# Exploration and Development of Geothermal Resources in the United States, 1968–1975

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## ABSTRACT

From 1968 to 1975, exploration for geothermal resources in the Western United States increased rapidly. The pace accelerated in late 1973 due to the rise in the price of energy. Energy demand and a favorable economic climate should sustain geothermal development in the future.

Federal and state lands are now becoming available, and efforts are being made to speed the leasing programs.

Extensive exploration and development are ongoing at The Geyser's and there have been significant discoveries made in the Imperial Valley, California, and at the Valles Caldera, New Mexico. Exploration is continuing at Beowawe and Brady's Hot Springs, Nevada, and Surprise Valley, California. In addition, exploration has been increased in portions of Utah, Idaho, Oregon, and Arizona. Discoveries have been sparse, but should improve as land becomes available and exploration is expanded.

Exploration and utilization technology is advancing, but a greater effort is required to meet the demand.

Environmental, legal, and institutional problems are still delaying exploration and development; however, increased coordination of federal, state, and local government regulatory programs has been proposed and if undertaken could speed development.

The federal government is heavily financing research and development, including exploration and utilization technology and solutions to environmental, legal, and institutional problems.

## INTRODUCTION

Exploration of geothermal systems in the United States increased steadily through the late 1960s and the first half of the '70s. Stimulus came from continued successful development of geothermal electricity at The Geysers, California, from legislation enabling the leasing of public land for geothermal exploration, and from increases in costs of traditional forms of energy.

Significant discoveries were made in the Valles Caldera of New Mexico (Figure 1). Wells of potential importance were drilled in three widely separated areas of the Imperial Valley of California (Heber, East Mesa, North Brawley), at Roosevelt, Utah, and in the Carson Desert of western Nevada. Drilling continued in varying degrees in previously explored areas of Surprise Valley, California; Beowawe, Nevada; and near Niland in Imperial Valley. However, several areas previously thought attractive, such as Steamboat Springs, Nevada, and Long Valley, California, were not drilled further. Part of the reason for this may be the continued unavailability of public land in these regions. Wildcat wells were drilled with little or no success at numerous locations in Oregon (La Grande, Lakeview), Idaho (Mountain Home), California (Honey Lake, Sierra Valley, Mono Lake, Kelly Hot Springs), Utah (Brigham City), Arizona (Casa Grande, Chandler), and Nevada (Tipton). Deep exploratory holes were drilled at varying distances from the proven productive area at The Geysers. Certain of these resulted in extension of the known steam field to the north, east, and south. Others were not productive. Finally, public funds were used to finance drilling for research purposes at Marysville, Montana, Raft River, Idaho, Kilauea, Hawaii (not shown on map), and west of the Valles Caldera of New Mexico.

Beginning in the middle 1960s, several states have passed laws to allow the leasing of state land for geothermal exploration. Leases of state land in California were granted as early as 1968. This has been followed by sale of geothermal leases by Oregon, Idaho, and New Mexico. The Geothermal Steam Act of 1970 established the legal framework for leasing of geothermal resources on federally administered public lands. Procedures for the actual leasing of public land required approximately three years to formulate, and the first applications were accepted in January 1974. Since that time, leases of approximately 100 000 acres of public land have been sold on a competitive basis in four states (California, Oregon, Nevada, Utah), and noncompetitive leases have been granted on about twice that acreage in Utah and Nevada. This has a potentially vast importance in furthering exploration, as nearly two-thirds of the total land in the western United States is publicly owned. For example, the important prospect at Roosevelt, Utah, is on federal acreage.

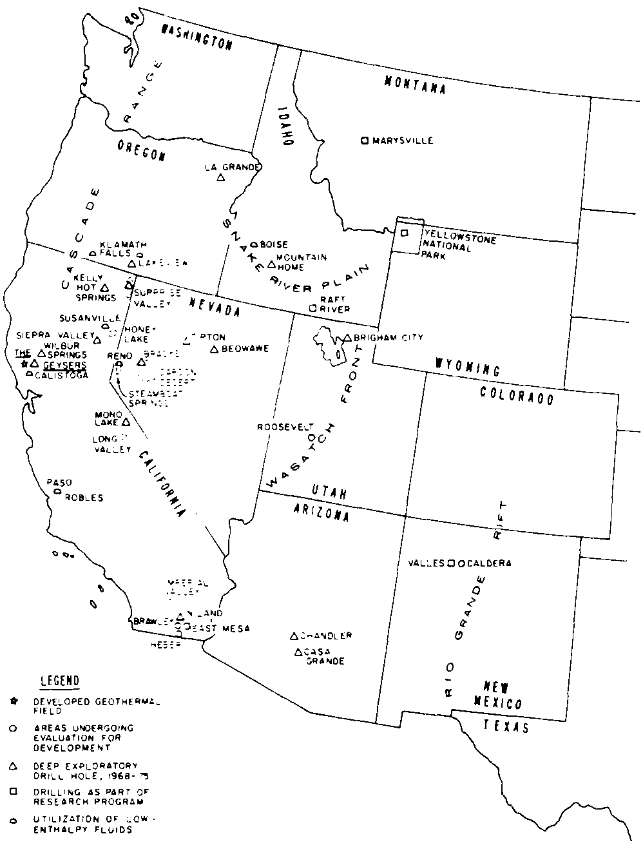


Figure 1. Geothermal exploration and development in the western United States, 1968–1974.

The Department of the Interior has a stated goal of awarding 1 000 000 acres in geothermal leases by the end of 1975. This represents approximately 10 percent of the total acreage covered in applications for lease.

## LEGAL AND ENVIRONMENTAL PROBLEMS

As problems have decreased concerning the availability of land in the past 18 months, problems have arisen concerning the compatibility of geothermal exploration and development with the legal requirements of environmental protection. These problems have erupted into conflicts over the issuance of specific leases of public land or permits to drill, especially in the state of California, with its stringent environmental act (California Environmental Quality Act).

Environmental safeguards are stipulated in leases of public land. Further, certain classes of public land (national parks and monuments, for example) are closed to geothermal exploration, and there is wide discretion to deny leases for land in national forests and other areas of designated use.

Concurrently, there have continued to be problems (often involving court action) over the nature of the geothermal resource, its relationship to water resources, and its ownership in cases where ownership of surface rights is severed from ownership of mineral rights. Several states, following the implicit definition in the Geothermal Steam Act of 1970, have declared geothermal resources to be *sui generis*, a separate category of resource subject to legislation and regulation specific to it. This has not stopped legal and administrative efforts in several states to make geothermal exploration and development subject to regulation under water rights law. Most recently, several states have considered legislation to give ownership of geothermal resources to the state.

## FINANCING

Financing for geothermal exploration, research, and development has become more plentiful in the past few years, from both private and public sources. This has been accompanied by improved access to markets as electric utilities, government agencies, and major industrial users of energy have expressed greater willingness to develop and consume geothermal energy.

The federal budget for geothermal research, development, and regulation has grown to about $50 million at this writing. This has funded research by the U.S. Geological Survey, and by numerous research laboratories, universities, and private companies. This has included assessment of the quantity and nature of the geothermal resource, testing of exploration methodology, development of instrumentation and technology for utilization, and attempts to resolve various legal, institutional, and environmental problems. Not all of these research projects have born fruit.

Because there is no adequate assessment of the extent of geothermal resources in the United States, companies have tended to lease extensive acreage prior to carrying out detailed exploration. Because of the difficulties in assembling large blocks of acreage (legal and title problems, federal holdings, land withdrawals), leasing has been competitive and increasingly expensive. Data of exploration largely are proprietory. Even the specifics of which surveys are used under which field conditions tend to be kept confidential.

## EXPLORATION PROCEDURES

There has been increased use of geoelectric surveys (dc-resistivity, electromagnetic soundings, magnetotelluric surveys), as well as temperature-gradient drilling, hydochemical surveys, and passive seismic surveys in the past decade, and lessened reliance upon aerial infrared surveys or aeromagnetic and gravity surveys. Increasing attention has been given to the geologic delineation of geothermal provinces on the basis of regional structures, plate tectonic theory, and extrapolation outward along previously identified features. Drilling of temperature-gradient holes has become the most widely used exploration tool in The Geysers area.

### The Geysers, California

Although there is far less drilling of deep exploratory holes without prior geological, geophysical, and hydrochemical exploration than in previous decades, several companies continue to drill deep holes solely on the basis of land control. As the availability of obvious targets has lessened, so has the success rates of these random holes.

Drilling has progressed to greater depths, in response to the increased value of steam, improved methods of exploration, and a decrease in obvious, shallow targets. Average well depth at The Geysers is 2 300 m. Wildcat drillings elsewhere have gone to as great a depth as 3 300 m. Few significant holes are drilled to less than 1 200 m.

Generation capacity at The Geysers presently is about 500 mW. Four additional plant sites have been chosen, for the generation of an additional 400 mW. These may come on line in 1978. Nearly 200 deep holes have been drilled at The Geysers. Its area of proven productivity is greater than 40 km$^2$, and exploration is continuing at its present margins. Estimates of total sustainable yield run to 2 000 mW or more.

Geologically, the source of heat is related to late Quaternary volcanism and shallow intrusion in an area north and east of The Geysers. The region of extrusion and intrusion may exceed 600 km$^2$ in area, and an area in excess of 1 500 km$^2$ may be abnormally hot at depth. The reservoir is fractured, brittle, Mesozoic Franciscan graywacke of great thickness and lateral extent and is vapor dominated. Blowdown from the power plant cooling towers is reinjected into the reservoir, both on environmental grounds and to maintain mass and pressure within the reservoir. Reinjection comprises about 20 percent of production.

Hot water reservoirs of lower enthalpy have been encountered by drilling at distances of 20 to 40 km to the north (Clear Lake, not shown on map), northeast (Wilbur Springs) and southeast (Calistoga) in areas underlain by Franciscan graywacke, Tertiary volcanic rocks, and Mesozoic mafic and ultramafic rocks. Conditions at depth across the intervening distances are unknown.

Local opposition to geothermal development, based on the desire to preserve rural values, has slowed exploration through widespread use of regulatory and appellate hearings.

## Jemez Mountains, New Mexico

The Jemez Mountains of northwestern New Mexico have as their principal feature a Quaternary caldera over 100 km$^2$. Within the Valles Caldera, 15 holes have been drilled to an average depth of almost 2000 m near the southwestern caldera margin. Extensive field tests of reservoir capacity and performance are scheduled for the summer of 1975, and the operator is negotiating with a local electric utility for the construction of a power plant. The reservoir contains hot water at temperatures that exceed 250°C. Its extent is unknown. To the west of the caldera, holes have been drilled for research purposes into Precambrian crystalline rock of the Nacimiento uplift. Attempts are being made to fracture the hot, essentially impermeable amphibolite and gneiss. This is the so-called hot, dry rock experiment. Other companies have taken leases in the vicinity and geophysical exploration is active.

## Imperial Valley, California

Exploratory holes have been drilled at four locations across an 80-km distance in the Imperial Valley. Reservoirs contain hot waters of varying salinities. Highest temperatures (over 300°C) and enthalpies (250 cal/gm) are found in the area of greatest salinity (over 250 000 ppm TDS) at Niland. Exploratory drilling and research into treatment of the high salinity brine have continued at Niland, without satisfactory resolution of problems of corrosion, scaling, and waste disposal. On the East Mesa, the U.S. Bureau of Reclamation is attempting desalination of water using the thermal energy of low salinity (15 000 ppm) geothermal brines. At Brawley, three holes have been drilled into a low salinity reservoir; six holes have been drilled at Heber. In each of these, evaluation of reservoir conditions is continuing. Temperatures at 2000 m probably do not greatly exceed 200°C at any of these areas. Fractured, cemented sands of Pliocene age form the reservoir. Crystalline basement probably is deeper than 5 km in each of these areas, and it may be possible to locate a deeper, higher enthalpy reservoir in one or more of these areas. However, permeability is known to decrease rapidly with depth. Heat source probably is related to conductive and convective transfer of heat from a very shallow mantle (less than 20 km in places).

## Other Areas

Recent news items have dealt with exploratory drilling near Roosevelt, Utah, where four relatively shallow holes have been drilled in an area of opalitized and steaming ground, and are undergoing evaluation. Roosevelt is one of several prospects along the Wasatch front of Utah, an area characterized by Tertiary intrusions and mineralization, and by development of deep, sedimentary basins in late Tertiary and Quaternary time.

Another area of active exploration is the Carson Desert of Nevada, where four companies have drilled five holes in the past 18 months. A major sale of federal leases is planned there for June 1975. Temperatures are known from past exploration at Brady's Hot Springs to exceed 200°C. Permeability is questionable. The Carson Desert is an extensive region of downwarp or downdrop, within which pre-Tertiary basement may be depressed 2000 to 3000 m in places. Late Tertiary or Quaternary intrusions are suspected as the source of heat, although total crust is thin (30 to 35 km) across the Basin and Range province, and heat transfer mechanisms may be similar to those of the Imperial Valley. Drilling depths have reached 2300 m.

Research by the U.S. Geological Survey is continuing in Yellowstone National Park. Although exploratory drilling barely exceeded 300 m in depth, field temperatures of 250°C or higher are projected on chemical and thermodynamic bases, and a molten body of batholithic dimensions is suspected at relatively shallow depth. Private companies now are beginning exploration of areas of Quaternary volcanism to the west and southwest in the Snake River plain of Idaho.

Increased costs of heating fuels have refocused attention on utilization of low enthalpy waters for space heating, agricultural use, and industrial processing. Research and development activity is underway in several localities in widely differing geologic terrains (Paso Robles, California—thermal fish farming; Susanville, California, Boise, Idaho, and Klamath Falls, Oregon—municipal heating; Lakeview, Oregon, and Calistoga, California—greenhouse heating; and Reno-Steamboat Springs, Nevada—municipal and commercial heating). In general, drilling depth does not exceed 600 m and is often less than 100 m, and high capacity, low salinity, hot water aquifers are sought.

Research into utilization of low enthalpy aquifers has led to drilling of a 1500-m-deep hole at Raft River, Idaho, where 150°C conditions were encountered.

Widespread drilling for hydrocarbons on the Gulf Coast of Texas and Louisiana (not shown on map) has allowed improved definition of the low salinity, geopressured, hot water aquifers found at depths greater than 3500 m. Methane dissolved in the hot water provides both an additional recoverable energy resource and an expanding gas drive to lift these fluids to the surface. Heat source is thermal gradient plus exothermic diagenetic changes in Tertiary sediment. The reservoir is faulted, wedge-shaped sands deposited in the high-energy environment. Temperatures to 270°C at 400 m are reported. The geopressured system is believed to be extensive. Exploratory drilling is thought to be imminent.

Oil and gas exploration have continued to identify high temperature aquifers elsewhere.

Continued exploration is forecast within the Carson Desert of Nevada, along the Wasatch front of Utah, in the Rio Grande rift of New Mexico and Colorado, within the Snake River Plain of Idaho and Oregon, and along the Oregon Cascade Range of Quaternary volcanoes, in addition to development drilling in the Imperial Valley, the Valles Caldera, and the vicinity of The Geysers.