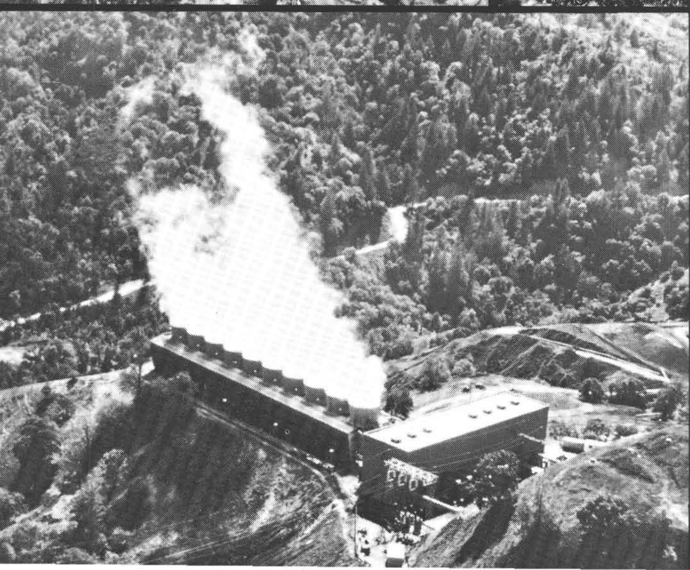
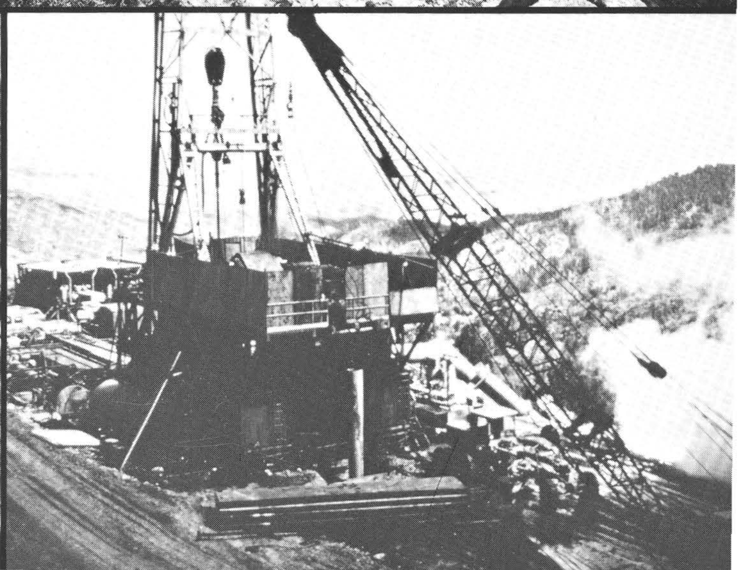
THE

GEOTHERMAL RESEARCH PROGRAM

OF THE U.S. GEOLOGICAL SURVEY

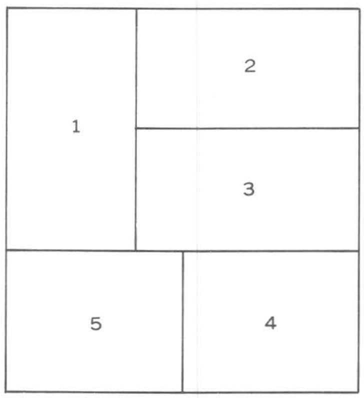
GEOLOGICAL SURVEY CIRCULAR 862





COVER

These photographs illustrate the sequence of activities leading to the production of electricity from geothermal energy. In practice, the number and scope of studies undertaken during exploration differ from area to area. In general, knowledge gained from a combination of geologic, geochemical, hydrologic, and geophysical studies leads to recommendations for drill sites; and if a productive reservoir of hot water or steam is found during drilling, the geothermal energy may be used to generate electricity.



1, Geologist examining rock at outcrop during field mapping.
2, Geochemist collecting sample of thermal water for subsequent laboratory analysis.
3, Geophysicist reading gravimeter at outcrop during field survey.
4, Drill rig in operation over target defined by results of foregoing field and laboratory studies.
5, An electrical generating plant powered by geothermal steam. Condensate from cooling towers is visible.

The Geothermal Research Program of the U.S. Geological Survey

By Wendell A. Duffield and Marianne Guffanti

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ILLUSTRATIONS

TABLE

CONVERSION FACTORS

Length:	1 kilometer (km) = 0.6214 mile (mi)
Area:	1 km^2 = 0.3861 mi^2
Temperature:	Degrees Celsius (°C) = 5/9(degrees Fahrenheit−32)
Temperature gradient:	1°C/km = 2.90°F/mi
Energy:	1 joule (J) = 0.239 calories (cal)
	= 9.480×10^{-4} British thermal unit (Btu)
	10^{18} J $\simeq$ 10^{15} Btu = 1 quad $\simeq$ 6×10^{9} barrels of oil
Power:	1 megawatt (MW) = 10^{6} J/s

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INTRODUCTION

Geothermal energy is naturally occurring thermal energy (heat) within the Earth. Measurements in boreholes indicate that temperature increases downward within the Earth's crust at an average rate of about 30°C/km, and from this average geothermal gradient it has been calculated that about 4×10^{26} J of thermal energy, assuming a surface temperature of 15°C, is stored within the outer 10 km of the crust (White, 1965). However, only a very small fraction of this vast storehouse of energy can be extracted and used at the Earth's surface. Like other natural resources, such as ore minerals and solid or liquid fuels, geothermal energy is exploitable only where it occurs in accessible, anomalously high concentrations. The process of mining so intangible a commodity as thermal energy places another constraint on the exploitation of geothermal systems. Although most of the energy is stored in rocks, water and (or) steam that are contained in fractures and pore spaces of the rocks are the only naturally occurring media available for transferring this energy to the Earth's surface. Thus, both high temperature at relatively shallow (drillable) depth and sufficient water or steam to transfer thermal energy to the surface are needed to exploit geothermal systems.

Naturally occurring systems of this sort, known as hydrothermal systems, are being increasingly developed and utilized as the cost of traditional forms of energy escalates. Moreover, considerable research within the geothermal community is presently aimed at forcing circulation of water through hot rocks that are dry and impermeable in their natural state in order to increase the amount of thermal energy that may be mined and used at the surface. Future technologic and economic developments will dictate what proportion of the overall content of thermal energy in the Earth's crust may actually be exploitable. Although prediction of such developments is difficult, it is noteworthy that the worldwide rate of growth in electrical generating capacity from geothermal energy has been 7 percent per year since about 1945, whereas the projected rate of growth in the near future ranges as high as 19 percent per year (Muffler and Guffanti, 1979). Geothermal energy is also being increasingly developed for nonelectrical applications. It seems likely that the economic climate responsible for such growth in the recent past will prevail for some time to come and that advances in technology will continue to accrue, thus promoting increased development of geothermal resources.

BIRTH OF THE GEOTHERMAL RESEARCH PROGRAM

Geothermal energy was first developed to generate electricity in 1904 at Larderello, Italy; yet as recently as 15 years ago such energy was considered little more than a curiosity in the United States. Such natural manifestations of geothermal energy as geysers, boiling mudpots, and hot springs provided a basis for establishing national parks (for example, Yellowstone) and spas, and in a few places geothermal water was used for space heating (for example, Boise, Idaho, and Klamath Falls, Oregon); but no large-scale, systematic efforts were undertaken to assess and develop geothermal energy as a national resource.

By the late 1960's, it was clear worldwide that a continuously growing demand for energy could not long be satisfied by available supplies of petroleum, the chief fuel being used to meet increased demand. This generally deteriorating relation between supply and demand was dramatized in 1973, when an embargo on petroleum export from the Middle East severely disrupted supplies of petroleum-derived fuel in the United States. Most U.S. citizens first became acutely aware of a growing energy problem while waiting in lines for hours to purchase gasoline for their automobiles.

As part of a national effort to decrease dependence on petroleum through the development of alternative domestic energy resources, a Federal

Geothermal Program was established in the early 1970's. The U.S. Geological Survey played a major role in planning and implementing this program, and in 1971 the Survey's own Geothermal Research Program was formally established.

The Geological Survey was well prepared to play a key role in the newly formed Federal Geothermal Program because years of ongoing field and laboratory research in several disciplines had accumulated a readily available base of knowledge and expertise with regard to geothermal fluids, volcanoes, and the thermal structure of the Earth's crust. For example, by 1970, studies of geothermal systems in Yellowstone National Park, probably the most abundantly endowed natural laboratory in the world for such research, had already yielded clues to the recognition of some fundamental differences between types of geothermal systems (White and others, 1971) and to the determination of their temperatures at depth (Fournier and Rowe, 1966) from analysis of water collected at surface hot springs. Similarly, studies of the generation and flow of heat within the Earth provided a scientific framework critical to a regional resource assessment of geothermal energy (Lachenbruch, 1970; Sass and others, 1971), and studies of volcanoes (for example, Smith and Bailey, 1968) provided an understanding of the formation and accumulation of magma, the inferred source of thermal energy that underlies and drives high-temperature hydrothermal systems in the Earth's crust.

Accordingly, by the early 1970's, when the Nation embarked on a major effort to develop domestic energy resources, the U.S. Geological Survey was well equipped with a team of talented researchers and an advanced understanding of geothermal energy, and thus assumed a key role in characterizing and assessing geothermal resources in support of the Federal Geothermal Program.

ORGANIZATION

The research of the Geothermal Research Program is carried out by the Water Resources and Geologic Divisions of the Survey, and is administered by the Geologic Division. The overall direction of the program is handled by a program coordinator (presently Wendell A. Duffield, Menlo Park, California), who operates under the authority of the chief of the Office of Geochemistry and Geophysics (presently Benjamin A. Morgan, Reston, Virginia). Donald E. White (Menlo Park, California), in his capacity as senior scientist in geothermal research, serves as advisor to the program. Franklin H. Olmsted (Menlo Park, California) coordinates the part of the program carried out by the Water Resources Division, and Donald W. Klick (Reston, Virginia) manages a component of the program devoted to research through grants and contracts to non-Survey organizations.

The program's inhouse research consists of a host of geologic, geochemical, geophysical, and hydrologic projects, nearly 90 of which have been active each year since 1975. The component of research supported by grants to and contracts with organizations outside the Survey was established in 1975, and since then approximately 15 percent of the program's budget has been allocated each year to such outside investigations, which supplement and complement the inhouse studies.

The Geothermal Research Program is organized and administered separately from the classification, evaluation, and leasing of Federal lands for geothermal development, activities that are carried out by the Conservation Division of the Geological Survey. However, much of the information generated by the program bears directly on the Conservation Division's geothermal projects, and timely exchange of this information is accomplished through regular contacts between the program coordinator, other scientists, and the Conservation Division's geothermal staff, which is headquartered in Menlo Park, California.

The U.S. Department of Energy's Division of Geothermal Energy is the lead agency in the Federal Geothermal Program, a role that is reflected in a budget which has remained about 15 to 20 times larger than that of the Geological Survey's Geothermal Research Program. The Department of Energy emphasizes site-specific studies of reservoir confirmation and evaluation, the development of advanced technology related to geothermal exploration and exploitation, and investigation of the institutional and legal barriers to geothermal development. This emphasis seeks to promote development of geothermal resources by private industry. The Geothermal Research Program has a legislated mandate to assess the Nation's geothermal resources and thus concentrates its efforts on more generic and regional studies, aimed at the characterization and fundamental understanding of all types of geothermal systems and at an overall national assessment of the distribution and magnitude of geothermal resources. The programs of the two agencies are complementary and closely coordinated. The Survey maintains a scientist (presently Charles G. Bufe, Reston, Virginia) on assignment to the Department of Energy in Washington, D.C.; Morgan and Klick, the other key staff members headquartered in the Washington, D.C., area, supplement Bufe's day-to-day liaison activities and coordinate activities of common interest with other Federal agencies.

OBJECTIVES

The principal objectives of the Geothermal Research Program are to characterize all types of geothermal systems, to map their distribution, and to assess their potential as sources of thermal energy. These objectives are designed to provide information on the geothermal component in planning national energy policy. Important derivative objectives are to develop and improve methods of exploration for geothermal resources and to examine environmental problems, such as ground subsidence, seismicity, and hydrologic changes, that may be induced by exploitation of geothermal fields.

FISCAL HISTORY

Funding for the Geothermal Research Program since 1972 has varied considerably (fig. 1). After a 3-year period of initial growth, funding remained near the $9 million to $10 million level through 1978. In 1979 the budget was supplemented by $2 million earmarked primarily for research contracted outside the Geological Survey. This increase was for 1979 only and so was dropped from the 1980 budget; during 1981, further reduction of the program's budget by about $2.3 million reflects a relatively higher priority for studies of other kinds of energy resources. When this reduced budget is adjusted for inflation, buying power is seen to be considerably less. The 1981 budget of about $7.7 million is equivalent to about $2.5 million (1972 dollars) when adjusted for the Consumer Price Index (CPI) inflation rates published annually by the U.S Department of Commerce, or to about $4.5 million (1972 dollars) when adjusted for an annual inflation rate of 6 percent (fig. 1). The Survey's program has maintained a high level of productivity in spite of such great erosion of the real buying power of its research funds. However, the rate at which the Survey can accomplish its mandated mission necessarily diminishes in response to budget reductions.

The allocation of funds in 1980 illustrates a typical year in the history of the program. The multidisciplinary character of the research is evident from the list of the Geological Survey's organizational units that have participated in the program (table 1); this broad character reflects the need to study both water and rocks and the host of complex interactions between the two. The $1,014,723 in support of research outside the Survey in 1980 was nearly 50 percent less than the average amount spent in each of the previous 5 years. The $2.3 million budget reduction for 1981 is partly accommodated by decreasing this level further as current contracts terminate, and the balance by a general reduction in inhouse projects.

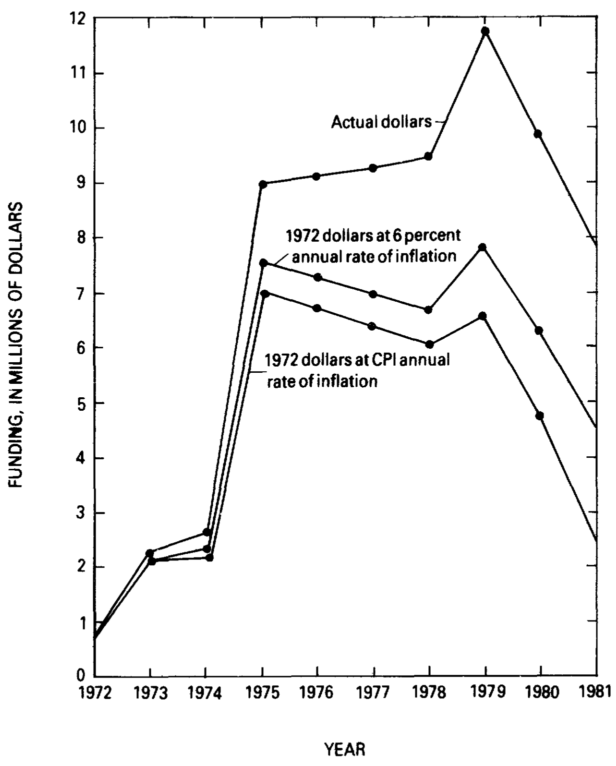

FIGURE 1.— Funding of Geothermal Research Program since 1972. CPI, Consumer Price Index.

The 1980 budget may also be viewed in terms of general topics of research or of the three principal categories of expenditure that constitute an individual project (fig. 2). The preponderance of funds spent on resource characterization and inventory reflects the primary mission of the Survey's Geothermal Research Program within the overall Federal Geothermal Program.

ACCOMPLISHMENTS

Major accomplishments of the Geological Survey's Geothermal Research Program are documented in the nearly 800 reports and maps published since its inception. A current listing of these publications is maintained in the program coordinator's office, Menlo Park, California, and in the Office of Geochemistry and Geophysics, Reston, Virginia, and is available on request (see addresses on inside back cover). Copies of reports and maps generally may be found at one or more of the Geological Survey libraries (Menlo Park, California; Denver, Colorado; Reston, Virginia), and some may be obtained directly from the authors.

Space does not permit a summary of the many scientific accomplishments of the program to date, but a few highlights are indicative of its overall productivity. Fundamental progress has resulted from studies of the chemical and physi-

TABLE 1.—*Summary of fund distribution of the Geothermal Research Program for 1980.*

Geologic Division	
Office of Energy Resources	
Branch of Oil and Gas Resources	$148,950
Total	148,950
Office of Mineral Resources	
Branch of Alaskan Geology	47,510
Branch of Western Mineral Resources	19,428
Branch of Resource Analysis	137,036
Total	203,974
Office of Regional Geology	
Branch of Engineering Geology	20,000
Branch of Central Regional Geology	308,535
Branch of Western Regional Geology	61,883
Total	390,418
Office of Geochemistry and Geophysics	
Branch of Experimental Geochemistry and Mineralogy	546,024
Branch of Field Geochemistry and Petrology	1,354,213
Branch of Isotope Geology	351,409
Branch of Regional Geophysics	540,517
Branch of Electromagnetism and Geomagnetism	528,813
Branch of Petrophysics and Remote Sensing	263,959
Total	3,584,935
Office of Earthquake Studies	
Branch of Seismology	1,123,422
Branch of Ground Motion and Faulting	127,348
Branch of Tectonophysics	723,054
Total	1,973,824
Office of Geochemistry and Geophysics program functions	
Geothermal Research Program coordination and support	160,841
Extramural grants and contracts	1,014,723
Total	1,175,564
Geologic Division total	7,477,665
Water Resources Division total	2,398,335
Grand total	$9,876,000

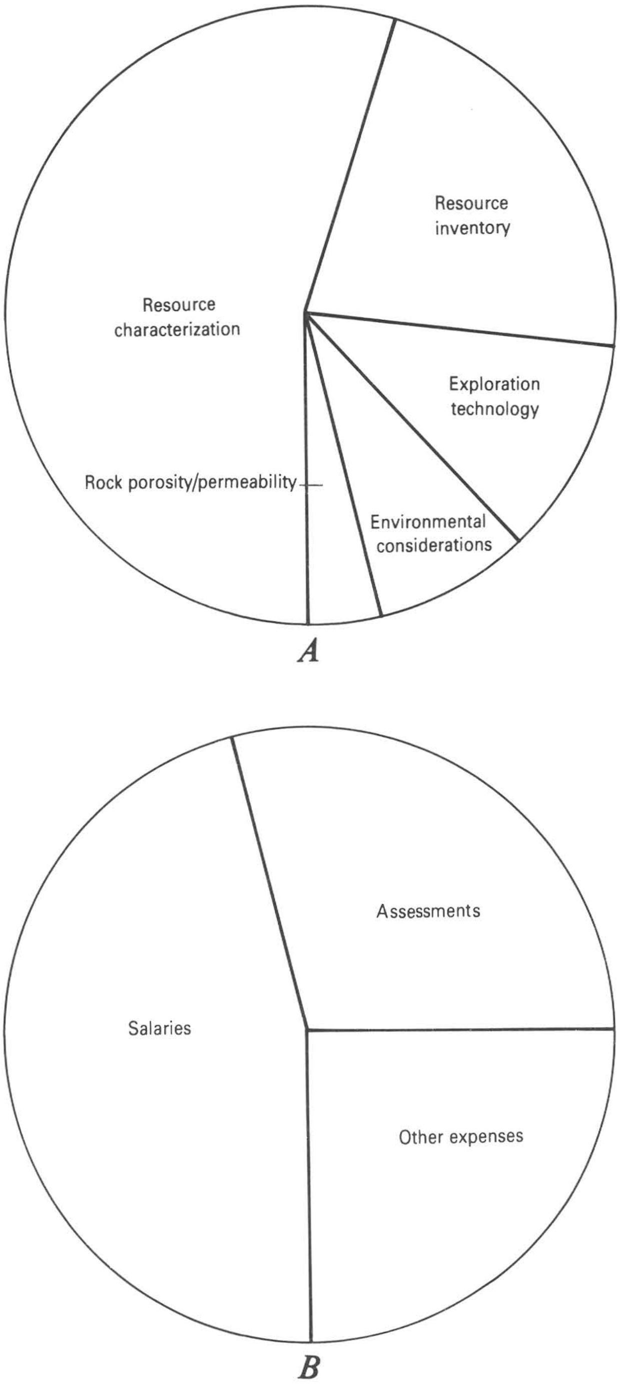

FIGURE 2.— Allocation of 1980 budget of Geothermal Research Program by general research topics (A) and the three principal categories of a typical project (B). "Assessments" designates nonsalary, overhead costs of operating the U.S. Geological Survey; "Other Expenses" designates direct research costs, such as field and laboratory expenses.

cal properties of geothermal fluids (fig. 3). Research carried out before formal establishment of the Geological Survey's Geothermal Research Program led to a distinction between vapor-dominated (dry steam) and hot-water convective hydrothermal systems, on the basis of the chemistry of the fluids that leak to the surface from such systems (White and others, 1971). Vapor-dominated systems are developed to produce electricity at Larderello, Italy; Matsukawa, Japan; and The Geysers, California. Such systems are attractive for development because wells drilled into them produce superheated steam that can be routed directly through a turbine without the need to separate steam from water or to dispose of large volumes of waste water—relatively costly procedures that attend the exploitation of hot-water systems (figs. 4*A*, 4*B*). Thus, recognition of vapor-dominated systems from the study of geothermal fluids collected at the surface is clearly of great economic value.

Simultaneously with the recognition of these two types of convective hydrothermal systems and as a continuing research effort, several techniques have been developed to estimate the temperature in an underlying geothermal reservoir

FIGURE 3.— Geochemist sampling gas dissolved in thermal water from a research well in Yellowstone National Park. Geochemical studies of fluids from such wells and from hot springs allow scientists to distinguish vapor-dominated from hot-water geothermal systems and to estimate subsurface temperatures.

from the chemistry of the thermal water that leaks to the Earth's surface (for example, Fournier and Truesdell, 1973; Truesdell and Fournier, 1976, 1977; Fournier, 1977, 1979, 1981; Fournier and Potter, 1979). The successful development and widespread use of these chemical geothermometers has resulted in economic benefits that already exceed the total cost of the Survey's Geothermal Research Program, by greatly increasing the chances of finding a high-temperature hydrothermal system during drilling. In broad recognition of their value, such geochemical studies, pioneered by the Survey, are now applied as standard exploration tools worldwide.

Because most high-temperature geothermal systems are within or adjacent to volcanic fields that are less than 2 million years old, early program emphasis was on understanding the formation and evolution of crustal magmatic systems that constitute the roots of such fields. Building on the results of their earlier Survey research in volcanology, Smith and Shaw (1975, 1979) developed a method for calculating the thermal energy contained within a magmatic system on the basis of the age and volume of volcanic rocks erupted from that system. Other studies examined how the state of stress in the Earth determines the size, shape, orientation, and growth of magmatic conduits (Pollard and Muller, 1976), and how magma solidifies in such conduits during flow to the surface (fig. 5; Delaney and Pollard, 1982). In addition, several volcanic fields of the Western United States were targeted for intensive study to provide the information needed to evaluate the geothermal potential of each field. As a result, major progress has been made in understanding the histories of volcanism in the Geysers-Clear Lake area (Donnelly-Nolan and others, 1981;

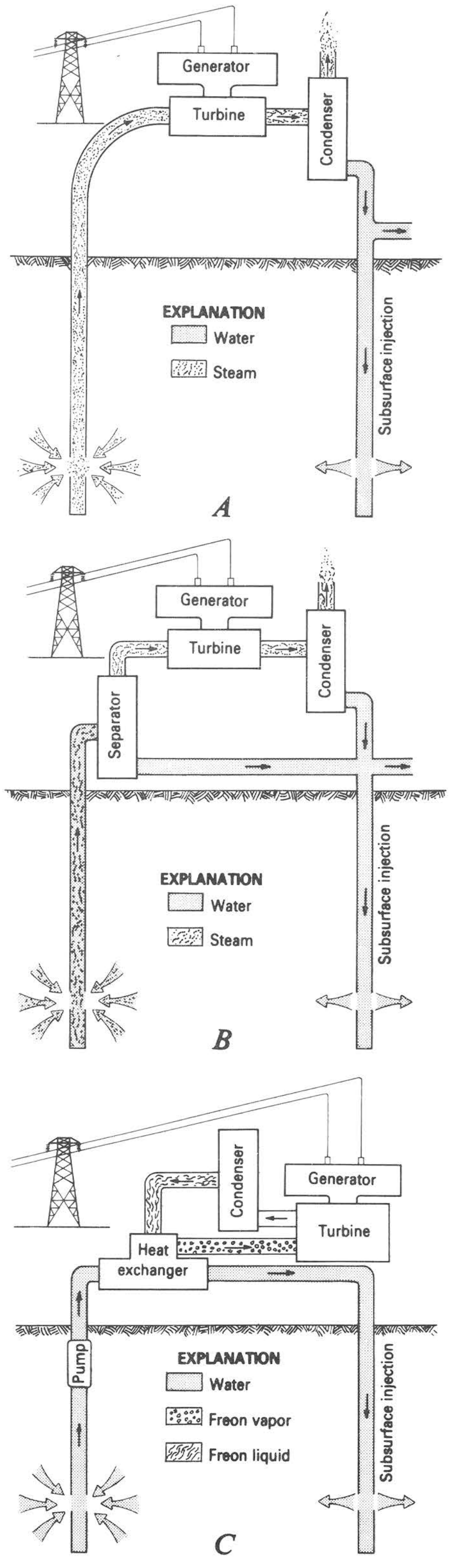

FIGURE 4.— Schematic diagrams illustrating the generation of electricity from geothermal systems (from Muffler, 1977). *A*, Vapor-dominated system; dry steam goes directly from wellhead to turbine. *B*, Hot-water system; waste water leaving separator and condenser is much more abundant than for a vapor-dominated system. *C*, Low-temperature hot-water system; geothermal fluids are used to heat a second fluid with a lower boiling temperature that is routed through a turbine.

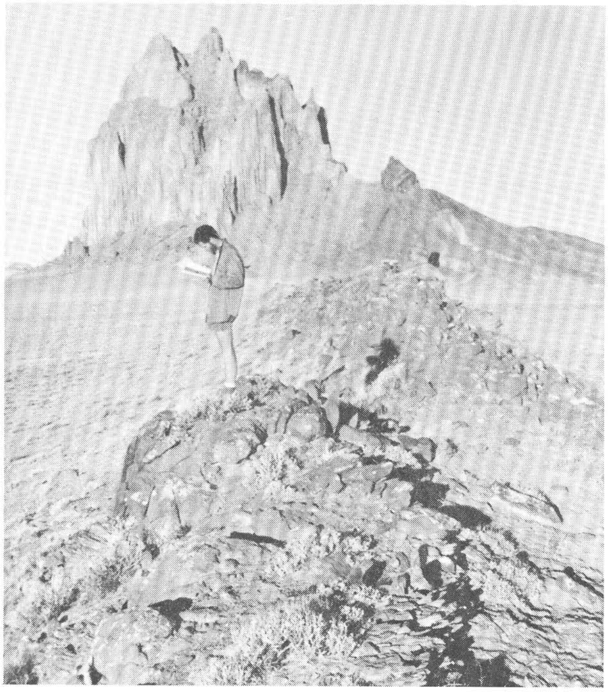

FIGURE 5.— Geologist mapping dike at Ship Rock, northwestern New Mexico. Such studies help explain how fractures form in the Earth's crust and how magma moves within the crust.

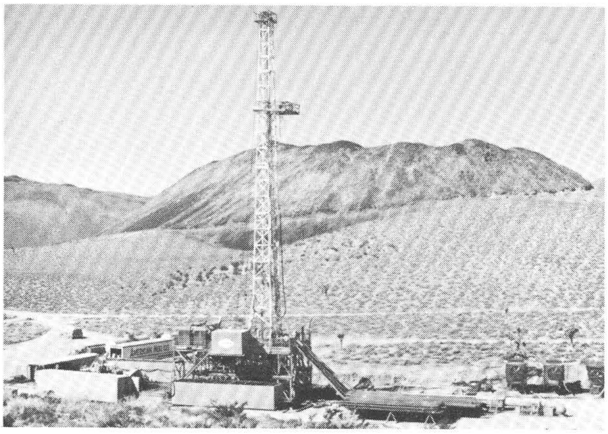

FIGURE 6.— Drilling of a 1,477-m-deep test hole at Coso geothermal field, California. Study of rhyolite dome in background and other nearby rhyolite domes in the area suggests that partially molten rock may be present at several kilometers depth and may serve as a source of heat for hydrothermal system penetrated by this drill hole.

Hearn and others, 1981), Long Valley (Bailey and others, 1976) and Coso (fig. 6; Duffield and others, 1980), California; at Newberry Volcano, Oregon (MacLeod, 1978); in the San Francisco Mountains, Arizona (Moore and Wolfe, 1976; Ulrich and others, 1979); at Ship Rock, New Mexico (Delaney and Pollard, 1981); and at Yellowstone National Park (Christiansen, 1982). Research continues on these and other volcanic regions, such as the Cascade Range of Washington, Oregon, and northern California, and the Snake River Plain of southern Idaho. In general, these studies of volcanic fields and magmatic systems have greatly increased our knowledge of the processes by and rates at which material and thermal energy move within magmatic and associated hydrothermal systems—knowledge that is critical to understanding the creation, functioning, and longevity of exploitable geothermal resources.

To characterize the magmatic roots of volcanic systems further, a seismic technique has been developed to map zones of relatively low seismic velocity that may represent molten or partially molten rock within the Earth's crust and upper mantle. These seismic studies have demonstrated that such low-velocity material underlies volcanic fields at Long Valley, California (Steeples and Iyer, 1976); at Yellowstone National Park (Iyer, 1979); in the Geysers-Clear Lake area, California (Iyer and others, 1979); at Coso, California (Reasenberg and others, 1980); at Roosevelt Hot Springs, Utah (Robinson and Iyer, 1979); and in the San Francisco Mountains, Arizona (Stauber, 1980). In each of these volcanic fields, the existence of magma at depth has been independently inferred from the history of volcanism reconstructed through geologic studies. Thus, the geologic and seismic data together provide important constraints on any understanding of magma-related geothermal systems, and in specific areas they confirm that magma exists today as the source of heat for such systems. Geophysicists can also detect the flow of magma within the Earth's crust from precise measurements of ground deformation at the surface (Swanson and others, 1976). Theoretical models (Pollard and Holzhausen, 1979) of the interaction between magma-filled fractures and the surface allow an estimate of fracture location, size, and heat content from such measurements.

By mapping the paths of seismic waves generated by controlled explosions, the seismic structure of the Earth's crust beneath the Imperial Valley, California, one of the most richly endowed geothermal areas in the United States, has recently been delineated; geothermal systems were found to be associated with zones of relatively high seismic velocity in the sediment that fills the valley (Fuis and others, 1982). These velocity anomalies are inferred to arise from concentrations of minerals that were deposited in pore spaces of the valley-filling sediment by convective hydrothermal fluids. Thus, this seismic technique provides a tool for exploring sediment-filled valleys and may be especially valuable in such geologic settings to help locate convective hydrothermal systems that have no such surface manifestations as hot springs and fumaroles.

Geothermal systems with temperatures between about 90° and 150°C are dominated by hot water and commonly result from deep circulation of water of surface origin along faults and fractures in areas of relatively high geothermal gradient. Such a system exists at the Raft River, Idaho, where Geological Survey studies guided exploration for wells to support a recently completed experimental binary-cycle electric powerplant (fig. 4*C*; Williams and others, 1976; Mabey and others, 1978; Mabey, 1980).

Measurements of the temperature gradient in the Earth's crust have led to the recognition of several large regions of differing heat flow and have defined local areas of higher than average heat flow that provide targets for further study. A recently updated map of heat flow for the conterminous United States (Sass and others, 1981a) is widely used by researchers interested in heat flow and the thermal regime of the Earth's crust. Considerable effort has been focused on the Western United States, especially the Basin and Range province in Nevada and Utah, where heat flow is generally high but varies. Theoretical analysis indicates that such elevated heat flow may result from the intrusion of mantle-derived magma into the crust in response to ongoing crustal extension (Lachenbruch and Sass, 1978), an interpretation consistent with the tectonic regime indicated by other geologic and seismic data. Additional measurements have enlarged the known area of high heat flow in the Basin and Range from an originally rather restricted part of Nevada (the so-called Battle Mountain high) to a broader region that includes southern Idaho, southeastern Oregon, and possibly the Cascade Range in Oregon and northern California.

To reduce the traditionally high costs incurred in measuring heat flow, the Geothermal Research Program's heat-flow project has successfully developed a probe that saves time and money in determining heat flow in unconsolidated sediment by eliminating the need to case the borehole and reenter it for temperature measurements after thermal equilibrium has been attained (Sass and others, 1979, 1981b).

Because most geothermal systems are more electrically conductive than the surrounding cooler rocks, geoelectrical techniques can be used to map the lateral and vertical extent of a geothermal system during surface exploration. The Geothermal Research Program has contributed to development of the versatility and variety of such methods. The standard exploration technique of direct-current (d-c) soundings is now augmented by self-potential (SP), audiomagnetotelluric (AMT), and magnetotelluric (MT) techniques, each differing in terms of the source of energy for the survey and in the range of frequencies and, thus, the effective depths examined. Using a combination of these techniques, the electrical structure of the Earth's crust and upper mantle can now be examined to depths of several tens of kilometers. Such relatively shallow probing techniques as d-c soundings and SP and AMT have been used to locate drilling targets by outlining the apparent extent of geothermal reservoirs within the upper 2 to 3 km of the crust (Zohdy and others, 1973; Hoover and Long, 1976; Zohdy, 1978). At Kilauea Volcano in Hawaii, a high-temperature (365°C) well, the first such well to confirm the existence of an exploitable convective hydrothermal system at Kilauea, was sited principally on the basis of SP mapping (Zablocki, 1977). Deeper probing techniques, chiefly MT, can provide information on the positions of bodies of magma and other heat sources, and thus complement the geologic and seismic studies.

Interpretation of the data gathered during geoelectrical and seismic surveys is limited by incomplete knowledge of the behavior of rocks at the temperatures and pressures characteristic of geothermal environments. To address this limitation, the Geothermal Research Program has helped establish a laboratory to determine various rock properties under simulated geothermal conditions. Research in this laboratory, one of the best equipped in the world, yields information that is invaluable in improving the interpretation of geophysical data collected during field surveys (Hunt and others, 1979).

To obtain reliable geophysical data directly from high-temperature geothermal wells, a variety of well-logging equipment has been developed within the Geothermal Research Program. One especially useful innovation is the acoustic televiewer (fig. 7), which provides information on the size, orientation, and position of fractures that provide permeable pathways and allow hot fluids to be extracted from many geothermal systems (Keys and Sullivan, 1979).

The component of the Geothermal Research Program that supports non-Survey organizations has resulted in considerable progress in geothermal research. This component of the program both supplements and complements inhouse projects, and promotes contacts that further collaboration among university, industry, and Government scientists.

Two key publications of the Geothermal Research Program have synthesized the results of a myriad of individual projects to address one of the principal objectives of the program: a quantitative assessment of the Nation's geothermal resources. Publication of Geological Survey Circular 726, "Assessment of Geothermal Resources of the United States—1975" (White and Williams, 1975), represented the first such national assessment based on a consistent, well-documented methodology and constrained by tabulated data on the physics and chemistry of known geothermal systems. Geothermal resources were calculated as that fraction of thermal energy stored in the crust that might be recoverable at the surface, with reasonable assumptions of future technology and economics.

Three years later, after the Geothermal Research Program had existed long enough to have completed studies of several of the Nation's principal geothermal systems, an updated assessment was published as Geological Survey Circular 790, "Assessment of Geothermal Resources of the United States—1978" (Muffler, 1979). Though differing in some details because of the large body of new data amassed between 1975 and 1978, both assessments estimate that the Nation's geothermal resources are many times greater than the amount that is being used today. For example, identified geothermal resources in 215 hydrothermal-convection systems with subsurface temperatures greater than 90°C to a depth of 3 km were estimated in Circular 790 to be 400×10^{18} J, equivalent to 23,000 MW-electric annual yield for 30 years (assuming that only about 10 percent of the thermal energy extracted at the surface is convertible to electricity). Such information contained in these assessments is the principal basis for planning the geothermal component of national energy policy and provides guidelines for establishing goals of electrical production within the overall Federal Geothermal Program.

The Geothermal Research Program maintains a computerized data file on geothermal resources (GEOTHERM), so that the large number of accumulated data is readily available to Geological Survey researchers, State and other Govern-

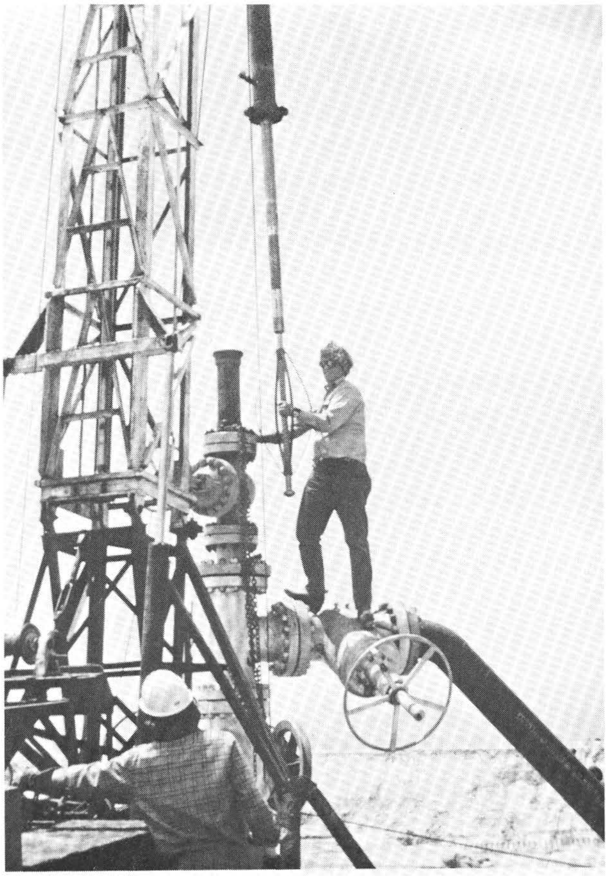

FIGURE 7.— Acoustic televiewer being inserted into a geothermal well at Roosevelt, Utah, to map fractures in walls of borehole.

ment agencies, and the general public. GEOTHERM contains information on the physical characteristics, fluid geochemistry, geology, and hydrology of hydrothermal-convection systems and thermal springs and wells (Teshin and others, 1979). GEOTHERM was used extensively to support the 1978 assessment of geothermal resources and is currently being used in the assessment of geothermal resources with subsurface temperatures less than 90°C. The retrieval of data from the file may be requested in writing (see address on inside back cover). Data in the GEOTHERM file on thermal wells and springs are also available through the General Electric Information Services Network.

PRESENT EMPHASIS

At the present time, a considerable part of the Geological Survey's Geothermal Research Program is devoted to multidisciplinary study of the Cascade Range of Washington, Oregon, and northern California. Geologic, geophysical, geochemical, and hydrologic projects will contribute the information needed to assess the geothermal potential of this volcanic region. In February 1980, the Geothermal Research Program sponsored a conference at which more than 150 participants, representing private enterprise, academia, and State and Federal agencies, reported progress of their studies in the Cascade Range (Bacon, 1980).

The Cascade Range is somewhat enigmatic to geothermal researchers; in spite of abundant active volcanoes that suggest the presence of underlying magma bodies as heat sources for convective hydrothermal systems, there are only a few, widely scattered surface manifestations of such systems. Many researchers hypothesize that this absence reflects drowning of geothermal systems at shallow depths by percolating snowmelt and cool rainwater. Brook and others (1979) estimated that at least $1,140 \times 10^{18}$ J (the U.S.A. presently consumes energy at the rate of about 100×10^{18} J per year) of geothermal energy lie hidden beneath such a blanket of cold ground water in the Cascade Range. Recent results of research drilling by the Geological Survey at Newberry Volcano on the east side of the Cascade Range in Oregon indicate that considerable geothermal energy is, indeed, present beneath a cooler shallow zone. Temperatures in the upper 631 m of this borehole never exceeded 99°C, and the temperature profile to this depth clearly was perturbed by shallow groundwater. However, temperatures in the bottom part of the hole increased at a rapid rate to a maximum of 265°C at 932 m (fig. 8), where geothermal fluids were encountered in permeable rock (Sammel, 1981). One important objective of the Geological Survey's studies of the Cascade Range is to identify parts of this 1,000-km-long chain of volcanoes where similarly promising drilling results may be expected.

Additional thrusts of the Geological Survey's present program include a continuing attempt to calculate the recoverable energy contained in geopressured geothermal systems of the Gulf Coast region and a thorough review of the state of knowledge of geothermal resources in the northern Great Basin. Geopressured systems are characterized by hot water and dissolved methane trapped in deeply buried porous sedimentary rocks, and assessment of their energy potential depends critically on data that can be obtained only during closely monitored long- and short-term flow of wells. Accordingly, the Survey's research is coordinated with a program of well testing sponsored by the Division of Geothermal Energy of the U.S. Department of Energy. Review of the information available on the Great Basin will lead to recommendations of additional studies needed to upgrade existing assessment of resources within this region of anomalously high heat flow.

As a followup to Circulars 726 and 790, the first quantitative assessment of geothermal resources with subsurface temperatures less than 90°C is underway. Low-temperature geothermal fluids are appropriate for such nonelectrical uses as space heating, industrial drying, and agricultural applications. Future assessment needs include consideration of the geothermal energy that may be recoverable through hot-dry-rock technology (that is, a manmade geothermal reservoir created by forced circulation of water through rocks that are hot but essentially dry and impermeable in their natural state). Initial experiments by researchers at Los Alamos National Laboratory in New Mexico have yielded results that hold promise for further evaluation of the technology and economics of such systems. A need for periodic updating of the assessments of all types of geothermal systems will persist as more of their physical and chemical characteristics are determined, as new techniques for exploiting them are developed, and as the demand for energy grows.

Many other facets of the Geological Survey's Geothermal Research Program, too numerous to detail here, address the general goals of understanding the nature, distribution, and magnitude of the Nation's geothermal resources. A listing of current projects is available from the program coordinator (see address on inside back cover). Figure 9 shows the locations of field-oriented research projects for 1980.

GEOTHERMAL DEVELOPMENT

The impetus to develop alternative sources of energy is reflected in the recent trend of installed geothermal electrical capacity. Present installed capacity is about 2,500 MW worldwide, and announced development plans suggest that the rate of growth of this capacity may more than double during the 1980's from its previous rate of 7 percent per year (fig. 10; DiPippo, 1980). In the United States, considerable growth in generating capacity is underway at The Geysers in California, the site of most of the geothermal electrical power production in the United States at this time (fig. 11). The present 908-MW capacity at The Geysers is roughly equivalent to that of a modern nuclear-powered generating plant and is sufficient for a city of about 1 million people; about 500 MW of additional capacity is expected to be installed in the next few years (Reed, 1981). Recently, 20 MW of geothermal electrical power from a high-temperature hot-water system (fig. 4*B*) and a low-temperature, hot-water system (fig. 4*C*) came on line at Brawley and East Mesa, respectively, in the Imperial Valley of California. These developments represent the first production of electricity from hot-water geothermal systems in the United States. Additional electrical generation is anticipated from other hot-water fields in the Imperial Valley and in the Valles caldera, New Mexico; and at Roosevelt Hot Springs, Utah; Raft River, Idaho; and Puna, Hawaii, within the next few years.

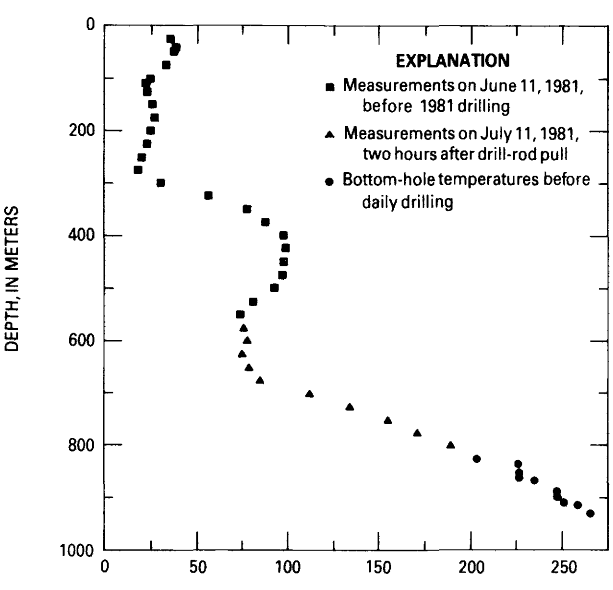

FIGURE 8.—Temperature against depth in research borehole, Newberry caldera, Oregon (after Sammel, 1981).

Worldwide installed capacity for nonelectrical uses of geothermal energy is about 8,000 MW (Gudmundsson and Palmason, 1981), and about 115 MW of this capacity is in the United States. Japan, Hungary, and Iceland together account for 85 percent of the worldwide capacity. Iceland, where nearly 80 percent of all buildings are heated with geothermal water, is the world leader in this particular nonelectrical application of geothermal energy. Data generally are not available to chart the rate of growth of nonelectrical installed capacity, but active development programs in several countries suggest considerable growth, similar to installed geothermal electrical capacity.

Geothermal electrical power is included among the so-called alternative sources of energy and thus commonly appears in lists with solar, wind, biomass, tidal, and ocean thermal-energy conversion, among others. Such grouping, however, is misleading, because within this group, geothermal is the only source of energy that is producing considerable electricity now and developing rapidly. Similarly, the technology for nonelectrical uses of geothermal fluids is well established, and exploitation has already resulted in a growing contribution to national and world energy needs. In a world troubled by foreseeable limitations on conventional sources of energy, an aggressive program of research supporting the exploration and exploitation of geothermal systems is highly desirable.

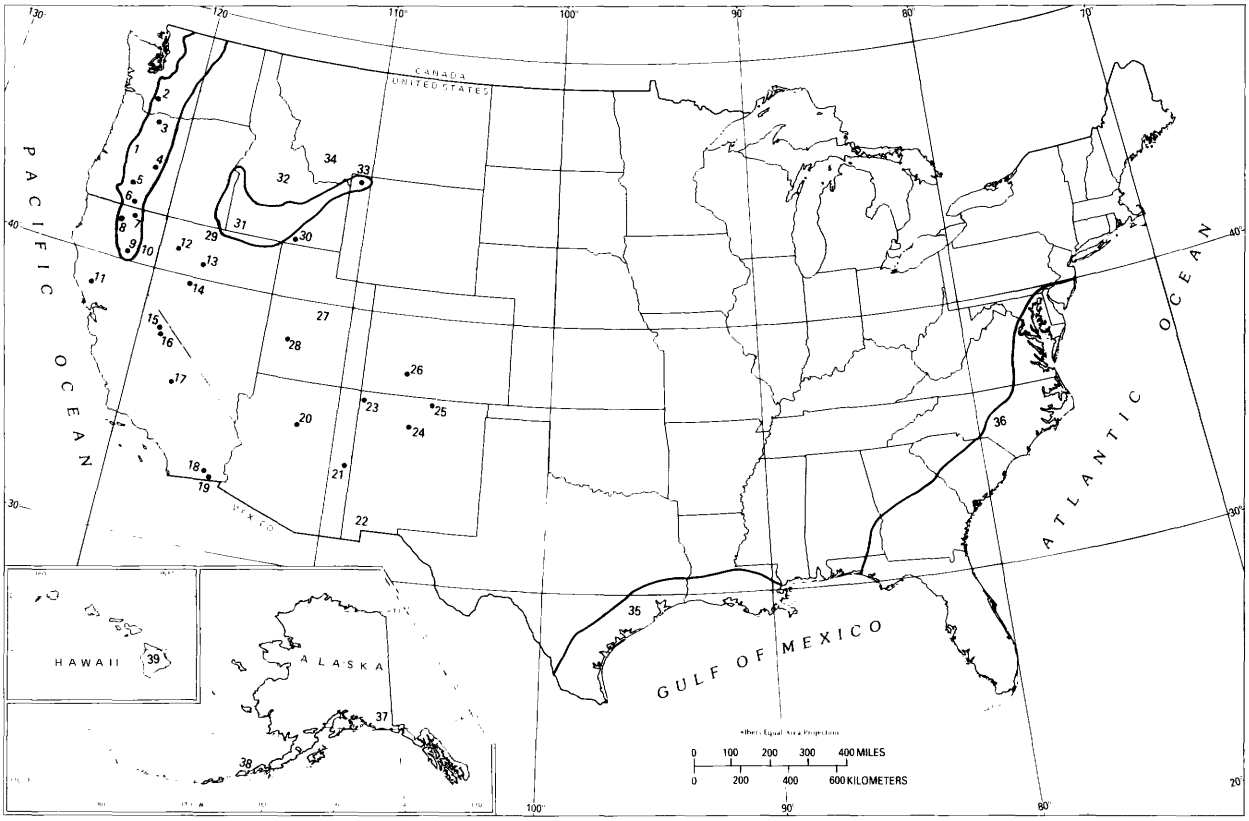

FIGURE 9.— Locations of field-oriented projects of the Geological Survey's Geothermal Research Program for 1980. 1, Cascade Range—hydrothermal alteration, hydrology, geology, fluid geochemistry, paleomagnetism, heat flow, aeromagnetic survey, geoelectric studies, seismicity, resource assessment, gravity; 2, Mount St. Helens—seismic studies; 3, Mount Hood—gravity, magnetics, geology, hydrology, fluid geochemistry, hydrothermal alteration, seismicity, thermal infrared sensing; 4, Newberry/Three Sisters Volcanoes—geology, hydrology, geoelectric studies; 5, Mount Mazama (Crater Lake)—geology, petrology, geochronology, geophysics; 6, Klamath Falls—hydrology, hydrologic modeling; 7, Medicine Lake Volcano—geology, petrology, geochronology, geochemistry; 8, Mount Shasta—geology, petrology, geochronology; 9, Lassen Peak—geology, hydrothermal alteration, fluid geochemistry, geochronology, geoelectric studies. 10, Northeastern California Cascades—geology; 11, Geysers-Clear Lake area—geology, geochronology, seismicity, subsidence, fluid geochemistry, precision gravimetry; 12, Black Rock Desert—hydrology, geophysics, geochemistry, hydrologic modeling; 13, Leach Hot Springs—heat flow, hydrologic modeling; 14, Dixie Valley—subsidence; 15, 16, Mono basin—Long Valley—geology, petrology, fluid geochemistry, geochronology, temperature logging, heat flow, seismicity, hydrology; 17, Coso area—geology, geochronology, geoelectric studies, seismicity, fluid geochemistry, gravity, aeromagnetics; 18, Imperial Valley—subsidence, seismicity, fluid geochemistry; 19, East Mesa—hydrologic modeling, temperature logging, seismicity, self-potential; 20, San Francisco Mountains—geology, geoelectric studies, seismicity, geochronology, gravity, paleomagnetism; 21, Springerville volcanic field—geology; 22, Rio Grande rift and southwestern New Mexico—geoelectric studies, geology; 23, Ship Rock—geology; 24, Valles caldera—isotopic studies, hydrology; 25, Cuesta—geology, petrology, geochronology; 26, Creede—geology, geochronology, fluid-inclusion studies; 27, Utah—heat flow, fluid geochemistry, geology; 28, Roosevelt Hot Springs—seismicity, subsidence, borehole logging, fluid geochemistry; 29, Northern Nevada—hydrology of hydrothermal systems, heat flow, regional geophysics, fluid geochemistry, geoelectric studies; 30, Raft River—geology, borehole logging, subsidence, hydrologic modeling, heat flow, seismic reflection, geoelectrical studies, fluid geochemistry; 31, Snake River Plain—geology, heat flow, seismicity, geoelectric studies, gravity, paleomagnetism, geochronology, hydrology, fluid geochemistry; 32, Idaho batholith—fluid geochemistry; 33, Yellowstone National Park—hydrothermal mineralogy and geology, fluid geochemistry, isotope studies, heat flow, seismicity, seismic refraction, hydrology, geoelectric studies, volcanic geology and petrology, ground deformation; 34, Southwestern Montana—regional hydrology; 35, Gulf Coast geopressured zone—hydrology, fluid geochemistry, stratigraphy and sedimentation; 36, Atlantic Coastal Plain—heat flow, subsurface geology; 37, Wrangell Mountains—geology, geochronology; 38, Aleutian-arc volcanoes—geology, eochronology, fluid geochemistry; 39, Hawaiian volcanoes—seismicity, ground deformation, fluid geochemistry, paleomagnetism, magma reservoirs, geophysics, geology.

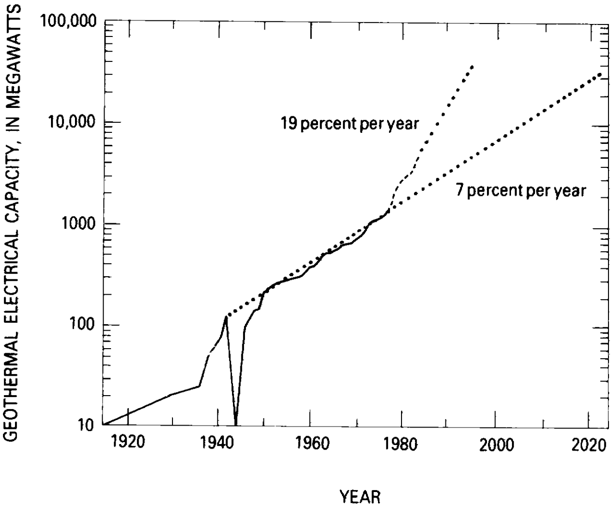

FIGURE 10.— Worldwide installed geothermal electrical capacity as a function of time (from Muffler and Guffanti, 1979). Dashed line indicates plants under construction or committed up to 1983. Dotted extrapolations can be interpreted as upper and lower limits of expected growth.

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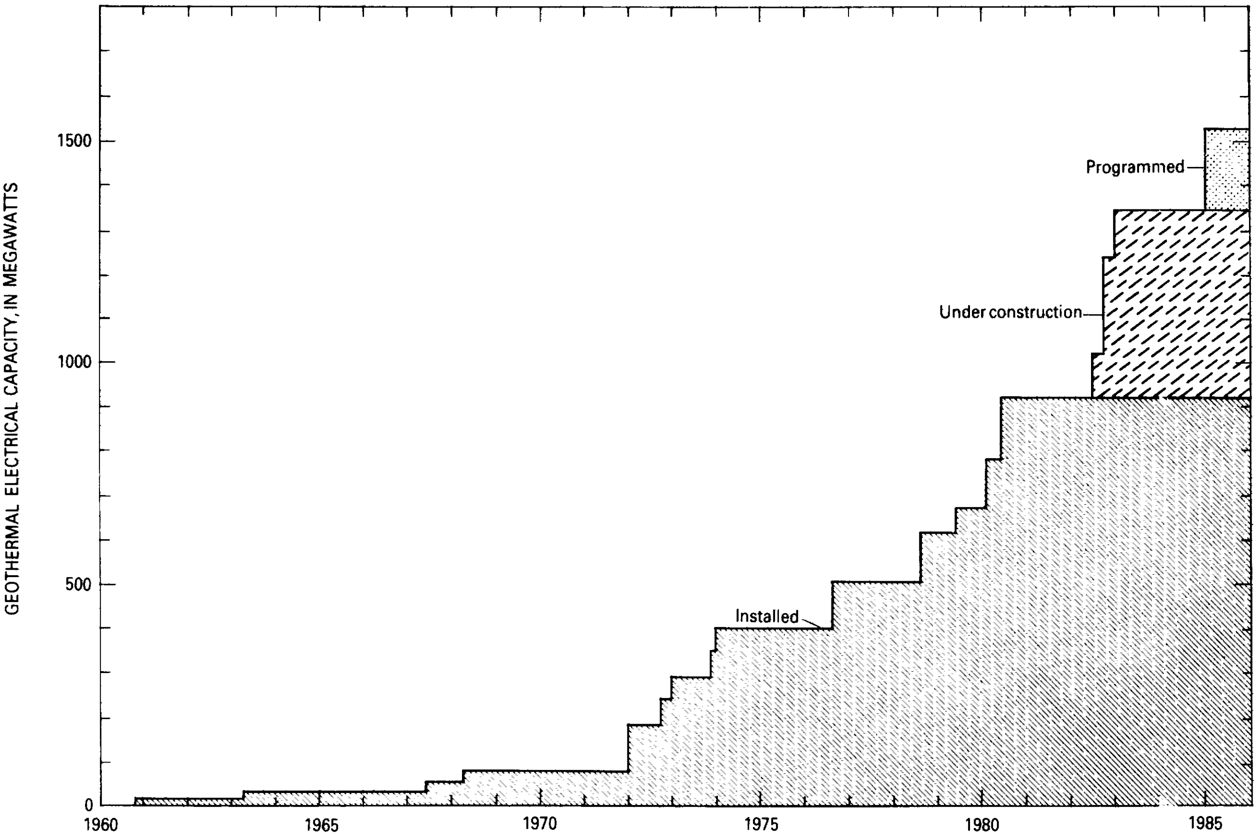

FIGURE 11.— Installed and expected generating capacity at The Geysers, California, as a function of time. Data collated by L. J. P. Muffler (written commun., 1980).

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