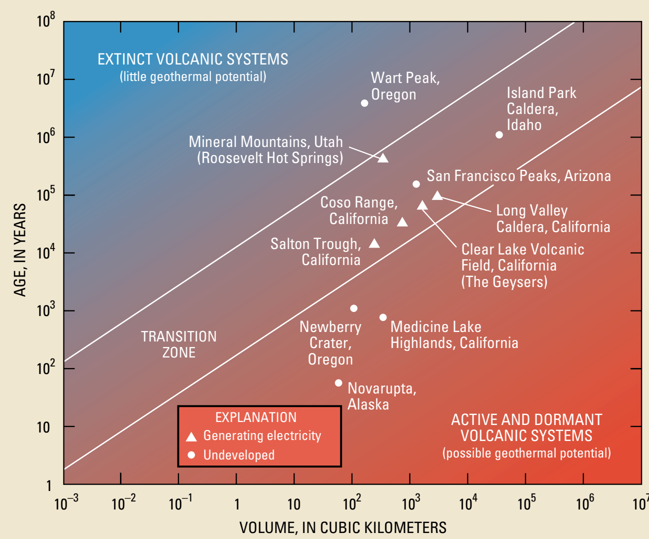
Another key point of the method is the calculation of about how long it takes for a body of magma to cool in the crust. Such calculations of heat-lost-through-time have resulted in a three-part classification of volcanic areas—those with high geothermal potential, those with low geothermal potential, and an intervening "transition zone" within which the geothermal potential of a volcanic area cannot be accurately determined from available information (see accompanying graph). Simply put, a relatively large body of magma of relatively young age is far more likely to be a potent source of geothermal heat today than is a smaller and older body of magma.

Because the information needed to calculate geothermal potential includes the age and volume of the youngest eruptions for a given volcanic area, several field projects of the USGS were designed to address this need. For example, the results of field studies carried out during the 1970s led to the conclusion that hundreds of cubic kilometers of magma of at least 650°C are in the crust today beneath the Coso volcanic area of California. Though the age/volume information for Coso plots in the transition zone of resource potential, subsequent exploration and development have confirmed a substantial geothermal resource there. About 270 megawatts of turbine-generator units are powered by geothermal steam today, providing sufficient electricity for an American city with a population of about 270,000 people. The Coso geothermal area is not yet fully explored or developed.

USGS field studies of the 1970s and 1980s led to the conclusion that the Medicine Lake Highlands volcanic area of northern California (see graph) holds an even higher degree of promise of a geothermal resource. Subsequent drilling has confirmed a substantial resource that awaits possible development. A similar analysis of the San Francisco Peaks volcanic area in Arizona, indicates a possible geothermal resource, an example that falls within the intermediate of the three resource-potential categories. No drilling has occurred to date, so the resource potential remains an open question. A relatively small and old volcanic area, such as Wart Peak, Oregon, is calculated to contain little or no geothermal potential.

Field studies have shown that 15 cubic kilometers of magma was erupted in 1912 at Novarupta to produce a volcanic deposit that partly fills the Valley of Ten Thousand Smokes in Alaska. Accordingly, the model suggests the presence of a magma body at about 650°C and around 100 cubic kilometers in volume. This large amount of geothermal energy and the even larger amount calculated for Yellowstone are protected from development by their National Park status.

In addition to a hot water-steam (hydrothermal) component, by far the majority of the thermal energy associated with a magma-volcano environment resides in the magma itself and in hot-but-dry rock around it. Using current technology, only the hydrothermal component can be exploited; meanwhile, studies are in progress to demonstrate the feasibility of possible future exploitation of the nonhydrothermal components of geothermal energy.



Ages of selected volcanic eruptions versus volumes of their associated magma bodies for several areas in the United States.

nations along the circum-Pacific Ring of Fire, such as the United States, Japan, New Zealand, and Mexico.

Comparison with Other Natural Resources

Geothermal resources are similar to many mineral and energy resources. A mineral deposit is generally evaluated in terms of the quality or purity (grade) of the ore and the amount of this ore (size or tonnage) that can be mined profitably. Such grade-and-size criteria also can be applied to the evaluation of geothermal energy potential. Grade would be roughly analogous to temperature, and size would correspond to the volume of heat-containing material that can be tapped. For mineral and geothermal deposits alike, concentrations of the natural resource should be significantly higher than average (the background level) for the Earth's crust and must be at depths accessible by present-day extraction technologies before commercial development is feasible.

However, geothermal resources differ in important ways from many other natural resources. For example, the exploitation of metallic minerals generally involves digging, crushing, and processing huge amounts of rock to recover a relatively small amount of a particular element. In contrast, geothermal energy is tapped by means of a liquid carrier—generally the water in the pores and fractures of rocks—that either naturally reaches the surface at hot springs, or can readily be brought to the surface through drilled wells. The extraction of geothermal energy is accomplished without the large-scale movement of rock involved in mining operations, such as construction of mine shafts and tunnels, open pits, and waste heaps.

Geothermal energy has another important advantage. It is usable over a very wide spectrum of temperature and volume, whereas the benefits of other natural resources can be reaped only if a deposit exceeds some minimum size and (or) grade for profitable exploitation or efficiency of operation. For example, at the low end of the spectrum, geothermal energy can help heat and cool a single residence. To do so requires only the burial of piping a few meters underground, where the temperature fluctuates little with the changing seasons. Then, by circulating water or some other fluid through this piping using a geothermal heat pump, thermal energy is extracted from the ground during the coldest times of the year and deposited in the ground during the hottest times. Together, the heat pump and the Earth's thermal energy form a small, effective, and commercially viable heating and cooling system. Heat pump systems are already in use at more than 350,000 buildings in the United States.

Toward the high end of the spectrum, a single large-volume, high-temperature deposit of geothermal energy can be harnessed to generate electricity sufficient to serve a city of 1 million people or more. For example, at The Geysers in northern California, fractures in rocks beneath a large area are filled with steam of about 240°C at depths that can easily be reached using present-day drilling technology. This steam is produced through wells, piped directly to conventional turbine generators, and used to generate electricity. With a generating capacity of about 1,000 megawatts electric, The Geysers is presently the largest group of geothermally powered electrical plants in the world. At current rates of per capita consumption in the United States, 1 megawatt is sufficient to supply a community with a population of 1,000.

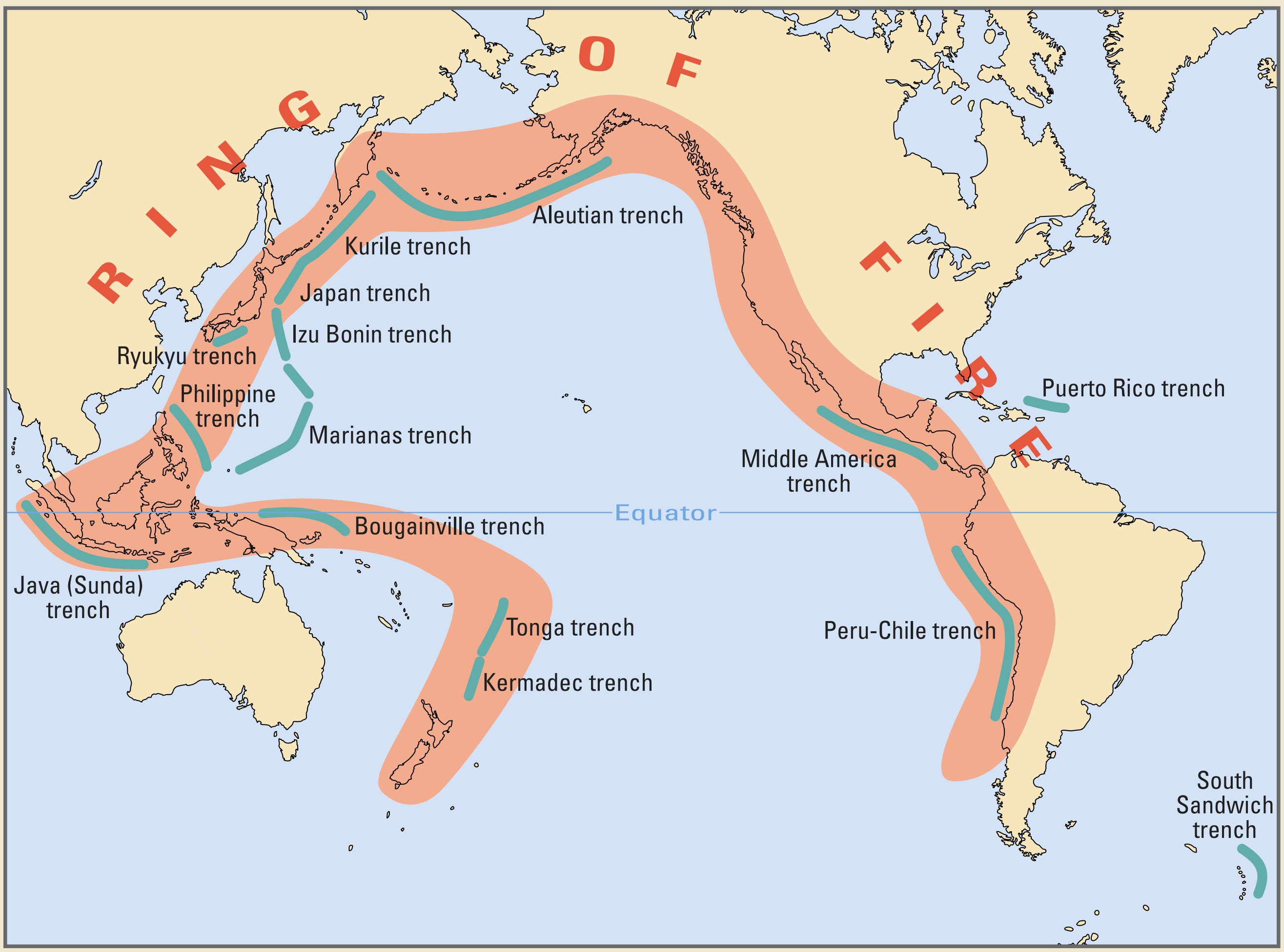
Between these relatively extreme examples are geothermal resources that encompass a broad spectrum of grade (temperature) and tonnage (volume). The challenge, for governmental agencies and the private sector alike, is to assess the amount and distribution of these resources, to work toward new and inventive ways to use this form of energy, and to incorporate geothermal into an appropriate energy mix for the Nation and the world.

Geothermal Energy and the Ring of Fire

The volcanically active and earthquake-prone region rimming the Pacific Ocean is known as the "Ring of Fire." This region could also be called the Ring of Geothermal Energy, because it contains many high-temperature geothermal systems associated with active volcanoes. Hundreds of volcanoes girdle the Pacific Basin from the Aleutian Range of Alaska, through the Kamchatka Peninsula, Japan, the Philippines, Indonesia, New Zealand, the Andes, Central America, Mexico, and the Cascade Range of the Pacific Northwest and Canada. Projects to harness geothermal energy are either underway or on line in all of these areas.

Many active volcanoes form a long chain that approximately parallels the Pacific Coastal Plain across Mexico, Guatemala, Honduras, El Salvador, Nicaragua, and Costa Rica to Panama. Abundant geothermal features—hot springs, fumaroles, and boiling mud pots—are associated with these volcanoes. Some Central American countries have hydroelectric resources that help satisfy national energy demands. Still, considerable amounts of petroleum are imported to the region to fuel economies and to supply the energy demands of rapidly growing populations. Geothermal energy is a viable and developing alternative energy source to petroleum in these regions.

El Salvador and Nicaragua began generating electricity with geothermal energy in the mid-1970s, and, at present, geothermal energy provides about a fourth of the



Volcanic arcs and oceanic trenches partly encircling the Pacific Basin form the so-called *Ring of Fire*, a zone of frequent earthquakes and volcanic eruptions. The trenches are shown in blue-green. The volcanic island arcs, although not labelled, are parallel to, and always landward of, the trenches. For example, the island arc associated with the Aleutian Trench is represented by the long chain of volcanoes that make up the Aleutian Islands (modified from *http://pubs.usgs.gov/publications/text/fire.html*).

A geothermal well is vented to the atmosphere in 1999, for the occasion of inaugurating the first geothermal powerplant to come on line at Berlin, El Salvador. (Photograph by Wendell Duffield.)

electrical power needs of El Salvador. With increasingly favorable political and economic climates, these two countries probably could satisfy much more of their electrical demand from geothermal resources. In Costa Rica, about 55 megawatts of generating capacity came on line at Miravalles in 1994. Subsequent exploration and development at Miravalles have boosted the total generating capacity to nearly 145 megawatts, thus providing about 25 percent of that nation's electricity. Other promising geothermal-resource areas are presently being explored in Costa Rica.

Guatemala has installed about 28 megawatts of geothermal electricity capacity at Zunil, and additional areas are under exploration and development. With an abundant hydroelectric option, the Guatemalan Government could blend hydropower and geothermal in a way that reduces and minimizes the proportion of national demand now satisfied by imported petroleum and other conventional energy sources.

Honduras has little Pacific Ocean coastline and therefore includes little of the Ring of Fire. Nonetheless, several geothermal prospects have been identified in Honduras, and some of these are hot enough to produce electricity. For example, wells drilled during the mid-1980s at Platanares revealed a hydrothermal system at 165°C, a temperature sufficient to generate electricity. Additional drilling at this and other locations is needed to better characterize the geothermal resources of that nation.

Mexico has sufficient petroleum resources to export part of its annual production. Yet, in spite of such energy abundance, Mexico also supports a vigorous geothermal program. At somewhat more than 850 megawatts of installed capacity, Mexico is the world's third leading producer of geothermal electricity, some of which is sold to the United States across the border with southern California.

Thus, in several developing countries around the Ring of Fire, the use of geothermal energy is enhancing social as well as economic stability by reducing reliance on costly imported petroleum and coal.

Geothermal Environments and Energy Potential

Thermal energy is contained in a broad range of geothermal environments, and these commonly are classified by temperature and amount of fluid—water and (or) steam—available for carrying the energy to the Earth's surface. The magma environment is the highest temperature and a relatively water-poor part of this classification. Magmas range in temperature from about 650 to 1,300°C, depending on chemical composition. For comparison, common steel melts at about 1,500°C. Even the most water-rich magmas contain no more than a few weight percent of water, an amount insufficient and unavailable for geothermal use. These bodies of magma in the crust are termed "dry" and are the ultimate sources of heat for most other geothermal environments.

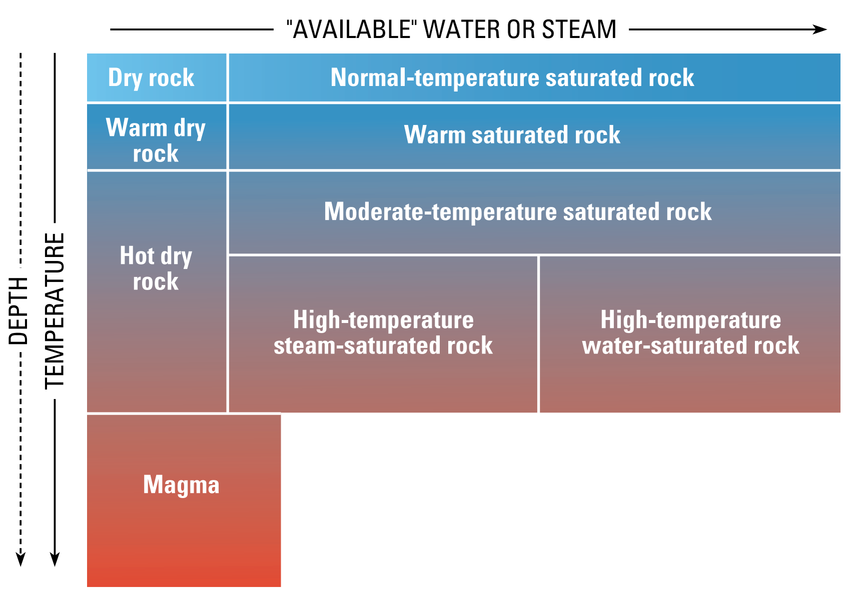
With decreasing temperature, the magma environment grades into what is called the hot-dry-rock environment. This is characterized by hot, solid rock that contains little or no available water because it has few pore spaces or fractures to store (the open space within a rock is called porosity) and transmit water (the capacity of a porous rock to transmit fluid is called its permeability). With the increasing presence of water, the hot-dry-rock environment gives way to a broad category of fluid-saturated rocks with variable porosity, permeability, and temperature. Within this category are relatively high-temperature rock, saturated either with steam or liquid water or a mixture of both, and rocks saturated only with water at increasingly lower temperatures. Geothermal environments through which available water circulates freely are called hydrothermal-convection, or simply, hydrothermal systems.

In nature, the various geothermal-energy environments commonly occur in close proximity, separated by boundaries that can be either relatively abrupt or gradual. For example, a body of magma in the Earth's crust is enveloped by hot, solid rock whose temperature decreases outward from the magma. With or without an associated body of magma, hot dry rock and fluid-saturated, high-temperature rock environments generally coexist within a well-defined, anomalously hot part of the Earth's crust, the distinction between them being in the amount of available fluid and permeability. In contrast, moderate- to normal-temperature hydrothermal systems may occur in isolation, if circulating water is heated solely by flowing through warm crustal rocks, without input from an adjacent, high-temperature magmatic heat source.

Determining whether or not heat can be extracted from a particular geothermal environment is critically dependent on depth. The pertinent question is whether the geothermal target is within economically drillable depths, roughly 4 kilometers or less with current technology. Each of the geothermal environments can occur over a range of depths, depending upon the geologic characteristics of a given geographic site. For example, most magma bodies in the Earth's crust are estimated to lie between the depths of 5 and 10 kilometers, although some bodies of molten rock pond in craters at the Earth's surface during volcanic eruptions and cool and solidify there under their own thin but growing crust. Exploitable geothermal energy in hydrothermal systems with temperatures around 250°C may be discovered at depths from one to several kilometers, depending upon the local geothermal gradient and the vigor of upward flow of hot fluids. For optimum exploitation, a major challenge is to locate geothermal environments of high temperature at shallow depth.

Hydrothermal Systems

Geothermal potential also is highly dependent on rock porosity and permeability. For a given reservoir temperature, the greater the porosity and permeability of a hydrothermal system, the greater its production of available water and thus energy yield. With current and foreseeable technologies, the hydrothermal environment is the only commercially exploitable form of geothermal energy for generating electricity. New



Different types of geothermal environments in the Earth's upper crust. Generally, temperature increases with depth, but the depth line is dashed to indicate that the rate of temperature increase varies within the crust. "Available" refers to water and steam in rocks that can be tapped by a well and produced at the Earth's surface. High- and moderate-temperature rocks with considerable available water and (or) steam are the only geothermal environments that can currently be developed to generate electricity.

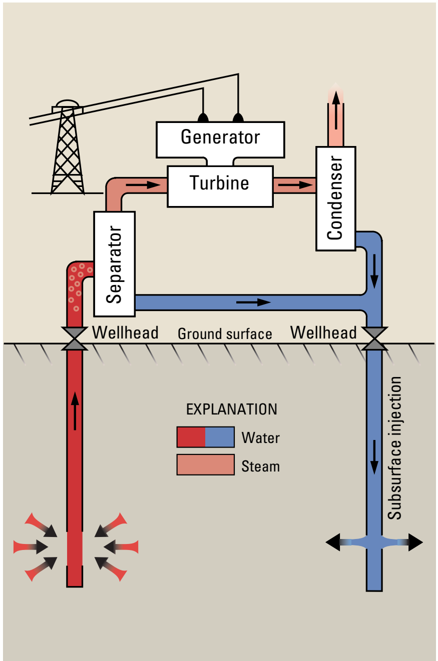


Diagram showing how electricity is generated from a hot-water hydrothermal system. The part of the hydrothermal water that flashes to steam is separated and used to drive a turbine generator. Wastewater from separator and condenser is injected back into the subsurface to help extend the useful life of the hydrothermal system.

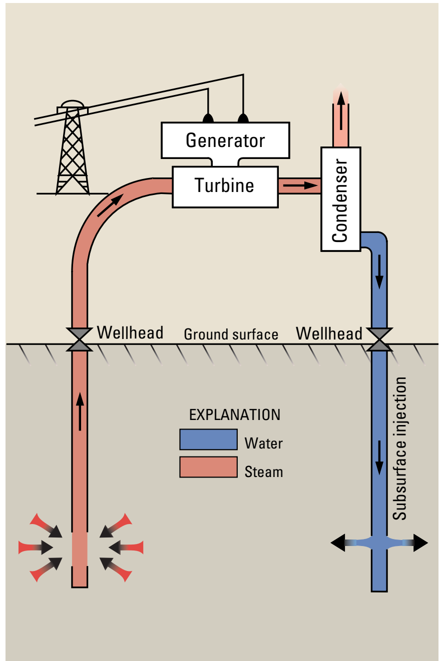


Diagram showing how electricity is generated from a vapor-dominated hydrothermal system. Steam is used directly from wells to drive a turbine generator. Wastewater from the condenser is injected back into the subsurface to help extend the useful life of the hydrothermal system.

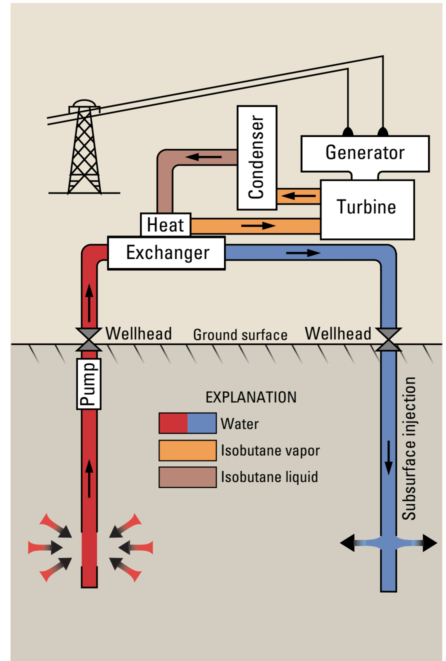


Diagram showing how electricity is generated from a moderate-temperature hydrothermal system using a "binary" system. The geothermal water is used to boil a second fluid (isobutane in this example) whose vapor then drives a turbine generator. The wastewater is injected back into the subsurface to help extend the useful life of the hydrothermal system

technologies must be developed to extract the thermal energy associated with the dry geothermal environments.

Electrical-Grade Systems: Power Generation

As the name implies, an electrical-grade hydrothermal system is one that can generate electricity by means of driving a turbine with geothermal fluids. At present, only high- and moderate-temperature hydrothermal systems can be so used. The temperature that separates electrical-grade from cooler hydrothermal systems changes with technology, but it falls within the 100 to 150°C range. There are three types of electrical-grade hydrothermal systems: hot-water, vapor-dominated, and moderate-temperature water (binary) systems.

Hot-water hydrothermal systems of about 200°C or more are capable of producing steam at pressures sufficient to drive turbine generators. These systems are in porous and permeable rock saturated with water, which partly boils to steam when it rises up production wells. This steam is routed to a turbine generator to produce electricity. A prime example of a hot-water system is the geothermal field at Coso in south-central California.

Less commonly, the pore spaces of rocks of a high-temperature hydrothermal system are saturated with steam, rather than liquid water; such systems are called vapor-dominated. The origin of these systems requires a combination of a potent heat source and a restricted source of water recharge. In these situations, only steam is produced through the wells, and this steam can be routed directly into turbine generators. Because the vapor-dominated systems do not require the separation of steam from water, the energy they contain is relatively simple and efficient to harness; accordingly, such systems are most desirable for electrical power production. Like most highly sought after commodities, vapor-dominated systems are rare compared with their valuable but less-simple-to-develop counterparts, the hot-water systems. The largest vapor-dominated system developed in the world is at The Geysers in northern California.

Moderate-temperature hydrothermal systems are incapable of producing steam at high enough pressure to directly drive a turbine generator. They are, however, hot enough to produce a high-pressure vapor through heat transfer to a second "working" fluid, which in turn drives a turbine generator. The power-generation technique that transfers the geothermal heat to another fluid (for example, isobutane), whose boiling temperature is lower than that of water, is called a binary-cycle, or simply, a binary system. A binary system that produces geothermal electricity is in operation near Mammoth Lakes, east

Tapping the Geothermal Potential of the Great Basin

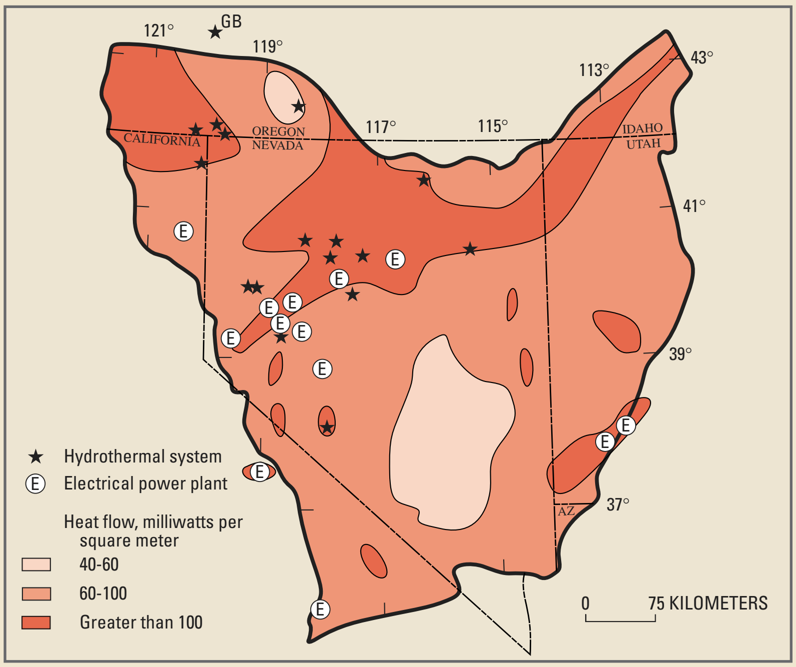
The Basin and Range physiographic province of the Western United States covers most of Nevada and parts of adjoining states. Between 50 and 10 million years ago, this region experienced considerable lateral stretching and thinning of the crust, processes still active in some areas. The northern part (also known as the Great Basin) of the Basin and Range is higher in elevation, has higher heat flow, and is more tectonically active than the southern part, which includes the Mojave and Sonoran Deserts.

The Great Basin contains the largest number of geothermal power plants in the United States, although most geothermal electrical production is at two sites elsewhere—The Geysers and Imperial Valley of California. Installed capacities of Great Basin plants range from 1 to 270 megawatts of electricity. Total installed capacity is 500 megawatts electric, about 17 percent of the national total. However, 500 megawatts electric is far less than the potential resource predicted (roughly 3,000 megawatts electric) by the U.S. Geological Survey (USGS) in the 1970s. Failure to reach this potential can be attributed in part to market forces and in part to overly optimistic assumptions about the character of Basin and Range geothermal reservoirs.

More than half of the geothermal electricity from the Great Basin is produced at Coso, in south-central California. The Coso area was long recognized as a potential geothermal resource, because it contains boiling mud pots and fumaroles within an area of many volcanoes whose little-eroded shapes indicate geologic youth. During the mid 1970s, a team of government and university scientists carried out a variety of field studies that suggested a potential geothermal resource of several hundred megawatts electric. Subsequent drilling has resulted in about 270 megawatts electric on line by 2000; exploration and development continue.

A geologically similar, though smaller, resource has been developed at a young volcanic area called Roosevelt Hot Springs, Utah, but most geothermal resources of the Great Basin are not associated with volcanoes. Typically, resources occur where groundwater circulates deeply along the major fault zones that bound blocks of the highly extended crust of the region. This groundwater simply is heated as it circulates downward within the zones of fractured and therefore permeable rock.

In 2000, the Great Basin became a major focus of the U.S. Department of Energy's (DOE) outreach initiative entitled "Geopowering the West" (*http://www.eren.doe.gov/geopoweringthewest/*). The Great Basin Center for Geothermal Energy, which is affiliated with the University of Nevada, Reno, and with the Desert Research Institute in Nevada, has been funded by DOE to help identify additional geothermal resources in the region. The USGS is a partner of DOE and university-based researchers in this effort.



Map of the Great Basin showing the distribution of heat flow, location of electrical powerplants, and identified hydrothermal systems

Steam is vented from the Dixie Valley Power Plant in Nevada during maintenance operations. The Stillwater Range forms a formidable backdrop. (Photograph by Dick Benoit.)

First geothermal well drilled at Coso geothermal area, south-central California, by private industry. It, together with a few other wells, has been developed to feed steam into the initial powerplant.

The Geysers, California—World's Largest Producer of Geothermal Electricity

The Geysers, a vapor-dominated hydrothermal system in northern California, has grown into the world's largest geothermal electrical development. At its peak in the late 1980s, about 2,100 megawatts of generating capacity were in operation. For comparison, 2,100 megawatts is roughly the equivalent of twice the electrical energy that can be generated by the turbines of Glen Canyon Dam, Arizona. Despite its name, there never were true geysers (periodically spouting hot springs) in the area; the surface features before drilling were restricted to weak steam vents, warm springs, and mudpots, whose unimpressive character belied the huge resource below. Indeed, The Geysers is an unusual geothermal field in that its wells produce nearly pure steam, with no accompanying water.

It took decades for people to recognize the huge energy potential of The Geysers. The surface geothermal features were known to settlers in the region by the mid-1800s, but it was not until 1924 that the first production wells were drilled and a few kilowatts of electrical power were generated for use at a local resort. During the 1950s, wells were drilled as deep as 300 meters, and the main steam reservoir was thus discovered. At that time, however, few people had any idea that the steam reservoir could be developed to the extent that it was by the 1980s. Accordingly, development proceeded cautiously, from the first powerplant of 12 megawatts electric in 1960 to a total installed capacity of 82 megawatts by 1970. Major growth during the 1970s brought the electrical capacity to 943 megawatts by 1980, and even faster growth during the 1980s pushed capacity to over 2,000 megawatts by the end of the decade. Twenty-six individual powerplants had been constructed by 1990, ranging from 12 to 119 megawatts. More than 600 wells had been drilled by 1994, some as deep as 3.2 kilometers, and capital investment by then was more than $4 billion.

Located in mountainous, sparsely inhabited terrain approximately 120 kilometers north of San Francisco, the production area at The Geysers geothermal field is distributed over nearly 80 square kilometers and is surrounded by an area 10 times as large in which the amount of heat flowing upward through the Earth's crust is anomalously high. The Geysers is located southwest of and adjacent to the Clear Lake volcanic field, whose most recent volcanic eruptions occurred only a few thousand years ago. Accordingly, it is likely that The Geysers geothermal field is sustained by hot or molten rock at depths of 5 to 10 kilometers.

As a result of the rapid development at The Geysers during the 1980s and some subsequent but slower development, there has been a decline in the rate of steam production (and electrical generation) due to loss of pressure in production wells. Steam production peaked in 1988, and has declined since then.

Most of the geothermal energy of this system remains intact, stored in hot, rocks that constitute the hydrothermal reservoir. A team of private industry and governmental agencies has devised a clever and effective solution to mitigate the decline of steam pressure in production wells and thereby extend the useful life of the resource. The solution also addresses how best to dispose of increasing volumes of wastewater from nearby communities. Simply put, the wastewater of treated sewage is injected underground through appropriately positioned wells. As it flows toward the intake zones of production wells, this wastewater is heated by contact with hot rocks. Production wells then tap the natural steam augmented by vaporized wastewater.

By 1997, a 50-kilometer-long pipeline began delivering about 30 million liters of wastewater a day for injection into the southern part of The Geysers geothermal field. This quickly resulted in the recovery of 75 megawatts of generating output that had been "lost" to the preinjection pressure decline.

This initial injection experiment is considered so successful that construction of a second pipeline is on schedule to deliver another 40 million liters a day by late 2003, to the central part of the field. Together, these two sources of "make-up" water will replace nearly all of the geothermal fluid being lost to electricity production. The injection program is expected to maintain total electrical output from The Geysers at about 1,000 megawatts for at least two more decades, and possibly much longer. The Geysers injection project shows how once-troublesome wastewater can produce electricity by one of the world's most Earth-friendly means. Industry, sanitation districts, the public, and the environment all win.

The Geysers near the city of Santa Rosa in northern California is the world's largest electricity-generating geothermal development. Most of the wells are about 3,000 meters deep, or somewhat less, and produce nearly pure steam. Pipes carry steam to turbine generators and associated condensers. Vapor plumes from condensers are visible here. Generators range from about 10 to 100 megawatt ratings; many are about 50 megawatts. Several steam wells feed into a single generator. After geothermal development, the land is available for other purposes, such as grazing. (Photograph by Julie Donnelly-Nolan, U.S. Geological Survey.)

Electricity From Moderate-Temperature Hydrothermal Systems

Many hydrothermal systems contain water too cool to directly power steam-driven turbine generators, yet hot enough to boil another fluid whose vapor can drive a turbine. This method of power production—called a binary system—utilizes the combined properties of geothermal water and a second so-called "working fluid" in the energy-conversion cycle. A geothermal development employing binary technology with isobutane as the working fluid is currently in operation near Mammoth Lakes, east of the Sierra Nevada in central California.

Three binary-cycle powerplants near Mammoth Lakes account for a total net generating capacity of 37 megawatts electric. The plants are located within Long Valley Caldera, which contains numerous hot springs and other surface features of an active hydrothermal system. Wells, each about 200 meters deep, supply the binary powerplants with 170°C water. Heat exchangers transfer thermal energy from this water to the isobutane, which vaporizes and drives the turbine generators, is then condensed and revaporized to repeat the turbine-driving cycle.

The geothermal water for this development is kept liquid using pumps to maintain appropriate pressure and is injected through wells back into the subsurface reservoir once heat has been transferred to the isobutane. This injection avoids problems, such as chemical precipitation, often associated with boiling of geothermal water, and it minimizes decline in reservoir pressure while maximizing recovery of thermal energy stored in rocks of the reservoir. A flow rate of about 1,000 kilograms per second of geothermal water from the production wells is required for maximum powerplant output. In general, binary-cycle powerplants can produce electricity profitably from geothermal water at temperatures as low as 100°C.

The geothermal power plants near Mammoth Lakes are built on both private and public lands. A portion of the revenue generated from these plants is returned through taxes and royalties to local, State, and Federal agencies to offset costs incurred in permitting and regulating their operation. The geothermal development is in an environmentally sensitive region that is a popular year-round resort. A program designed to monitor the effects of development on the local environment has been successfully implemented through a cooperative effort among the private developer, various regulatory agencies, and the U.S. Geological Survey.

Europe has many hydrothermal systems that could be harnessed to generate electricity with binary technology. An engineering-economic evaluation of one of these systems is currently underway by personnel from GeoForschungZentrum in Potsdam, Germany.

Binary-cycle geothermal powerplants near Mammoth Lakes, California. Mammoth Mountain in background on right. (Photograph by Edward Evans.)

of the Sierra Nevada in central California. By taking advantage of the more widespread distribution of moderate-temperature geothermal water, binary systems can add significantly to the overall contribution to geothermally generated electricity.

As of the end of 2002, geothermally powered generating capacity was about 2,000 megawatts electric in the United States and 9,000 megawatts electric worldwide.

Warm-Water Systems: Direct Use

Before the development of high-temperature drilling and well-completion technology, geothermal resources were limited to nonelectrical (that is, direct-use) applications. Thermal water too cool to produce electricity can still furnish energy for direct uses that range from heating swimming pools and spas, to heating soil for enhanced crop production at cool-climate latitudes, to heating buildings. The total capacity for direct use in 2000 amounted to about 600 megawatts thermal nationwide, substituting annually for the equivalent energy from 1.6 million barrels of petroleum. Worldwide, comparable figures are 11,300 megawatts thermal and 20.5 million barrels of petroleum. Low-temperature geothermal water is a relatively low-grade "fuel" that generally cannot be transported far without considerable thermal-energy loss, unless piping is extremely well-insulated and rate of flow through the piping is rapid. Yet, much of the world geothermal energy supply is consumed for direct-use applications. Warm-water systems—the most widely distributed of the hydrothermal systems—can locally complement or supplant conventional energy sources.

Extensive development of the warm-water systems, most commonly found in volcanic areas but also in a few nonvolcanic areas, can significantly improve the energy balance of a nation. For example, the use of geothermal water for space heating and other direct-use applications in Iceland substantially benefits the economy of that nation. Similarly, people living in Klamath Falls, Oregon, and Boise, Idaho, have used geothermal water to heat homes and offices for nearly a century, though on a smaller scale than in Iceland.

Great potential exists for additional direct use of geothermal energy in the Western United States. It might be advantageous for industry and municipalities to invest in installation (particularly retrofit) costs if energy prices stay at or near their current levels. To date, only 18 communities in the Western United States have geothermal district heating systems, whereas more than 270 communities have geothermal reservoirs suitable for the development of such systems.

Geopressured Systems

A type of hydrothermal environment whose hot water is almost completely sealed from exchange with surrounding rocks is called a geopressured system. This type of system typically forms in a basin that is being rapidly filled with sediment, rather than in a volcanic area.

Geopressure refers to the hydrothermal water being at higher-than-normal pressure for its depth (that is, these systems are overpressured). Such excess pressure builds in the pore water of sedimentary rocks when the rate at which pore water is squeezed from these rocks cannot keep pace with the rate of accumulation of the overlying sediment. As a result, geopressured systems also contain some mechanical energy, stemming from the fluid overpressure, in addition to the thermal energy of the geothermal water. Moreover, these systems also contain potential for combustion energy, because considerable methane gas (otherwise known as natural gas) is commonly dissolved in the geothermal water. The bulk of the thermal energy of geopressured systems is accounted for by roughly equal contributions from the temperature of the water and the dissolved methane. During the 1970s and early 1980s, the Texas-Louisiana Gulf Coast served as a natural laboratory for offshore studies of geopressured systems sponsored by the U.S. Department of Energy (DOE). Presently, however, the economics of exploiting the geopressured environment are not favorable, and industry has shown no interest in following up the DOE studies.

Normal-temperature reservoirs

Though not associated with volcanism and related magma systems for their thermal energy, shallow geothermal reservoirs of normal-geothermal gradient are included for the sake of completeness. This type of reservoir consists of ordinary near-surface rock and soil, ranging from dry to water saturated. The term "geoexchange" is commonly used to describe the process of tapping this source of thermal energy. See "Geothermal Heat Pumps" for a detailed discussion.

"Dry" Geothermal Environments

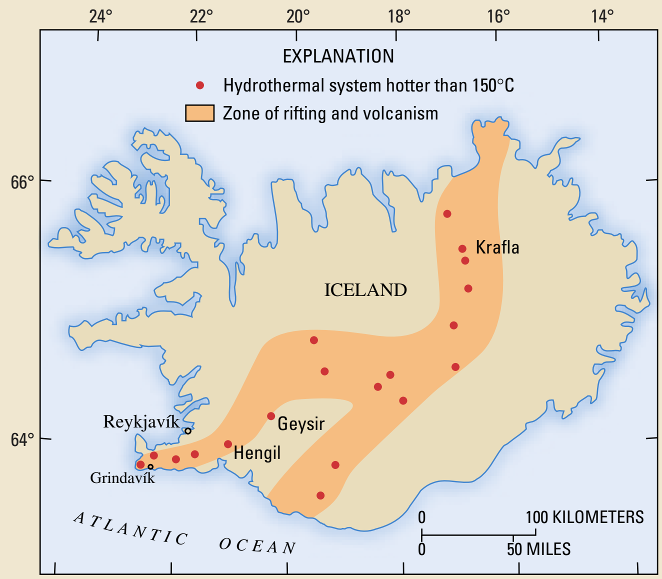
With current technology, the abundant thermal energy in high-temperature geothermal environments with little or no available water or with insufficient permeability for well production—hot dry rock and magma—cannot be tapped, but these environments are the focus of research to explore the feasibility of harnessing their energy. In terms of temperature, magma has the highest geothermal energy potential known. Though of lower temperature, hot dry rock is present in most drillable parts of the Earth's crust; it may be able to contribute to energy needs of broad geographic areas, if the currently experimental techniques of energy extraction are improved to a commercially competitive status. In contrast to the widespread potential of hot dry rock, energy from magma could be obtained at only a few sites. Nonetheless, if significant technological problems are overcome, a large amount of energy could be extracted from these few sites because of the high temperature of magma. See "Mining the Earth's Heat" and "Enhanced Geothermal Systems" for further discussion.

Geothermal Space Heating—A Boon to Iceland's Economy

One of the earliest and simplest applications of geothermal energy was to use naturally hot water to heat space. This still is the most common direct-use application of the Earth's heat. Space heating with geothermal water in Iceland has a significant positive impact on that nation's economy. Somewhat more than 45 percent of the country's primary energy use comes from geothermal sources. Hydropower provides nearly 17 percent, whereas oil and coal account for the balance.

Situated astride one of Earth's globe-girdling belts of active volcanoes, Iceland has abundant geothermal resources of both electrical and nonelectrical grade. The country also has abundant surface-water resources, and a bit more than 80 percent of the nation's electricity is generated from hydropower. However, 87 percent of all buildings are heated with geothermal water. The geothermal water (or fresh surface water heated with geothermal water through a heat exchanger) for space heating in Reykjavík, Iceland's capital, is piped as far as 25 kilometers from well fields before being routed to radiators in buildings. Very little thermal energy is lost in transit because a high rate of flow is maintained through well-insulated pipes.

Typically, the water delivered to homes and other buildings is of a quality sufficient for other direct uses (for example, bathing and food preparation) in addition to space heating and therefore is also piped to taps. The size of space-heating developments varies from large enough to serve all of Reykjavík (population of about 145,000, which is about 40 percent of the country's population) to appropriately small enough for a single-family residence in a rural setting. Geothermal water also is used in Iceland to heat greenhouses, so that flowers and vegetables can be grown year round.



Iceland straddles an irregular boundary between two of the Earth's lithospheric plates that are moving apart. The country literally grows—by this plate motion (rifting)—in a roughly east-west direction at an average rate of about 12 centimeters per year. The plate boundary is the locus of many earthquakes, active volcanoes, and associated geothermal systems. Because the entire country consists of geologically young volcanic rocks, warm water can be encountered in holes drilled almost anywhere.

Aerial view of the zone where Iceland is spreading (rifting) apart. Linear ridges and cliffs in foreground mark traces of fractures that form during rifting. Plumes of steam are from geothermal wells at Hengil.

Eruption of a thermal pool, whose Icelandic name "geysir" (spelled geyser elsewhere) is now used worldwide for such geothermal features. Geothermal water of the Geysir area is used to heat greenhouses for growing vegetables. With the aid of artificial lighting in winter, such greenhouses produce vegetables year round. (Copyrighted photograph by Barbara Decker, Double Decker Press.)

Interior of rotating restaurant on top of hot-water storage tanks in Reykjavík, Iceland. (Photograph by Gudmundur E. Sigvaldason, Nordic Volcanological Institute, Reykjavík, Iceland.)

Exterior of rotating restaurant on top of hot-water storage tanks in Reykjavík, Iceland. (Photograph by Gudmundur E. Sigvaldason, Nordic Volcanological Institute, Reykjavík, Iceland.)

Direct-Use Geothermal Applications—Paris, France, and Klamath Falls, Oregon

Geothermal heat can be the dominant source of energy for direct-use applications—such as space heating and industrial processing—as in Iceland, or it can play a smaller scale but important role. For example, in the region around Paris and within the Aquitaine Basin of southwestern France, some 200,000 apartment-housing units are heated by 60 to 80°C water obtained from geothermal wells about 1.5 to 2 kilometers deep. This geothermal water also heats water for other domestic uses. Once its useful thermal energy has been extracted, the relatively cool geothermal water is pumped back underground where it is reheated by contact with deep rocks. These heating systems displace the consumption of about 170,000 tons of oil, whose burning would add nearly 650,000 tons of carbon dioxide (CO_2) per year to the atmosphere.

Tubing carries geothermal water whose heat melts snow on this walkway in Klamath Falls, Oregon. (Photograph by Kevin Rafferty, Geo-Heat Center, Oregon Institute of Technology.)

The city of Klamath Falls, Oregon, is located in the southern part of the Cascade Range in an area of abundant near-surface geothermal water of temperatures appropriate for direct-use applications. For more than a century, citizens of this community have used this resource in innovative ways. Hundreds of residents have drilled shallow wells on their property to tap geothermal energy for home heating. Commonly, no hot water is pumped to the surface, but heat is instead extracted by circulating cold city water through a loop of pipe lowered into the well. This technique greatly extends the life of the geothermal resource, because no water is removed from the hydrothermal system. During winter, many residents circulate geothermally heated water through pipes embedded in the concrete of driveways and sidewalks to melt the abundant snow that Klamath Falls usually receives.

A large-scale direct-use system provides heat for several government and commercial buildings in the downtown area of Klamath Falls, including the Oregon Institute of Technology (OIT). Geothermal water also is used by local industry in greenhouses, at fish farms, and by dairies. The Geo-Heat Center at OIT leads the Nation in research and development related to direct uses of geothermal water (an informative web site is available at *http://geoheat.oit.edu*).

A geothermally heated greenhouse is one of many industrial applications of low- to moderate-temperature geothermal water in and near Klamath Falls, Oregon. (Photograph by Kevin Rafferty, Geo-Heat Center, Oregon Institute of Technology.)

Geothermal Heat Pumps

Geothermal heat pumps can be used for heating and cooling buildings virtually anywhere. Though initial installations costs exceed those for conventional heating and cooling systems, monthly energy bills are always lower. Thus, within a few years, cumulative energy savings equal the extra up-front cost of installation. Thereafter, heating and cooling costs are less than those associated with conventional systems.

A heat pump is simply a machine that causes thermal energy to flow up temperature, that is, opposite the direction it would flow naturally without some intervention (see accompanying sketches). Thus, a heat pump is commonly used for space heating and cooling, when outside ambient air temperature is uncomfortably cold or hot, respectively. The cooling and heating functions require the input of "extra" work (usually electrical energy) in order to force heat to flow upstream, and the greater the "lift," or difference in temperature between the interior of a building and the outside, the more work is needed to accomplish the function. A geothermal heat pump increases the efficiency of the heating and cooling functions by substantially decreasing the thermal lift.

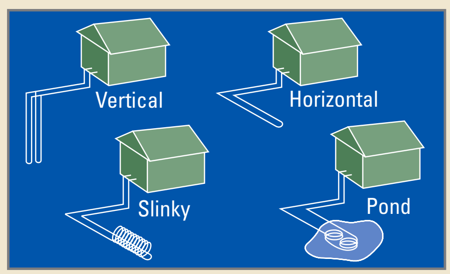
Because rocks and soils are good insulators, they respond little to wide daily temperature fluctuations and instead maintain a nearly constant temperature that reflects the mean temperature averaged over many years. Thus, at latitudes and elevations where most people live, the temperature of rocks and soil only a few meters beneath the surface typically stays within the range of 5 to 10°C.

For purposes of discussion, consider the functioning of a conventional air-source heat pump in a single-family residence, a system that exchanges thermal energy between air indoors and outdoors. Whereas such a heat pump must remove heat from cold outside air in the winter and deliver heat to hot outside air in the summer, a geothermal heat pump exchanges heat with a medium that remains at about 8°C throughout the year. As a result, the geothermal-based unit is almost always pumping heat over a temperature lift much smaller than that for an air-source unit, leading to higher efficiency through less "extra" energy needed to accomplish the lift.

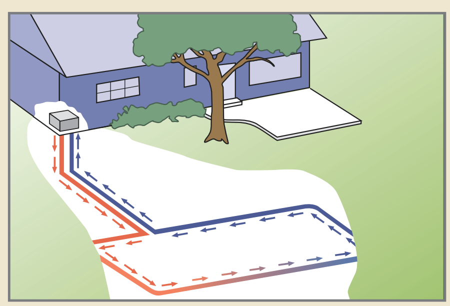
Some consumer resistance to geothermal heat pumps exists because initial purchase-and-installation cost is greater than that for an air-source system. The additional cost comes mostly from the need to bury piping through which fluid (water or antifreeze) is circulated to exchange heat with the ground or by drilling a shallow well to use ground water as the heat source/sink. Additional cost varies with the capacity and subsurface design of a given system. Experience to date indicates that the extra expense can be amortized in as little as 3 or 4 years for some systems. Other systems carry a longer pay-off period, but eventually all geothermal heat pumps provide savings that accrue as lower-than-normal utility bills.

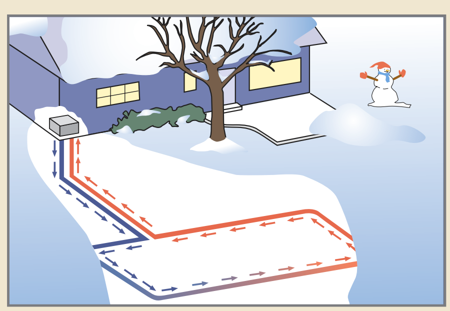
Heat pumps provide significant energy savings, more than 75 percent as compared to electric baseboard heating and between 30 and 60 percent relative to other methods of heating and cooling. Many utilities, particularly in the Eastern United States, have subsidized the installation of geothermal heat pumps, also known as geoexchange systems, to help reduce peak demand for electric power. The lower electrical usage associated with the widespread use of geothermal heat pumps has allowed utilities to avoid or postpone construction of new power plants in areas where suitable land and transmission facilities are very difficult to acquire.

Worldwide, there are currently more than a half million geothermal heat pumps installed, for a total thermal output of over 7,000 megawatts. The United States accounts for most of these developments, with roughly 350,000 units whose combined output is about 5,000 megawatts.



Configurations of heat exchange piping either underground or underwater for geothermal heat pumps.





Heat-flow directions are reversed between summer and winter. Heat is collected from the building and transferred to the ground in summer. In winter heat is collected from underground and transferred to the building.

"Mining" the Earth's Heat

To date, only those hydrothermal systems with a sufficiently high temperature and permeable water-saturated rock have been developed. However, systems having both these characteristics are not widespread. Yet, rocks with temperatures high enough for direct-use applications, or possibly for generation of electricity, are present everywhere at drillable depths, whether or not they are permeable and water saturated. Accordingly, if current experimental techniques are perfected, the thermal energy could be "mined" from those vast areas of the Earth containing sufficiently hot rock but insufficient available water. Such regions potentially represent a huge inventory of geothermal energy. The spectrum of potential geothermal resources ranges from those presently being exploited, through those marginal systems that can be enhanced with appropriate technologies, to those that are devoid of permeability.

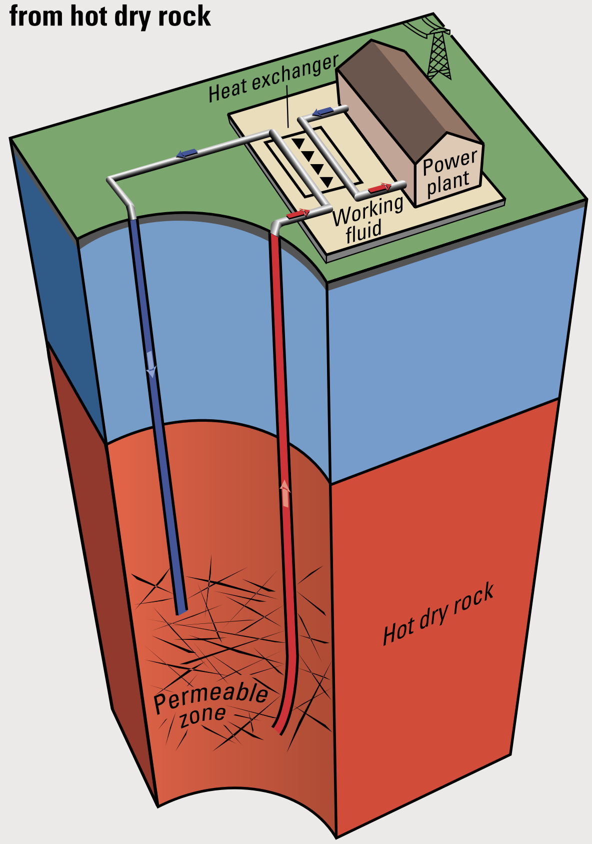
Hot dry rock

Research has been conducted at several locations worldwide, and the technical feasibility of mining heat from high-temperature, water-poor rocks has been demonstrated; however, the costs of doing so are not economically competitive.

For completely impermeable rocks, this technology has been dubbed hot-dry-rock (HDR) to emphasize the fact that these potential geothermal resources are either dry or too impermeable to transmit contained water at useful rates. Necessary permeability can be, and has been, created by adapting methods used in the petroleum industry to enhance the recovery of oil and gas.

The initial HDR experiment was conducted by Los Alamos National Laboratory at Fenton Hill, on the western margin of the Valles Caldera in New Mexico. A small hydrothermal reservoir was created by pumping water down a borehole at pressure high enough to fracture the surrounding rock. These new fractures then allowed water to flow through hot rock to a second, nearby, well, thus creating a continuous loop of fluid flow, which was maintained for nearly 20 years. Much knowledge was gained from the experiment, but the project was terminated without demonstrating commercial viability. The primary problem was that high pumping pressure was required to maintain even a modest amount of water circulation.

Mining thermal energy from hot dry rock



Two wells are drilled into the rock, and a permeable zone (pattern near base of wells) is then created by hydraulic fracturing. Cold water (blue) is then pumped down one well, becomes heated as it flows through the permeable zone, and returns as hot water (red) through the second well. At the surface, thermal energy is extracted in a heat exchanger and transferred to a working fluid, then the cooled water begins another circulation cycle.

Similar projects are currently under way in Europe and Japan. These, however, are more properly called enhanced geothermal systems (EGS) rather than HDR, because they involve rocks with significant initial permeability. Fundamentally, the projects are attempting to enhance existing natural permeability enough to create economically competitive geothermal resources.

Magma

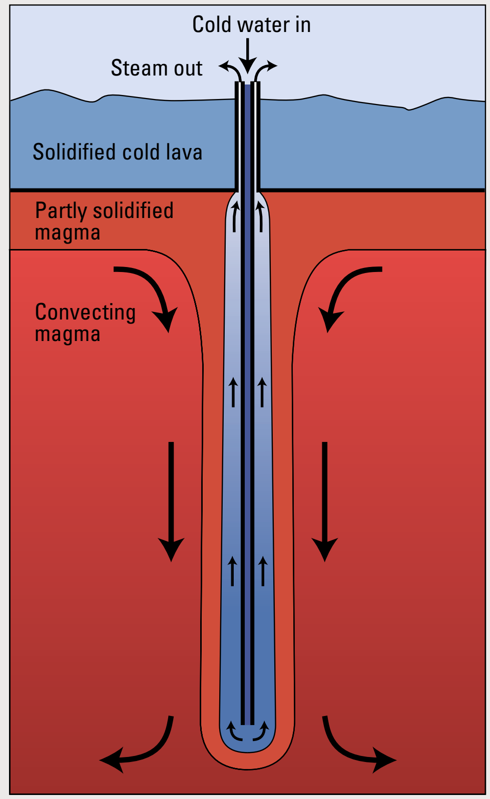
Rock materials in the Earth's crust that are molten—called magma—have the highest heat content, with temperatures that range from about 650 to 1,300°C. Applying terminology from the mining industry, magma is the purest form (or highest grade) of geothermal "ore." Magma is, in fact, the ultimate source of all high-temperature geothermal environments in the crust, including both wet (hydrothermal systems) and dry systems (hot dry rock).

The size, distribution, and frequency of volcanic eruptions provide direct evidence that magma is widespread within the crust. Much of this magma is within about 5 kilometers of the surface—depths easily reached using current drilling technology. The 15 cubic kilometers of magma erupted in 1912 to produce the volcanic deposits in The Valley of Ten Thousand Smokes, Alaska, was probably at drillable depth before eruption. Had it been possible to mine this magma's thermal energy before eruption, using heat exchangers lowered into the magma through drill holes, the output would have been the equivalent of about 7,000 megawatts of electricity for a minimum of 30 years—equal to the combined power of 7 hydropower stations the size of the one at Glen Canyon Dam, Arizona, producing at top capacity for 30 years.

The economic mining of useful energy from magma is not likely to be achieved any time soon, even though technical feasibility to do so has been examined theoretically and demonstrated both in the laboratory and in the field. The field experiments were carried out during the 1980s within the still-molten core of a lava lake that formed in Kīlauea Iki Crater, Hawai'i, in 1959. The long-term economics of mining heat from magma are unknown, at least in part because of uncertainties in the expectable life span of materials in contact with magma during the mining process. Finding materials that can withstand extremely high temperatures and the corrosive nature of magma is one of the main obstacles to overcome before magma-energy technology can be widely tested. Scientists at the Sandia National Laboratories, New Mexico, are leaders in the field of research and development devoted to solving these problems.

Another impediment to tapping the thermal energy contained in magma is in unambiguously locating the magma body before drilling begins. Although experts agree that many bodies of magma are within the drillable part of the Earth's crust, their exact locations can be verified only by drilling, and drilling is expensive. The possibility of the drill missing the target adds to the uncertainties related to longevity of materials in a hot corrosive environment. For the present, these uncertainties definitely make any attempt to mine the heat of magma a high-risk endeavor.

Mining thermal energy from magma



A pipe is drilled and (or) pushed into magma. Cold water is pumped down the pipe, becomes heated by magma in contact with pipe, and rises buoyantly back to the surface as steam. Magma that solidifies against the pipe forms an insulating layer that must somehow be sloughed off into the magma body to maximize rate at which heat is mined. This sort of system was successfully tested in a crusted-over pond of magma (lava lake) at Kīlauea Iki Crater of Kīlauea Volcano on the Island of Hawai'i in the 1980's.

Enhanced Geothermal Systems (EGS)

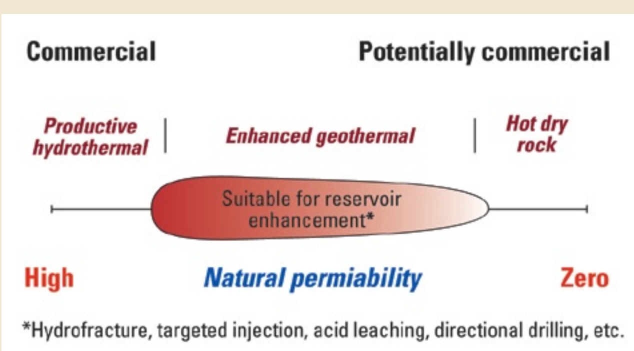
Many hydrothermal systems have been discovered and evaluated, only to be left undeveloped, usually because of insufficient permeability. Some systems of this sort, though not economic under present market conditions, could become competitive with increased permeability and (or) with increased efficiency for conversion of heat to electricity. Currently uneconomic zones around the margins of developed hydrothermal reservoirs also are targets for these types of enhancements.

As the hot dry rock (HDR) experiment in New Mexico (see section called "Mining the Earth's Heat") illustrated, HDR reservoirs are not economic under current technological and market conditions. Nonetheless, techniques developed specifically for creating reservoirs in HDR can be used to increase permeability in marginally productive natural hydrothermal systems. Thus, this technology is appropriate for a broad class of targets between the extremes of currently commercial and hot dry rock systems. This middle ground is defined as encompassing candidates for enhanced geothermal systems (EGS).

Stimulation of permeability in EGS can be undertaken in a variety of geologic environments. The technology includes fault and fracture analysis, hydraulic fracturing to increase permeability, directional drilling to intersect fractures that are oriented favorably, and injection of groundwater or wastewater at strategic positions to replenish fluids and to reverse pressure declines. Taken together, these remedial measures can extend the productivity and longevity of an existing hydrothermal reservoir, allow hitherto uneconomic reservoirs to be brought on line, or increase the size and output of existing reservoirs by allowing development of previously unproductive portions of the field.

Twilight at the drill site at Soultz sous Fôrets, France, northern Rhinegraben. (Photograph courtesy of BESTEC GmbH.)

The HDR projects currently being pursued in Europe (Soultz sous Fôrets) and, until recently, Japan (Hijiori, Ogachi) are more properly characterized as EGS projects in that they seek to increase the productivity of existing hydrothermal reservoirs rather than creating new ones from impermeable rock. The injection programs at The Geysers (California) and Dixie Valley (Nevada) are also good examples of EGS projects. Currently, the U.S. Department of Energy is cosponsoring several EGS projects in the western United States to provide additional geothermal resources.



Range of permeability within which enhanced geothermal productivity can be achieved.

Hot Springs "Remember" Their Deeper, Hotter Origins

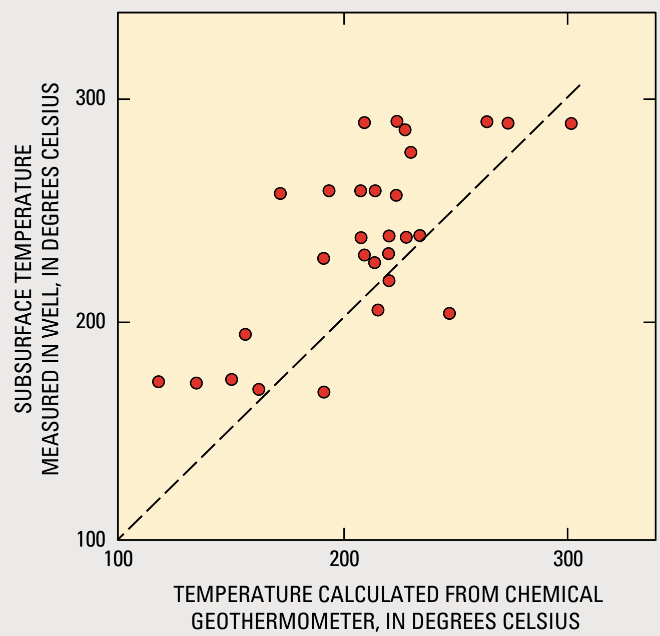
Hot water circulating in the Earth's crust dissolves some of the rock through which it flows. The amounts and proportions of dissolved constituents in the water are a direct function of temperature. Thus, if geothermal water rises quickly to the Earth's surface, its chemical composition does not change significantly and bears an imprint of the subsurface temperature. Field and laboratory studies show that this deeper, hotter temperature is commonly "remembered" by thermal waters of hot springs. Subsurface temperatures calculated from hot-spring-water chemistry have been confirmed by direct measurements made at the base of holes drilled into hydrothermal systems at many locations worldwide. The technique of determining subsurface temperature from the chemistry of hot-spring water is called "chemical geothermometry."

Quartz (SiO_2) is a common mineral in the Earth's crust and has almost ideal characteristics for chemical geothermometry. The solubility of quartz is strongly temperature dependent, dissolved quartz does not readily react with other common dissolved constituents, and dissolved quartz precipitates very slowly as temperature is lowered. The quartz geothermometer is especially useful in the range of about 150 to 240°C. If upflowing geothermal water mixes with cool shallow ground water, or partly boils in response to decreasing pressure, appropriate adjustments must be made to the calculated subsurface temperature.

Feldspars—the most common minerals in the Earth's crust—contribute the elements sodium, potassium, and calcium to geothermal waters, in ratios also dependent on temperature. An advantage of dealing with ratios of elements is that boiling or dilution by mixing with cool, shallow ground water changes the ratios little, if any. The ratio between the elements magnesium and lithium, which are also introduced into geothermal water from dissolution of rock, has also proved to be an accurate geothermometer.

Isotopes (atoms of the same chemical element but with different atomic weights) of individual elements also distribute themselves according to temperature. For example, virtually all hydrothermal waters contain dissolved sulfate, and isotopes of oxygen distribute themselves between the sulfate and its solvent, water, according to a temperature-dependent relationship that can also indicate the subsurface temperature of a hydrothermal system. In practice, scientists generally use a combination of geothermometers, rather than relying on any single one, to determine subsurface temperature from the chemical composition of hot-spring water. In so doing, uncertainties associated with results obtained using only one method may be reduced or resolved with reference to the results from other methods.

Chemical geothermometry is perhaps the most powerful tool of surface exploration for geothermal resources. If geothermometry suggests only low subsurface temperatures, the decision about whether or not to drill that initial expensive exploration well may be "no." For a young volcanic area such as the San Francisco Volcanic Field of northern Arizona, which has no hot springs, the lack of geothermometer temperatures may discourage drilling, in spite of several other positive indicators of a potential resource (see section called "Magma, Volcanoes, and Geothermal Energy").



Graph of temperatures measured in wells drilled into hydrothermal systems versus temperatures calculated from compositions of hot-spring water or steam, before drilling. Dashed line shows where points should plot if measured and calculated values agreed perfectly. Dots somewhat above this line show that calculated temperatures tend to slightly underestimate measured temperatures, but still are very useful in guiding exploration strategies.

Geothermal Energy and Environmental Impact

As with other types of energy resources, geothermal energy should be developed using methods that minimize environmental impacts. Compared with most other forms of power production, geothermal is environmentally benign. A typical geothermal plant using hot water and steam to generate electricity emits about 1 percent of the sulfur dioxide (SO_2), less than 1 percent of the nitrous oxides (NO_x), and 5 percent of the carbon dioxide (CO_2) emitted by a coal-fired plant of equal size. Airborne emissions from a binary geothermal plant are essentially nonexistent because geothermal gases are not released into the atmosphere. The experience gained in drilling and completing wells in a variety of geothermal environments, combined with regulatory conditions imposed by the permitting agencies, serves to minimize the risks of accidental releases of geothermal fluids.

Land areas required for geothermal developments involving power plants and wells vary with the local reservoir conditions and the desired power outputs. A well field to support a 100 megawatt geothermal development (for generating electricity) might require about 200 to 2,000 hectares. However, while supporting the powerplant, this land still can be used for other purposes, for example livestock grazing, once the powerplant and associated piping from wells are completed. As with any new power plant, whatever the type of fuel to be used, land-area requirements, visual and noise impacts, and risks of production-related accidents must be adequately addressed during the development phase of a geothermal project.

Although geothermal energy is sometimes referred to as a renewable energy resource, this term is somewhat misleading because the available hot water, steam, and heat in any given hydrothermal system can be withdrawn faster than they are replenished naturally (see section called "The Geysers—World's Largest Producer of Geothermal Electricity"). It is more accurate to consider geothermal energy as a sustainable resource, one whose usefulness can be prolonged or sustained by optimum production strategy and methods. Indeed, the concept of sustainable (versus renewable) production of geothermal resources is the current focus of intensive studies by scientists and other specialists. Major questions being addressed include: How many hundreds or thousands of years are required to replenish a hydrothermal system? What is the best method for replenishing and sustaining a system to increase its longevity?

In practice, choices must always be made between maximizing the rate of fluid withdrawal (energy production) for a short period of time versus sustaining a lower rate for a longer period of time. For example, a decline in steam pressure in wells at The Geysers, California, was a result of too-rapid development of this field to the level of 2,100 megawatts during the 1980s. Nonetheless, it is anticipated that production from The Geysers at the current rate of about 1,000 megawatts electric can be sustained for decades to come, now that injection has been increased by importing wastewater from nearby communities. Incremental development of any hydrothermal system, coupled with monitoring for possible production-induced hydrologic and chemical changes, is the best way to determine the optimum rate of production for maximizing the longevity of a hydrothermal system.

Another important issue is the disposal of cooled geothermal water left after heat extraction or steam separation during the energy-production cycle. In the earliest geothermal developments, such "waste" water was disposed of in surface ponds or rivers. Now, in almost every geothermal development worldwide, this water is injected through wells back into the subsurface. This now common practice not only minimizes the chance of contaminating surface waters, but it also provides replenishing water to help sustain a hydrothermal system, thereby increasing the total amount of heat that can be extracted over its productive life.

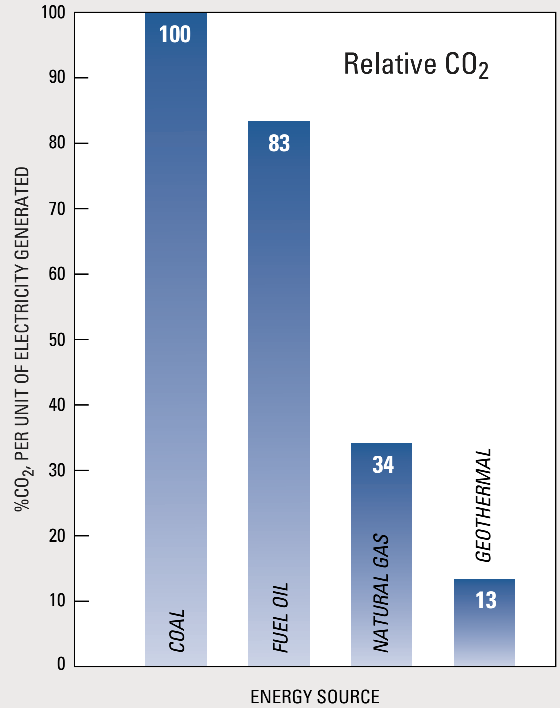
In areas with natural surface thermal features, such as hot springs and steam vents, subsurface depletion of geothermal fluids by production wells can change the rate of flow and vigor of these features, which may also be scenic and recreational attractions. Experience suggests that adverse effects can be minimized by proper siting of injection and production wells to maintain reservoir-fluid pressure at near preproduction levels. A program of continuous monitoring of hot-spring behavior and subsurface reservoir conditions is required to identify potential problems early enough to allow timely mitigation measures.

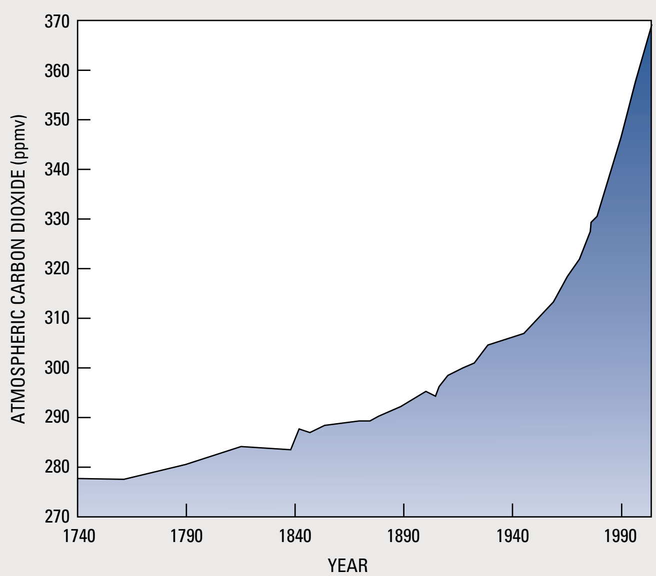
Geothermal Energy is Cleaner than Conventional Energy

Coal and fossil-fuel hydrocarbons are the principal sources of energy for the United States. Together, they account for about 95 percent of our Nation's energy consumption. Combustion of bituminous coal emits about 900 kilograms of carbon dioxide (CO_2) per megawatt-hour, and even the relatively clean-burning natural gas releases more than 300 kilograms per megawatt-hour under these conditions. In contrast, geothermally driven power plants are much cleaner, releasing about 120 kilograms per megawatt-hour. Binary geothermal power plants emit zero carbon dioxide, simply because geothermal fluids are never vented to the atmosphere. A similar contrast between geothermal and conventional fossil fuels exists for the emission of sulfurous gases.

Without dispute, geothermal energy is a clean source of electrical power. Moreover, once on line generating electricity, geothermal power plants are not only less polluting but also are remarkably reliable. On average, geothermal power plants are off line only about 5 percent of the time.

Carbon dioxide is a greenhouse gas, whose increasing abundance in the Earth's atmosphere may be one cause of global warming. The scientific community generally believes that long-term global warming is occurring. Debate continues, however, regarding its cause—whether it is simply part of long-term climatic cycles or whether it is manmade to a significant extent. Nonetheless, the data clearly show that the concentration of carbon dioxide in the atmosphere began to increase measurably with the world industrialization and rapid population growth that has occurred during the past 150 years. The rate of increase has accelerated greatly during the past 50 years. Combustion of fossil fuels is a major contributor to this buildup of carbon dioxide in the atmosphere. As scientists sort through the accumulating data and work to improve computer models that forecast long-term climate trends, using geothermal energy in place of fossil-fuel resources provides one environmentally friendly energy option.





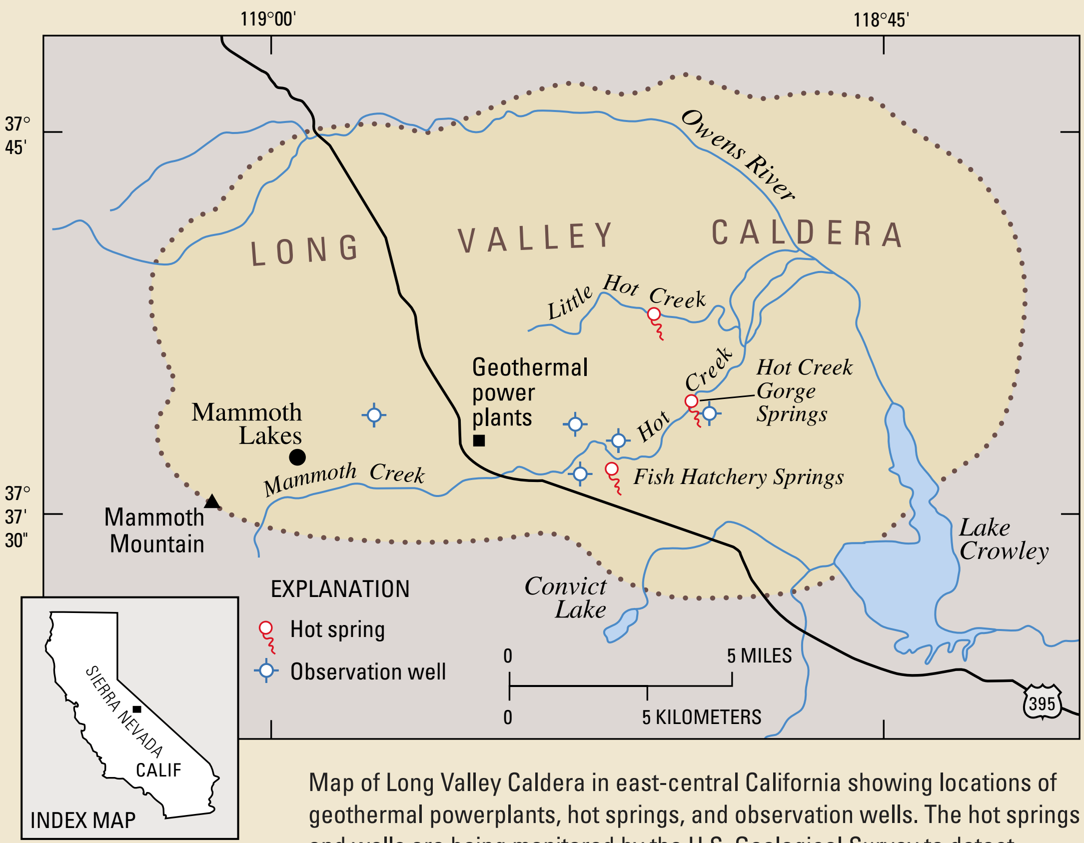
Amount of carbon dioxide in the atmosphere, in parts per million by volume, from 1740 to 2000. Data prior to 1958 are from analyses of gases trapped in Greenland ice cores. Post-1958 data were gathered at Mauna Loa Observatory on the Island of Hawai'i.

Long Valley Caldera—Monitoring Hydrologic Changes Caused by Geothermal Development

A geothermal feature at the Earth's surface has a natural life cycle—birth, maturation, and eventually death—and the geologic record contains many "fossil" geothermal systems. The life cycle of a hot spring is generally very long—lasting centuries to millennia—compared to the human life cycle. However, rapid geothermal change can be caused not only by powerful geologic events, such as earthquakes and landslides, but also by human intervention.

Hot water produced through geothermal wells will inevitably alter the natural subsurface conditions of a hydrothermal system. At the surface, a geothermal feature's response to such effects from nearby geothermal development may range from no measurable change to drying up, or possibly, to increased vigor. There are social and political reasons to avoid human-induced change to the natural condition, and considerable research is aimed at doing so through controlled and monitored development. Subsurface hydrothermal conditions can be monitored, enabling the early recognition of any human-induced change and the initiation of any needed mitigating measures. Such hydrologic monitoring is currently being conducted at the Long Valley Caldera in east-central California.

Active hot springs are common in the Long Valley Caldera region, where the most recent eruptions occurred about 250 years ago. Following surface exploration and test drilling during the 1970s and early 1980s, a geothermal binary powerplant was constructed there in 1985. Two more binary powerplants came on line in 1990, and additional geothermal exploration and development are ongoing. Moreover, the ski-resort town of Mammoth Lakes, within the caldera, has drilled several wells to evaluate producing geothermal fluids for direct-use applications. These geothermal-energy developments, combined with a growing need for cool ground water for municipal consumption,



Map of Long Valley Caldera in east-central California showing locations of geothermal powerplants, hot springs, and observation wells. The hot springs and wells are being monitored by the U.S. Geological Survey to detect hydrologic changes that may result from geothermal development.

highlight the greatly increased demands on the region's hydrologic resources and the need to balance the benefits of geothermal and other ground-water development with the long-standing recreational activities of the area. To address such issues, the Long Valley Hydrologic Advisory Committee (LVHAC) was formed in 1987; it is composed of members from private companies and government agencies.

A major purpose of the LVHAC is to oversee hydrologic monitoring focused on early detection of changes in hot springs and streams that might be induced by geothermal and other ground-water developments. In addition, the committee advises permitting agencies of significant hydrologic changes and may recommend mitigation actions as appropriate to minimize or perhaps reverse such changes. The advice and suggestions of the LVHAC are not legally binding, but they form the basis for regulatory decisions by permitting agencies, such as the U.S. Forest Service, the Bureau of Land Management, and the Mono County government. The U.S. Geological Survey is responsible for collecting and compiling baseline hydrologic data of the monitoring program and for furnishing this information to the committee on a quarterly basis.

Thermal springs are present in the central and eastern parts of Long Valley Caldera. Most important from an environmental-protection standpoint are the springs in Hot Creek Gorge and at the Hot Creek State Fish Hatchery. Monitoring at these and other springs includes continuous or periodic measurements of rate of water flow, temperature, and chemical composition; numerous wells in the region also allow the monitoring of pressure (or water level), temperature, and water chemistry. Similar monitoring data from the production and injection wells of the geothermal development area are collected and compiled by the powerplant operator (see, for example, *http://lvo.wr.usgs.gov/HydroStudies.html*).

The formation of the LVHAC facilitated approval of the current geothermal developments in the Long Valley Caldera by providing a forum for discussion of the key issues and concerns relative to potential adverse effects on thermal springs from pumping and injecting geothermal fluid. An important function of the committee is to ensure that economically reasonable, environmentally sound compromises can be made after consideration of the different concerns of various interest groups.

Boiling hot springs in Hot Creek Gorge, located within Long Valley Caldera, approximately 15 kilometers east of the town of Mammoth Lakes in east-central California.

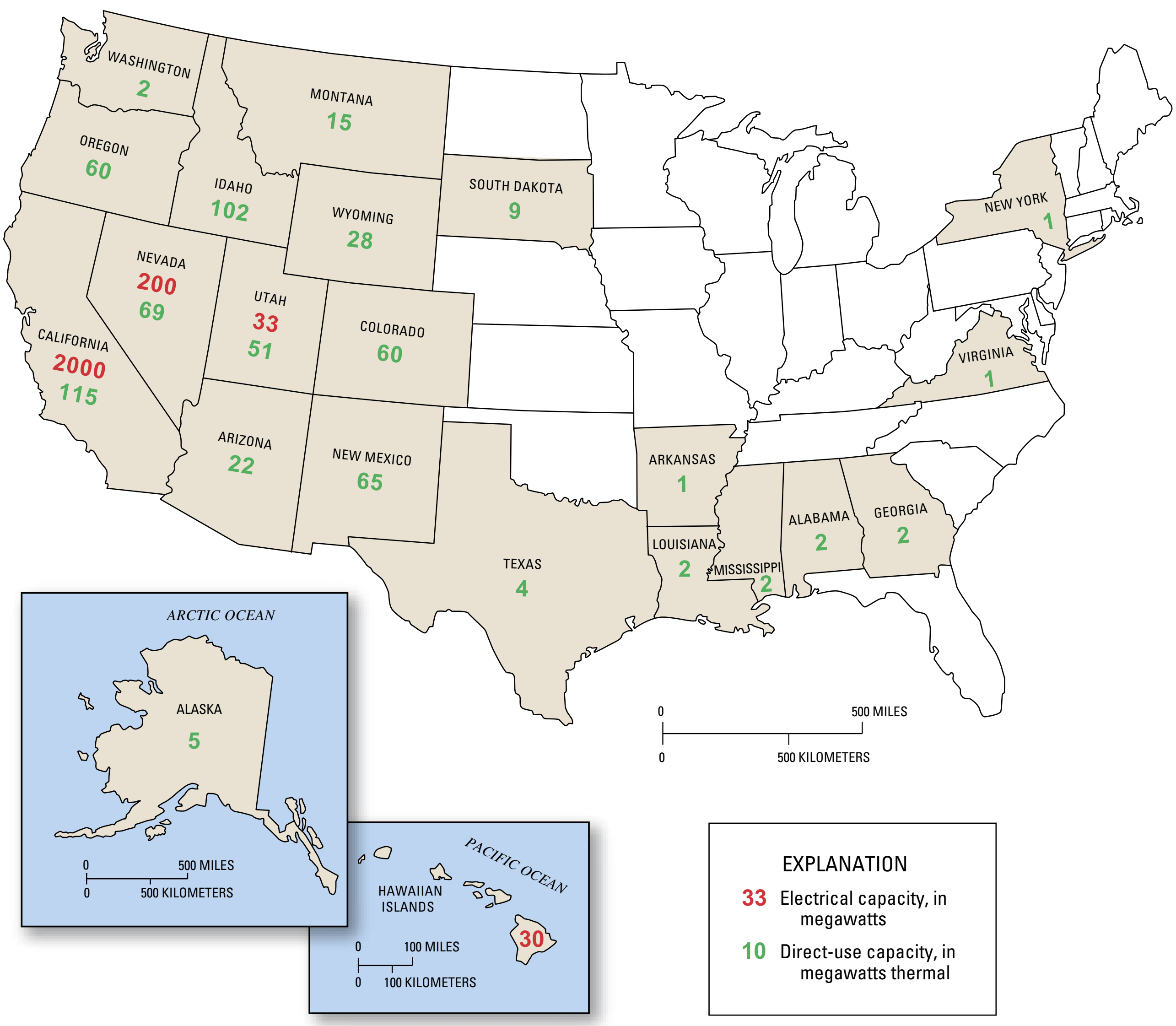
A Look Toward the Future

Given the uneven global distribution of natural energy resources and the fact that many experts foresee a near- to intermediate-term depletion of the most heavily used of these resources, alternative energy sources must be developed to meet future demand. Geothermal energy is a proven alternative, and technology for exploitation of its hydrothermal component is available and improving. For geothermal energy to satisfy more of the Nation's energy appetite during the 21st century, continued efforts are needed to support the following activities:

Supporting New Exploration

About 20 geothermal fields in the United States are currently being exploited to generate electricity. These include the steam field at The Geysers, California, and several high- and moderate-temperature hot-water fields in the Western United States. In addition, geothermal energy is being harnessed from hydrothermal systems at more than 1,300 sites for direct-use applications. All these developments share a common trait; they involve hydrothermal systems that were among the easiest to discover and commercially develop. We now need to discover other exploitable systems that are not obviously expressed at the surface.

For example, considerable promise may exist for the discovery of moderate- to high-temperature geothermal resources within the Basin and Range physiographic province, the Cascade Range, the Salton Trough, the Rio Grande Rift, and the northern part of the Great Plains physiographic province. The Basin and Range, in particular, is characterized by geologic conditions favorable for the occurrence of hydrothermal systems. Presently known high-temperature systems associated with young volcanic activity are concentrated along the mar-



Total capacities of electrical and nonelectrical geothermal developments in the United States as of 2000. (From Geo-Heat Center, Oregon Institute of Technology.)

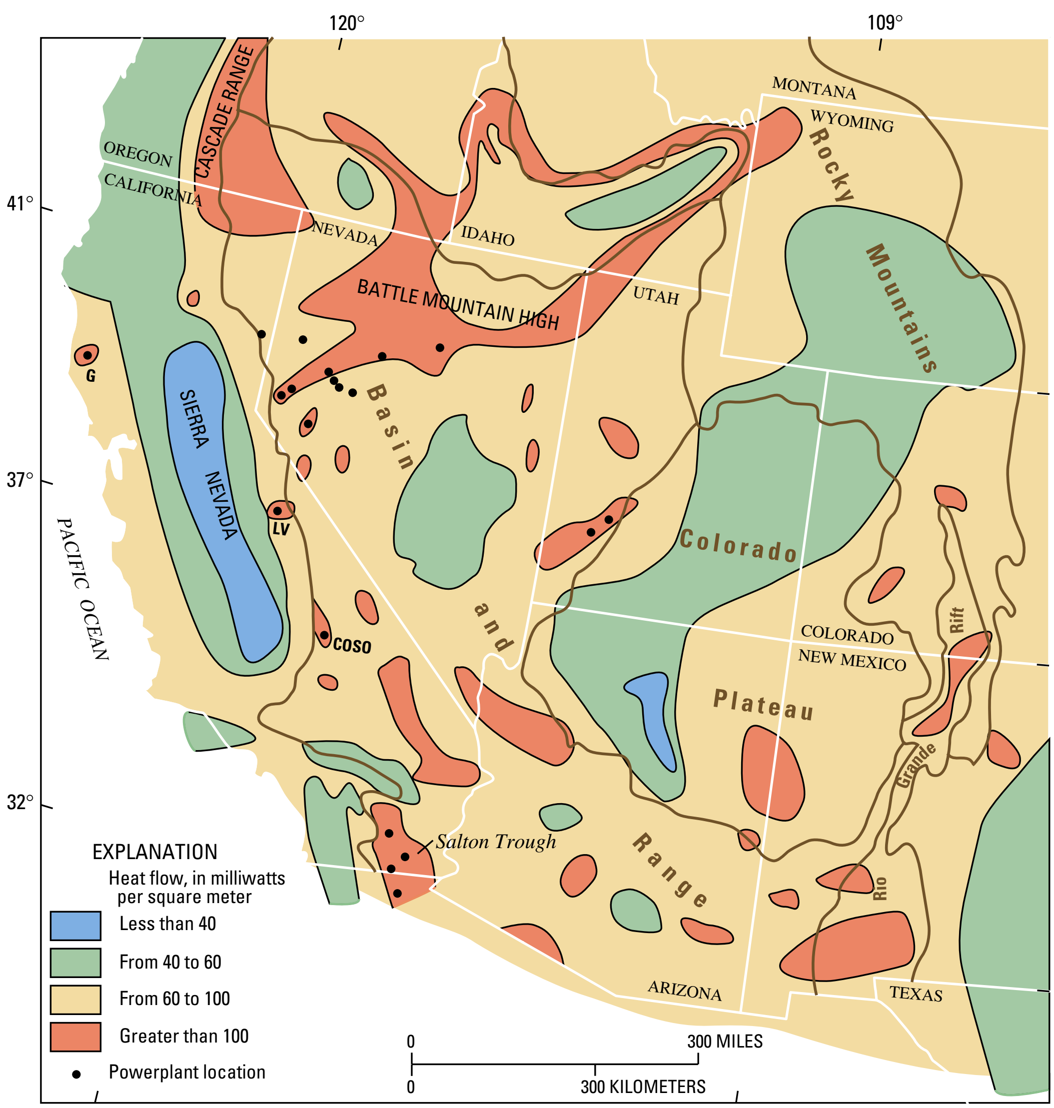
gins of this physiographic province—along its western margin in California, Nevada, and Arizona and along its eastern margin in Idaho and Utah. Other hydrothermal systems, not obviously expressed at the surface, could be present within the interior parts of the province. To date, only a few such systems have been developed. Discovery of additional geothermal systems within the Basin and Range Province would be enhanced by new geophysical studies and drilling at selected locations. Such work might be efficiently accomplished under the type of government-industry-coupled program that successfully produced a series of state geothermal-resource assessments during the 1970s and 1980s.

Another region that merits continued study is the Cascade Range in Washington, Oregon, and northern California. Hydrothermal systems have been identified and partially explored at Medicine Lake Highlands in California, Newberry Crater in Oregon, and at Mount Meager in British Columbia, Canada. Ongoing research by the U.S. Geological Survey (USGS) is focused on understanding the evolution of the Cascade volcanoes. Drilling of selected geothermal target areas would complement such studies.

Searching for Deeper Hydrothermal Systems

Because all hydrothermal systems with surface expression have been found and explored to some degree, an important line of research is to develop techniques and strategies to discover hidden systems at greater depths. This research requires deep drilling. Given the relatively high risk of such ventures, this work seems appropriate principally for the public sector, perhaps on a cost-sharing basis with the private sector.

Additional research into the origins of vapor-dominated systems is also needed, and target areas should include The Geysers, California, and Larderello, Italy—two areas where this uncommon but highly sought after geothermal environment exists. Current understanding of how these exceptionally high-grade steam systems originate and persist over geologic time is poor, despite the fact that these are the electrical-grade resource most easily developed. In addition, recent drilling at The Geysers and Larderello has revealed high-pressure, hot-water regimes adjacent to the developed steam zones. This exciting discovery invites an entirely new thrust for the study of deeper, higher pressure underpinnings (so-called root zones)

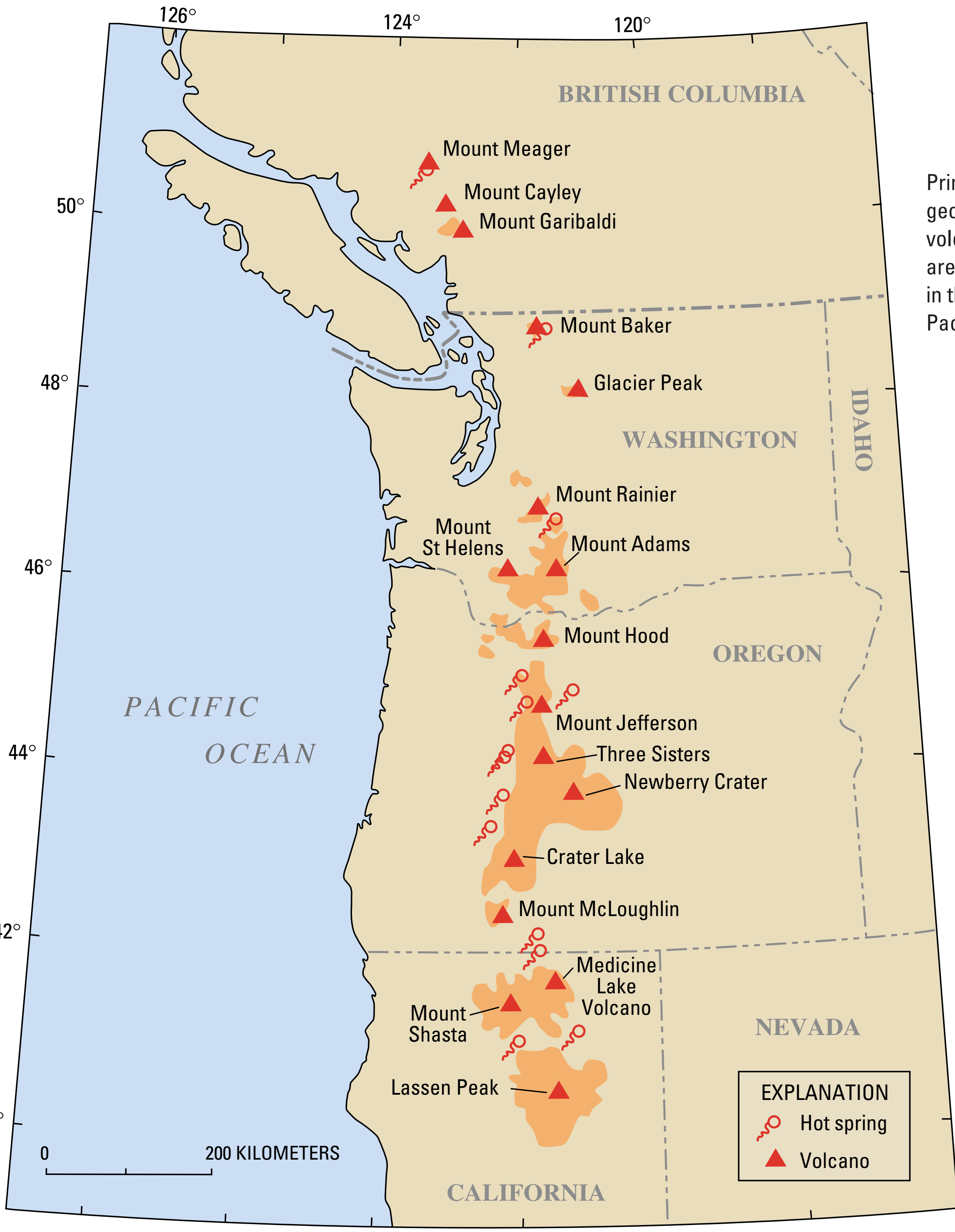


Map of physiographic provinces, other geographic features of geothermal interest, and heat flow in the southwestern United States. G, The Geysers; LV, Long Valley.

of hydrothermal systems. Overpressured, high-temperature hydrothermal environments may be common near magma bodies within the temperature range where the physical behavior of rocks changes from brittle (capable of fracture) to ductile (capable of flow). Research into the deeper parts of magmatic hydrothermal systems, in tandem with advances in the technologies for drilling deeper and at higher temperatures, could lead to the identification of substantially more high-grade geothermal resources for the United States and the world.

Developing Reservoir-Enhancement Technology

Many rocks at cost-effective drilling depths are hot enough to provide large amounts of potentially usable thermal energy, but they are not sufficiently permeable to form a natural hydrothermal reservoir (see Enhanced Geothermal Systems). In such cases, additional thermal energy can be recovered by increasing permeability. This can be accomplished by creating new fractures through injection of water at high



Principal volcanoes, geologically young volcanic rocks (orange areas), and hot springs in the Cascade Range, Pacific Northwest.

pressure. Potentially attractive targets for reservoir enhancement include all currently developed hydrothermal systems and others that have been considered uneconomic because of low permeability.

Tapping into the vast store of thermal energy in hot, low-permeability rock may release much more of the Earth's abundant natural heat to benefit humankind in the 21st century and beyond. First, however, further testing of reservoir-enhancement technologies must demonstrate the commercial viability of such heat extraction.

Geothermal Energy In Our Nation's Future

We face many uncertainties about future energy supplies in the United States and the world. Most of the energy currently used comes from fossil-fuel resources such as coal, oil, and gas. One certainty is that dramatically increasing world population and the continued spread of industrialization will result in increased energy demands both at home and abroad, attempts to conserve energy resources notwithstanding. Another certainty is that our traditional fossil-fuel resources are finite.

How can these increasing energy demands of the future be met in ways that are both environmentally sound and economically beneficial? Using current technology, geothermal energy can contribute as much as 10 percent to the Nation's energy supply, if all known resources are fully developed. Moreover, reasonably expectable advances in both exploration and resource-development technologies will allow us to tap into the huge storehouse of geothermal heat that is known to exist in the Earth's crust. An added benefit is that geothermal energy is far cleaner than any of the fossil fuels that now dominate our energy supply.

Scientific Drilling in Geothermal Systems

During the past three decades, shallow- to intermediate-depth research wells have been drilled in the Imperial Valley (the Salton Sea, California, Scientific Drilling Project), at the Inyo Domes, California, in the Valles Caldera, New Mexico, and in the Cascade Range of the Pacific Northwest. In addition, reconnaissance-style drilling to determine heat flow and hydrologic characteristics was completed over much of the Western United States. The U.S. Geological Survey (USGS) participated in most of these multidisciplinary, multiagency projects. Among the drilling projects with implications for geothermal resources are the U.S. Department of Energy's (DOE) Long Valley Caldera Exploratory Well (LVEW), California, the USGS Creede Caldera Project, Colorado, a corehole at Hilo, Hawai'i (funded by the National Science Foundation), and multiagency projects at The Geysers, California. Foreign drilling projects with geothermal applications include those at Soultz sous-Forêt (France), Iceland, Tyrniauz (Russia), and several projects in Japan (for example, Kakkonda). USGS personnel were involved in the planning of scientific experiments at each of these sites.

Drilling near the center of Long Valley Caldera was envisioned initially as a probe into a near-magmatic regime to test the hypothesis that molten rock was present at drillable depth, to assess the extent and composition of corrosive geothermal gases and fluids, and to test various drill-hole casing and heat-exchanger materials under natural near-magmatic conditions. However, changes in funding sources and associated priorities shifted the focus toward exploration of the hydrothermal resource beneath the central and western parts of the caldera. The third and final phase of drilling near the center of the caldera (LVEW) involved continuously coring from 2 to 3 kilometers depth. It was a pioneering effort, involving the first deployment of a "hybrid" coring system (mining-type coring equipment coupled with an oilfield type rig) developed by the U.S. scientific-drilling consortium DOSECC (Deep Observation and Sampling of the Earth's Continental Crust). It also featured a completely digital data-gathering facility and the first deployment of on-site science equipment by the Operational Support Group International Continental Scientific Drilling Program (IDDP). Despite many scientific "firsts" and successes, the LVEW failed to find evidence of a hydrothermal system in that part of Long Valley. Since then, the well has been converted to an underground USGS volcano laboratory

The two coreholes of the Creede Caldera Project were designed to sample ancient lake-bottom sediments in this

On-site scientist demonstrates the digital core scanner to a tour group at the Long Valley, California, drillsite. (U.S. Geological Survey photograph.)

25-million-year-old caldera. These sediments constituted the reservoir for convecting hydrothermal fluid responsible for the deposition of silver and base-metal ores in the adjacent Creede Mining District. The study provides a useful background to studies of active hydrothermal systems at the Salton Sea, Valles Caldera, Inyo Domes, and Long Valley Caldera. At Creede, much of the fossil geothermal system has been exposed through erosion and thus is more readily accessible by drilling than are the younger and deeper active systems.

In response to the declines in steam production and quality, a scientific coring project at the bottom of an existing 1,340-meter-deep production well at The Geysers geothermal field penetrated another several hundred meters into its steam reservoir. This DOE-funded study, the Geysers Coring Project, provided much needed core material from the Geysers region and new constraints on the timing of magmatism, volcanism, and the onset of vapor-dominated conditions in the area. Currently, an "enhanced geothermal systems" (EGS) project is being proposed for The Geysers. It involves drilling below the current production zone into the high temperature (greater than 350°C) zone, the creation of a reservoir by hydraulic fracture, and the mining of heat to supplement that being obtained from the existing steam reservoir.

Another EGS project in the planning stage is the Iceland Deep Drilling Project (IDDP). Iceland presently has the capacity to produce about 200 megawatts of electric power along the part of the Mid-Atlantic Rift system that traverses that country. The reservoirs are hot water-brine systems at temperatures between 200 and 300°C. There is some opposition to developing new hydrothermal systems, mainly on aesthetic grounds, and the IDDP is seeking to gain a better understanding of the deeper temperature regime (400 to 500°C) at one or more of the existing reservoirs to assess the feasibility of mining heat from these zones in addition to what is being produced from the conventional reservoirs. This would allow significant increases in energy output without disturbing otherwise pristine areas.

Initial deployment of the DOSECC (Deep Observation and Sampling of the Earth's Continental Crust) hybrid coring system was at Long Valley California. Shown, is the hydraulic coring head suspended from the mast of a large oilfield drilling rig. (U.S. Geological Survey photograph.)

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