UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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

by

Wendell A. Duffield
Marianne Guffanti

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Introduction

Geothermal energy is the 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 per kilometer, and from this average geothermal gradient it has been calculated that about 4 x 10^{26} joules of thermal energy, above a surface temperature assumed to be 15°C, are 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. Analogous to 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 such an intangible commodity as thermal energy poses another constraint to the exploitation of geothermal systems. Most of the energy is stored in rocks, but water (and/or steam) that is contained in fractures and pore spaces of the rocks is the only naturally occurring medium available to transfer this energy to the Earth's surface. Thus, 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, called hydrothermal systems, have been developed and are being utilized as the cost of traditional forms of energy increases. Moreover, substantial effort within the geothermal community is presently aimed at forcing the 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 exploited. Although predicting 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 to the present, and the projected rate of growth in the near-future ranges up to 19 percent per year (Muffler and Guffanti, 1979). Geothermal energy is also being increasingly developed for non-electrical applications. It seems likely that the economic climate responsible for such growth in the recent past will prevail for some time 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, but as recently as 15 years ago such energy was considered little more than a curiosity in the United States. Natural manifestations such as geysers, boiling mud pots, and hot springs provided a basis for establishing national parks (e.g. Yellowstone) and spas, and in exceptional instances geothermal water was used for space heating (e.g. Boise, Idaho, and Klamath Falls, Oregon). But no large-scale, systematic efforts were made to assess and develop geothermal energy as a national resource.

By the late 1960's, it was clear both at home and abroad 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 from the Middle East caused considerable disruption in petroleum-derived fuel supplies in the United States. Most citizens of the United States 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 become less dependent upon petroleum through the development of a variety of alternate 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 Geothermal Research Program was formally established.

The 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 a variety of disciplines had accumulated a readily available base of knowledge and expertise. This reservoir of knowledge, especially that part gained from studies of geothermal fluids, volcanoes, and the thermal structure of the Earth's crust, provided the initial building blocks for successful implementation of the Survey's role in the Federal Geothermal Program. 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 and to the determination of their temperatures at depth from analysis of water collected at surface hot springs (White and others, 1971, Fournier and Rowe, 1966). Similarly, the results of studies of the generation and flow of heat within the Earth provided a framework critical to regional assessment of geothermal energy (Lachenbruch, 1970; Sass and others, 1971), while studies of volcanoes (Smith and Bailey, 1964) 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 program to develop a variety of 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 as part of the newly established Federal Geothermal Program.

Organization

Research of the Geothermal Research Program is carried out in the Water Resources and Geologic Divisions of the Survey, with administration of the program vested in 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 Robert I. Tilling, Reston, Virginia). The position of Program Coordinator rotates every few years to another Survey scientist. Donald E. White, in his capacity as senior scientist in geothermal research, serves as advisor to Duffield and Tilling. Franklin H. Olmsted (Menlo Park, California) coordinates the part of the program carried out in the Water Resources Division, and Donald W. Klick (Reston, Virginia) manages a component of the program that is devoted to research through grants and contracts to non-Survey organizations.

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

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

The Department of Energy's Division of Geothermal Energy is the lead agency of the Federal Geothermal Program, a role that is reflected in a budget that has remained about 15 to 20 times larger than that of the 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 investigations of institutional and legal barriers to geothermal development. This emphasis is aimed at promoting development of geothermal resources by private industry. The Survey's Geothermal Research Program has the 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 the various 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 liaison (presently Charles G. Bufe) on assignment to the Department of Energy in Washington, D. C. Tilling 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 the various types of geothermal systems, to map their distribution, and to assess their potential as sources of thermal energy. These objectives are aimed at providing the information for the geothermal component in national energy policy, and they address some major needs of the Department of Energy's Geothermal Program. Important derivative objectives are to develop and improve methods of exploration for geothermal resources and to examine environmental problems, such as ground subsidence and seismicity that may be induced by exploitation of geothermal fields.

Fiscal History

Figure 1 summarizes funding for the Geothermal Research Program since 1972. After a three 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 primarily earmarked for research contracted to organizations outside the Survey. This increase was for one year only and was thus removed from the 1980 budget; in 1981 the program's budget was reduced by about $2.3 million more, reflecting a relatively higher priority for studies of other types of energy resources. When the reduced budget is adjusted for inflation, buying power is considerably less. The budget's 1981 level of about $7.7 million is equivalent to somewhat more than $2 million (1972 dollars) when adjusted for Consumer-Price-Index inflation rates published annually by the 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 diminishes in response to budget reductions.

The allocation of 1980 funds illustrates a typical year throughout the history of the program. When viewed in the context of organizational units of the Survey, a multidisciplinary character that includes many elements of the organization is clearly evident (table 1), reflecting the need to study both water and rocks and a host of complex interactions between the two. The $1,014,723 in support of research outside the Survey in 1980 is nearly 50% less than the average level of the previous five years. The $2.3 million budget reduction for 1981 is partly accommodated by decreasing this level

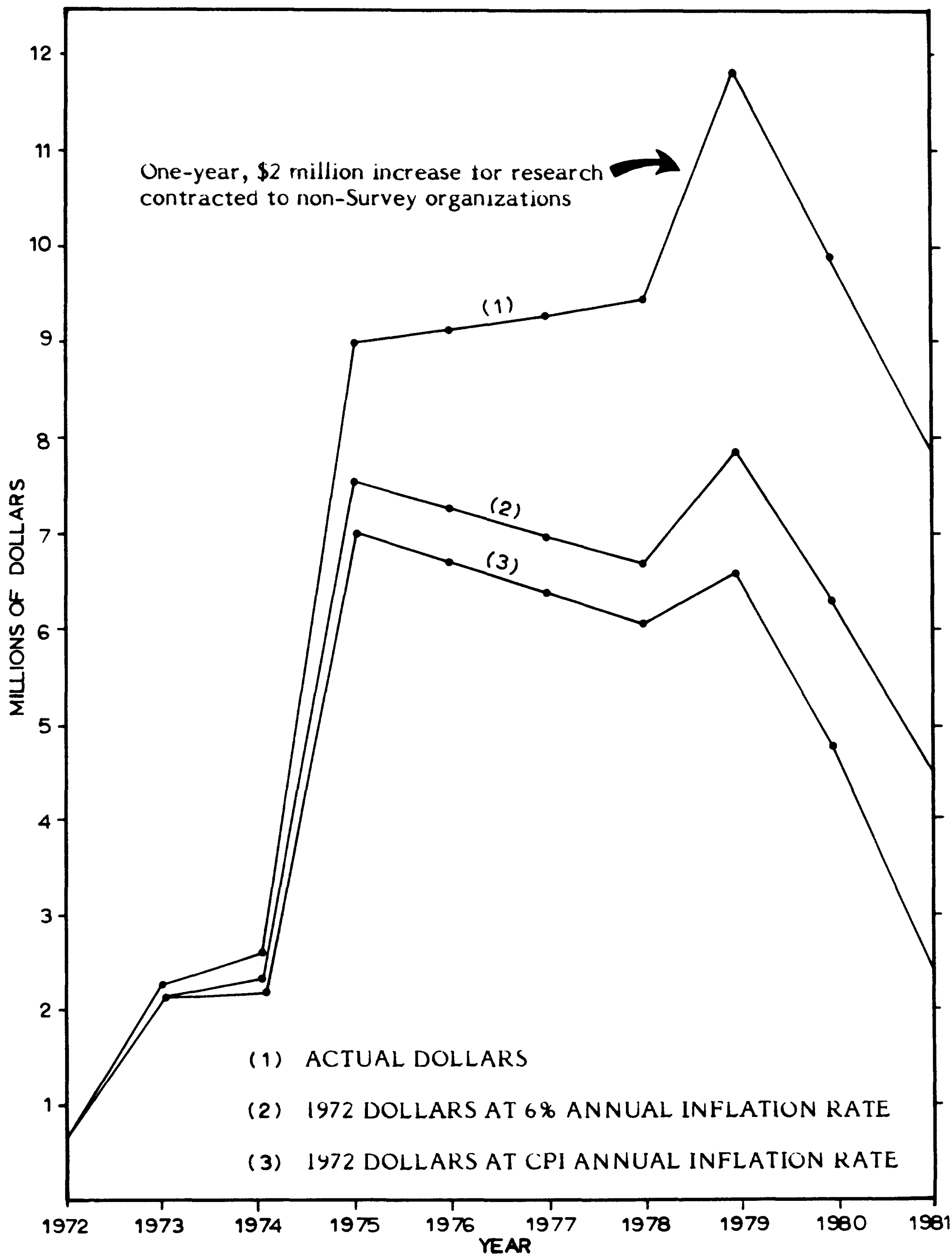


Figure 1. Graph of funding of Geothermal Research Program since 1972. CPI = Consumer Price Index. See text for further discussion.

Dollar Amounts			
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		
Office of Resource Analysis	137,036		
Total		203,974	
Office of Environmental Geology			
Branch of Engineering Geology	20,000		
Branch of Central Environmental Geology	308,535		
Branch of Western Environmental Geology	61,883		
Total		390,418	
Office of Geochemistry and Geophysics			
Branch of Experimental Geochemistry & 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	2,398,335		
Water Resources Division Total			2,398,335
GRAND TOTAL			9,876,000

Table 1. Distribution of funds of the Geothermal Research Program for 1980.

further as current contracts terminate. The balance of the 1981 budget reduction is accounted for by fewer in-house projects.

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

Accomplishments

Major accomplishments of the Survey's Geothermal Research Program are documented in nearly 800 reports and maps published since the inception of the program. A current listing of all 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 of back cover). Copies of reports and maps generally may be found at one or more of the U.S. Geological Survey libraries (Menlo Park, California; Denver, Colorado; Reston, Virginia) or, in some instances, may be obtained directly from the authors.

Space does not permit a summary of all of the scientific accomplishments of the program to date, but a few noteworthy highlights are indicative of its overall productivity. Fundamental progress has resulted from studies of the chemical and physical properties of geothermal fluids. Research carried out before the formal establishment of the Survey's Geothermal Research Program led to a distinction between vapor-dominated (dry steam) and hot-water convective hydrothermal systems, by means of chemical characteristics of fluids that leak to the surface from such systems (White and others, 1971). Vapor-dominated systems are presently 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 is 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 (fig. 3 a, 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 from chemical characteristics of thermal water that leaks to the Earth's surface (e.g. Fournier and Truesdell, 1973; Fournier and Potter, 1979; Fournier, 1977, 1979, 1981; Truesdell and Fournier, 1976, 1977). The successful development and widespread use of these chemical geothermometers has resulted in economic benefits that 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

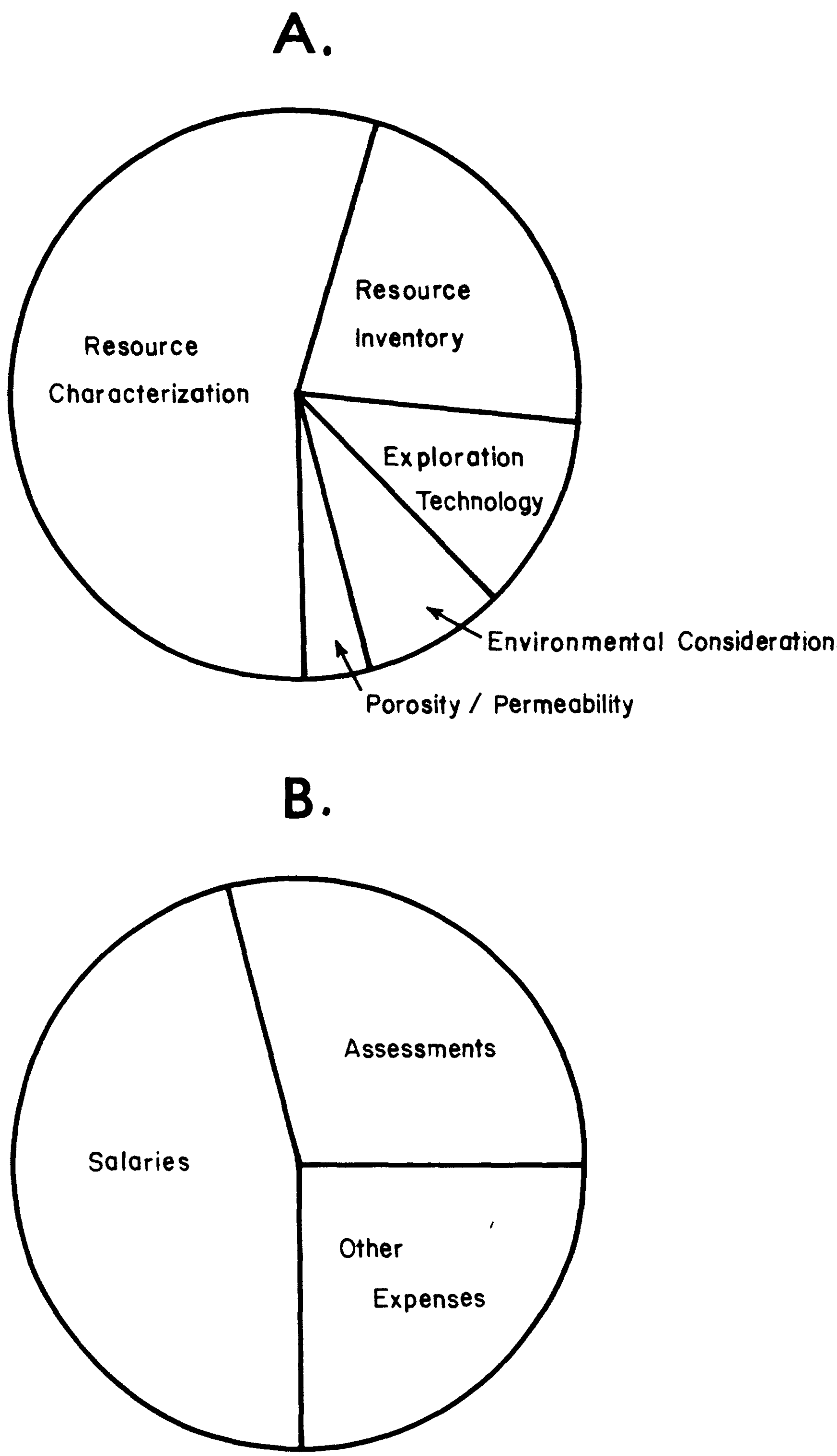
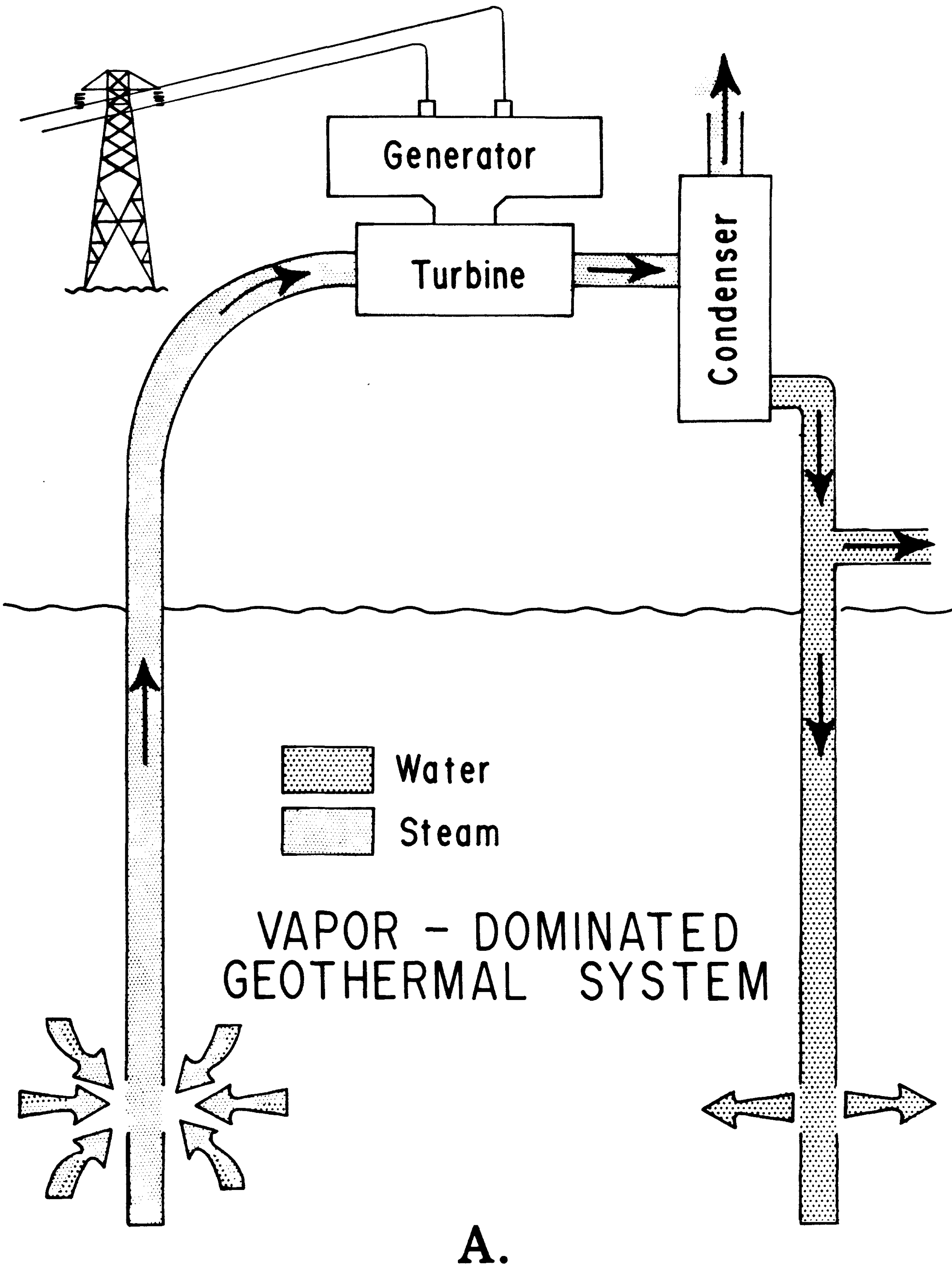


Figure 2. Allocation of 1980 budget of Geothermal Research Program by (A) general research topics and (B) the three principal categories that comprise a typical project. "Assessments" represents the non-salary, overhead costs of operating the U.S. Geological Survey, and "Other Expenses" represents direct research costs other than salaries, such as field and laboratory expenses.



Schematics illustrating the generation of electricity from geothermal systems (from Muffler, 1977).

Figure 3A. Vapor-dominated system; dry steam goes directly from wellhead to turbine.

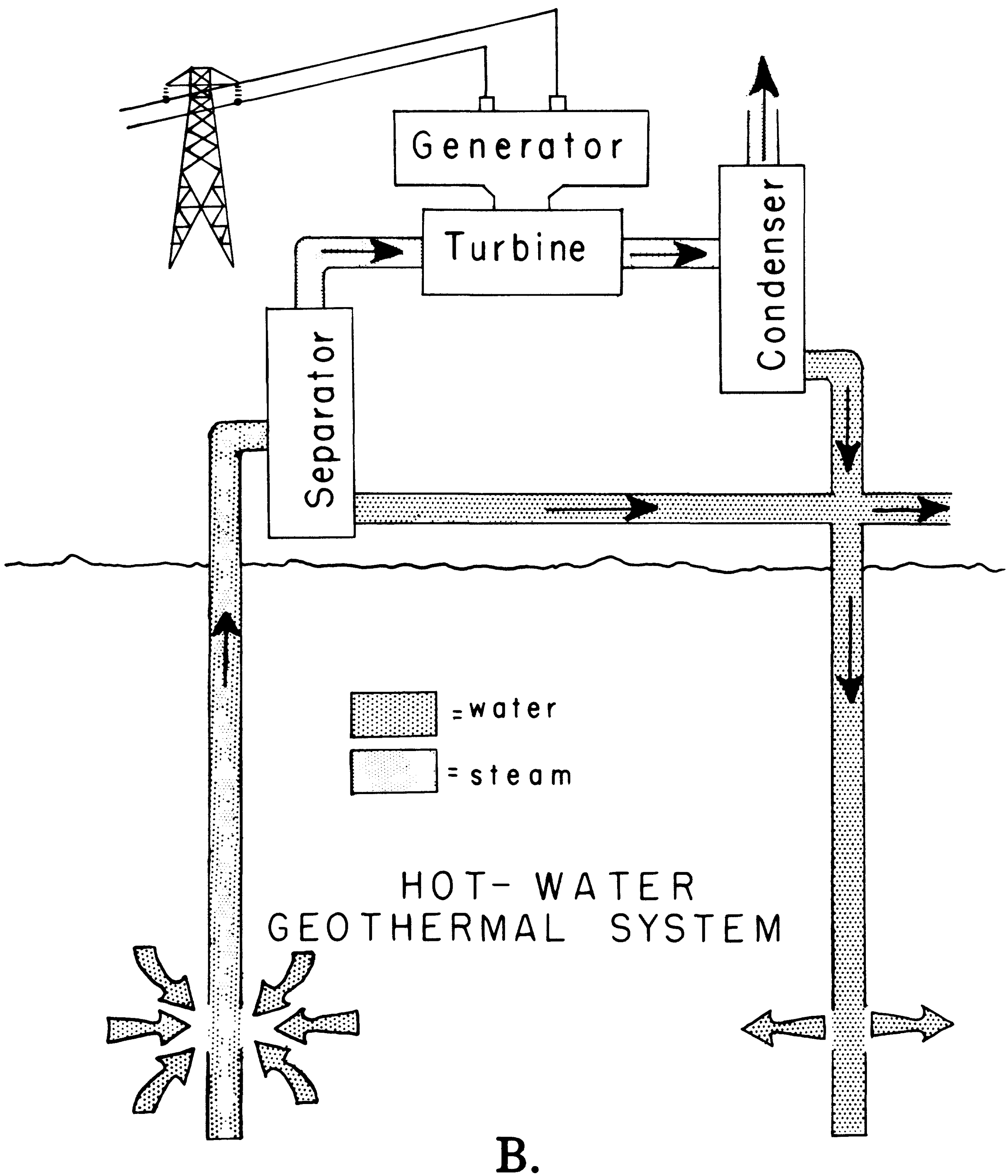


Figure 3B. Hot-water system; waste water leaving separator and condenser is much more abundant than for a vapor-dominated system.

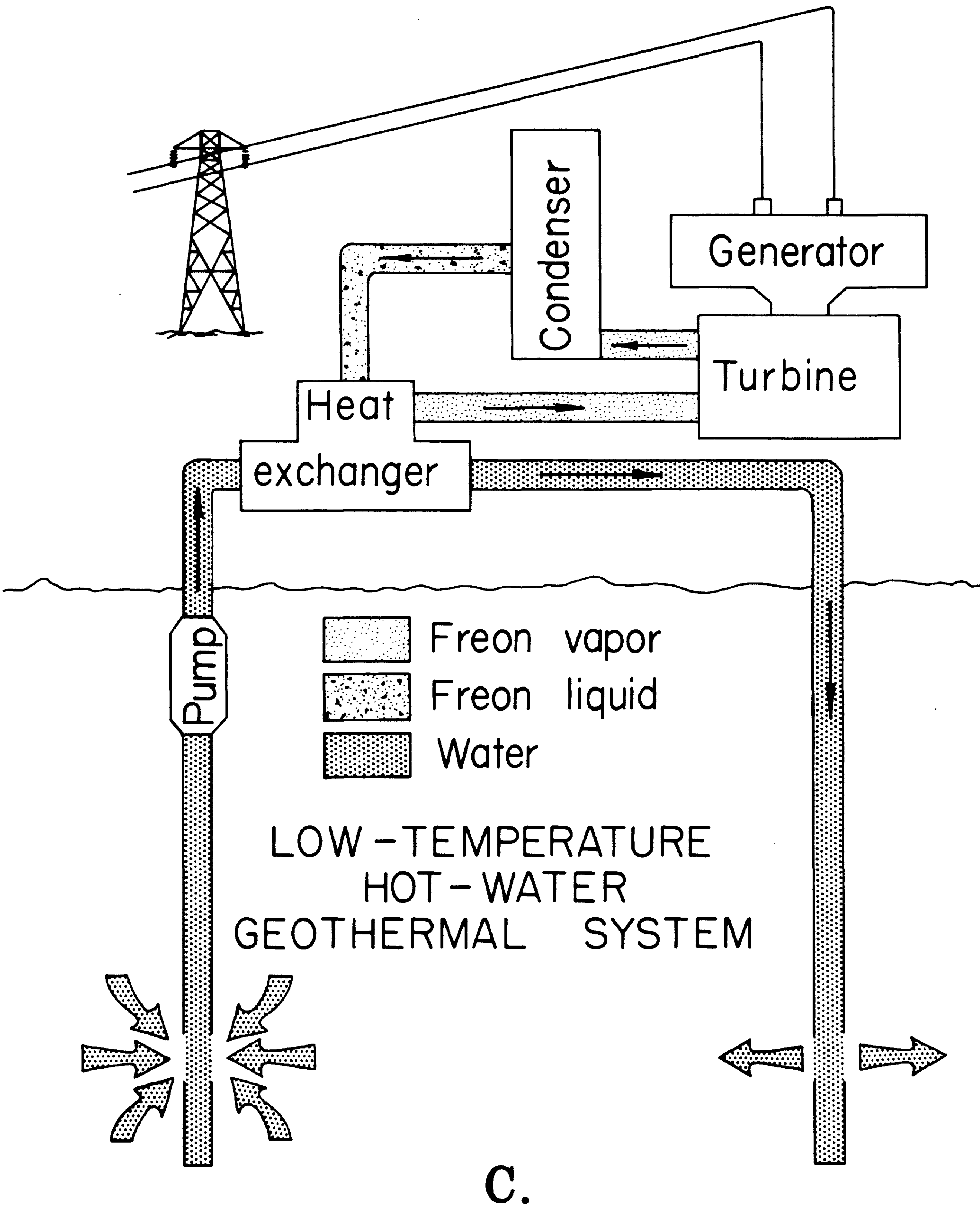


Figure 3C. Low-temperature hot-water system; geothermal fluids are used to heat a second fluid with a lower boiling temperature that is routed through a turbine.

broad recognition of their value, such geochemical studies, pioneered within the Survey, are 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 aimed at understanding the formation and evolution of crustal magmatic systems that represent the roots of such fields. Building on the results of their earlier Survey research in volcanology, Smith and Shaw (1975, 1979) developed a method to calculate the thermal energy 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 (Delaney and Pollard, in press). 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 occurred in understanding the histories of volcanism at The Geysers-Clear Lake (Hearn and others, in press; Donnelly and others, in press), Long Valley (Bailey and others, 1976) and Coso (Duffield and others, 1980) in California, at Newberry Volcano in Oregon (MacLeod, 1978), at the San Francisco Peaks in Arizona (Ulrich and others, 1979; Moore and Wolfe, 1974), at Ship Rock in New Mexico (Delaney and Pollard, in press), and at Yellowstone National Park (Christiansen, in press). 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. The studies of volcanic fields and magmatic systems in general have greatly increased knowledge of the processes by and rates at which material and thermal energy are moved within magmatic and associated hydrothermal systems, knowledge that is critical to understanding the creation, functioning, and longevity of exploitable geothermal resources.

To further characterize the magmatic roots of the volcanic systems, a seismic technique was developed to map zones of relatively low seismic velocity that may represent molten or partly molten rock within the Earth's crust and upper mantle. The seismic studies have demonstrated that such low-velocity material underlies volcanic fields at Long Valley, California, (Steeples and Iyer, 1976); Yellowstone National Park (Iyer, 1979); The Geysers/Clear Lake, California, (Iyer and others, 1979); Coso, California, (Reasenberg and others, 1980); Roosevelt Hot Springs, Utah, (Robinson and Iyer, 1979); and the San Francisco Mountains, Arizona, (Stauber, 1980). At each of these areas, the existence of magma has been independently inferred from the history of volcanism reconstructed through geologic studies. Thus, the geologic and seismic data together provide important constraints on an understanding of magma-related geothermal systems, and in specific instances they provide confirmation that magma exists today as a source of heat for such systems. Geophysicists can also detect the flow of magma within the Earth's crust using precise measurements of ground deformation at the surface (Swanson and others, 1976). Theoretical models (Pollard and Holghausen, 1979) of the interaction between magma-filled fractures and the surface allow one to estimate 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 California's Imperial Valley, one of the most richly endowed geothermal areas in the United States, was recently delineated; geothermal systems were found to be associated with zones of relatively high seismic velocity in the sediments that fill the valley (G. S. Fuis, pers. commun.). These velocity anomalies are inferred to arise from concentrations of minerals that were deposited in pore spaces of the valley-filling sediments by convective hydrothermal fluids. Thus, this seismic technique provides a tool for the exploration of sediment-filled valleys and may be especially valuable in such geologic settings to help locate convective hydrothermal systems that do not have surface manifestations such as hot springs and fumaroles.

Intermediate-temperature (90°-150°C) geothermal systems 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 Raft River, Idaho, where Survey studies guided exploration for wells to support a recently completed experimental binary-cycle electric power plant (fig. 3c; Mabey, 1980; Mabey and others, 1978; Williams and others, 1976).

Measurements of temperature gradients 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 provides a current reference to be widely used by researchers interested in heat flow and the thermal regime of the Earth's crust (Sass and others, in press). Considerable effort has been focused on the western United States, especially on the Basin and Range province in Nevada and Utah where heat flow is generally high but variable. 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), consistent with the tectonic regime indicated by other geologic and seismic data. Additional measurements have enlarged a 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, southeast Oregon, and possibly the Cascade Range in Oregon and northern California.

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

Because most geothermal systems are more electrically conductive than surrounding cooler rocks, geoelectrical techniques may be used to map the lateral and vertical extent of a geothermal system during surface exploration. The Geothermal Research Program has continued to expand the versatility and variety of such methods. The standard exploration technique of direct current (DC) soundings is now augmented by self-potential (SP), audio-magnetotelluric (AMT), and magnetotelluric (MT) techniques, each differing in terms of source of energy for the survey and the range of frequencies, and thus the effective depths, examined. With a combination of techniques, the electrical structure of the crust and upper mantle may now be examined to depths of several tens of kilometers. Relatively shallow-probing techniques such as SP, DC soundings, 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 (e.g. Hoover and Long, 1976; Zohdy and others, 1973; Zohdy, 1978). At Kilauea Volcano in Hawaii, a high-temperature (365°C) hydrothermal well, the first well to confirm the existence of an exploitable geothermal system at Kilauea, was sited principally on the basis of SP mapping (Zablocki, 1977). Deeper-probing methods, chiefly MT, may yield information on the location of bodies of magma and other heat sources, complementing some of 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 temperatures and pressures characteristic of geothermal environments. To address this limitation, the Geothermal Research Program 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, produces information that is invaluable in improving the interpretation of geophysical data collected during field surveys (Hunt and others, 1979).

In order 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. An especially useful innovation is the acoustic televiewer which provides information about the size, orientation, and location of the fractures that provide permeable pathways and allow hot fluids to be extracted from many geothermal systems (Keys and Sullivan, 1979).

Two key publications of the Geothermal Research Program synthesized the results of a myriad of individual projects to address one of the principal objectives of the program -- quantitative assessment of the nation's geothermal resources. Publication of U.S. Geological Survey Circular 726, "Assessment of Geothermal Resources of the United States - 1975," represented the first such national assessment that was based on a consistent, well-documented methodology constrained by tabulated data on the physical and chemical nature of known geothermal systems. Geothermal resources were evaluated as the fraction of thermal energy above 15°C stored in the crust that might be recovered at the surface, with reasonable assumptions of future technology and economics.

Three years later, after the Survey's 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 U.S. Geological Survey Circular 790, "Assessment of Geothermal Resources of the United States - 1978." Though different 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 52 hydrothermal convection systems greater than 150°C to a depth of 3 km were estimated in Circular 790 to be 220 x 10^{18} joules, equivalent to 23,000 megawatts of electricity for 30 years (assuming about 10% of the thermal energy extracted at the surface can be converted to electricity). Such information contained in the assessments is the principal basis for planning the geothermal component of national energy policy and provides guidelines for establishing goals of electrical production for the overall Federal Geothermal Program.

The Geothermal Research Program maintains a computerized data file on geothermal resources, GEOTHERM, so that the large amount of accumulated data is readily available to Survey researchers, state and other government 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 used in the assessment of geothermal resources less than 100°C. The retrieval of data from the file may be requested in writing (see address on inside of back cover). Data of the GEOTHERM file on thermal wells and springs are also available through the General Electric Information Services Network.

The component of the program devoted to the support of research by non-Survey organizations has resulted in considerable progress in geothermal research. This part of the program supplements and complements in-house projects, and promotes contacts that further collaboration among university, industry, and government scientists.

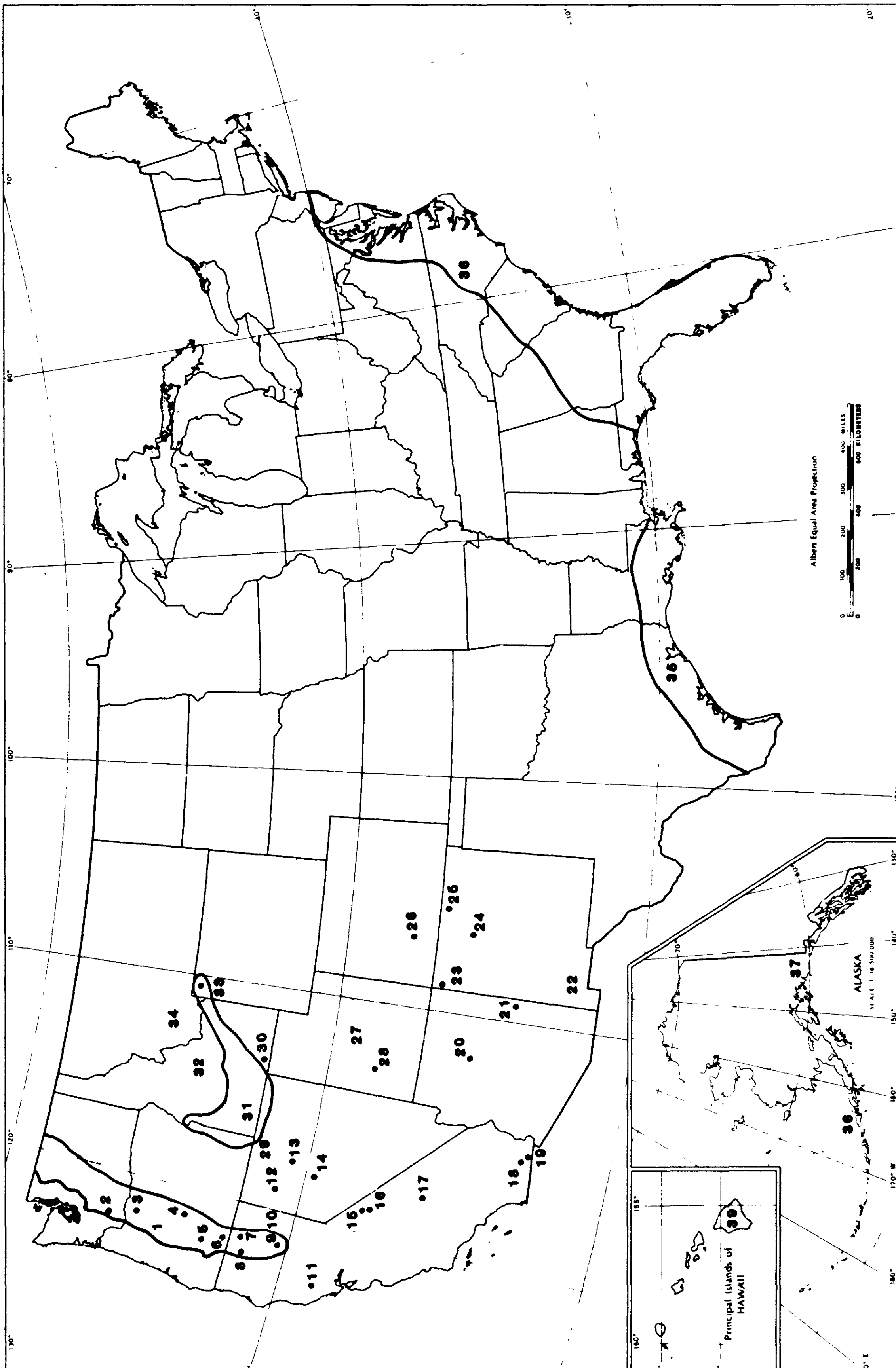
Present Emphasis

At the present time, the principal thrust of the Geothermal Research Program is a multidisciplinary study of the Cascade Range of Washington, Oregon, and northern California. Geologic, geophysical, geochemical, and hydrologic projects will contribute information needed to assess the geothermal potential of this volcanic region. Surface manifestations of geothermal systems, in the form of hot springs and fumaroles, are relatively rare in the Cascade Range, but the fact that several Cascade volcanoes have erupted in historic time suggests that magma-related geothermal systems are present. The reawakening of Mount St. Helens in March of 1980 dramatically illustrates that magma is indeed present locally within the crust beneath the Cascade Range. An important objective of the Cascade studies is to identify the most promising parts of this 1000-km-long range to attract interest in commercial drilling. In February of 1980, the Geothermal Research Program sponsored a "Cascades Conference" at which more than 150 participants, representing academia, state governments, private enterprise, and the federal government, reported on their studies (Bacon, 1980). Similar conferences are anticipated as the Cascade studies progress.

Additional thrusts of the 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. The 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 upon 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 that is sponsored by the Division of Geothermal Energy of the Department of Energy. The review of information on the Great Basin will lead to recommendations in 1981 of additional studies needed to upgrade existing assessment of resources within this large area of anomalously high heat flow.

As a follow-up to USGS Circulars 726 and 790, the first quantitative assessment of geothermal resources less than 100°C is now underway. Low-temperature geothermal fluids are appropriate for non-electrical uses such as space heating, industrial drying processes, and agricultural applications. Future assessment needs include consideration of the geothermal energy that may be recovered through hot-dry-rock technology (i.e. a man-made geothermal reservoir produced 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 assessment 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 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 projects in the section entitled "Projects of the Geothermal Research Program for 1980" provides additional information. Locations of field-oriented research projects of the Geothermal Research Program for 1980 are shown on a map of the United States (figure 4).


Albers Equal Area Projection
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Principal Islands of HAWAII
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Figure 4. Map showing locations of field-oriented projects of the Geothermal Research Program for 1980. Place names and general description of project work are given for each numbered location.

1. Cascade Range - hydrothermal alteration, hydrology, geology, fluid geochemistry, paleomagnetism, heat flow, aeromagnetic survey, geoelectric studies, seismicity, resource assessment, gravity.
2. Mt. St. Helens - seismic studies.
3. Mt. Hood - gravity, magnetics, geology, hydrology, fluid geochemistry, hydrothermal alteration, seismicity, thermal infra-red sensing.
4. Newberry/Three Sisters Volcanoes - geology, hydrology, geoelectric studies.
5. Mt. Mazama (Crater Lake) - geology, petrology, geochronology, geophysics.
6. Klamath Falls - hydrology, hydrologic modeling.
7. Medicine Lake Volcano - geology, petrology, geochronology, geochemistry.
8. Mt. Shasta - geology, petrology, geochronology.
9. Lassen Region - geology, hydrothermal alteration, fluid geochemistry, geochronology, geoelectric studies.
10. Northeast California Cascades - geology.
11. The Geysers/Clear Lake - 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 Mtns. - 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 Mtns. - geology, geochronology.
38. Aleutian Arc Volcanoes - geology, geochronology, fluid geochemistry.
39. Hawaiian Volcanoes - seismicity, ground deformation, fluid geochemistry, paleomagnetism, magma reservoirs, geophysics, geology.

Geothermal Development

The impetus to develop alternate sources of energy is reflected in the recent trend of installed geothermal electrical capacity. Announced development plans suggest that the rate of growth of installed geothermal electrical capacity (worldwide) may more than double in the next decade from its previous rate of 7 percent per year (fig. 5; also 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. 6). The present 908-megawatt 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 megawatts of additional capacity is expected to be installed in the next few years (Reed, 1981). The first geothermal electrical power from a hot-water system in the United States recently came on-line at the Brawley field in the Imperial Valley, California, and additional electrical generation is anticipated from other hot-water fields in the Imperial Valley, California, at the Valles Caldera, New Mexico, Roosevelt Hot Springs, Utah, Raft River, Idaho, and Puna, Hawaii within the next few years.

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

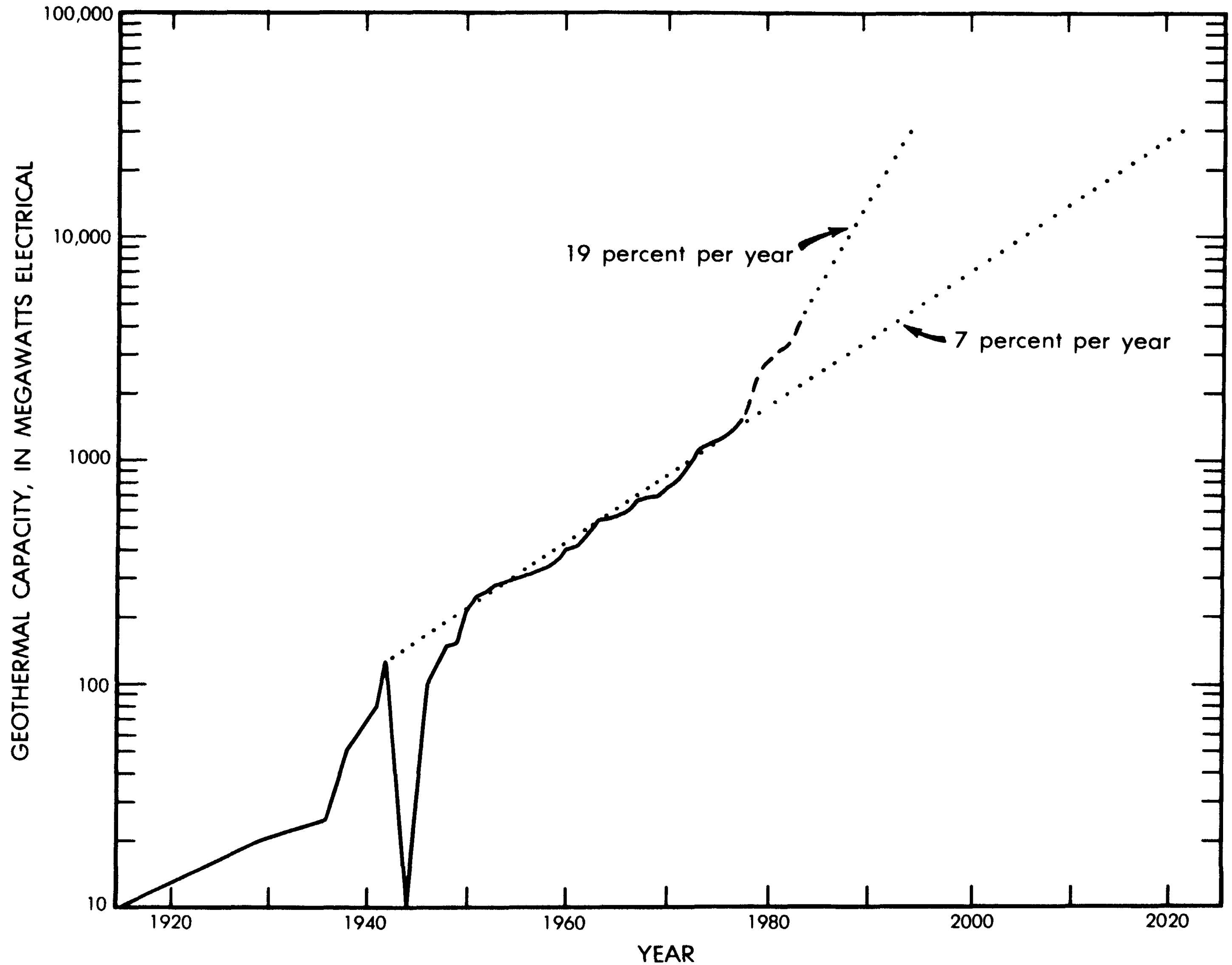

Figure 5. Graph showing worldwide installed geothermal electrical capacity as a function of time (from Muffler and Guffanti, 1979). Dashed line indicates plants under construction or committed up to 1983. The dotted extrapolations can be interpreted as upper and lower limits of expected growth.

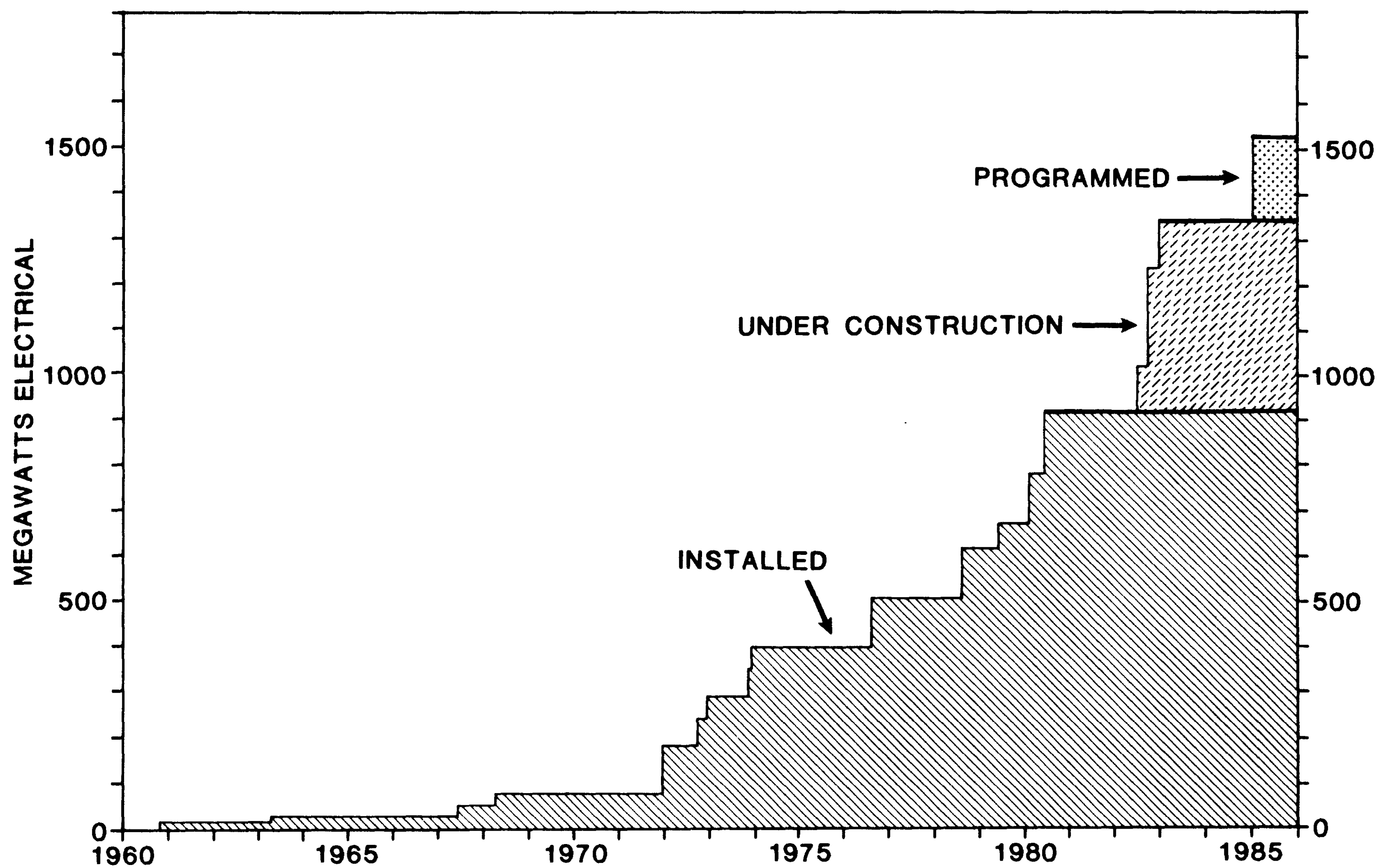

Figure 6. Installed and expected generating capacity at The Geysers, California, as a function of time. Data collated by L.J.P. Muffler (written communication, 1980).

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Projects of the Geothermal Research Program for 1980

Projects are subdivided into 6 topical research categories. A project that pertains to more than one topic is assigned to the single category that represents the principal focus of the project to avoid multiple listing. To quickly locate a project by project chief or principal investigator, refer to table 2. An asterisk indicates research by a non-Survey organization funded by the Geothermal Research Program through grants and contracts. Any questions concerning project status or the status of material listed as being in preparation should be directed to Wendell A. Duffield, Geothermal Program Coordinator (address on inside back cover).

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Table 2. Index of projects of the Geothermal Research Program for 1980, listed by project chief with project title and text page given. Asterisks indicate research by non-Survey organization.

Project chief | Page

Project Chief | Page

Project Chief Page

VOLCANIC SYSTEMS AND MAGMA CHAMBERS

Project Title: Volcanic Evolution of the Crater Lake Region

Project Chief: Charles R. Bacon
(Menlo Park, California)

Project Objectives: To study the geology and petrology of Mt. Mazama and the Crater Lake area of Oregon, with emphasis on developing an understanding of processes that lead to the emplacement of shallow silicic magma bodies. To document the chronology of eruption, chemical variation of eruptive products, and tectonic deformation through detailed geologic mapping supported by ^{14}C and potassium-argon dating, paleomagnetic studies, and chemical analyses. To develop a model of volcanic and tectonic evolution of the Crater Lake area that may be used to recognize similar volcanic systems that possess shallow silicic magma reservoirs but have not progressed to the climactic stage of eruption exemplified by Mt. Mazama. To examine relations among silicic magma bodies, high-temperature geothermal systems, and processes of ore deposition.

Project Status: Detailed geologic mapping of the walls of Crater Lake caldera and extensive sampling of eruptive products have provided evidence for a new interpretation of events immediately prior to and during the climactic eruption of Mt. Mazama. Many deposits previously thought to be of glacial origin are now recognized as the products of pyroclastic flows. As a result of this first phase of work the volcanic stratigraphy of much of Mt. Mazama has been established. Hydrothermally-altered volcanic rocks exposed in the caldera walls provide evidence of a fossil geothermal system that may have overlain the shallow silicic magma chamber that fed the climactic eruption. Related studies by C. H. Nelson and D. L. Williams have revealed the presence of as much as 100 m of sediment and the probable emission of geothermal fluids on the floor of the lake.

Project Title: Geology of Long Valley-Mono Basin Geothermal Area

Project Chief: Roy A. Bailey
(Reston, Virginia)

Project Objectives: To provide, primarily by means of detailed geologic mapping and petrochemical studies, basic volcanologic petrologic, and structural information needed to understand the physical, chemical, and thermal evolution of the magma chambers and geothermal systems associated with Long Valley Caldera and the Mono Craters ring-fracture system of California.

Project Status: Since initiation of the project in 1972, a preliminary paper on the geology of Long Valley Caldera has been published, and two open-file maps, one of the Casa Diablo geothermal area (scale 1:20,000) and another of Long Valley caldera (scale 1:62,500), have been made available. Both maps are presently being prepared for publication in full color. A third map of the entire Long Valley - Mono Basin Known Geothermal Resource Area (scale 1:125,000) is planned. Petrologic (microprobe and major - and trace-element) studies are in progress on several volcanic rock groups associated with the caldera: 1) precaldera basalts and quartz latites; 2) rhyolites of Glass Mountain; 3) postcaldera rhyolites; 4) postcaldera basalts and quartz latites; and 5) the rhyolites of the Inyo-Mono craters. Separate petrologic reports on each group are planned. A more general, comprehensive report on the volcanism, structure, and general petrology of the Long Valley Caldera is in preparation.

Project Title: Petrology of the Yellowstone Plateau Volcanic Field

Project Chief: Robert L. Christiansen
(Menlo Park, California)

Project Objectives: To study in detail the mineralogy, geochemistry, and petrology of the voluminous rhyolite-basalt association of the Yellowstone Plateau and Island Park region in order to interpret origin and evolution of the magmas and their relation to regional evolution of the crust and upper mantle, possible future volcanism, and existing high-temperature hydrothermal systems. To study aspects of the petrology of other voluminous silicic volcanic systems for comparative analysis and to do experimental studies of differentiation mechanisms in silicic magmas.

Project Status: A large suite of samples has been collected that represents most recognized emplacement units of the Yellowstone Plateau volcanic field. Systematic major- and trace-element and isotopic analyses have been started for most of the rhyolitic units, and a first data set has been nearly completed for the voluminous rhyolitic ash-flow tuffs of the field. Detailed electron-microprobe analyses have been started on minerals and glasses for many of these same units. At this point, only reconnaissance studies have been done on the basalts. Field and petrologic studies of the Bishop Tuff of eastern California and of the Katmai-Valley of Ten Thousand Smokes system in Alaska have also been completed as parts of the comparative study.

Project Title: Volcanology and Petrology of the Mount Shasta Region

Project Chief: Robert L. Christiansen
(Menlo Park, California)

Project Objectives: To study the volcanic evolution and the mineralogy, geochemistry, and petrology of the calc-alkalic volcanic association of Mount Shasta, California and surrounding parts of the Cascade volcanic chain in order to intepret origin and magmatic evolution of the late Cenozoic magmatic system and its relation to regional evolution of the crust and upper mantle, possible future volcanism, and geothermal potential of the Cascade Range in northernmost California.

Project Status: The project grew out of the evaluation of a Wilderness Area in 1976, but only a small amount of geologic mapping has been done since that time because of administrative assignments of the project chief. A detailed geologic map of Mount Shasta has been compiled, and brief reconnaissance field studies have been carried out in the Cascade chain between the Klamath and McCloud Rivers. Work is now resuming on the study.

Project Title: Volcanic Hazards

Project Chief: Dwight R. Crandell
(Denver, Colorado)

Project Objectives: To study late-Quaternary volcanic rocks in order to infer the kinds and frequency of eruptive events they represent. To provide information needed for evaluating potential hazards to communities, reservoirs, recreation facilities, and proposed nuclear powerplants which could be affected by future eruptions. To provide data to help evaluate the geothermal potential of volcanic regions in the Western United States.

Project Status: During 1980, USGS Bulletins were completed on recent eruptive histories and potential hazards at Mount Hood, Oregon, and Mount Shasta, Oregon. A manuscript was completed on Holocene eruptive history and potential hazards from future eruptions of Glacier Peak, Washington. A manuscript was completed for a USGS Bulletin on pyroclastic flows and lahars from Mount St. Helens, Washington. Detailed stratigraphic and paleomagnetic investigations of the eruptive activity of Mount St. Helens during the last 450 years are continuing in order to evaluate evidence for eruptive cycles. Detailed stratigraphic investigations were started in the Mono Craters-Inyo Craters volcanic chain, California, to determine the kinds, frequency, and extent of eruptive activity during the Holocene in that region. Studies are also in progress to assess the state of evolution of Mount St. Helens and Mount Shasta (with R. L. Christiansen) to attempt to predict the nature of future eruptions. These studies will review temporal chemical variations in eruptive products, evaluate past eruptive behavior, and examine evidence for possible evolutionary or cyclic trends.

Project Title: Hawaiian Magma Reservoirs

Project Chief: Robert W. Decker
(Hawaiian Volcano Observatory)

Project Objectives: To determine the surface and subsurface characteristics of areas of magma occurrence. To establish the in situ physical properties of magma and its host rocks. To determine the heat transfer budget and mechanisms between magma bodies and adjacent ground water systems. To determine other significant parameters of magma bodies to aid in the exploration for geothermal energy resources by collecting and synthesizing a variety of geologic, seismic, geoelectric, geophysical and geochemical data.

Project Status: This is a long-term ongoing project that is part of the research program at the Hawaiian Volcano Observatory. Several topical papers concerning magma-related electro-magnetic sounding surveys on Kilauea, fumerole inventory of Hawaiian volcanoes, and volatile budget for Hawaiian volcanoes are published or in press.

Project Title: Medicine Lake Volcano

Project Chief: Julie Donnelly-Nolan
(Menlo Park, California)

Project Objectives: To assess the geothermal potential of Medicine Lake Volcano, California through detailed geologic mapping, isotopic dating, and chemical analysis of lavas. To interpret the volcanic history and tectonic setting, together with geophysical information from other projects in terms of magmatic source regions and shallow magma reservoirs that may serve as a heat source for geothermal resources.

Project Status: At least 5 late Holocene silicic flows and numerous late Holocene basaltic flows are present, making Medicine Lake volcano a prime target for geothermal exploration. Since June 1979, an area of nearly 200 km^2 on the northwestern and eastern sides of Medicine Lake Volcano has been mapped in detail. The mapping has revealed a complex volcanic stratigraphy, significantly revised from earlier studies. An undated andesite ignimbrite previously thought to be the volcano's basal unit, is normally polarized and is actually in the upper 20 percent of the volcanic pile. Significant volumes of silicic lavas predated the andesite ignimbrite, notably a previously unrecognized rhyolitic ash flow that is thicker and more widespread than the later andesitic one. A complex sequence including basalt, andesite, dacite and rhyolite flows was erupted between the two ignimbrites. A similar complex sequence postdates the andesitic ash flow. Thus the volcano is not a basaltic shield as thought by some previous workers.

Project Title: Coso Mountains

Project Chief: Wendell A. Duffield
(Menlo Park, California)

Project Objectives: To evaluate the geothermal potential of the Coso Range area of California through geologic mapping, geochronology and chemical studies of the Coso volcanic field, in conjunction with complementary studies such as aeromagnetics, gravity, electromagnetics, seismicity, heat flow, ground deformation, hydrology, and drilling.

Project Status: Many of the original goals of the Coso project have been achieved with the publication of a colored geologic map (in press) and 11 papers in the May 1980 issue of the Journal of Geophysical Research. Two of the JGR papers are direct products of this project and document geologic evidence for the nature and extent of volcanic, tectonic, and geothermal activity in the area. The other papers present geophysical and geochemical data from related studies. Isotopic, geochemical, and mineralogic studies of Coso volcanic rocks are continuing.

Drilling of a 1477 m-deep test hole at the Coso geothermal field, California. The youthfulness of the rhyolite dome in the background and many other domes in the area suggests that partially-molten rock may be present several kilometers beneath the hydrothermal system penetrated by this drill hole.

Project Title: Geothermal Paleomagnetic Studies

Project Chief: Sherman Grommé
(Menlo Park, California)

Project Objectives: To use paleomagnetic measurements on volcanic rocks as an aid in geologic studies of volcanoes. To measure secular variation and polarity reversals of the geomagnetic field as a way to date and correlate volcanic events in individual volcanic fields.

Project Status: The areas of principal investigation to date have been the Snake River Plain of Idaho and Wyoming, the Cascade Range of California, Oregon, and Washington, and the island of Hawaii. Secular variation has proved to be a remarkably strong tool for assigning ages to many otherwise undated lavas at Kilauea Volcano. Future work will concentrate on the Cascade Range at Newberry Caldera, Oregon, the Three Sisters area, Oregon, Mt. Mazama, Oregon, and the Medicine Lake Highlands-Modoc Plateau area, California.

Project Title: Geology of The Geysers-Clear Lake Area, California

Project Chief: B. Carter Hearn, Jr.
(Reston, Virginia)

Project Objectives: To map, isotopically date, chemically analyze, and determine remanent magnetism of the Clear Lake Volcanics of California to determine the age, eruptive sequence, structure and petrology of the magmatic system and evaluate its potential for geothermal resources beyond the present production area of The Geysers steam field. To locate active faults and document ongoing deformation in the area. To coordinate with ground-based and airborne geophysical studies to determine sub-surface structure, tectonic activity, the presence of a magma chamber, and potential for future eruptive activity. To sample springs and wells for chemical analysis and interpretation of subsurface geothermal reservoirs.

Project Status: Field work is completed and the project is in the writing and laboratory-work stages. Prof. Paper 1141, Compendium of Geysers-Clear Lake Studies, is in press. Compilation of a 1:24,000-scale geologic map is in progress. Most of the mapping has already been open-filed. A map showing springs and faults is nearly completed. Coordination with on-going geophysical studies such as measurement of ground deformation, detection of a magma chamber and the analysis of thermal fluids is continuing, as is the interpretation of cuttings from geothermal exploration holes to correlate subsurface units with mapped units and to determine patterns of hydrothermal alteration. Further detailed petrologic study to determine the origin and evolution of magma awaits results of electron probe analyses. Potassium-argon dating and strontium-isotopic study are completed. Oxygen-isotopic study has been started.

Project Title: Seismic Studies of Hawaiian Magma Reservoirs

Project Chief: Fred W. Klein
(Hawaiian Volcano Observatory)

Project Objectives: To gather and analyze seismic data to determine the detailed structure, location, size, and physical properties of magma chambers and conduits within Kilauea Volcano, Hawaii.

Project Status: The project helps support the computer-assisted reduction and analysis of earthquake data recorded on the Hawaiian Volcano Observatory's seismic network. The timing, accuracy, and ease of handling of data which is possible with computer-based processing has markedly improved the number and quality of earthquake locations since such processing began in early 1979. The high quality of earthquake locations helps to locate magma conduits within Kilauea's east rift zone (revealed by earthquakes at the leading edges of intrusive dikes) to an accuracy of a few hundred meters. Magma storage pockets are inferred from the initiation points of intrusive dikes. Digital seismograms will be used for studies of seismic attenuation within Hawaii's volcanoes.

Project Title: Geothermal Geochronology

Project Chief: Marvin Lanphere
(Menlo Park, California)

Project Objectives: To provide geochronologic and related isotopic studies in support of volcanologic studies associated with geothermal research and exploration. To determine the age and rate of evolution of volcanic centers as a method of evaluating geothermal potential. To develop thermoluminescence as a radiometric dating technique for volcanic rocks in the age range (10^3 - 10^5 years) of geothermal interest.

Project Status: The project, which began in 1972, has placed major emphasis on detailed potassium-argon (K-Ar) geochronology of several selected areas of major interest to the geothermal program. Studies have been completed on Long Valley, California; Coso Range, California; Wrangell Mountains, Alaska; and Alaska Peninsula, Alaska. Two major papers on these studies have been published in outside journals and two more are in press. Two open-file reports and one USGS MF-Map have also been published. Additional K-Ar studies in the Snake River Plain, Idaho, and Mt. Shasta, California and a strontium-isotopic study in the San Francisco Volcanic Field, Arizona, are in progress. Support from the geothermal program for development of thermoluminescence (TL) as a dating technique began in 1975. Considerable success has been achieved using sanidine from silicic volcanic rocks. Two manuscripts on sanidine TL dating are currently in preparation. Research on the TL properties of plagioclase from intermediate composition volcanic rocks has been initiated and the preliminary results are promising, although more work will be needed before a TL dating method for these types of rocks is complete.

Project Title: Roots of Calderas and Fossil Geothermal Systems

Project Chief: Peter W. Lipman
(Denver, Colorado)

Project Objectives: To undertake a regional reconnaissance of the transition between volcanic and plutonic environments of silicic igneous systems in the western U.S. To examine caldera-related structures in the southern Rocky Mountains that are sites of fossil geothermal systems and hydrothermal ore deposits. To determine the geometric structural relations between volcanic and plutonic features as precisely as possible and to use the constraints in investigating pressure-temperature-composition conditions of alteration and mineralization by geochemical and experimental petrologic techniques.

Project status: About 200 km^2 of structurally complex Tertiary volcanic and intrusive rocks within and adjacent to the 23 m.y.-old Red River caldera near Questa, New Mexico, have been mapped at a scale of 1:24,000. Petrologic, major- and minor-element geochemical, potassium-argon and fission-track geochronologic, and paleomagnetic studies are also underway, in an attempt to decipher space-time relations in the evolution of a large silicic magmatic system, now exposed both as surficial volcanic deposits and as a highly evolved granitic intrusive complex, truncated by the frontal fault of the Sangre de Cristo Mountains. Petrologic comparisons between the intrusive and extrusive rocks will aid understanding of magmatic processes that are cogenetic with silicic volcanism, caldera collapse, development of large-scale hydrothermal systems, and associated molybdenum ore deposits. The project will include a mineral-potential evaluation of the Hondo-Columbine roadless area.

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*Project Title Laboratory Investigations of the Seismic and Thermal Properties of Basalt to Melting Temperatures
(Grant No. 14-08-0001-G-576)

Principal Investigator: Murli H. Manghnani
University of Hawaii at Manoa
Honolulu, HI 96822

Project Objectives: To investigate in the laboratory the physical, seismic, and thermal properties (thermal diffusivity and conductivity and specific heat) of basalts and basaltic magmas as a function of composition and structure of the rock, fluid content, pressure and temperature (to melting temperature).

Project Status: The water-saturation technique, helium pycnometer and mercury porosimeter have been used to determine the porosity, and the scanning electron microscope has been used to study the pore and microcrack size-distribution structure. Extensional and tortional attenuation and longitudinal- and shear-wave velocities have been measured as a function of confining pressure on both dry and saturated samples. Both extensional and tortional attenuation have been successfully measured in an alkalic basalt melt in the temperature range of about 1200-1400°C over a frequency range of 0.5 to 3 MHz by continuous wave interferometric technique. Both types of attenuation are relatively independent of frequency. The feasibility of a continuous-wave technique for measuring velocity and attenuation in melts has been demonstrated. Satisfactory results were obtained with ordinary radio-frequency oscillators generating 10-20 volt sine waves. High signal-to-noise ratios can be easily achieved with a lock-in amplifier without the sophisticated electronics.

Project Title: Tephra Hazards from Cascade Range Volcanoes

Project Chief: Donal R. Mullineaux
(Denver, Colorado)

Project Objectives: To document the sequence of Holocene tephra erupted from Mount Mazama, Oregon, in order to assess potential hazard from future eruptions of that type and magnitude. To evaluate through cooperative efforts, processes recorded by changes in chemical and mineralogic compositions of tephras from Mount St. Helens, Washington, for possible use in evaluating cyclic activity and future eruptions. To provide data on magmatic systems that may be used to assess associated geothermal potential.

Project Status: Detailed study of tephra deposits and eruptive history of Mount St. Helens continues. The investigation of thicknesses of single, thick beds of tephra from Mount St. Helens and Mount Mazama continues in order to outline their stratigraphy and to determine what thicknesses of tephra might fall at various distances from explosive Cascade volcanoes during future eruptions.

Project Title: Yellowstone Seismic Analysis

Project Chief: Andrew M. Pitt
(Menlo Park, California)

Project Objectives: To locate the earthquakes occurring in the Yellowstone National Park region on a timely basis to define the pattern of hypocenters, source mechanisms, energy release, frequency of occurrence, and signal character of P and S waves as a basis to better understand the fluid circulation, thermal regime, crustal structure, and comtemporary tectonics of the region.

Project Status: Signals from a 16-station seismograph network in the Yellowstone region of Wyoming are now telemetered directly to Menlo Park (beginning in January, 1980), greatly facilitating the promptness and reliability with which the data can be processed. An open-file map of seismic activity in the Yellowstone-Hebgen Lake region from 1973 through 1978 was released in May 1979, and a catalog of the earthquake parameters for the years 1973-1975 was released in October 1980. A catalog for the years 1976-1978 will be released in 1981. A paper on the magnitude-6 earthquake in Yellowstone National Park in 1975 was published in February 1979, and papers on focal mechanism studies, crustal structure, and earthquake-induced changes in thermal area activity are in preparation.

Project Title: Radiocarbon

Project Chief: Stephen W. Robinson
(Menlo Park, California)

Project Objectives: To determine radiocarbon ages of volcanic events, and to use radiocarbon as a tracer for geothermal processes.

Project Status: The project continues to provide radiocarbon dating in support of other geothermal projects. Radiocarbon in Clear Lake, California, has been monitored since March 1979. Extensive collections of vegetation from geothermal areas in Lassen Volcanic National Park, California, are being analyzed to determine the impact of geothermal carbon. A new technique of uranium-thorium isochron dating is being applied to young volcanic rocks from the Lassen region in northeastern California.

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*Project Title Partial Melting, Three-Dimensional Melt Topology, and Electrical Conductivity in Granitic and Basaltic Rocks of Geothermal Environments
(Grant No. 14-04-0001-G-631)

Principal Investigator: Michael P. Ryan
University of Hawaii at Manoa
Honolulu, HI 96822

Project Objectives: To measure electrical conductivity in granitic and basaltic partial melts. To develop criteria for aggregate changes in direct-current electrical conductivity in granitic and basaltic rocks with regard to rock microstructure, mineralogy, the nature of melt-crystal contacts, and water diffusivity and diffusion pathways. To apply labortory results to granitic and basaltic magma chambers using numerical heat-transfer modeling.

Project Status: Research objectives completed thus far are: (1) scanning electron microscopy of melt microstructures, including the effects of voids (discrete gas phase); (2) electron probe microanalysis of melt chemistry and the compositional range; (3) compilation of available English, American, Soviet, Japanese and European data on transport properties of silicate melts, including electrical conductivity, viscosity, and cation-diffusion coefficients; (4) development of a three-dimensional model for mechanically constraining the three-dimensional geometry of magmatic chambers at depth. The model uses a mathematical approach for predicting displacement components associated with the draining of magmatic fluid from a rectinlinear cavity whose width, thickness, depth of burial, and geometric aspect ratio in the horizontal plane may be independently varied.

Project Title: Kinetics of Igneous Processes

Project Chief: Herbert R. Shaw
(Menlo Park, California)

Project Objectives: To assess the kinetic processes of magma generation and ascent in the earth (including the heat and mass transfer processes affecting the evolution of magma chambers) as they bear on the energy budget of igneous-related geothermal resources.

Project Status: Papers have been published describing igneous-related thermal energy classifications (with R. L. Smith), a theory of chemical evolution of silicic chambers (with R. L. Smith and E. W. Hildreth), and theories of magma ascent. Rates of eruption for the Hawaiian-Emperor volcanic chain were calculated over the past 70 m.y. (with E. D. Jackson and K. E. Bargar). Current work involves evaluation of models of chemical evolution of magma chambers.

Project Title: Regional Volcanology

Project Chief: Robert L. Smith
(Reston, Virginia)

Project Objectives: To classify, characterize, and evaluate volcanic systems for geothermal and related purposes. To develop models for the evolution of volcanic systems, their magma chambers and associated geothermal systems, based on field reconnaissance, mapping, sample collection and analysis. To compile and publish special-purpose volcanic maps at a scale of 1:1,000,000 (and other scales as appropriate), covering the eleven contiguous western states, Alaska, and Hawaii.

Project Status: Since its inception in 1972 this project has produced criteria useful for geothermal exploration, developed a rationale for estimating thermal energy in igneous systems, and provided the national estimate of the geothermal resource base related to igneous systems for the first two times that such estimates have been made, in USGS Circulars 726 and 790 respectively. The project is also producing a series of maps at 1:1,000,000 scale showing the composition, distribution, and age of late-Cenozoic volcanic rocks of the United States. Two of these maps, I-1091 A and B, have been published, C is near color proof stage, D is in review by the authors, and E and F are compiled at 1:1,000.000 but require several months additional work by the authors. A synthesis of data from the map series will follow. The project chief participated in the Alaskan Geothermal Project (Thomas P. Miller, Project Chief), from which several maps and papers have been published.

Project Title: Geophysics of Young Volcanic Systems

Project Chief: David L. Williams
(Denver, Colorado)

Project Objectives: To improve understanding of young volcanic systems and their associated geothermal resources through a variety of geophysical tools, primarily gravity and magnetics. To integrate the geophysical results with the results of other studies to develop a general model of a volcanic system.

Project Status: The project began in 1977. The results of magnetic, gravity, thermal, and structural geology studies at Mt. Hood, Oregon, are in press. Reports on structure and heat flow at the summit of the volcano are in preparation. Work at Crater Lake, Oregon, includes heat flow measurements and coring in the lake floor and a gravity study of the area. A report on the heat flow, metal genesis and physical limnology of Crater Lake is in preparation. Gravity data from Crater Lake and the Medicine Lake volcano in California are currently being reduced.

Project Title: San Francisco Volcanic Field

Project Chief: Edward W. Wolfe
(Flagstaff, Arizona)

Project Objectives: To interpret the processes and evolution of magmatic activity in the San Francisco volcanic field of northern Arizona based on petrographic studies, chemical analyses, complementary geophysical investigations (gravity, seismic refraction, teleseismic delay, heat flow, microearthquake, magnetotelluric), strontium-isotopic measurements, potassium-argon (K-Ar) dating, and magnetostratigraphy. To determine whether hot, possibly molten, rock exists in the crust under the San Francisco volcanic field.

Project Status: The project began in 1974. Geologic mapping of the younger part of the volcanic field (about 6000 km^2) has been completed at a scale of 1:50,000. An additional 2000 km^2 has been mapped for compilation of the Flagstaff 1^o x 2^o quadrangle (in press), which provides a regional framework for the geothermal study. A major report, aimed at accomplishing the principal objectives of the project, is in preparation.

Geophysicist drills outcrop in the San Francisco volcanic field in Arizona to collect core of volcanic rock for subsequent paleomagnetic study in the laboratory.

Project Title: Springerville Volcanic Field

Project Chief: Edward W. Wolfe
(Flagstaff, Arizona)

Project Objectives: To map the late Cenozoic Springerville-White Mountains volcanic field. To study the petrography and chemistry of its lavas. To interpret the magmatic history in terms of the geothermal potential of the area. To understand the geologic significance of the lavas, particularly with regard to their relationship to the boundary between the Colorado Plateau and Basin and Range provinces.

Project Status: One summer of geologic mapping in the area of Quaternary basalt flows and vents has been completed by C. D. Condit, L. S. Crumpler, and J. C. Aubele. Mapping will continue and will serve as a basis for thesis studies.

Project Title: Potential-Field Methods for Mapping Magma at Kilauea Volcano, Hawaii

Project Chief: Charles J. Zablocki
(Reston, Virginia)

Project Objectives: To characterize geophysically the magma bodies in Kilauea Volcano, with the purpose of extracting meaningful in situ bulk physical property and configuration information on magma and the attendant hydrothermal regime. To develop a system for monitoring temporal changes in the measured properties related to movement of magma. To provide supplemental information needed for interpreting self-potential (SP) and very-low-frequency (VLF) data that already exist and are clearly related to geothermal phenomena.

Project Status: This project began in 1975. Through 1978 most efforts were concentrated on the application of magnetic, electrical, and electromagnetic techniques to the study of shallow magma bodies and their attendant hydrothermal fluids at Kilauea Volcano, Hawaii. These efforts generated over 15 technical reports, papers, and abstracts describing the results. Of note were: 1) the development of an hypothesis that explains the large SP anomalies that are associated with thermal areas in Kilauea; 2) the demonstrated utility of the VLF induction method to delineate shallow magma bodies; 3) the location of the water table of Kilauea using DC resistivity soundings; and 4) the successful application of the SP method in siting the HGP-A geothermal well in Puna. Since 1979 the major effort has been focused on delineating deeper-seated thermal zones at Kilauea by using a large-separation and extra-low-frequency (ELF) induction system.

Precise measurements to 14 km source-receiver separations using a specially designed, large-moment transmitter source and a high-sensitivity cryogenic magnetometer receiver have been made. The results to date have defined parts of Kilauea's geoelectric section to depths of 5 km. The proven application of this deep-sounding ELF system prompted the establishment of two permanent monitoring sites on Kilauea's summit in 1979 in an attempt to detect changes in the conductance in the region of Kilauea's magma chamber. To date, no perceptible changes have been observed, but good baseline data have been obtained for comparison with future magmatic activity. In March and April, 1978, low-level aeromagnetic and airborne VLF surveys were made over Kilauea's and Mauna Loa's rift zones as was an island-wide, high-level aeromagnetic survey. The reduction and compilation of these data are nearly completed.

HYDROTHERMAL SYSTEMS AND FLUID GEOCHEMISTRY

Project Title: Geochemical Studies of Geothermal Systems

Project Chief: Ivan Barnes
(Menlo Park, California)

Project Objectives: To collect and analyze liquid and gas samples from thermal springs and wells for chemical and isotopic data that can be used to estimate reservoir temperatures, outline favorable areas for geothermal exploration, identify possible pollution problems, and estimate recharge-discharge relations.

Project Status: Earlier emphasis on geochemical studies of thermal waters has evolved toward studies of CO_2 in geothermal and volcanic areas, with special attention on the origin of the CO_2 and its role in volcanic eruptions. Publications during the past year include a paper in Geology on the role of CO_2 in volcanic explosions and a map showing locations of spring-deposited travertine in eleven western states. A paper on CO_2 and seismicity is in press.

Project Title: Hydrothermal Alteration in the Cascades

Project Chief: Melvin H. Beeson
(Menlo Park, California)

Project Objectives: To gain an integrated geologic understanding of geothermal systems of the Cascade Range and their relation to (1) the regional structure of western Oregon, Washington, and northern California, (2) the 40 to 15 m.y.-old intrusive rocks of the Western Cascades, and (3) the young volcanic rocks of the High Cascades.

Project Status: Project objectives are pursued principally through detailed field mapping and laboratory petrological and mineralogical studies of selected active and fossil geothermal systems of the Western and High Cascades. Areas of hydrothermal alteration on and around Mount Hood, Oregon, and along the Clackamas River, Oregon, drainage basin have been sampled. The alteration on the edifice of Mount Hood is mostly associated with a northwest-trending fault system that runs from Iron Creek across the southwest flank of Mount Hood, Old Maid Flat, and into the Bull Run Reservoir area. Alteration is also prominent near the Laurel Hill and Still Creek intrusions that crop out on the south west side of Mount Hood.

The alteration in the Clackamas River area seems to be associated with (1) north- and northwest- trending normal faults, (2) numerous small pre-Cascade intrusions, and (3) rocks that originally contained much glass. Alteration of these volcanic and volcaniclastic rocks resulted in the formation of abundant zeolites, and lesser amounts of silica, carbonate, clay, pyrite, epidote and cinnabar.

A study of fumerolic alteration around Mount St. Helens, Washington, and around Crater Lake, Oregon, is underway. Cataloging and examination of cuttings from heat-flow and exploration drill holes in the Northern Oregon Cascades is also underway.

Project Title: Yellowstone Thermal Areas

Project Chief: Melvin H. Beeson
(Menlo Park, California)

Project Objectives: To understand the hot-spring systems of Yellowstone National Park through: (1) Petrologic study of 1980 m of drill core obtained in 1967-1968, with emphasis on the hydrothermal minerals produced by interaction of water with rhyolite at temperatures up to 250°C; (2) Determination of paragenesis and compositional ranges of hydrothermal minerals and an evaluation of factors that may have controlled paragenesis and composition; (3) Geologic mapping of hot-spring basins emphasizing the nature of the hot-spring deposits and alteration products, structural controls of the hot springs, relationships with young volcanism and glaciation, and relationships of the geology and petrology to the chemistry of hot-spring waters.

Project Status: This project began in 1967. Fieldwork has been completed for geologic maps of Upper Geyser Basin (at the scale of 1:2,400 and 1:4,800), Lower Geyser Basin (at 1:2,400), and Pocket

Basin (at 1:2,400). The Upper and Lower Geyser Basin maps are in press. Analytical work has been essentially completed on all drill core. A report on well Y2 and a report on scanning-electron-microscope mineralogy are in press. A report on wells Y11, Y3, and Y3 plus a topical report on feldspars are scheduled for completion in 1981.

Project Title: Earthquake Studies in The Geyser-Clear Lake Region

Project Chief: Charles G. Bufe
(Menlo Park, California)

Project Objectives: To determine the relation of earthquakes in The Geysers-Clear Lake region of California to regional tectonics and to local deformation resulting from geothermal processes and/or steam extraction. To evaluate the usefulness of microearthquakes for geothermal exploration. To determine crustal structure and attenuation using P and S waves from local and regional earthquakes.

Project Status: The project, which began in 1977, utilizes data from 14 telemetered stations and 13 portable digital seismographs to determine locations, fault plane solutions, and source parameters for earthquakes in The Geysers-Clear Lake region. The telemetered network is scheduled for completion this year. The portable digital seismograph and playback facility are also in the final debugging process. It is anticipated that these systems will also find use in other geothermal areas. A report describing temporal-spatial patterns of seismicity at The Geysers since 1975 is in press, and a statistical study of seismicity is completed and in review. Current work includes an investigation of seismic attenuation in the steam field, determination of the three-dimensional velocity structure, and a regional refraction study.

Project Title: Gas Geochemistry in Hawaii

Project Chief: Thomas J. Casadevall
(Hawaiian Volcano Observatory)

Project Objectives: To determine the nature and location of thermal activity and gaseous emissions from Hawaiian volcanoes. To measure the contribution to the atmosphere made by outgassing of Hawaiian volcanoes and to document the variations in these contributions due to changes in climatic conditions and volcanic activity. To investigate the mechanisms by which Hawaiian volcanoes outgas and the effects which these gases have on the enclosing rocks.

Project Status: An inventory of thermal areas on Kilauea and Mauna Loa volcanoes is in press. Since June, 1979, nearly daily measurements of sulfur dioxide emission have been made using a correlation spectrometer. For this same time period weekly collections of condensates and sublimates have been made from three sites on Kilauea. Reports of the results of these studies are in preparation.

Project Title: Physical Chemistry of Stable Isotope Fractionation in Hydrologic Processes

Project Chief: Tyler B. Coplen
(Reston, Virginia)

Project Objectives: To investigate equilibrium and non-equilibrium fractionation processes involving fluids and rocks in geothermal systems. To study the geohydrology of hot-water geothermal systems, especially the origin, history, and nature of geothermal fluids through the study of light stable isotopes.

Project Status: Water and rock samples have been collected from the Imperial Valley of southern California, Yellowstone National Park, and Cerro Prieto geothermal field in Baja California, Mexico. Analyses of these samples for stable isotopes of hydrogen, carbon, and oxygen have been used to determine the origin of the geothermal fluids and to investigate the geohydrology of these geothermal areas.

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*Project Title Isotopic and Chemical Studies of Geothermal Gases
(Grant No. 14-08-0001-G-361)

Principal Investigator: Harmon Craig
Scripps Institution of Oceanography
University of California
San Diego, CA 92093

Project Objectives: To study geothermal gases in order to delineate important sources for the various components of dissolved and free gases in geothermal regions. To apply isotopic exchange equilibria to the measurements of reservoir temperatures in geothermal fields. To use compositional and isotopic variations in gases and waters in locating areas of maximum potential for geothermal development.

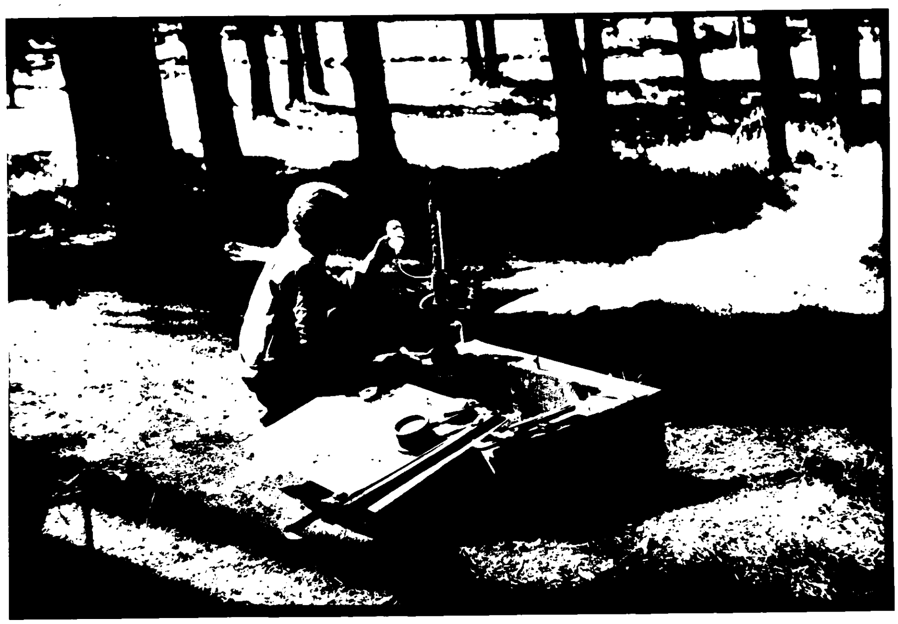
Project Status: Extensive sampling has been done at Yellowstone National Park, as well as collection of geothermal waters and gases in the Imperial Valley, California, Cerro Prieto, Mexico, and other localities. Analysis performed on these samples determined the content of stable isotopes of nitrogen, hydrogen, and methane; deuterium and ^{18}O; total carbon and ^{13}C; and helium forO$^{3}He/^{4}He$ measurement. The accuracy required for isotopic studies resulted in a number of improved analytical techniques.

Project Title: Rock-Water Interactions

Project Chief: Robert O. Fournier
(Menlo Park, California)

Project Objectives: To understand the processes that control the physical and chemical nature of hydrothermal solutions, particularly those associated with magmatic systems. To develop criteria for using compositions of thermal waters and gases from springs and wells to estimate subsurface temperatures deep in geothermal systems through (1) laboratory investigations of water-rock reactions at temperatures and pressures appropriate for hydrothermal systems, and (2) library and field investigations to determine the distribution and compositions of natural thermal fluids.

Project Status: Chemical geothermometers and mixing models that are widely used in exploration and evaluation of geothermal resources were formulated and/or revised under this project. Evaluation of other chemical and isotopic parameters is continuing. Studies of the aqueous geochemistry of the hydrothermal systems at Long Valley and Coso, California, have been completed. Studies are continuing on the hydrothermal systems at Yellowstone National Park; Lassen Volcanic National Park, California; Clear Lake, California; and Zunil, Guatemala. An equation for the solubility of quartz in water has been developed for conditions ranging from 20° to $900^\circ C$ and specific volume of solution 1 to 100. Laboratory experiments are underway to determine the effect of NaCl on the solubility of quartz in hydrothermal solutions.



Geochemist samples gas dissolved in thermal water from a research well in Yellowstone National Park.

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*Project Title: Reconnaissance Study of Thermal Springs and Wells and the Deposits of Recently Extinct Thermal Springs in the Peninsular Ranges Province of Southern and Baja California
(Grant No. 14-08-0001-G-547)

Principal Investigator: R. Gordon Gastil
San Diego State University
San Diego, CA 92182

Project Objectives: To locate surface hydrothermal features less than 5 m.y. old in southern and Baja California and relate them to local and regional structure, host rocks, and recent volcanism. To determine the history and evolution of the thermal springs. To characterize the source of the thermal waters by chemical analysis. To measure the rate of travertine accumulation using ^{210}Pb dating.

Project Status: Data collection has been completed, as well as most of the laboratory analyses. Warm and mineralized spring waters have been analyzed and compared with available records. The following preliminary results are of particular significance: 1) Contouring of chemical constituents has lead to recognition of several distinct thermal-water provinces. 2) Cold carbonate springs appear to be fed from high-temperature reservoirs based on both Na-K-Ca-Mg and silica geothermometers; spatially these cold springs are associated with warm springs more than are other types of mineralized springs. 3) Spatial correlation between earthquake-epicenters (magnitude 4 and greater) and thermal springs and wells indicates an association of warm waters with seismicity.

Project Title: National Center for the Thermodynamic Data of Minerals

Project Chief: John L. Haas, Jr.
(Reston, Virginia)

Project Objectives: To provide critically-evaluated descriptions of the thermodynamic properties of minerals and other geological materials over the ranges in temperature, pressure, and composition that are observed in the geological environment.

Project Status: The project began at the Geological Survey in 1977 at the urging of the National Bureau of Standards' Office of Standard Reference Data. It is operating on a continuing basis to collect and evaluate experimental data on geological materials. Prior to the beginning of the project, a computer-based evaluation procedure was developed that permitted an evaluator to scan large sets of experimental data for a group of minerals in a chemical system after the data had been corrected to a standard state of one atmosphere. The program was used to determine the thermodynamic properties of 25 phases in the lime-alumina-silica-water system between 200 K and the upper stability limit or 1800 K, whichever was lower. These procedures have been enlarged to include the fitting of volumetric data, including expansivities and compressibilities. An improved equation for water was also adopted. These changes eliminated the need to reduce the data to a standard state of one atmosphere and eliminated most operator errors in extracting the experimental data and entering them into the evaluation routines. Other results include critical evaluation of the thermodynamic properties of vapor-saturated NaCl solutions and calcium-aluminum silicates, and an estimate of the solubility of methane in NaCl solutions.

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*Project Title Mapping of Volcanic and Conductive Heat Flow Sources for Thermal Springs in the Western United States Using Helium Isotopes and Other Rare Gases (Grant No. 14-08-0001-G-541)

Principal Investigator: William J. Jenkins
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Project Objectives: To map volcanic and conductive heat sources for thermal springs of the western United States in relation to helium-isotopic and other noble-gas isotopic abundances determined in geothermal gas and water samples and selected holocrystalline and glassy rock samples. To make other rare-gas measurements as required to interpret more complicated cases.

Project Status: Measurements of helium-isotopes suggest that The Geysers steam field in California has a volcanic heat source, a conclusion that is consistent with the results of geologic and geophysical studies. Evidence from helium isotopes at Steamboat Springs, Nevada, is less compelling but helium-isotope ratios similarly suggest that this geothermal system has a volcanic heat source. On the other hand, Raft River, Idaho, has a helium-isotopic ratio indicative of a crustal conductive heat source. Field collections have been completed in southern Montana and the Rio Grande Rift in New Mexico, and data analysis is proceeding with these as well as other samples from continental and oceanic areas.

Project Title: Trace Element Reactions and Attenuation Processes in Waters of Geothermal Origin

Project Chief: Everett A. Jenne
(Menlo Park, California)

Project Objectives: To obtain reliable chemical analyses (involving modification and development of methods) for trace and major constituents and carry out chemical modeling and geochemical interpretations on Cerro Prieto, Mexico, geothermal waters. To study and interpret the partitioning of trace elements among water, various solid inorganic phases (sinter, Mn and Fe oxides, carbonates and sulfides), organic detritus and biota in order to develop equilibrium and kinetic models for investigations of solubility controls and for identifying those processes which might be used in pollution abatement technology. To utilize trace-element data to understand and interpret geochemistry and hydrology of hot-water systems.

Project Status: Present efforts focus on analytical problems encountered with samples of very high silica concentration (as much as 1000 mg/L). The formation of polymerized silica after sample collection is thought to cause the loss of dissolved silica and other constituents upon standing even in 1/10 field dilutions. To test this idea various dilutions were prepared in the field (both acidified and non-acidified) of each sample taken at Cerro Prieto in March, 1980, in order to determine the stability of dissolved silica and other major constituents in the various dilutions with time. These dilutions are to be analyzed by plasma spectrometry immediately (within one week) after collection and 3 to 12 months after collection.

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*Project Title Thermophysical Properties of Water and of Aqueous Solutions (Grant No. 14-08-0001-G-342)

Principal Investigator: Joseph Kestin
Brown University
Providence, R. I. 02912

Project Objectives: To measure the viscosity of water and selected brines over the temperature range 38-300°C. To participate in the international standardization of the properties of the solvent.

Project Status: Tabulated values of the dynamic and kinematic viscosity of potassium chloride and sodium chloride have been completed and have been accepted for publication.

Project Title: Chemical and Isotope Studies of Thermal Waters of the Western United States

Project Chief: Robert H. Mariner
(Menlo Park, California)

Project Objectives: To collect and analyze gases and water discharging from thermal springs and wells in the Western United States. To determine the origin of the dissolved constituents, the recharge areas for individual systems, and provide better estimates of reservoir temperatures. To investigate the relationship of the thermal systems to the general hydrologic setting in order to clarify mixing relationships.

Project Status: All available chemical and isotopic data for the thermal springs and wells of Oregon have been collected, interpreted, and submitted for publication as an open-file report. Isotopic data are being analyzed to determine recharge areas for Breitenbush and Belknap Hot Spring in the Oregon Cascades. Possible mineral sources for isotopically-depleted sulfate observed in some thermal waters in New Mexico, Nevada and the Cascades are being analyzed. Thermal, warm, and cold CO_2-charged waters from the Cascades are being examined to see if any systematic relationships exist in the chemical and isotopic data.

Project Title: Geology of Pre-Tertiary Rocks in The Geysers-Clear Lake Area, Sonoma, Lake, and Mendocino Counties, California

Project Chief: Robert J. McLaughlin (Menlo Park, California)

Project Objectives: To determine structure of Pre-Tertiary rocks and its relation to geothermal resources in The Geysers-Clear Lake, California, geothermal area. To prepare geologic maps and structure sections of pre-Tertiary rocks using surface and subsurface geology. To determine distribution of landslides and active faults that may affect geothermal development. To investigate structure and sedimentology of Late Cenozoic deposits along major faults zones, where critical to understanding fault tectonics. To correlate Pre-Tertiary geology with data from geochemical and geophysical studies in the area.

Project Status: Geologic field investigations for this project began in 1973 partly in conjunction with a study of the Clear Lake volcanic field by B. Carter Hearn. A 1:24,000 scale geologic map with structure sections, encompassing the region considered to be underlain by a vapor-dominated geothermal reservoir, was open-filed in 1978. A major report on the structure and tectonics of this area in relation to geothermal resources, is included in U.S.G.S. Professional Paper 1141 (in press). Numerous other topical reports, maps, and abstracts, some of which are co-authored with Hearn and others, have been published. Other reports, including a fault-seismicity map and a regional cross-section from the Pacific Ocean through the Clear Lake volcanics, are in preparation. In late 1978 the project began a new phase, and mapping emphasis was shifted northeastward to areas of the Clear Lake geothermal region considered to be underlain by one or more hot-water geothermal systems. This work is now well underway, with mapping northeast of Clear Lake largely completed, along with other mapping around the northwest and southwest side of the Lake. The project goal of mapping all pre-Tertiary rocks surrounding the Clear Lake volcanics and of correlating these rocks with deep geothermal well data from wells drilled through the volcanics should be met by the end of 1981. Study of the lithology and hydrothermal mineralogy of cuttings from a 3050 m-deep geothermal well recently drilled at the Sulphur Mound mine south of Mt. Konocti is in progress. Three abstracts were published in March 1980. Two concern Neogene pull-apart basin tectonics along the Maacama fault zone southwest of The Geysers steam field; the third concerns the age and structural relations of Late Mesozoic rocks in the Wilbur Hot Springs geothermal area northeast of Clear Lake. The mapping in the Wilbur Springs area and in the Highland Springs area on the southwest side of Clear Lake should be open-filed in early 1981.

Project Title: Lassen Region of Cascades

Project Chief: Patrick Muffler
(Menlo Park, California)

Project Objectives: To evaluate the regional tectonic and petrologic setting of approximately 5,500 km^2 of the southeasternmost Cascade Range in northeastern California as a basis for geothermal evaluation.

Project Status: This project is an outgrowth of an earlier project to study the thermal areas of Lassen Volcanic National Park (LVNP). Geologic maps of the thermal areas at scales of 1:2,000 and 1:12,000 have been completed, and a geologic map at 1:24,000 has been prepared for approximately 150 km^2 in the southern part of LVNP and adjacent areas. Beginning in 1979, project work focused on 1:62,500 mapping in the Lassen Peak, Burney, and Jellico quadrangles. This work, together with additional mapping in the Little Valley and Mt. Harkness quadrangles, will be combined with the late Gordon Macdonald's published maps of the Manton, Manzanita Lake, Prospect Peak, and Harvey Mountain quadrangles in a regional tectonic, volcanic, and geothermal synthesis of the southeasternmost Cascade Range.

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*Project Title Chemical Mass Transfer Between Circulating Fluids and Rocks in Modern Geothermal Systems
(Grant No. 14-08-0001-G-534)

Principal Investigator: Denis L. Norton
University of Arizona
Tucson, AZ 85721

Project Objectives: To develop a numerical solution of coupled partial differential equations constrained by characteristics of thermal springs and bore-hole fluids in order to quantitatively predict subsurface conditions in active geothermal systems. To compute chemical-composition changes for fluids along idealized flow and reaction paths and to compare the results with natural systems. To simulate heat and mass transport by thermodynamic analysis of the phase relations between alteration minerals and fluids commonly encountered in geothermal systems.

Project Status: The compatibility of aqueous solutions and minerals has been investigated in view of theoretical phase relations and empirical petrologic and hydrologic observations. Emphasis is on the consequences of substitutional order/disorder and compositional variation in minerals on the chemical characteristics of geothermal reservoir fluids. Compositional phase relations have been calculated for pressures and temperatures corresponding to the liquid-vapor equilibrium for water and indicate the extent to which minerals of variable composition react with aqueous solutions during geothermal processes.

Project Title: Oxygen Isotopes

Project Chief: James R. O'Neil
(Menlo Park, California)

Project Objectives: To conduct research on the stable-isotope relations in natural and laboratory systems of geothermal interest. To provide state-of-the-art operational facilities and technical staff to determine light stable-isotope ratios in geothermal materials. To provide aid in planning and data interpretation to those scientists using stable-isotope variations in their investigations of geothermal areas.

Project Status: The origins and temperatures of fossil hydrothermal fluids were determined in skarn deposits in the Osgood Mtns., California, and Elkhorn Mtns., Montana, in the jasperoid bodies at Drum Mtns., Utah, in recent ore deposits with current geothermal activity at Bodie, California, the Baguio District, Philippines, and the Tolfa and Monte-delle-Fate Districts, Italy. Determinations were made of the relative exchange rates of ^{18}O and D between clay minerals and water. A compilation was made of all measured and calculated stable-isotope fractionation factors of geochemical interest. In submarine hydrothermal systems, the first identification of a high-temperature smectite was made, and the low-temperature (35°C) origin of "hydrothermal" minerals in the altered trachyte on the Hess Rise was characterized. A new geothermometer based on ^{13}C (calcite-graphite) was developed for high-grade carbonate rocks. Three mass spectrometers were automated and a new method of rapid deuterium analysis of brines is being developed.

Project Title: Stable Isotopes and Ore Genesis

Project Chief: Robert O. Rye
(Denver, Colorado)

Project Objectives: To carry out detailed stable-isotope studies of the thermal system at Yellowstone National Park as a means of constraining possible geochemical models of the Yellowstone system. To develop fundamental principles of stable-isotope geochemistry of hot spring systems. To investigate fossil geothermal systems by stable-isotope studies of Tertiary ore deposits and associated volcanic complexes.

Project Status: Considerable progress has been made in understanding the stable-isotope geochemistry of the Yellowstone geothermal system. A large reservoir of deep thermal water has been identified, and the isotopic effects of boiling and dilution evaluated in a published report. A preliminary report on the sulfur-isotope geochemistry of the system has been published and an open-file report pinpointing the probable recharge area for the entire deep thermal reservoir is in preparation. Results of preliminary stable-isotope studies of the fluid of the Cerro Prieto, Baja California, Mexico, geothermal field have been published. Topics currently under investigation at the fossil geothermal system at Creede, Colorado, include the chemistry of the fluids as indicated by fluid inclusion studies, the early potassium-metasomatism fluids, the influence of Lake Creede on the system, and the effect of boiling in the upper part of the system where a multibillion dollar ore deposit is located. A report on the origin of the hydrothermal fluids has been published and a paper on the sulfur-isotope geochemistry of the system is in preparation. Initial oxygen-isotope studies on the ash sheets and rhyolite domes demonstrating the absence of significant meteoric water involvement in the Valles caldera, New Mexico, magmas have been completed.

Project Title: Electrochemistry of Minerals

Project Chief: Motoaki Sato
(Reston, Virginia)

Project Objectives: To develop and field test instruments for in situ monitoring and telemetering of CO_2, H_2, and other reactive components of volcanic and geothermal gases in order to understand the nature of chemical and physical processes such as magma injection, vent obstruction and opening, and interaction of meteoric water with hot rock.

Project Status: The project currently operates 2 hydrogen-monitoring stations at Kilauea and Mauna Loa volcanoes, jointly with the Hawaiian

Volcano Observatory, and 2 stations at Krafla Volcano, Iceland, jointly with the University of Iceland and Icelandic Energy Authority. The CO_2-monitoring system has been tested at Sulfur Bank, Hawaii, and is now being improved. An infrared multi-gas monitoring system is being developed on the basis of modification of a commercial model.

Project Title: Geochemical Indicators

Project Chief: Alfred H. Truesdell
(Menlo Park, California)

Project Objectives: To develop an understanding of the isotopic, chemical, and physical processes occurring in natural and exploited geothermal systems and to establish isotopic and chemical indicators of subsurface temperatures, pressures, chemistry, fluid state, and flow paths.

Project Status: The geochemical indicators project which began in 1971 is currently involved in studies of subsurface isotopic and chemical processes in the hot-water geothermal system of Cerro Prieto, Baja California, Mexico, and in the vapor-dominated systems of The Geysers, California, and Larderello, Italy. These studies include 1) collection and analysis of fluids from producing wells at Cerro Prieto and The Geysers and 2) modeling of chemical and physical reservoir processes both natural and induced by exploitation. A smaller program in development of geochemical methods of exploration for geothermal resources consists of collection, analysis and interpretation of surface geothermal fluids from Lassen Volcanic National Park, California, Yellowstone National Park, and other hot spring systems of the western United States. Methods utilizing gas and water chemistry have been developed to indicate subsurface temperatures, flow directions and liquid water/rock ratios in vapor-dominated systems and subsurface temperatures and mechanisms of aquifer boiling and cold-water entry in hot-water systems. More general studies include investigations of the origin of geothermal fluids through isotopic characterization of hydrocarbon gases, analyses of deuterium in hot and cold groundwaters, and correlation of changes in solution compositions with metamorphic reactions.

Project Title: Geothermal Studies of the Ag-Pb-Zn Vein System at Creede, Colorado

Project Chief: Pamela H. Wetlaufer
(Reston, Virginia)

Project Objectives: To establish the thermal, isotopic and chemical evolution in both time and space of the ore-forming fluids at Creede, Colorado. To define different fossil hydrothermal reservoirs, and to establish their characteristics and trace the variations in their relative contributions to ore deposition throughout the life of the system.

Project Status: A newly designed fluid-inclusion heating/freezing stage has been constructed, refined, and calibrated. Its unique capability to rapidly determine homogenization and freezing temperatures has permitted very detailed thermal documentation keyed to mineral paragenesis at several sample localities. Oxygen-, deuterium-, carbon-, and sulfur-isotope data have been collected and suggest the former presence of three different hydrothermal reservoirs. More detailed isotopic work and chemical analysis of the fluid inclusions, both keyed to detailed mineral paragenesis, are underway. Potassium-argon dating of samples has also been initiated for documenting the several hydrothermal systems active through time and of samples covering spatially the probable extent of the culminating ore-forming hydrothermal system at Creede.

Project Title: Thermal Waters

Project Chief: Donald E. White
(Menlo Park, California)

Project Objectives: To acquire a better understanding of the origins and characteristics of geothermal systems of all kinds and to apply this understanding to the discovery and utilization of geothermal energy resources and hydrothermal ore deposits (fossil geothermal systems that formed valuable mineral deposits).

Project Status: The project has made major contributions to the characterization of active geothermal systems. Present thrusts include:

1. Completion of Yellowstone National Park studies, including Norris Basin and the thermal areas of Yellowstone Lake - Yellowstone River. These areas include all vapor-dominated systems and the largest hydrothermal explosion craters of the Park.
2. Continuation of emphasis on fossil geothermal systems that have formed valuable ore deposits in the past. Studies of active systems

contribute to better understanding of the fossil systems, and vice versa.
3. Continuation of hydrothermal alteration studies, especially of the active and recently active systems, as critical parts of 1 and 2, above.

GEOPRESSURED GEOTHERMAL SYSTEMS

Project Title: Stratigraphy and Sedimentation of Geopressured Zones

Project Chief: Richard Q. Foote
(Corpus Christi, Texas)

Project Objectives: To analyze geopressured zones of the U. S. Outer Continental Shelf (OCS) and selected onshore areas in order to: (a) characterize their stratigraphic framework and depositional environments, and (b) develop the capability to predict the extent and characteristics of source beds and reservoir rocks which could generate and trap methane gas or waters charged with methane gas. To contribute information needed to assess the production potential of geopressured areas and specific prospects.

Project Status: Geological and geophysical data were acquired during the first year of the project, 1979, and two research grants were awarded. Efforts in 1980 have focused on subsurface mapping of normal and geopressured sands and shales of Miocene and Pliocene ages in the western Louisiana and the northern Texas OCS area and analysis of geological and geophysical data on three deep wells. On one research grant, equipment was assembled and tests are being conducted to examine possible decreased methane solubility in the presence of clay particles. On the other research grant, studies of cuttings, cores and well logs are being conducted on Jurassic strata across the western part of the Alabama Gulf Coastal Plain.

Project Title: Geochemistry of Geopressured Systems

Project Chief: Yousif Kharaka
(Menlo Park, California)

Project Objectives: To collect water, gas, and rock samples from geopressured geothermal systems for chemical, mineralogic, and isotope analyses. To study the chemistry and controls on the chemistry of water in the systems. To provide basic data needed for estimating recoverable resources and identifying possible pollution, waste-disposal, and corrosion problems. To carry out membrane and water/rock interaction laboratory studies and construct digital computer models that will aid in understanding the geopressured systems.

Project Status: Chemical and isotopic analyses of about 150 water and about 30 gas samples from 5 major geopressured-geothermal areas in Texas and Louisiana have been completed. Membrane and water-rock experiments that aid in understanding geopressured-geothermal systems have been performed. The study of geopressured-geothermal resources in California has been initiated. Results have been presented at numerous meetings and published in several journals.

Project Title: Geopressured-Geothermal Resources of the United States

Project Chief: Raymond H. Wallace, Jr. (Bay St. Louis, Mississippi)

Project Objectives: To describe, analyze, and interpret the hydrogeology of geopressured deposits in deep sedimentary basins of the United States. To identify and map geopressured aquifers and their structural controls. To determine the hydraulic characteristics of the aquifers, the significant hydrodynamic controls, the chemistry and salinity distribution of interstitial water, and the geothermal regime. To describe deep aquifers so that quantitative appraisal of their potential as sources of energy and water can be made.

Project Status: This project, which began in 1973, produced in 1975 the first USGS assessment of the geopressured-geothermal resource base in the northern Gulf of Mexico basin. A revised and expanded assessment was published in 1979. Current research is directed to providing an estimate of recoverable geopressured-geothermal energy. Data on rock and fluid properties are being acquired for use in computer models to be developed for estimating recoverable geopressured-geothermal energy in selected areas. One such model will be based upon a detailed investigation currently underway of the Cretaceous Tuscaloosa "trend" in Louisiana. To date geophysical well logs of eight deep Gulf Coast wells have been digitized. The digitized data will provide input to the recently acquired system of computer programs for accurate calculation of reservoir rock and fluid properties to supplement the 87,000 measurements of these properties currently in our computer files. Results of well tests sponsored by the Department of Energy are being factored into this effort as they are acquired. Because dewatering of shale may be an important factor in reservoir producibility, an effort to determine the extent to which this occurs is being conducted. Geopressured-geothermal water is being sampled and chemically analyzed to determine variation in content of naturally occurring radionuclides. Samples from five wells have been analyzed to date. Other major ongoing activities include upgrading the hydrogeologic data bases and preparing maps of depth-to-geopressure and depth-to-geotherm.

GEOTHERMAL SYSTEMS: HEAT TRANSFER AND STORAGE

Project Title: Intermediate-depth Drilling

Project Chief: J. Glenn Blevins
(Menlo Park, California)

Project Objectives: To prepare bid specifications and select qualified drillers for the drilling and testing of boreholes to provide information needed by other projects in the Geothermal Research Program.

Project Status: Present drilling activity is in Nevada, Idaho, and at Mt. Hood in Oregon. Drilling is planned and supervised in coordination with the Chief of the project involved. The boreholes generally range in depth from a few meters to about 1,000 meters, and are designed to provide geological and hydrological data needed for a particular project.

Project Title: GEOTHERM - Geothermal Resources File

Project Chief: James D. Bliss
(Menlo Park, California)

Project Objective: To maintain a computerized data base on geothermal systems for use by the Geothermal Research Program, state and other government agencies, and the general public.

Project Status: Computerized methods of filing data on (1) geothermal fields, (2) thermal wells/springs and (3) geothermal wells have been designed and implemented. The computer-stored data may be manipulated and retrieved in various ways, and were used extensively in the assessment of geothermal resources that resulted in the publication of USGS Circular 790. The GEOTHERM project is collaborating with the

Department of Energy in its state-coupled program of resource assessment. All the thermal well and spring data compiled for that program are being added to GEOTHERM. Preliminary designs have been completed for a heat-flow file and a file on references to data in GEOTHERM. In December 1979 the data file on thermal wells/springs was entered into the General Electric Information Services Network where it is available directly to subscribers of that network.

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*Project Title: Faults and Occurrences of Geothermal Anomalies (Contract No. 14-08-0001-16310)

Principal Investigator: George E. Brogan
Woodward-Clyde Consultants
Orange, CA 92668

Project Objectives: To study faulting in relation to hydrothermal systems in order to identify the character and genesis of faults that pass through a hydrothermal reservoir and influence the heat source. To relate hydrothermal systems to large-scale regional structures. To catalog fault characteristics and geothermal data in a computerized data file that can be used to correlate significant features.

Project Status: Faults associated with three hot-water hydrothermal areas have been studied: Bradys Hot Springs, Nevada, Leach Hot Springs, Nevada, and Roosevelt Hot Springs, Utah. Faults were located for field study using low-sun-angle aerial photography, other remote-sensing imagery, and geologic maps. Local maxima in fault displacement were mapped at Bradys and Leach Hot Springs. At Bradys, the maximum displacement is north of the surface thermal manifestations where deep exploration drill holes are sited. If maximum displacement correlates with enhanced permeability within the fault zone, the deep drill holes may not be located in the zone of greatest potential for fluid production.
At Leach Hot Springs, maximum displacement at the hot springs themselves is suggested by detailed profiles across the fault zone. Such detailed profiles, maps of fault-related geomorphic features and soils, and trenchs across fault zones have been completed at Bradys and Roosevelt Hot Springs.

Project Title: Modeling of Transport Phenomena

Project Chief: John Czarnecki
(Reston, Virginia)

Project Objectives: To better understand the physics of flow and transport in hydrologic sytems. To analyze existing quantitative methods that describe energy and mass transport in porous media involving both single and multiphase flow. To modify and expand these methods, if necessary, and to apply these methods to a variety of related field problems.

Project Status: A computer code is being modified to describe behavior of the geothermal reservoir at Raft River, Idaho. Modifications needed to handle heat and fluid-flow boundary conditions and to solve long time-scale problems of geologic interest have been made and several problems pertinent to the Raft River system have been tested with a 1-dimensional, 5-layer vertical column. After a more thorough review of publications dealing with the Raft River system, a 3-dimensional model will be developed to match the natural conditions of heat and mass flow and to analyze the effects of fluid production and reinjection.

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*Project Title A Study of Gravity Variations as a Monitor of Water Levels at Geothermal Sites
(Grant No. 14-08-0001-G-297)

Principal Investigator: John M. Goodkind
University of California at San Diego
La Jolla, CA 92093

Project Objectives: To study the effect of groundwater level on gravity measurements in order to monitor groundwater levels in geothermal wells. To investigate the influence of magma chambers on the response of local gravity to tidal forces and changes in barometric pressure. To attempt to minimize the noise-to-signal ratio in a superconducting gravimeter.

Project Status: Temporal gravity observations using a regular superconducting gravimeter are continuing at The Geysers geothermal field. It has been demonstrated that such continuous gravity observations at The Geysers may correlate with behavior of the geothermal reservoir. An automatic system was developed which continuously adjusts the suspension points of the gravimeter platform to maintain precise vertical alignment and thus virtually eliminate tilt-induced gravity effects. Data obtained to date reveal an anomalous relation between barometric pressure and gravity. Asimple model of mass transport between air and ground demonstrates that this effect could be of meteorological, hydrological, or geothermal origin. An adjustment for changes in barometric pressure is needed to improve the usefulness of the instrument in monitoring changes in the geothermal system itself.

Project Title: Transport Processes in Fluid Flow

Project Chief: William Herkelrath
(Menlo Park, California)

Project Objectives: To develop a quantitative description of the physics of combined flow of fluid and heat in porous granular and fractured materials at high temperature and pressure. To use analytical and numerical techniques to establish theories which are tested in laboratory experiments. To measure flow parameters of field samples in the laboratory to provide data for numerical models of the high-temperature flow regime in the field.

Project Status: Laboratory investigations of the transient flow of pure steam in sedimentary materials are nearly complete. Journal articles and open-file reports are being prepared which describe the experimental results and a steam-flow theory which has been developed.

Project Title: Active Seismology in Geothermal Areas

Project Chief: David P. Hill
(Menlo Park, California)

Project Objectives: To resolve the P- and S-wave velocity structure of the crust and upper mantle in geothermal areas using state-of-the-art field and data-processing methods of active seismology. To provide velocity models of the crust and upper mantle for the accurate location of earthquake hypocenters within and adjacent to the geothermal areas. To establish constraints on the composition, temperature, pore pressure, and state of stress for rocks within and surrounding geothermal areas using velocity and attenuation models obtained from seismic field measurements together with laboratory and drill-hole measurements of these properties.

Project Status: Active seismic experiments were completed in 1979 in the following areas of geothermal interest: Mauna Loa, Hawaii; the Yellowstone-Snake River Plain region of Wyoming and Idaho; Mt. Hood in the Oregon Cascades; and the Imperial Valley region, California. The latter three involved using a newly developed 100-unit cassette recording system. Most of the subsequent effort in this project has involved processing and interpreting the data obtained from these experiments. At this stage, data processing is essentially complete and papers describing the results are in review or in press.

Project Title: Teleseismic and Microearthquake Studies in Geothermal Areas

Project Chief: H. M. Iyer
(Menlo Park, California)

Project Objectives: To study seismicity, P- and S-wave delays, and seismic attenuation to understand the tectonic framework, structure, and nature of the heat source in geothermal areas. To detect and delineate magma bodies under geothermal areas by measuring P-wave delays from teleseisms and regional earthquakes. To study S-delay measurements to infer the physical properties of material in the geothermal reservoir and heat source.

Project Status: P-wave delay studies using fixed and portable seismic networks have been completed in the following areas: Yellowstone National Park, Wyoming; Long Valley, Coso, The Geysers-Clear Lake region, California; Mt. Hood, Oregon; Roosevelt Hot Springs, Utah; San Francisco Mountains, Arizona. Each of these geothermal areas, except Mt. Hood, seem to have a low-velocity body (interpreted as a magma chamber) in the crust and upper mantle. Preliminary results are available from P-delay studies in Eastern Snake River Plain, Idaho, Newberry Volcano, Oregon, and the Battle Mountain Region, Nevada. Seismicity studies have also been done under this project and in collaboration with other projects in Yellowstone National Park, Coso geothermal area and Mt. Hood. Currently a 32-station, state-wide seismic network is being installed in Oregon to study in detail the seismicity and deep structure of the Cascades. A detailed seismic experiment using an array of short-period and intermediate-period seismic systems has been completed at the Lassen Peak region in California.

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*Project Title Heat and Mass Transfer in Fault-Zone Controlled, Liquid-Dominated Geothermal Systems (Grant No. 14-08-0001-G-628)

Principal Investigator: David Kassoy
University of Colorado
Boulder, CO 80309

Project Objectives: To study processes of heat and mass transfer in hot-water geothermal systems along fault zones as a mathematical problem posed in terms of single-phase flow in a rigid, saturated, thermally active, porous medium. To develop conceptual models based on geological, geophysical and bore-hole data from a variety of systems, most notably the East Mesa, California, system.

Project Status: Studies of heat and mass transfer in generic models of hot-water geothermal systems have been completed and a quasi-analytical solution developed for an axisymmetric model of fracture-zone controlled charging of a geothermal reservoir. Significantly more rapid cooling of the deep sections of the reservoir was found than was the case in the planar model. The dilution of a hot, narrow plume of heated water emanating from a fracture zone at a basement-sediment interface, into an aquifer containing cooler water, was examined. The entrainment of cold water by the upward convecting plume was observed to cause a significant reduction of the temperature. A purely numerical approach to the planar fault-zone-controlled charging model, considered previously for high Rayleigh number flows only, was completed. Simplifications of the most general liquid porous media flow equations were obtained by assuming only horizontal flow in the aquifer in an effort to produce solutions for arbitrary Rayleigh number.

Project Title: Multiphase Fluid Flow in Geothermal Systems

Project Chief: Susan Werner Kieffer
(Flagstaff, Arizona)

Project Objectives: To formulate a model for fluid flow in geothermal reservoirs and during eruptions of geysers (and, by application and analogy, in drilled wells and volcanoes) which allows one to use observed surface phenomena (photographic, seismic, geochemical) to infer source conditions at depth. To describe the relation between thermodynamic and geochemical properties of water-gas, water-steam and solid-liquid-gas magma mixtures and their fluid flow properties during eruption. To test the model against field observations at active geysers and, if available, volcanoes and drilled wells. To formulate a model for interactions of magma with ground water beneath geothermal areas and during volcanic and phreatic eruptions. To study theoretically and in the field the brecciation of host rocks during magmatic intrusions and the relation of fracture patterns.

Project Status: This project is new to the Geothermal Research Program as of 1980. Prior work has resulted in detailed equations of state and phase diagrams for H_2O, CO_2 and SO_2 particularly useful for fluid flow problems, and in equations of state for pseudo gas-liquid-vapor and solid-vapor mixtures. Prior field work has resulted in several hundred films of geyser eruptions in Yellowstone, Iceland, Nevada and New Zealand, and in reconnaissance seismic and geochemical work related to geyser eruptions in Yellowstone.

Scientists sample water erupted at Old Faithful, Yellowstone National Park. Chemical analysis of the water provides information needed to understand the mechanisms of geyser eruption.

Project Title: Heat Flow

Project Chief: Arthur H. Lachenbruch
(Menlo Park, California)

Project Objectives: To combine observations of heat flow, primarily in the western United States, with theoretical studies and geologic information to increase understanding of processes governing the generation, storage, and transport of heat in the crust and upper mantle, and the nature and geographic distribution of exploitable sources of geothermal energy in the United States. To develop new instrumentation for measuring rock temperatures, thermal properties, and heat flow, and to assist in the design of optimum strategies for the discovery and delineation of geothermal resources.

Project Status: Several reviews of the status of heat flow in the United States (including a series of both national and regional maps) have been published together with interpretive models of the tectonic, magmatic, and hydrologic regimes relative to regional heat flux. A system for in situ determination of heat flow during drilling has been developed and deployed, primarily in support of site-specific heat-flow studies near known or prospective geothermal areas. Manuscripts that describe heat flow in the western United States, regional heat-flow studies of the Californian Cascades, Coast Ranges, Mojave Block, and Sonoran Desert are in preparation.

Project Title: Geothermal Geophysics

Project Chief: Don R. Mabey
(Salt Lake City, Utah)

Project Objectives: To coordinate a Federal-State program to assess the geothermal resources of southern Idaho (1978-1980 period). To review all data relating to geothermal resources of the northern Basin and Range Province and to recommend a program to complete assessment of the resources of this region (1981 - ongoing).

Project Status: Some report writing remains to complete the work in southern Idaho. Reports are planned on the Raft River geothermal system, the Idaho National Engineering Laboratory, the Blackfoot lava field, and the Snake River Plain. A gravity map of southern Idaho will be prepared. The northern Basin and Range program will begin with a review of data obtained through the Department of Energy's Industry-Coupled Program.

Project Title: Mathematical Modeling of Energy Transport in Multiphase Ground-water Systems

Project Chief: Allen F. Moench
(Menlo Park, California)

Project Objectives: To understand the physical processes occurring in vapor-dominated geothermal systems. To improve numerical and analytical methods for analysis of steam pressure tests in wells. To account for the results of laboratory tests of steam pressure-transient behavior in porous materials. To account for observed vapor-dominated reservoir behavior and to predict reservoir response.

Project Status: Early work on the project led to the finding that vaporization of liquid water within reservoir pores and fractures causes a large increase in the apparent compressibility of steam. This is manifested by large pressure support and plays an important role in the longevity of vapor-dominated reservoirs. Analytical and numerical models have been developed to simulate pressure behavior in wells and laboratory experiments. Recently a two-dimensional numerical model for steam flow to a well in a vapor-dominated reservoir was developed. In this model the reservoir was assumed to be composed of low-permeability blocks saturated with liquid water and high-permeability fissures saturated with vapor. The model has been successfully tested using analytical methods and is presently being used to analyse well test data from The Geysers, California, steam reservoir. A report was published which successfully applied an early version of the model to data from an Italian steam well in a fissured reservoir. A recently published abstract describes how the model is being used to relate steam production at The Geysers to induced seismicity.

The effect of increased apparent steam compressibility has been observed in laboratory experiments on unconsolidated porous materials. These experiments, conducted at various temperatures from 100°C to 146°C, have been successfully simulated by mathematical modeling techniques.

Project Title: Geochronology

Project Chief: Charles W. Naeser
(Denver, Colorado)

Project Objectives: To study the effect of natural heating on fission-tracks in minerals through the use of samples from deep drill holes in geothermal areas.

Project Status: The laboratory work on fission-tracks in minerals from the Coso, California, drill holes is complete.

Project Title: Geothermal Reservoirs

Project Chief: Manuel Nathenson
(Menlo Park, California)

Project Objectives: To understand the thermal and fluid mechanical characteristics of geothermal systems in their natural state and under exploitation. To develop methods for regional assessment of geothermal resources.

Project Status: Field studies have been performed at Raft River, Idaho, and East Mesa, California. Temperature measurements in and water samples from wells at Raft River have been used to show that: 1) thermal waters move vertically at several locations and charge aquifers for subsequent horizontal flow and 2) the usual assumption that there is a geothermal water with a unique chloride content and enthalpy is not true. Additional work is planned to analyze data obtained in other bore holes at Raft River. Preliminary analysis of data from East Mesa shows that some part of the geothermal system is dominated by a horizontal flow of hot water losing temperature along its flow path and that shallow (less than 200m) temperature measurements are dominated by the effects of irrigation canal leakage. Further analysis of temperature data is planned. A statistical methodology for assessing the geothermal resources in hydrothermal convection systems was developed by this project for the 1978 resource assessment. For the assessment of low-temperature geothermal resources, this project is preparing a temperature-gradient map of the conterminous U. S. The map displays temperature gradients that exist over broad areas in a conductive thermal regime to 2 km. Preliminary results indicate that low heat flow in the east is commonly expressed by gradients less than 25°C/km, and high heat flow in the west is generally reflected by gradients greater than 25°C/km.

Project Title: Geothermal Petrophysics

Project Chief: Gary Olhoeft
(Denver, Colorado)

Project Objectives: To provide fundamental experimental data on the behavior of rock physical properties in geothermal environments, particularly those physical properties of use in the interpretation of field geophysical data. To use the experimental data to identify the physical and chemical mechanisms behind the observed properties so as to develop a petrophysical model to predict properties beyond the reach of current core and drill holes but where surface geophysics is still acquiring data. To perform experiments and model studies to help improve existing field geophysical techniques.

Project Status: Since the inception of this project in 1976, many experimental data have been acquired on the electrical, magnetic, and textural (permeability, porosity, etc.) properties of rocks in geothermal environments. The electrical properties of brine and brine-saturated rocks have been measured to 400°C, and the electrical properties of dry rocks have been measured to 1300°C. Seismic velocity and attenuation have been measured on molten basalt from 1250 to 1400°C. Magnetic properties and textural properties have been studied near room temperature and capabilities have been developed to study these properties up to 800°C. Measurements have been performed under both temperature and pressure to a depth equivalent of about 2 km, with pressure/depth capabilities to 40 km now existing. Preliminary petrophysical models of electrical properties have been developed.

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*Project Title Studies of Hydrogeothermal Circulation (Grant No. 14-08-0001-G-626)

Principal Investigator: E. M. Parmentier
Brown University
Providence, RI 02912

Project Objectives: To theoretically study thermal convection in a fluid-saturated layer of permeable material containing discrete, regularly spaced fractures which is heated from below. To study the control which fractures place on the form of the circulation for a range of parameters such as the permeability of rock between fractures, the hydraulic conductivity of the fractures, and the fracture spacing. To consider the cooling of dikes in permeable country rock by groundwater circulation using the results of several recent theoretical studies of natural convection. To determine the influence of natural convection on cooling of the dikes using field data on their thermal aureoles.

Project Status: Results to date indicate that the fractured, permeable layer being considered has impermeable and isothermal top and bottom boundaries. A linear stability analysis has been used to establish conditions for the marginal stability of two-dimensional convective modes in the layer. The results demonstrate that the convective mode with the smallest critical Rayleigh number depends on the ratio of the fracture spacing to the layer depth. Numerical studies of finite-amplitude convection show that the fractures control the vertical flow in the layer. As flow patterns evolve from their initial state, vertical flow becomes concentrated in the fractures. The study is being extended to investigate the effects of a permeable upper-boundary on flow in the layer.

Project Title: Rocks Under Geothermal Conditions

Project Chief: Louis Peselnick
(Menlo Park, California)

Project Objectives: To develop instrumentation for measuring elastic and anelastic properties of rocks at high pressure and temperature.

To determine anelastic properties of rocks at frequencies and strain amplitudes appropriate to seismic waves (0.1 to 10 Hz, and 10^{-7} strain amplitude). To interpret the experimental results in terms of the physical mechanisms of rock internal friction, with special application to geothermal systems.

Project Status: The laboratory determination of the compressional velocity in rocks of the Franciscan Formation at high pressure and temperature has provided data for seismic modeling of the crust in northern California. The results show that rock density determines the P-velocity. A shift of research emphasis from ultrasonic frequencies to the seismic frequency range (0.1 to 10 Hz) is underway. The redesigned high-pressure and high-temperature equipment should be in operation early in 1981. This laboratory facility should then provide a continuing output of data on internal friction as a function of pressure, temperature, frequency, and strain amplitude for rocks relevant to geothermal areas. Because a large increase in internal friction is to be expected when water in rocks transforms to steam, experiments are planned to measure, at various pressure and temperature, the internal friction in rocks of the Franciscan Formation that contain water and steam in pores. Such studies may provide methods for estimating physical properties for distinguishing between potential hot-water and vapor-dominated geothermal systems.

Project Title: Pressurized Fractures in Hot Rock

Project Chief: David D. Pollard
(Menlo Park, California)

Project Objectives: To study the processes of fracture, fluid flow, and heat transport associated with large, fluid-filled fractures such as natural igneous dikes and man-made hydraulic fractures in the rocks of geothermal regions. To increase our understanding of the form, stability, and growth of these fractures and of the transport of fluids and heat within the fractures and adjacent rock through research in theoretical continuum mechanics, field studies of dikes and hydraulic fractures, and laboratory model studies. To apply the results of our studies to the design and monitoring of hydraulic fractures for energy extraction and to the interpretation of geological and geophysical data from modern and ancient geothermal regions.

Project Status: An elastic solution for deformation around an arbitrary number of pressurized fractures has been derived and used to analyze fracture geometries found in nature. Solutions for fluid flow in fractures of varying cross-sectional form have been derived and used to study magma flow in dikes and volcanic necks. Heat transport in fluids and through the walls of fractures has been analyzed using new solutions for the transport equations. Each of these theoretical efforts has been tested by detailed field studies of natural fractures. Since the project began in 1974, results have been published in many reports whose topics include the form and stability of fractures subjected to gradients in stress, the interaction of fractures with the Earth's surface, the growth of en echelon fractures, the transition from dikes (fissures) to necks (volcanic vents), solidification of magma, and brecciation of the fracture wall.

Geologist maps dike at Ship Rock in northwest New Mexico. Such studies help explain how fractures form in the Earth's crust and how magma moves within the crust.

Project Title: Geothermal Resource Assessment

Project Chief: Marshall Reed
(Menlo Park, California)

Project Objectives: To quantitatively assess geothermal resources less than 100°C of the United States.

Project Status: This study began in 1980. Since the assessment relies heavily on data gathered by state agencies conducting geothermal studies funded by the Department of Energy, meetings have been held with all of these agencies to discuss the quality and type of data necessary for the assessment and the timing for submission of the data. Information on hot-water wells and springs goes directly to the USGS GEOTHERM computer file, and additional information comes directly to the assessment project. Methods are being developed to use the USGS hydrologic data base (WATSTORE) to estimate transmissivity and storage coefficient for low-temperature geothermal systems. Well known low-temperature geothermal systems are being identified to serve as case studies and then as models for estimating the recoverability of thermal energy in poorly-known areas.

Project Title: Subsidence and Related Aspects of Geothermal Systems

Project Chief: Francis S. Riley
(Denver, Colorado)

Project Objectives: To monitor vertical and horizontal displacements of the land surface, changes in subsurface pressure gradients, and changes in subsurface temperature and to attempt to explain if these are natural or induced by the extraction or injection of geothermal fluids. To analyze and interpret pertinent geodetic, geophysical and geologic data as a background for this investigation and to obtain the stress-strain parameters, and from these to appraise the behavior of geothermal reservoirs and accompanying groundwater systems.

Project Status: Measurements of horizontal and vertical control nets are continuing and/or are planned for geothermal areas in Imperial Valley, California; Raft River, Idaho; Roosevelt Hot Springs, Utah; and The Geysers, California. A reconnaissance of Dixie Valley, Nevada, was conducted, and a horizontal control net will be established there.

Project Title: Modeling of Geothermal Systems

Project Chief: Michael L. Sorey
(Menlo Park, California)

Project Objectives: To develop and apply mathematical and numerical modeling techniques to the study of single- and two-phase geothermal systems. To collect and analyze hydrologic, geologic, geophysical, and geochemical data from hydrothermal sytems within young calderas and in the Basin and Range province in order to develop realistic conceptual models for heat and fluid flow in these systems. To develop and test mathematical solutions for the response of geothermal wells to production under single- and two-phase reservoir conditions.

Project Status: Development of the computer code SCHAFF, for analyzing heat and fluid flow in hot-water geothermal systems under unexploited conditions is now complete. Successful applications of the code have been made to the analysis of heat transfer in hot-spring areas, cellular convection in porous media, and to models of the hydrothermal system in the Long Valley, California, caldera. Models of fluid circulation associated with Leach Hot Springs in Grass Valley, Nevada, have also been analyzed and a report on this work is in progress. Similar modeling work at Raft River, Idaho, and Klamath Falls, Oregon, is in progress. During 1978-1979, the project chief worked as a post-doctorate fellow in New Zealand on analysis of the response of the Wairakei geothermal field to production and on solutions for two-phase flow to wells. Work on comparisons of solutions from different numerical simulators for a set of standardized single- and two-phase geothermal problems is also in progress in cooperation with the Department of Energy.

Project Title: Physics of Geothermal Systems

Project Chief: T. C. Urban
(Menlo Park, California)

Project Objectives: To obtain a better understanding of the physics of geothermal systems through measurement of temperatures and other geophysical parameters that appear appropriate and practical. To integrate these data and other geological, geophysical and hydrological information in order to develop models suitable for describing specific geothermal systems and geothermal systems in general. To examine geological and geophysical data on a more regional basis to determine the nature and causes of the existence of geothermal systems.

Project Status: An average-elevation map of the conterminous United States at a scale of 1 to 2.5 million is in the final drafting stage for publication. This map and future modified versions will be compared to geologic and geophysical maps. A chapter on the geology and geophysics of geothermal systems was prepared for a book on the Production of Electricity from Geothermal Energy, edited by J. Kestin of Brown University. Equilibrium temperature logs were obtained in 24 holes at Raft River, Idaho. Analysis of these data should be completed within the next year. Temperature data obtained in intermediate depth holes in the eastern part of Long Valley Caldera, California, show that there is pervasive lateral subsurface spreading of hot water that rises from depth along deeply penetrating conduits.

Project Title: Geothermal Tectonic Seismic Studies

Project Chief: Craig Weaver
(Seattle, Washington)

Project Objectives: To investigate the relationships among contemporary seismo-tectonics, earth structure, and volcanic/geothermal areas within different tectonic frameworks.

Project Status: Three studies are virtually complete: crustal structure at Coso, California; focal mechanism at Yellowstone National Park; seismicity at Mt. Hood, Oregon. Papers on all three areas are in press. The eruption of Mount St. Helens, Washington, has caused a sudden re-ordering of project priorities, with a major commitment now directed to the volcano. Between March 21-31, 1980, six 5-day recorders and 8 telemetry stations were installed near Mount St. Helens. Collection of high quality data for this unique seismo-volcanic sequence has been given special emphasis. The seismic studies at Mount St. Helens are being conducted jointly with the University of Washington. Crustal refraction experiments have been run, using earthquakes beneath Mount St. Helens as the source of energy.

REGIONAL INVESTIGATIONS

*Project Title Heat Flow Study of the Snake River Plain and Margins, Idaho
(Grant No. 14-08-0001-G-425)

Principal Investigator: David D. Blackwell
Southern Methodist University
Dallas, TX 75275

Project Objectives: To evaluate the geothermal character of the Snake River Plain and margins, Idaho, by determination and analysis of heat flow values, and to use these data for mathematical modeling of the region. To obtain thermal data from the Snake River Plain aquifer by measurement of temperatures in deep wells and shallow drillholes, associated geochemical studies of aquifer water, and theoretical modeling of the thermal effects of aquifers. To analyze the resulting data for their regional tectonic and geothermal significance, in combination with ongoing studies in surrounding areas for a complete regional synthesis.

Project Status: A heat-flow survey has shown that heat-flow values of 125 milliwatts/m^2 (3 HFU) or greater are characteristic of the margins of the eastern Snake River Plain. Theoretical considerations suggest that heat flow should be similarly high throughout the entire eastern Snake River Plain, but negative values were observed in the center of area (near Idaho Falls) with a gradual increase to about 63 milliwatts/m^2 (1.5 HFU) to the west (near Hagerman-Twin Falls). The low and negative heat-flow values result from lateral flow of groundwater in the Snake River Plain Aquifer. Flow rates in the aquifer are as high as several meters per day. A theoretical model of the aquifer can explain the observed pattern of surface heat flow and suggests that high heat flow is present beneath the aquifer.

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*Project Title Geomagnetic Sounding in the Cascade Range of Washington State as a Geothermal Exploration Technique (Grant No. 14-08-0001-G-625)

Principal Investigator: John R. Booker
University of Washington
Seattle, WA 98195

Project Objectives: To make a detailed study of the Packwood, Washington, geomagnetic anomaly using an array of three-component flux-gate magnetometers in order to determine the depth and conductivity of the anomaly and its relation to Cascade volcanoes. To refine the original east-west geomagnetic sounding profile and to study the north-south variation of the anomaly.

Project Status: An east-west geomagnetic-sounding profile from the coast of Washington into the Cascade Range roughly midway between Mt. Rainer and Mts. Adams and St. Helens discovered a major anomaly near Packwood, Washington, where this profile crosses the volcanic front. The anomalous structure is believed to be in the crust, but may be deeper. Several subsequently run east-west profiles suggest that the geomagnetic anomaly extends northward from the Packwood area and projects toward Puget Sound just south of Seattle.

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*Project Title Evaluation of Detailed Seismic Refraction Profiling for Regional Geothermal Exploration and Application to Yellowstone and Snake River Plain (Grant No. 14-08-0001-G-674)

Principal Investigator: Lawrence W. Braile
Purdue University
West Lafayette, IN 47907

Project Objectives: To make a detailed seismic refraction profile in the Yellowstone-Snake River Plain region (Y-SRP) in order to evaluate the use of seismic refraction methods for regional geothermal exploration. To interpret the resulting seismic records in terms of the compressional- and shear-wave velocity structure and attenuation and the variations of these properties as a function of thermal environment along the Y-SRP.

Project Status: Field work in the Y-SRP was conducted during June and July, 1980 with three-component seismometers. Twenty-three shotpoints were utilized to record seismic refraction and reflection data along six profiles. In general, the seismic profiles yielded good to excellent data, particularly for stations within 20 km of shot points. Data reduction and digitizing of all seismograms is currently underway.

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*Project Title Delineation of Heat Flow Provinces in Utah (Grant No. 14-08-0001-G-544)

Principal Investigator: David S. Chapman
University of Utah
Salt Lake City, UT 84112

Project Objectives: To obtain heat-flow and heat-production measurements which will help delineate the following heat-flow provinces in Utah: a) Northern Basin and Range, b) Battle Mountain, c) South Bonneville, d) Northwest Colorado Plateau.

Project Status: A major effort has been directed toward measuring thermal conductivity, making topographic corrections at all relevant sites, and reducing heat flow values. Several new computer programs have been developed in order to store, retrieve and display data being accumulated. Thermal-conductivity behavior of all the major older (about 350 to 60 m.y.-old) lithologies of the central Utah-Colorado Plateau section has been characterized. This will greatly assist future estimates of heat flow where only temperature-depth results are known. Delineation of heat-flow provinces and evaluation of their geothermal resource potential are being made.

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*Project Title Aeromagnetic Measurements in the Cascades Range and Modoc Plateau of Northern California (Grant No. 14-08-0001-G-623)

Principal Investigator: Richard Couch
Oregon State University
Corvallis, OR 97331

Project Objectives: To obtain high quality aeromagnetic data (1.6 km-spaced east-west flight lines and 8 km-spaced north-south tie lines flown at a constant barometric altitude of about 600 m average terrain clearance) over a 30,000 square-km area in the Cascades and Modoc Plateau of northern California. To analyze the data in terms of structure, volcanic centers, regional trends, Curie-temperature isotherm depths, and the geothermal energy potential of the area.

Project Status: The data-collection phase of this project was completed, with over 250,000 data points recorded on approximately 20,000 miles of flight lines in 215 hours of flight time. Interpretation of the data is underway.

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*Project Title The Interpretation of Aeromagnetic Measurements from Southcentral Oregon for Geothermal Assessment (Grant No. 14-08-0001-G-698)

Principal Investigator: Richard Couch
Oregon State University
Corvallis, OR 97331

Project Objectives: To analyze aeromagnetic measurements from southcentral Oregon in terms of regional and local structures as delineated by the near-surface anomalies and source depths. To determine the depths of the Curie-point isotherm using two-dimensional spectral techniques.

Project Status: High-quality aeromagnetic data of the area between 42° and 43° N latitude and 121° and 122°30' W. longitude have been collected. This area includes the Klamath Graben and Klamath KGRA and the axis and east and west flanks of the Cascade Range, a sector of the zone of transition between Basin and Range and Cascade structures, and extends from just north of Crater Lake south to the Oregon-California border Data were collected along 1.6-km-spaced east-west lines and 8-km-spaced north-south lines. Analysis of data is underway.

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*Project Title: Regional Assessment of Intermediate-Temperature Geothermal Resources of Southwestern New Mexico (Grant No. 14-08-0001-G-630)

Principal Investigator: Wolfgang E. Elston
University of New Mexico
Albuquerque, NM 87131

Project Objectives: To assess the geothermal resources in southwestern New Mexico, by geologic mapping. To compile regional geologic and tectonic maps.

Project Status: The assessment of the geothermal potential of southwestern New Mexico has concentrated on three areas: 1) Lightning Dock KGRA, Animas Valley, Hidalgo County. A 1:48,000 geologic map of the KGRA and nearby parts of the Pyramid Mountains is being prepared for publication. Hydrologic and geochemical studies on waters of the Animas Valley are in progress. Preliminary indications suggest possible extension of the thermal anomaly southwestward from the KGRA; 2) Gila Hot Springs KGRA, and Mimbres Hot Springs, Grant County. Geologic mapping of poorly-known areas has been completed and preliminary geologic and tectonic maps have been compiled. At Gila Hot Springs, an unwelded zone of an ash-flow tuff appears to serve as an aquifer for thermal water. Mimbres Hot Springs seem to be localized at the intersection of a Basin and Range fault (Mimbres Hot Springs fault) and an older, caldera-related fault. Fractures in caldera-filling ash-flow tuff appear to act as conduits for hot water; 3) Geologic mapping of part of the Mangas Trench, southeastward from Lower Frisco Hot Springs KGRA (Grant and Catron Counties) is in progress.

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*Project Title: Basement Trends in Metamorphism, Plutonism, Structure and Heat Flow Under the Atlantic Coastal Plain for Potential Geothermal Resources (Grant No. 14-08-0001-G-685)

Principal Investigator: Lynn Glover, III
Virginia Polytechnic Institute and State Univ.
Blacksburg, VA 14061

Project Objectives: To understand the regional geologic framework of the Atlantic Coastal Plain in order to locate radiogenic heat sources in the basement. To investigate the apparently systematic eastward decrease in ages of plutons and in ages of amphibolite-facies metamorphic thermal maxima across the crystalline terrain.

Project Status: This study is based on a model which proposes that radiogenic heat sources will normally be syn- to post-metamorphic granites having concentrations of U and Th that are several times background. Such plutons may heat overlying sedimentary rocks of low thermal conductivity, including aquifers suitable for development for space heating and other non-electrical applications. Rocks recovered from drill holes near Lumberton and Camp LaJeune, North Carolina, are being studied to test the model. Petrographic, geochemical and geochronologic studies are underway.

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*Project Title Volcanology and Structural Geology of the Southeastern Part of the Cascade Range, Northeastern California (Grant No. 14-08-0001-G-624)

Principal Investigator: L. Trowbridge Grose
Colorado School of Mines
Golden, CO 80401

Project Objectives: To investigate the volcanic, tectonic, and hydrologic framework and evolution of the southeastern part of the Cascade Range in northeastern California. To estimate the geothermal potential of the area and to determine additional studies needed to improve this estimate.

Project Status: The study area is bounded on the west by the east flank of the Lassen Peak-Mt. Shasta axis, on the north by the Pit River Valley and the Medicine Lake Highlands, on the east by the Modoc Lava Field and the Basin and Range Province, and on the south by the Sierra Nevada. The methods of investigation include reconnaissance and detailed geologic mapping, petrography and K-Ar geochronology. All field data have been collected and the synthesis of these data, including geologic maps and cross sections, is underway.

Project Title: Imperial Valley Geothermal Studies

Project Chief: Carl E. Johnson
(Pasadena, California)

Project Objectives: To develop an understanding of the seismotectonic processes that affect the geothermal resources of the Imperial Valley, California, one of the few places in the world where an oceanic ridge system encroaches onto a continental regime. To study the dynamic balance between fault breakage and hydrothermal healing of this seismically active geothermal area.

Project Status: The field work associated with a refraction experiment is complete. Preliminary analysis of data has resulted in knowledge of crustal structure in the Imperial Valley of unprecedented detail. These results are being combined with earthquake data from a permanent 25-station Imperial Valley network to provide better control of seismicity distribution and focal mechanisms. Interpretations based on these data show that the geothermal areas are associated with zones of complex fracturing. Crack extension apparently occurs during earthquake swarms.

Project Title: Magmatic Gas Geochemistry

Project Chief: David Johnston
(Menlo Park, California)

Project Objectives: To sample and analyze volcanic gas emissions from active and dormant volcanoes, particularly calc-alkaline volcanoes of Alaska and the Cascades. To examine major volatile-element contents of magmas primarily by analysis of glass inclusions within phenocrysts. To understand the processes by which magmatic gases evolve and escape from magma chambers.

Project Status: Volcanic gases have been sampled from 6 volcanoes in Alaska, 3 in the Cascades, from Kilauea in Hawaii, and 2 thermal areas in the Azores. Gases from Augustine Volcano, Alaska have been sampled repeatedly since its 1976 eruption, and glass inclusion studies have disclosed its 1976 magma to be volatile-element-rich.

Note: David Johnston was lost at Mount St. Helens during the violent eruption of May 18, 1980.

Project Title: Regional Geothermal Hydrology of Southwestern Montana

Project Chief: Robert B. Leonard
(Helena, Montana)

Project Objectives: To describe the thermal waters of southwestern Montana in terms of temperature, discharge, chemical character, areal distribution, and depth of occurrence. To determine the nature of local and regional hydrogeologic controls on the occurrence of thermal water. To develop conceptual models of selected hydrothermal systems as a guide to appraisal and potential development of the geothermal resource.

Project Status: The project began in August 1975. Reconnaissance geological, geochemical, and hydrologic studies of 24 hot-spring areas have been completed, and the data collected through 1978 have been released to the open file. Detailed surface geological studies and additional hydrologic studies have provided a description of the basic structural controls of hot-spring systems and have been released to the open file. Test holes were drilled at two sites, one representative of systems in fractured crystalline rock and the other in a sediment-filled valley. Results of surface and borehole geophysical surveys, pumping tests, seepage studies, and chemical analyses of water samples describe the hydrothermal systems at six sites where access to thermal wells was obtained. Field work was essentially completed in March 1980. Basic data reports and several interpretive reports have been published or released to the open file. Final reports are in preparation.

Project Title: Oregon Geothermal Reconnaissance

Project Chief: Norman S. MacLeod
(Menlo Park, California)

Project Objectives: To evalulate the geothermal potential of southeastern and central Oregon, an area of about 125,000 km^2 that is underlain almost exclusively by middle and upper Cenozoic volcanic rocks, and to provide concepts and data useful for geothermal exploration. To identify possible geothermal systems that may be associated with cooling igneous bodies in the west half of the Crescent two-degree sheet, including Newberry Volcano.

Project Status: This project is now winding down. All field work is complete and maps are nearly ready for publication. A final report will be prepared upon completion of analytical work and potassium-argon dating that is now in progress.

Project Title: Alaska Geothermal

Project Chief: Thomas P. Miller
(Anchorage, Alaska)

Project Objectives: To make a reconnaissance evaluation of the geothermal resources of Alaska. To study the geology, geochronology, and petrology of the Quaternary volcanic centers in the Aleutian volcanic arc and the Wrangell Mountains. To define the nature and character of the volcanic centers that may have near-surface magma chambers.

Project Status: The reconnaissance aspects of the project are now largely completed for all major Quaternary volcanic centers on the Alaska Peninsula, the eastern Aleutian Islands, and some of the Wrangell Mountains. Pilot studies are completed on Mt. Drum in the Wrangells and have begun on Peulik Volcano on the Alaska Peninsula. Topical papers and maps have been published, and more are in preparation.

Project Title: Hydrologic Reconnaissance of Geothermal Areas in Nevada and California

Project Chief: Franklin H. Olmsted
(Menlo Park, California)

Project Objectives: To develop and evaluate geohydrologic reconnaissance techniques chiefly related to shallow test drilling for exploration of several hydrothermal systems in northern and central Nevada. To formulate conceptual models of the systems for which the most data are available.

Project Status: This project began in early 1972 with a hydrologic reconnaissance of 7 hydrothermal systems in northern and central Nevada: Bradys Hot Springs, western Carson Desert (Soda Lakes), Stillwater, Leach Hot Springs, Gerlach Hot Springs, Buffalo Valley, Hot Springs, and Sulphur Hot Springs (Ruby Valley). The release of USGS Open-File Report 75-56 ended the first stage of the project. The second stage involved the selection of 3 of the 7 systems for more intensive investigation: Bradys Hot Springs, western Carson Desert (Soda Lakes), and southern Grass Valley (Leach Hot Springs and vicinity). A short time later, the Beowawe hydrothermal system and the Upsal Hogback system (northeast of Soda Lakes in the western Carson Desert) were added to the list of study areas. In addition, evaluations were made of the utility of temperature measurements at 1-m depth in delineating thermal anomalies at greater depths, using both conventional methods (thermistor measurements) and the Pallmann (sugar-solution) method of temperature integration. Fieldwork is nearly complete in all the areas except Bradys Hot Springs and papers describing the hydrogeology of southern Grass Valley, Stillwater area, and western Carson Desert are in various stages of preparation. It is expected that all the presently ongoing work will be completed during 1981.

Project Title: Geothermal Drilling at Mt. Hood, Oregon

Project Chief: James H. Robison
(Menlo Park, California)

Project Objectives: To help assess the geothermal potential of the Mt. Hood area by drilling observation wells to determine temperature gradients and to characterize the subsurface geology and hydrology.

Project Status: This project is part of an interagency study (U.S. Department of Energy, U.S. Forest Service, U. S. Geological Survey, and Oregon Department of Geology and Mineral Industries) of the geothermal potential of a young Cascade stratovolcano. In 1979 four wells were drilled on the cone of the volcano including one to 610 m near Timberline Lodge. In 1980 the well near the Lodge was deepened to 1,220 m, one of the other wells was deepened, and three new wells were drilled. Temperature gradients vary from about 30°C/km to 84°C/km. The cone of Mt. Hood is comprised mostly of pyroxene andesite, both as lava flows and fragmental deposits. Near Timberline Lodge, pre-Mt. Hood rocks (altered andesitic lavas and eipclastic debris, with secondary mineralization) lie below an altitude of about 900 meters. Perched, water-saturated zones occur locally within the cone. In the 1,220-m-deep well near the Lodge the water table is 573 meters below the surface, substantially deeper than expected. A production test of this well is planned; temperature in the production zone is expected to be more than 70°C. Deepening and possible testing is proposed for two others wells.

develop and test mathematical solutions for the response of geothermal wells to production under single- and two-phase reservoir conditions.

Project Status: Development of the computer code SCHAFF, for analyzing heat and fluid flow in hot-water geothermal systems under unexploited conditions is now complete. Successful applications of the code have been made to the analysis of heat transfer in hot-spring areas, cellular convection in porous media, and to models of the hydrothermal system in the Long Valley, California, caldera. Models of fluid circulation associated with Leach Hot Springs in Grass Valley, Nevada, have also been analyzed and a report on this work is in progress. Similar modeling work at Raft River, Idaho, and Klamath Falls, Oregon, is in progress. During 1978-1979, the project chief worked as a post-doctorate fellow in New Zealand on analysis of the response of the Wairakei geothermal field to production and on solutions for two-phase flow to wells. Work on comparisons of solutions from different numerical simulators for a set of standardized single- and two-phase geothermal problems is also in progress in cooperation with the Department of Energy.

Project Title: Physics of Geothermal Systems

Project Chief: T. C. Urban
(Menlo Park, California)

Project Objectives: To obtain a better understanding of the physics of geothermal systems through measurement of temperatures and other geophysical parameters that appear appropriate and practical. To integrate these data and other geological, geophysical and hydrological information in order to develop models suitable for describing specific geothermal systems and geothermal systems in general. To examine geological and geophysical data on a more regional basis to determine the nature and causes of the existence of geothermal systems.

Project Status: An average-elevation map of the conterminous United States at a scale of 1 to 2.5 million is in the final drafting stage for publication. This map and future modified versions will be compared to geologic and geophysical maps. A chapter on the geology and geophysics of geothermal systems was prepared for a book on the Production of Electricity from Geothermal Energy, edited by J. Kestin of Brown University. Equilibrium temperature logs were obtained in 24 holes at Raft River, Idaho. Analysis of these data should be completed within the next year. Temperature data obtained in intermediate depth holes in the eastern part of Long Valley Caldera, California, show that there is pervasive lateral subsurface spreading of hot water that rises from depth along deeply penetrating conduits.

Data collected from an observation well being drilled near Mt. Hood, Oregon, will help assess the geothermal potential of that region.

Project Title: Geothermal Hydrology of Lower Coachella Valley, Southeastern California

Project Chief: James H. Robison (Menlo Park, California)

Project Objectives: To describe the general geohydrologic framework of Lower Coachella Valley, California, especially as related to geothermal systems. To evaluate geologic, geochemical, and geophysical data that may indicate geothermal potential. To determine additional work needed for geothermal evaluation of high-potential areas.

Project Status: A drilling program of temperature-gradient holes and piezometers at 11 sites near Oasis was completed in 1979. Drillers' geophysical, and temperature logs have been made of the wells, which average 150-m deep, with maximum temperatures to 47°C and gradients as high as 107°C/km. Water samples from 8 piezometers have been analyzed. The project chief is temporarily committed full-time to hydrologic study at Mt. Hood, Oregon.

Project Title: Hydrogeologic Reconnaissance of Geothermal Areas in Oregon

Project Chief: Edward A. Sammel
(Menlo Park, California)

Project Objectives: To describe the hydrologic environment of several identified but unevaluated geothermal systems in Oregon and northern California. To interpret geologic, geochemical, geophysical, and hydrodynamic data in terms of the size, shape, and hydraulic characteristics of the geothermal reservoirs. To provide a basis for quantitative assessment of energy contained in the reservoirs. To apply existing numerical models to data obtained from several types of low- to moderate-temperature Basin and Range geothermal systems utilizing existing hydrologic, geologic, and geophysical knowledge in order to define the extent and functioning of these systems.

Project Status: USGS Professional Paper 1044-G that describes and evaluates the Klamath Falls, Oregon, geothermal area has been published. Core-hole drilling to a depth of 610 m in the crater of Newberry Volcano, Oregon, has increased our knowledge of this Cascade volcano; deeping of this hole to about 915 m is planned for 1981. A report that describes the hydrology and evaluates the high-temperature geothermal resource in Warner Valley, Oregon, is near completion. More sophisticated numerical models are currently being tested on the Klamath Falls geothermal system. A more precise understanding of boundary conditions and flow relations in this system is necessary for a reliable estimate of the geothermal resource.

Project Title: Studies of the Geothermal Systems in the Western Black Rock Desert, Nevada

Project Chief: Alan Welch
(Carson City, Nevada)

Project Objectives: To develop an understanding of the geothermal systems of the western part of the Black Rock Desert through a variety of geologic, geophysical, geochemical and hydrologic studies.

Project Status: The first phase of the study, which includes results from gravity, thermal scanner, and 1-m-deep temperature surveys, is being prepared as an open-file report. Work is continuing on shallow test drilling, geochemical sampling, and the collection of hydrologic data. Numerical modeling of heat and mass flow will be used to assess conceptual models of the thermal system.

Project Title: Geothermal Studies of the Snake River Plain, Idaho

Project Chief: Paul L. Williams
(Denver, Colorado)

Project Objectives: To locate, map, and geologically define areas in and near the eastern Snake River Plain, Idaho, that may have geothermal potential. To provide a 3-dimensional geologic framework for further geological and geophysical interpretations by combining surface mapping with subsurface data. To provide geological expertise for the interpretation of the deep geothermal test well at Idaho Falls. To develop exploration concepts and case histories.

Project Status: This project began in 1974 and has supported geologic mapping and related studies in areas of rhyolite volcanism throughout the eastern Snake River Plain region. In areas of active geothermal exploration and development (Raft River Basin and Rexburg-Sugar City) subsurface studies are being carried out in cooperation with hydrologists and geophysicists. Present focus is on completing final reports for Raft River and Idaho Falls areas, completing mapping and petrographic studies of silicic volcanic rocks, and contributing to an assessment of geothermal resources of the Snake River Plain region.

Project Title: Geothermal Investigations in Idaho

Project Chief: H. W. Young and R. E. Lewis
(Boise, Idaho)

Project Objectives: To determine the occurrence, nature, and flow regime of geothermal fluids at selected sites, including Bruneau - Grand View, southwest Idaho, and parts of the Idaho batholith.

Project Status: Collection and interpretation of data from southwest Idaho and parts of north-central Nevada have been completed, and a final report has been published discussing the hydrology and geochemistry of the area; residence time, recharge, and thermal energy of the reservoir are estimated. Investigation of the geochemistry of hot springs in the Idaho batholith has been divided into the drainage areas of the Payette, Salmon, and Boise rivers. Collection of data has been completed from the Payette and Salmon river drainages, and a report summarizing the results for the Payette River drainage has been completed. Data collection from the Boise drainage is underway.

DEVELOPMENT OF GEOTHERMAL-EXPLORATION TECHNIQUES

Project Title: Engineering Geophysics

Project Chief: Hans D. Ackermann (Denver, Colorado)

Project Objectives: To determine relationships between rock properties within geothermal systems and their seismic-wave transmission properties by seismic measurements in the field. To apply these relationships to geothermal exploration.

Project Status: A vibroseis seismic reflection survey consisting of 35 km of line was done under contract by the Colorado School of Mines in the Raft River, Idaho geothermal area. The results show a highly complex geologic section. Sonic logs from the wells in the area have been digitized to aid in the final interpretation.

Project Title: Electromagnetic Modeling and Inversion of Controlled Source Measurements

Project Chief: Walter L. Anderson (Denver, Colorado)

Project Objectives: To develop new numerical techniques and associated computer programs for electromagnetic (EM) modeling and inversion of controlled-source data. To investigate enhancements of existing forward and inverse programs and to study advanced techniques for further development of one- to three-dimensional EM problems.

Project Status: A comprehensive collection of one-dimensional forward and inverse programs for dipolar and grounded-wire sources over layered-Earth models were developed for both frequency and time domains. Two field studies in geothermal areas (Raft River, Idaho and Randsburg, California) were performed, and the results of data inversion published. Two-dimensional (2D) forward and inverse programs have been purchased and in some cases, modified to suit specific needs of the geophysical studies. One particular 2D modification describes EM scattering due to a plane-wave source using an integral equation solution. An important new concept was discovered for integrating related Hankel transforms of orders 0 and 1 by adaptive digital filtering. This new technique saves computer time (e.g., 50-80 percent faster than direct convolution methods) for forward and inverse programs using loop sources. Present research is aimed at three-dimensional (3D) EM modeling for conductors in a horizontally stratified Earth using natural or controlled sources at the surface.

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*Project Title Magnetotelluric Interpretation Procedures for Three Dimensional Earth Structures in Geothermal Areas (Grant No. 14-08-0001-G-629)

Principal Investigator: Francis X. Bostick
University of Texas
Austin, TX 78712

Project Objectives: To develop procedures for interpretation of magnetotelluric (MT) data acquired over three-dimensional Earth structures and to test them against existing models. To develop techniques that provide for more efficient processing of MT data, particularly at low frequencies.

Project Status: Time-domain methods for estimating MT impedance functions utilize auto- and cross-correlation functions of the time-varying electric (E) and magnetic (H) fields. These methods were tested using synthetic data generated by three different techniques. One technique derives theoretical expected values of the auto- and cross-correlation functions from an assumed power density spectrum of the H field. Another technique uses synthetic data generated by a time-domain model in the form of a recursive digital filter. The third technique uses synthetic data generated using Fourier Transform techniques.

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*Project Title: Mercury and Other Trace Elements in Soils as Geochemical Tracers for Geothermal Activity (Grant No. 14-08-0001-G-593)

Principal Investigator: Peter R. Buseck
Arizona State University
Tempe, Arizona 85281

Project Objectives: To study the distribution of mercury (Hg) and other selected elements in soil and rock samples in the vicinity of hot-water and vapor-dominated geothermal systems in order to develop a technique of exploration for new geothermal areas. To measure radon contents in soil gas from several geothermal areas to determine if radon anomalies occur and if they correlate with Hg anomalies. To investigate the occurrence of Hg in lake sediments from Clear Lake, California and Yellowstone National Park to determine variations of geothermal activity with time.

Project Status: Data gathered to date indicate a relationship between observed Hg-anomaly patterns and geologic structure of geothermal areas. Trace-element data from Lassen region, California, enable the modeling of transportation and distribution processes of trace elements in geothermal systems and serve as a general model for the evaluation of other geothermal areas.

Project Title: Physical Properties of the Crust/Upper Mantle by Geomagnetic Variation and Laboratory Studies

Project Chief: David V. Fitterman
(Denver, Colorado)

Project Objectives: To develop a geomagnetic sounding technique for evaluating the physical state of the crust and upper mantle. To develop self-potential modeling techniques. To measure streaming-potential coefficients at elevated temperatures.

Project Status: Development of software and documentation for transcribing geomagnetic array data has been completed. Most of the work on software for automatically computing induction vectors has been completed. The remaining software and documentation is in preparation. Self-potential modeling techniques for several geometries useful in geothermal exploration have been developed, including an inversion technique for certain types of data.

Project Title: Stable Isotopes

Project Chief: Irving Friedman
(Denver, Colorado)

Project Objectives: To evaluate the use of the Pallman and Ambrose methods of temperature integration in assessing the geothermal potential of a region. To improve the obsidian-hydration dating method and to apply the technique to the dating of young volcanic rocks. To develop methods for the long-term continuous monitoring of hot-spring features.

Project Status: The Pallman method of temperature integration was applied to over 60 sites in and near Yellowstone National Park, in areas remote from known hot springs. Data on ground temperatures to be used in deriving hydration rates for obsidian used in geologic dating was collected. An area of anomalous heat flow was located near Slough Creek in the north central part of Yellowstone. A new type of temperature-integrating device, the Ambrose cell, has been modified for field use and is presently being compared to the Pallman solution at a number of sites in Yellowstone. Pallman ground temperature measurements were carried out at two geothermal sites in Nevada. Integration periods of 1 year and 3 months were compared with traditional ground temperatures measured monthly at depths of 1 meter and 15 meters and good correlation was found at one geothermal area. The other area in Nevada has a much smaller thermal anomaly, and neither the Pallman measurements at 1 and 2 meter depths nor the traditional thermistor measurements were able to pick up this anomaly. A new laboratory has been set up to study the hydration of obsidian at temperatures from 0° to 40°C. A newly developed micrologger has been purchased to monitor water flow, water temperature, and specific conductivity of hot springs. The data are collected hourly and are stored on a tape cassette. The equipment is about the size of a cigar box and will run for over 6 months on internal flashlight batteries.

Project Title: Geophysical Instrumentation and Field Support

Project Chief: Frank Frischknecht
(Denver, Colorado)

Project Objectives: To develop new geophysical instrumentation. To repair and maintain existing equipment. To provide technical support as required by field operations. To assist in procurement of commercially available equipment as required to meet the needs of other geophysical projects in the geothermal program.

Project Status: Instrumentation needed in the development and application of electromagnetic methods for geothermal studies is not generally available from commercial sources. Since the beginning of the project in 1976, several new instruments have been developed and constructed including: 14 digitally recording instruments for magnetometer-array-induction studies; two magnetotelluric (MT) systems using SQUID magnetometers; one microcomputer-based in-field MT processing system; two telluric-profiling instruments; self-potential monitoring equipment; controlled-source extra-low-frequency (ELF) systems and audiomagnetotelluric (AMT) systems. Modifications and improvements have been made in other equipment, including the airborne very-low-frequency (VLF) system. The staff has assisted several other projects with a variety of MT, controlled-source electromagnetic (EM), AMT, and airborne VLF and magnetometer surveys and has repaired and maintained existing, commercially obtained, and newly constructed instruments. Open-file reports on some of the new equipment have been prepared.

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*Project Title: Statistical Separation of Random and Non-Random Components of the Spatio-Temporal Seismicity Distribution for Correlation with Geothermal Systems (Grant No. 14-08-0001-16379)

Principal Investigator: David M. Hadley
Sierra Geophysics, Inc.
Arcadia, CA 91006

Project Objectives: To group earthquakes at geothermal areas into random and non-random components and correlate each component with geological and geophysical characteristics of the geothermal reservoirs such as gravity, heat flow, magnetics, resistivity, and structural geology in order to determine what earthquake characteristics are related to geothermal systems.

Project Status: Analysis has been completed for average magnitude 1.75 - 2.5 earthquakes for the Imperial Valley, Lassen, Coso and The Geysers. Comparison of these four geothermal areas with one non-geothermal area (San Jacinto fault zone) reveal several similarities and certain notable differences which lead to a possible definition of a geothermal earthquake. It was determined that 75% of the earthquakes are clustered temporally within 18 hours and spatially within 10 km in the geothermal areas. The average clustering time in the non-geothermal area is 5 or more days, and the average spatial separation is greater than 10 km. The significant exception is The Geysers area in which no temporal clustering of earthquakes is observed. This contrasts to the Lassen area which is tightly clustered in time and is also a vapor-dominated reservoir. The spatial and temporal pattern of earthquakes at The Geysers suggests that the geothermal wells may affect the normal seismicity associated with the reservoir. At the Salton Sea and Coso, earthquake clusters tend to lie outside of regions of high heat-flow.

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*Project Title Precision Magnetotelluric Measurements in the Geothermal Environment (Grant No. 14-08-0001-G-627)

Principal Investigator: John F. Hermance
Brown University
Providence, RI 02912

Project Objectives: To apply electromagnetic geophysical techniques to studies evaluating physical processes in the geothermal environment, including interpreting deep electrical studies from representative rift regions of the world. To incorporate new developments in data-processing software into the new PDP 11-34 computing facility and develop precision numerical modeling techniques for optimizing the recovery of information from actual field surveys.

Project Status: A comparison between a magnetotelluric study in an inter-plate rift, Iceland, with a similar study in an intra-plate rift, the Rio Grande valley of New Mexico, suggests several common features: 1) an anomalous, highly-conductive layer at crustal levels appears to be intimately associated with rifting in both regions, 2) measurements in adjacent areas (pre-glacial volcanic area in Iceland; Colorado Plateau near the Rio Grande rift) indicate that, although the anomalous conducting crustal layer is absent, conductivities in the upper mantle change little with depth to 100 km.

Project Title: Shallow-Probing Electrical Techniques

Project Chief: Donald B. Hoover
(Denver, Colorado)

Project Objectives: To develop shallow- to medium-depth electrical techniques as effective tools for geothermal exploration, especially audio-magnetotelluric (AMT), E-field-ratio-telluric and self-potential (SP) methods. To address problems of signal noise and a lack of understanding of sourçe mechanisms associated with the self-potential method.

Project Status: The natural-source scalar AMT method has been demonstrated to be an effective reconnaissance tool for geothermal exploration. Numerous open-file and four summary and topical papers have been published on these results. Work is continuing on developing better instruments, both scalar and tensor; tensor capability will significantly improve the information contained in the AMT data. An international program in synoptic measurement of AMT fields is just getting started. The E-field-ratio-telluric method has been demonstrated to be an effective tool for defining faults along which thermal fluids migrate. Principal problems remaining under study are: 1) how to predict optimum times for field work, since natural signals are used; 2) how to extend the frequency range; and 3) how to obtain a better means of measuring the voltage ratios in the field.

The largest SP anomaly ever reported was measured on the slopes of Mt. Hood, Oregon. Work is underway to interpret this anomaly. A significant breakthrough appears to have been made recently in SP electrode design using a solid-state impermeable ceramic membrane rather than the conventional porous ceramic. The Department of Energy funds some research in this project to assess airborne electromagnetic surveys in geothermal areas.

Project Title: Borehole Geophysics as Applied to Geothermal Research

Project Chief: W. Scott Keys
(Denver, Colorado)

Project Objectives: To develop reliable geophysical well-logging equipment for obtaining data from high-temperature wells. To develop specific interpretation techniques for analyzing logs from geothermal reservoirs.

Project Status: The equipment-development phase of this project is decreasing because a comprehensive suite of high-temperature apparatus has been developed and successfully tested. The most important contribution to date has been the development and application of a high-temperature acoustic televiewer for logging fractures in geothermal wells. The location, apparent width, strike and dip can be derived from these logs. A number of high-temperature logging probes and the necessary cable have been developed and operated in geothermal wells at temperatures up to 260°C. These include flow meter, temperature, natural gamma, gamma spectra, neutron, single-point resistence, spontaneous potential, multielectrode resistivity, mechanical caliper, acoustic caliper, and acoustic televiewer. A high-temperature acoustic velocity probe is undergoing preliminary tests. Most of these probes have been utilized in wells at six different geothermal reservoirs in the western United States. The major effort is now equipment modification for improved performance. Progress has been made on the development of log-interpretation techniques for unique geothermal environments, but considerable work needs to be done on quantitative interpretation and development of computer algorithms to provide relative magnitude and character of porosity and permeability, lithology and correlation, thermal conductivity and heat flow, fluid quality and monitoring changes in the reservoir. Papers have been published or are in review on the following topics related to the application of borehole geophysics to geothermal reservoirs: problems and progress in geothermal logging; the physical character of the Raft River reservoir from borehole geophysics; the delineation of hydraulic fractures induced for geothermal well stimulation; borehole geophysics in igneous and metamorphic rocks; and a quantitative analysis of flowmeter logs made during an injection test of a geothermal well. Studies underway on the quantitative analysis of gamma spectra and fracture characterization by acoustic wave form analysis will have geothermal applications, and papers on these subjects are in review.

An acoustic televiewer is inserted into a geothermal well at Roosevelt, Utah, to study fractures in the reservoir rocks.

Well-logging operation at Roosevelt, Utah.

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*Project Title Magnetotelluric Modeling for a Crustal Environment (Grant No. 14-08-0001-G-643)

Principal Investigator: Theodore R. Madden
Massachusetts Institute of Technology
Cambridge, MA 02139

Project Objectives: To develop practical methods of dealing with magnetotelluric data in areas of complex resistivity structures.

Project Status: Complex resistivity structures distort the electric-current distributions so that simple interpretations of the data based on one- or two-dimensional models can give misleading results. The combination of generalized thin-sheet analysis and multiple-scale analysis seem to be a powerful method of dealing with the low-frequency response of a crustal region, although more work needs to be done to fully understand and optimize the multiple-scale analysis. Because of the preponderance of lenticular shapes in geologic structures, a thin-layer approach seems optimum for realistic modeling. Improving the multiple-scale methods applied to thin-layer modeling appears to be the most difficult aspect of developing a practical three-dimensional magnetotelluric modeling scheme. The difficulty has been traced to a specific operation and several ways of circumventing this operator are being examined. As expanding the thin layer analysis to a three-dimensional analysis is considered, the subtleties between different solution methods are more clearly understood. In earlier work on network analogies to two-dimensional EM problems a simultaneous solution of the entire network was used. In order to keep the network simply connected, simple impedance boundary conditions were needed at the boundaries of the system. This was accomplished by pushing the boundaries far enough away from the measurement surface so that the error effects at the boundaries caused negligible errors on the measurement surface. This technique avoided the use of an air admittance operator, and can be used just as well with the three dimensional approach.

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*Project Title Interpretation of Self-Potential Data from Geothermal Areas
(Grant No. 14-08-0001-16546)

Principal Investigator: Frank Morrison
University of California at Berkeley
Berkeley, CA

Project Objectives: To investigate the self-potential method of geothermal prospecting with emphasis on improvement of the quality of data and reduction of noise. To collect reliable self-potential data from geothermal areas where high-quality self-potential surveys have not yet been conducted and to analyze these data using the analytical methods currently being developed.

Project Status: Electrode response to changes in soil properties at a non-geothermal area (Law Ranch, California) and at Beowawe, Nevada, KGRA indicate that variations in potential caused by changes in measured soil properties (moisture content, pH, and conductivity) probably do not exceed about 10 millivolts where the soil is fairly uniform. In areas where soil properties vary more drastically these variations may reach a few tens of millivolts. Variations in soil properties at Beowawe show little or no correlation with a large dipolar self-potential anomaly (about 450 millivolts peak-to-peak) measured in the area of surface thermal activity. Results of a self-potential profile run with five different electrode types across a zone of sinter soil at the Steamboat Springs, Nevada, KGRA indicated that all of the electrode types gave essentially the same results, even in an area where soil type changed drastically from point to point, and the effects of cumulative error on data taken "leapfrog" fashion in such an area are severe. Analysis of self-potential data taken at the East Mesa, California, KGRA indicates that geothermal activity along fault zones inferred by previous investigations could account for the form of the anomaly, but that measurements of coupling coefficients at in situ temperature and pressure conditions are needed before any conclusion can be reached about the relative contributions of fluid and heat flow to the total anomaly. Consequently, a test cell for measuring thermoelectric coupling coefficients of rocks from geothermal reservoirs under in situ conditions has been designed and constructed. Core samples have been obtained for East Mesa and Cerro Prieto, Mexico, and are being tested.

Project Title: Magnetotelluric and Telluric Methods

Project Chief: Jim O'Donnell
(Denver, Colorado)

Project Objectives: To assess geothermal resource potential by determining the geoelectrical structure in geothermal areas in terms of geologic models at depths of approximately 1 to 30 km. To evaluate and define parameters which cause scatter in magnetotelluric soundings and evaluate methods which substantially reduce the cost of magnetotelluric surveys.

Project Status: Telluric current (TC) and magnetotelluric (MT) surveys have outlined resistivity lows in Island Park, Raft River and Soda Springs, Idaho; Vale, Breitenbush and Newberry Caldera, Oregon; Pinto Hot Springs, Steamboat Springs and Darrough Hot Springs, Nevada; Kilbourne Hole, New Mexico; Coso Hot Springs, Randsburg, Wendel-Amadee and Lassen, California; San Francisco Volcanic Field, Arizona. The data, analysis and interpretation of the TC surveys and part of the MT surveys have been published in open-file reports and outside journals. Results of MT surveys of Lassen and Randsburg, California, Newberry Crater, Oregon, and Soda Springs, Idaho, are in preparation.

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*Project Title Simultaneous Inversion of Data for Disparate Geophysical Experiments
(Grant No. 14-08-0001-G-536)

Principal Investigator: Wayne Peeples
Southern Methodist University
Dallas, TX 75275

Project Objectives: To determine whether the simultaneous inversion of geophysical data from disparate experiments, such as gravity and magnetotelluric (MT) studies, can produce additional information about structural features common to both the gravity and the magnetotelluric model.

Project Status: The basic model proposed is one in which a two-dimensional Earth model is divided into regions separated by non-planar boundaries. The Backus-Gilbert inverse procedure is applied to both theoretical and experimental data, and a complete statistical analysis of the tradeoff between precision and resolution of common structural parameters can be made. The two-dimensional boundary value problem for the gravity and magnetotelluric case (multiple layers separated by non-planar interfaces) has been solved for both TE and TM modes of propagation, and computer programs are operational. The inversion program has been rewritten for computational speed and is fully operational for the gravity inverse problems. The three-dimensional MT problem has now been fully derived. In addition, an analysis of the magnetotelluric effect of a perched geothermal system will be made.

Project Title: Geoelectric Sounding Studies

Project Chief: W. D. Stanley
(Denver, Colorado)

Project Objectives: To investigate the electrical structure of the crust to depths of 20 km using primarily the magnetotelluric technique as an aid to regional assessment of geothermal potential. To integrate the electrical data with other geophysical data and advance the technique of magnetotellurics.

Project Status: A major study of the Snake River Plain-Yellowstone region has been completed and a regional study of the Cascades and eastern Oregon is 50% complete. A real-time magnetotelluric system and companion software based upon microprocessors and a superconducting magnetometer have been completed. A major journal article on the Snake River Plain-Yellowstone work has been published and an open-file report on the Cascades work is in preparation. An open-file report on the real-time magnetotelluric system is in press.

Project Title: Geomagnetic-telluric Array Investigations of the Crust and Upper Mantle

Project Chief: James N. Towle
(Denver, Colorado)

Project Objectives: To develop and implement methods for the determination of geoelectrical structure of the Earth's crust at mid- and lower-crustal depths.

Project Status: The development of instrumentation for a 14-station geomagnetic-telluric array is essentially complete, allowing future studies to be conducted with the full complement of instrumentation. Studies in the Rio Grande Rift, New Mexico, Coso Range, California, and San Francisco Peaks, Arizona, have been conducted. Current field investigations are in the Cascade Range of Washington, Oregon, and California. Methods of data interpretation have been developed to permit rapid and direct determination of geoelectrical structure, allowing redeployment of the array during periods of moderate geomagnetic activity to obtain greater regional coverage. Descriptions of geoelectrical structure related to geothermal activity in the Rio Grande Rift and Coso Range are published. A preliminary report on the geoelectrical structure of the central part of the Cascades Range is in preparation.

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*Project Title Evaluation of Geothermal Systems Using Teleseisms (Grant No. 14-08-0001-G-426)

Principal Investigator:

Ronald W. Ward
University of Texas at Dallas
P.O. Box 688
Richardson, Texas 75080

Project Objectives: To develop and assess techniques which use the lateral variation of the spectra of teleseismic P waves produced by seismic attenuation to infer the location and extent of a geothermal system. To improve the generalized two-dimensional inversion procedure for interpreting areal changes in attenuation. To develop improved techniques of seismogram analysis to fit the entire P-wave seismogram in an attempt to determine the source spectrum and crustal reverberation as well as the seismic attenuation; to apply the technique to seismograms from geothermal areas.

Project Status: These studies complement P-wave traveltime-delay studies of lateral-velocity anomalies associated with geothermal systems. Seismic attenuation caused by of high rock temperature, partial melting, and fluid or gas saturation within the pores of rocks may be associated with a geothermal system, or a magma chamber at depth. A two-dimensional model of seismic attenuation at The Geysers-Clear Lake geothermal area has been developed. A zone of high attenuation is located in the middle crust centered southeast of Mount Hannah, roughly coincident with zones of gravity low and delayed arrival times for P-waves.

Project Title: Remote Sensing-Geothermal

Project Chief: Kenneth Watson
(Denver, Colorado)

Project Objectives: To develop thermal-infrared remote-sensing techniques for reconnaissance geothermal exploration. To evaluate data collected by thermal-infrared scanner for assessing minimum detectable heat-flux anomalies. To map differences in geologic materials as expressed in their thermal properties.

Project Status: Study at a regional scale uses thermal satellite data (equivalent noon and midnight data; 500-m resolution) and study at a more local scale uses aircraft scanner data (data at various times, 10-m resolution). Algorithms to map the near-surface thermal properties and goethermal heat flux have been developed for aircraft and satellite data. Image sets for aircraft data acquired of Mt. Hood, Oregon, Newberry Caldera, Oregon, and the island of Hawaii have been prepared and open-filed along with the ground station data acquired during the overflights.

Project Title: Resistivity Interpretation

Project Chief: Adel Zohdy
(Denver, Colorado)

Project Objectives: To make direct-current resistivity surveys in geothermal areas in order to define subsurface geologic structure and to help site deep test wells. To develop mathematical formulas, computer programs, and pocket-calculator programs for improved acquisition and refined quantitative interpretation of resisitivity data. To develop new theories, techniques, and field procedures for gathering high-resolution resistivity data over two- and three-dimensional structures.

Project Status: Deep resistivity soundings were carried out at the Idaho National Engineering Laboratory in Idaho Falls in the summers of 1978 and 1979. The results of this resistivity work, interpreted in the light of data from a subsequently drilled, 3 km-deep test well in the area of the survey, were presented at the 49th annual meeting of the International Society of Economic Geologists. Six new computer programs have been written in Enhanced BASIC for the HP-9845T to compute sounding curves obtained by 4 different types of electrode arrays over three vertical layers. An album of theoretical curves and the computer program for the full Schlumberger electrode array have been released in two open-file reports. An additional program for the Hankel Transform was written in Enhanced BASIC and converted from the original version of FORTRAN language. Three new albums of theoretical sounding curves have been computed for pole-pole, pole-dipole, and half-Schlumberger arrays expanded at right angles to three vertical layers. A manuscript on the theory of resistivity sounding over vertical layers is in preparation.

Conversion Factors

Length:	1 kilometer (km) = 0.6214 mile (mi)
Area:	1 km^2 = 0.3861 mi^2
Temperature:	$^{o}C = 5/9\ (^{o}F - 32)$
Temperature gradient:	1°C/m = 0.55°F/ft
Energy:	1 joule (J) = 0.239 calories (cal)
	= 9.480×10^{-4} British thermal units (Btu)
	10^{18} J $\approx 10^{15}$ Btu = 1 quad
Power:	1 megawatt (MW) = 10^{6} J/sec

Wendell A. Duffield, Coordinator
Geothermal Research Program
U.S. Geological Survey
345 Middlefield Road, MS 90-C
Menlo Park, CA 94025

Robert I. Tilling, Chief
Office of Geochemistry and Geophysics
U.S. Geological Survey
National Center, MS 906
Reston, VA 22092

Donald W. Klick
U.S. Geological Survey
National Center, MS 906
Reston, VA 22092

Franklin H. Olmsted
U. S. Geological Survey
345 Middlefield Road, MS 67
Menlo Park, CA 94025

Charles G. Bufe
DOE, Division of Geothermal Energy, RA-233
Federal Bldg., MS 3344
12th & Pennsylvania, N.W.
Washington, D.C. 20461

James D. Bliss
Project GEOTHERM
U.S. Geological Survey
345 Middlefield Road, MS 84
Menlo Park, CA 94025