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A National Drilling Program to Study the Roots of Active Hydrothermal Systems Related to Young Magmatic Intrusions

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A National Drilling Program to Study the Roots of Active Hydrothermal Systems Related to Young Magmatic Intrusions

Continental Scientific Drilling Committee
Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources
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PREFACE

The importance of studies of active hydrothermal-magma systems as part of a national continental scientific drilling program has been emphasized in numerous workshops and symposia, including (1) Los Alamos, New Mexico, Workshop on Continental Drilling for Scientific Purposes (U.S. Geodynamics Committee, 1979); (2) Sandia National Laboratories Workshop on Magma/ Hydrothermal Drilling and Instrumentation (Varnado and Colp, 1978); and (3) Ghost Ranch, New Mexico, Workshop on Continental Drilling (Shoemaker, 1975). The present report, prepared by the Panel on Thermal Regimes of the Continental Scientific Drilling Committee, both reinforces and expands on earlier recommendations.

The U.S. Geodynamics Committee 1979 report of the Los Alamos workshop, Continental Scientific Drilling Program, placed major emphasis on maximizing the scientific value of current and planned drilling by industry and government, supplementing these efforts with holes drilled solely for scientific purposes. Although the present report notes the importance of opportunities for scientific investigations that may be added on to current, mission-oriented drilling activities, the Panel on Thermal Regimes recognizes that such opportunities are limited and thus focused its study on holes dedicated to broad scientific objectives.

The Continental Scientific Drilling Committee endorses this report and the recommendations put forth by the Panel on Thermal Regimes. The Committee, noting that a national program for continental scientific drilling is forthcoming, welcomes comment from the scientific community and encourages participation in the implementation of research drilling projects to investigate the roots of active hydrothermal systems related to young magmatic intrusions.

1. SUMMARY AND RECOMMENDATIONS

Most of the processes occurring within the Earth are temperature sensitive and thermally driven. It follows that a complete understanding of geological processes demands as intimate a knowledge as possible of the Earth's internal thermal regime. At the broadest level, knowledge is needed of the regional background heat flux and of major regional anomalies with horizontal scales of hundreds of kilometers. More specifically, however, detailed studies of areally restricted hydrothermal-magma systems must be conducted to better understand the mechanisms of magma emplacement and water circulation and the bearing of such processes on ore deposition and geothermal energy. In addition, these studies will lead to a better assessment of volcanic and earthquake hazards.

Although research on background heat flux and major regional anomalies requires continued support, no new major funding initiatives are necessary to assure that regional heat-flow studies will continue to provide pertinent and timely data to constrain tectonic models. There is, however, a real need for a new major funding initiative to drill active hydrothermal-magma systems. At present, hydrothermal-magma processes can be studied only inferentially, using near-surface data, shallow-hole investigations, analogies with exhumed fossil systems, and extrapolation of laboratory experiments. These conventional studies alone cannot achieve the quantum jump needed to understand hydrothermal-magma systems; only with deep drilling can reliable in-situ field measurements be obtained of the parameters that are required to describe fully the dynamics of an actual hydrothermal system (e.g., pressure, temperature, state of stress, fluid pressure, fluid composition, mineralogy, and rock and mineral chemistry). Only by direct sampling of fluid and rock at currently existing and known conditions of pressure, temperature, and fluid composition can one establish with certainty the effects of fluid-rock interaction without concern for the changes that invariably occur in the samples during cooling.

It should be emphasized in this connection that petrologic and geochemical measurements on drill-core samples (particularly from continuous drill core) generally provide scientific return an order of magnitude greater than does outcrop sampling, even in areas of good exposures. Drilling allows sampling of otherwise inaccessible zones of the Earth's crust. There are clear advantages of having drill core from a dynamic environment in which geophysical measurements and fluid samples are simultaneously available. In short, there is a need for dedicated scientific drill holes (that is, holes drilled for a primary purpose of broad scientific investigations) into deeper and hotter levels of the Earth than have been penetrated to date.

We recommend that the United States should, therefore, initiate a new, highly focused scientific drilling program aimed at understanding the roots of hydrothermal systems related to young magmatic intrusions. A 10-year program is recommended involving a number of shallow and intermediate-depth drill holes in several major geothermal areas. This program would culminate in several deep holes reaching as high a temperature as possible before the limits of technology at the time of drilling are exceeded. With appropriate developments in drilling, logging, sampling, and analysis technology, it should be possible to drill to 6 or 7 km, reaching temperatures in excess of 500°C.

HYDROTHERMAL-MAGMA SYSTEMS

In order to determine research and drilling priorities, hydrothermal-magma systems in the United States may be grouped into five classes: dominantly andesitic centers, spreading centers, basaltic fields, evolved basaltic centers, and silicic caldera complexes. Application of eight scientific criteria and three social-relevance criteria (which include assessment of volcanic and earthquake hazards, as well as resource issues such as geothermal energy and mineral deposits) in this report leads to the conclusion that silicic volcanic complexes and spreading centers should be the highest-priority targets of a focused drilling program to investigate the roots of the associated hydrothermal systems.

SILICIC VOLCANIC COMPLEXES

Within the western conterminous United States there are three young, large silicic caldera complexes (Figure 1):

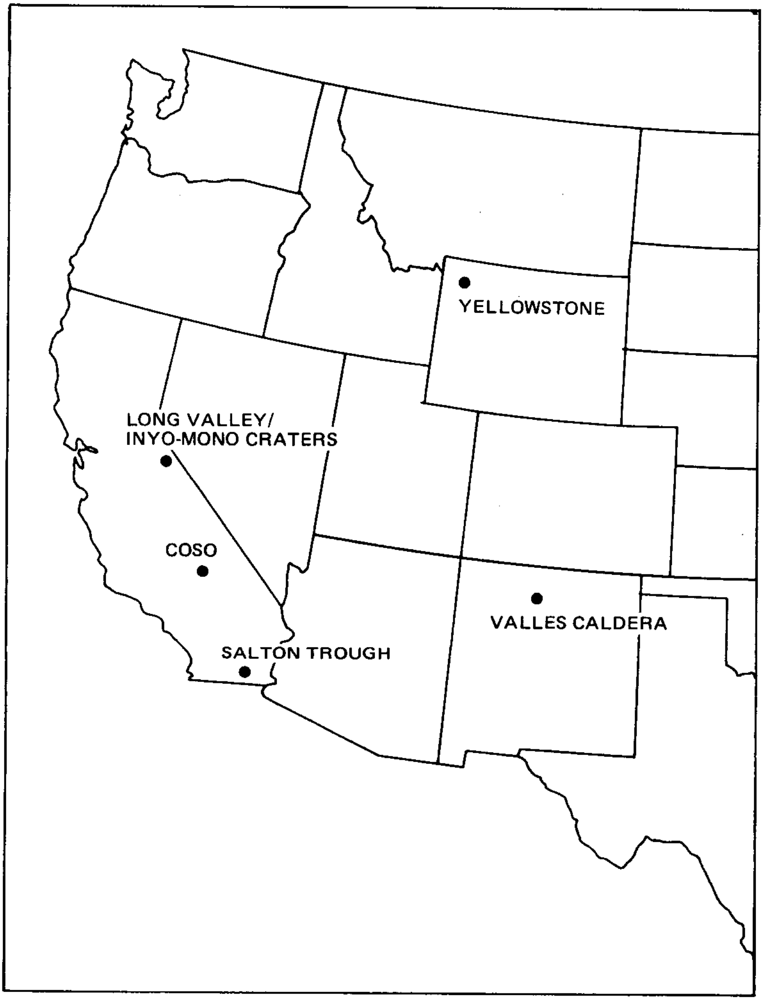

FIGURE 1 Map of the western United States showing locations of the scientific research drilling targets discussed in the text.

Yellowstone, Wyoming; Valles, New Mexico; and Long Valley, California. Yellowstone clearly represents the most intense magmatic and geothermal anomaly, but there is no opportunity for supportive industry drilling and the area is environmentally sensitive. Accordingly, while no deep drilling at Yellowstone is recommended at this time, it is urged that this area continue to be considered for possible research drilling in the future. In particular, the scientific merits of research drilling in Yellowstone should be more sharply defined, and full consideration should be given to the environmental impact of drilling in this area.

Valles Caldera

The Valles caldera was the classic-type example on which geologists developed their concepts of resurgent calderas. Because of its relatively recent volcanism (less than 100,000 years ago), its well-developed physiographic and geological features, and the presence of a well-documented high-temperature hydrothermal system, which has been drilled extensively by industry, we recommend that the Valles caldera be considered one of the prime targets for deep scientific drilling.

Long Valley

The Long Valley/Mono craters volcanic complex erupted more recently (about 500 years ago) than any of the other major caldera systems considered. In addition, recent tectonic deformation, seismicity patterns, and the reactivitation of fumarolic activity caused the U.S. Geological Survey to issue, on May 25, 1982, a notice that a potential volcanic hazard exists for the southwestern segment of the Long Valley caldera. An additional factor to consider in the Long Valley area is that several young volcanic systems nearby (Inyo Domes, Mono craters, and the Coso volcanic area, see Figure 1) are thought to be in precaldera stages of evolution. A systematic program of drilling in this area therefore provides the opportunity to sample and study a set of geologically related but geographically separated caldera systems at various stages of evolution. Hence, the Long Valley/Mono craters volcanic complex is another of our recommended major targets for deep research drilling.

Long-Term Drilling Program

The major problem in designing a long-term drilling program is that the site-selection data sets for the three silicic caldera complexes are not now comparable. Therefore, as a prelude to a deep drilling (to depths greater than 3 km) program at any site, intermediate-depth drilling as well as geological, geochemical, geophysical, and hydrologic field studies need to be carried out in conjunction with theoretical modeling of physical and chemical processes.

To this end, we recommend that scientific investigators and funding agencies develop the requisite data base and interpretational models as soon as possible. We recommend that scientific deep drilling in the major young silicic calderas proceed systematically through a series of progressively deeper holes in each of the major target calderas, beginning immediately with holes from shallow (to 300 m) to intermediate (300-3000 m) depths. In addition we emphasize that before a dedicated deep-drilling program can logically proceed, a carefully coordinated program of site surveys and intermediate-depth drilling needs to be completed.

SPREADING CENTERS

It is strongly recommended that programs continue to develop that take advantage of all available opportunities for investigations to be added on to industry drilling activities in the Salton Trough, one of the most impressive examples of an active continental spreading center in the world, and the only one in the United States. A broadly based program of geophysical, geological, geochemical, and hydrologic studies should be carried out in this area, with a view toward dedicated drilling in the near future. Toward this goal, every effort should be made to develop and define conceptual models based on information from preliminary surface studies, shallow to intermediate-depth research drilling, and cooperative research with industry.

SUMMARY OF RECOMMENDATIONS

The Panel on Thermal Regimes recommends the following:

1. Initiation of a focused drilling program to determine the evolution in space and time of hydrothermal-magma systems.
2. New drilling initiatives in the young silicic caldera systems, specifically the Long Valley-Inyo-Mono region and the Valles caldera.
3. Furtherance of understanding of the thermal regime of the Salton Trough, a spreading-center environment, in particular making use of all available opportunities to conduct research drilling investigations in the Salton Trough geothermal fields.
4. Intermediate-depth drilling as well as geological, geophysical, geochemical, and hydrologic field studies in conjunction with modeling of physical and chemical processes in the prospective target areas as a prelude to specifying deep-drilling targets and objectives.
5. Development of a scientific and operational plan for deep drilling in each target area.
6. Selection of one or more deep-drilling sites in each study area after collection and analysis of requisite background data and the development of conceptual models testable by deep drilling.
7. Development of technology for drilling, coring, logging, and other downhole instrumentation in high-temperature environments (500°C or more) containing corrosive and reactive solutions.

2. CATEGORIES OF PROBLEMS PERTAINING TO CONTINENTAL THERMAL REGIMES

Measurements of heat flow in shallow drill holes provide clues to various thermal regimes and heat transport mechanisms in the Earth's crust. The net outflow of heat across the Earth's surface contains information that can be related to the processes that generate, transport, and store heat in the Earth's crust. In turn, these processes can be related to the dynamics of the Earth's lithosphere.

REGIONAL BACKGROUND HEAT FLOW

The present heat loss from continents is about 10^{13} W. This heat loss is not uniform, and the differences in heat flow among the various thermal provinces provide significant constraints on models for their evolution and present tectonic regimes.

The number of reliable heat-flow observations in the conterminous United States is adequate to good in some regions but insufficient over a large fraction of the country; there are practically no data over much of the Great Plains province and the southern Coastal Plain. Nevertheless, even with this restricted data set, some simple gross patterns become apparent. Heat flow in the eastern half of the country is relatively low with a narrow range of variation. Mean heat flow in the West is higher, but there are large areas of both extraordinarily high and low heat flows. A closer look at the West (Figure 2) reveals that many of these areas of anomalous heat flow are related in a systematic way to the tectonics of the region.

ANOMALOUS THERMAL REGIMES

Within the present data set, thermal anomalies occur on both regional and local scales. Some of the more conspicuous regional anomalies in the Western United States are readily apparent from Figure 2. North of California, the Pacific Coastal provinces are characterized by uniformly low heat flow (about 1 heat-

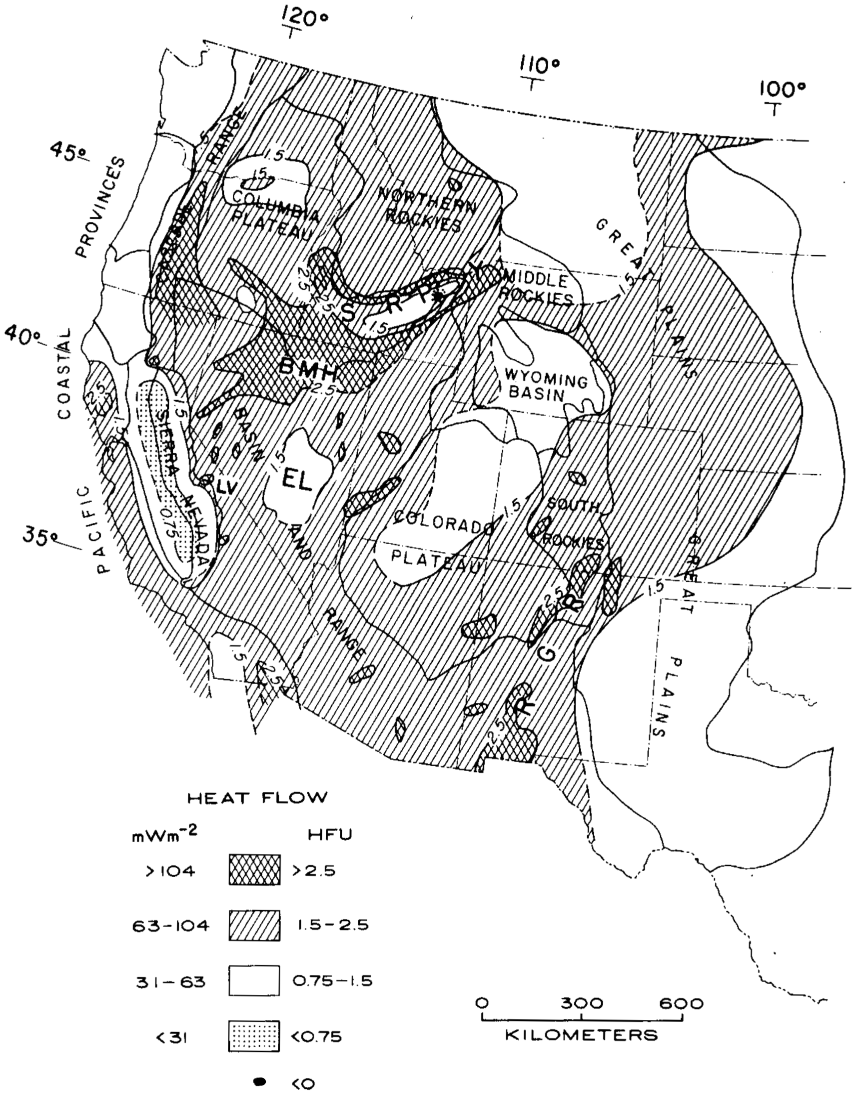

FIGURE 2 Map of the western United States showing heat-flow contours, heat-flow provinces, and major physiographic divisions. (BMH, Battle Mountain High; EL, Eureka Low; LV, Long Valley; RGR, Rio Grande Rift; SRP, Snake River Plain; Y, Yellowstone. Modified from Sass et al., 1981.)

flow unit--41.8 mW/m^2), probably resulting from the heat sink associated with subduction. The broad high in western California, associated with the trace of the San Andreas fault, is related to plate interactions along this transform fault. As might be expected, the southern Cascade Range is characterized by high heat flow. Low heat flow in the Sierra Nevada generally is attributed to the lingering aftereffects of Cenozoic subduction. Positive anomalies associated with the Battle Mountain high and Rio Grande Rift (BMH and RGR, respectively, Figure 2) are the results of intraplate tectonic processes, which at present are poorly understood. The Eureka Low (EL, Figure 2) is a regional anomaly probably caused by interbasin water flow with a downward component of velocity of a few millimeters per year.

Local heat-flow anomalies generally are the result of hydrothermal convection or a combination of magmatic activity and hydrothermal convection. In regional heat-flow studies, great care is taken to avoid areas of hydrothermal convection, and values of heat flow within 5-10 km of hot springs or other surface hydrothermal manifestations are regarded as suspect from a regional point of view. Heat-flow and hydrologic data near sites of hydrothermal discharge do, however, provide valuable constraints on models for the heat sources, and they are useful in calculations of the thermal budgets of the systems.

3. RESEARCH NEEDS

A broad understanding of the thermal regimes of the Earth's lithosphere and their associated dynamical processes is of central importance to a variety of basic scientific and social issues. It is important to recognize that major new research initiatives need to be carefully couched in terms of the present status and the need to support future ongoing studies of a variety of problems that are essential for obtaining the comprehensive understanding of thermal processes in the Earth's interior that we seek.

HEAT-FLOW GRID OF THE CONTERMINOUS UNITED STATES

A paucity of heat-flow data persists over much of the United States; a thorough understanding of the thermal regime of the United States will require a much greater density of observations. To a first approximation, significant lateral variations in heat flow are the result of subcrustal processes. Thus, if reliable determinations of heat flow are made with a horizontal spacing of a crustal thickness (i.e., 30 to 40 km), the regional flux will be characterized adequately. Near certain boundaries, profiles of more closely spaced heat-flow determinations will be required. By far the majority of heat-flow determinations to date have been acquired from holes or wells drilled for other purposes. In critical areas or sites where no drilling has been done for other purposes, dedicated drilling has been necessary. Generally the holes drilled specifically for heat flow yield more reliable determinations than do holes of opportunity. Several heat-flow groups are now being supported by funding from the National Science Foundation, the Department of Energy, and the U.S. Geological Survey. We recommend that the Continental Scientific Drilling Committee monitor the progress of regional heat-flow studies and offer specific recommendations when appropriate.

THERMAL HYDROLOGY OF SEDIMENTARY BASINS

Studies of the thermal regimes of sedimentary basins recently have taken on great importance for a variety of reasons. The realization that the evolution of hydrocarbons is very temperature-sensitive has aroused considerable scientific interest in the thermal evolution of basins and in the coupled thermal/hydrologic problem. Proposals to bury radioactive waste within basins have resulted in systematic studies of the hydrology of selected basins. Careful measurements of heat flow as a function of depth and between adjacent drill holes may provide a sensitive indicator of the advection of fluids and, when combined with appropriate hydrologic and other measurements, allow quantitative modeling of such critical parameters as nuclide migration rates.

THERMAL-MECHANICAL INTERACTIONS IN AREAS OF ACTIVE FAULTS

Thermal aspects of active fault systems have received considerable attention recently. A thorough understanding of the interaction of thermal and mechanical energy in regions of high stress concentration is essential to a predictive understanding of the mechanism of earthquakes. It is anticipated that within the earthquake component of the national Continental Scientific Drilling Program there would be some dedicated research drilling to learn more about materials properties, stresses, fluid pressures, temperatures, and other relevant parameters in active fault zones. To complement these studies, the thermal regimes of these areas should be studied systematically, with particular emphasis on the effects of shear heating on rock strength and deformation mechanisms.

HYDROTHERMAL CONVECTION NEAR ACTIVE FAULT SYSTEMS

Studies of heat flow near recently active fault systems should provide input into models of fault movement, the genesis of certain ores, and the "plumbing" of fault-controlled geothermal systems. These studies also would be defined mainly by other aspects of the national Continental Scientific Drilling Program and by other programs, and the Panel intends to follow closely the add-on aspects of the thermal research.

THERMAL HYDROLOGY OF RIFT SYSTEMS

By analogy to mid-ocean ridges, much of the thermal energy within continental rift systems is carried away by hydrothermal convection. This may be, in part, the explanation for the undulant and discontinuous nature of the heat-flow anomaly associated with the Rio Grande Rift (RGR, Figure 2). Studies of the coupled heat and mass flow problems associated with this convection should be an integral part of any rift investigation.

HYDROTHERMAL-MAGMA SYSTEMS

Spectacular manifestations of combined magmatic activity and hydrothermal convection occur at a small number of locations within regions of elevated heat flow in the western United States. The complex interactions among rock, magma, water, and steam are not well understood and will be completely understood only when one can observe them in situ. Dedicated drill holes to great depths involving very high temperatures will be required to achieve this goal. Drill holes that approach or exceed the limits of present drilling and logging technology are necessary. We believe that to address the questions in this research area, a major new research initiative is required at the national level.

4. RATIONALE FOR FOCUSED NEW STUDIES ON HYDROTHERMAL-MAGMA SYSTEMS

Although all the studies of thermal regimes outlined above represent important projects involving measurements that can be obtained only by drilling, the study of hydrothermal-magma systems is emphasized in this report. There is general agreement that such a drilling study will provide a great deal of new scientific information that cannot be obtained in any other way. Also, many of the other thermal research objectives can be achieved in conjunction with the efforts of other components in a national Continental Scientific Drilling Program, for example, studies of earthquakes, mineral resources, basement structures, and deep continental basins.

SCIENTIFIC IMPORTANCE OF DRILLING

The fundamental issue facing students of hydrothermal-magma systems is to understand the processes that take place when a body of magma is intruded into crustal material. Because the upper crust is normally saturated with water, the process of magma cooling is not simply a matter of thermal conduction but involves a complex pattern of meteoric water circulation combined to an uncertain degree with volatiles released from the magma. Furthermore, the magma itself may convect, thus augmenting the heat transfer, and the emplacement of the magma probably takes place over a substantial time interval, either continuously or episodically. The net result is a complex pattern by which heat and mass are transported through the crust, with the attendant formation of many types of mineral deposits.

At present, practically everything known about the deeper portions of hydrothermal systems is based on inference. It cannot be emphasized too strongly that the quantum jump in scientific information referred to in this report cannot be obtained without drilling into deeper levels of hydrothermal systems than have been penetrated to date. Given the level of drilling and sampling technology expected during the next decade, the fluid sampling, coring, and well-logging measurements should extend to as high temperatures as possible (500°C or more). Then, each hole should be further deepened as much as possible (tens to hundreds of meters or more), even though it may be possible to obtain only cuttings and temperature. Even such relatively poorly documented measurements and less reliable sample materials could provide important scientific return, because they come from the bottom of a well-documented hole at depths and temperatures hitherto unattained.

Four major areas of uncertainity concerning hydrothermal-magma system processes are mechanism of heat transfer, depth of circulation, longevity of an active system, and source of solutes.

Mechanism of Heat Transfer

The nature of the various processes that take place in hydrothermal-magma systems and their relationships are imperfectly understood. One of the major uncertainties concerns the mechanism (or mechanisms) by which heat is transferred from the magma to the overlying hydrothermal system. Mechanisms that have been proposed include (a) conduction, (b) transfer of heat by movement of fluids and volatiles out of the magma, (c) circulation of fluid through fractures controlled by regional tectonics, and (d) circulation of meteoric water into a thin zone of thermal cracking that migrates inward toward the magma with time as the rocks are cooled. Several recent investigations (Lister, 1974; Hardee, 1980, 1982; Hermance and Colp, 1982) have focused on the likely significance of this last mechanism, but major aspects are poorly understood. Among these are the thickness of the cracking zone, the temperature gradient across it, the temperatures at which it occurs (perhaps 350 to 450°C), and the chemical consequences of fluid-rock interaction in the zone.

Depth of Circulation

A related question involves the depth to which meteoric water can circulate in a magma-hydrothermal system. Does meteoric water circulate directly to and into the magma, or are there stacked circulation systems of differing salinity overlying the igneous body? If so, what are the mechanisms by which the salinity is generated? Do the deeper circulation cells have a significant component of magmatic fluids? Are the convecting fluids all liquid, is there a separate gas phase, or are there supercritical fluids? Do the deeper, more saline fluids control the site of ore deposition? Do temperature and pressure increase monotonically with depth, or are there significant discontinuities in these gradients? Do pressures increase abruptly from the hydrostatic to lithostatic?

Longevity of an Active System

The longevity of a hydrothermal system related to an intrusive body depends in great part on parameters specific to the intrusion (i.e., the size of the intrusion, whether the intrusion can support magmatic convection, and the degree to which magma is replenished with time from lower crustal or mantle bodies). In addition, the longevity of the hydrothermal-magma system depends critically on the nature of heat transfer from the magma, on the pattern of hydrothermal circulation, and on the evolution of permeability with time in response to thermal and chemical factors.

Source of Solutes

The fourth major area of uncertainity involves the source of the solutes carried in the hydrothermal fluids. Are they derived from fluids expelled from the magma, are they progressively leached from the magma as it cools or fractures, or are they leached from the country rock under the influence of the elevated temperatures? If all of these sources are involved, what is the relative importance of each for various environmental conditions?

DATA FOR MODEL DEVELOPMENT

To date, the processes that take place when a body of magma is intruded at depth into crustal material have not been studied directly. Geothermal drilling in hydrothermal-magma systems generally has been limited to those reservoirs having temperatures less than 360°C. Drilling into deeper, hotter environments is not at present economical for the geothermal industry, because of the high costs of deep drilling, the increased difficulties of drilling at high temperatures, the absence of logging tools usable at high temperatures, the difficulty of handling the high-temperature saline fluids produced, the uncertain physiochemical environment, and the absence of reliable predictive models. The hottest geothermal wells yet drilled are 380 and 410°C (both Italian research holes funded by the European Economic Community). However, at this time little is known about the high-temperature parts of these wells other than their maximum temperatures (measured by melting of calibrated alloys).

Because of the absence of direct information, knowledge of the processes taking place at depth in hydrothermal-magma systems is unavoidably inferential, based primarily on the following:

1. Laboratory studies in experimental petrology, high-temperature aqueous geochemistry, hydrothermal phase equilibria, and measurement of isotopic and element partition coefficients between minerals and fluids;
2. Field, petrologic, isotopic, and mineralogical studies of exhumed "fossil" hydrothermal-magma systems;
3. Theoretical modeling of heat flow, convection, and fluid flow in and around magma bodies;
4. Geophysical studies of present-day volcanic areas; and
5. Drilling to depths of 2 to 4 km and to temperatures of 300 to 400°C in certain hydrothermal systems, together with limited drill-core sampling and measurement of downhole geophysical parameters.

Data from these investigations have allowed development of several plausible models for hydrothermal-magma systems. However, no model has yet been confirmed, because of the lack of critical information on the intensive parameters in the hydrothermal-magma transition zone, their spatial relations, and their correlations with fluid and rock properties. This essential information can be determined only through measurements and investigations in drill holes that penetrate the hydrothermal-magma interface in an active system.

Much of the discrepancy among existing models of the hydrothermal-magma interface focuses on the nature of the temperature transition between the hydrothermal and magmatic regimes. Temperature models needing verification and evaluation include the following (each with a set of specific questions that can be addressed with drill hole information and samples):

1. A model in which there is a definite bottom to a circulating geothermal system of meteoric water, with an underlying steep linear conductive gradient to magma.

(a) Does this conductive zone act as an impermeable barrier, effectively isolating the meteoric convection cell from the magma and any exsolved aqueous magmatic fluids?

(b) Is this conductive zone impermeable owing to initial character, to metamorphism, to hydrothermal alteration, or simply to temperatures that are too high for the rock to sustain open fractures?

(c) Does the hydrothermal fluid at any point become supercritical, or is salinity high enough to preclude supercritical phenomena?

(d) Are there specific zones or environments particularly favorable for leaching of rock and for deposition of metals?

(e) What are the implications of this model to the question of longevity of hydrothermal-magma systems?

2. A model in which temperatures increase steadily and gradually to magmatic values.

(a) Is the hydrothermal fluid supercritical near the magma, or are salinities high enough to permit a subcritical liquid, perhaps coexisting with a vapor?

(b) Does the hydrothermal fluid remain of constant (meteoric) composition, or does it change gradually to an aqueous fluid of "magmatic" composition?

(c) To what degree does meteoric water penetrate toward or even into the magma?

3. A model in which temperatures increase stepwise, along with parallel increases in fluid salinity, to produce "stacked" convection cells with the fluid of each deeper cell being more saline and denser.

(a) Does each deeper convection cell have a greater "magmatic" component?

(b) Are the hotter, more saline brines richer in metals?

(c) Are the interfaces between convection cells loci for ore deposition?

4. A model in which temperatures increase abruptly at the base of a hydrothermal convection system in a zone of cracking that migrates progressively with time toward and into the pluton.

(a) What is the width of the zone of high-temperature gradient?

(b) Is this zone a locus of leaching of metals?

(c) How does permeability of the fracture zone vary as a function of temperature, time, abundance of fractures, and degree of hydrothermal alteration?

(d) What are the fluid compositions across the zone of high-temperature gradient, and how do they relate to any hydrothermal leaching, isotopic data, and experimental data (e.g., silica solubility studies)?

(e) To what degree do aqueous fluids of magmatic provinance escape into the fracture zone?

IMPORTANCE OF THE PROJECT TO SOCIETY

Deep drilling in magma-hydrothermal systems relates primarily to basic scientific understanding, which, in turn, has numerous obvious benefits that might accrue regarding societal problems.

Volcanic and Earthquake Hazards

Several types of hydrothermal-magma systems are known to cause violent explosive eruptions. In addition, some systems are associated with moderate to strong earthquake activity. In fact, purely from a scientific viewpoint, one would like to identify specifically some such system that is in an early evolutionary stage, prior to violent eruption. Information from deep drill holes in such environments may well provide the key to understanding the processes controlling the timing and magnitude of such an eruption.

Formation of Ore Deposits

Many ore deposits are formed in direct association with hydrothermal-magma systems; deep drilling will improve understanding of the formation of important national resources such as gold, silver, copper, lead, and zinc deposits. Such understanding will lead to better insight into how to explore for such deposits in older geological terranes and how to evaluate the nation's mineral resources (Continental Scientific Drilling Committee, in preparation).

Radioactive Waste Disposal

The direct measurement of the movement of hot water through rocks and the kinds of water-rock interactions involved in such phenomena have immediate and direct application to the understanding of the problems of radioactive element migration and dispersal. The important societal problem of radioactive waste disposal must be attacked in diverse ways; however, direct knowledge of high-temperature fluid movement and chemical exchange equilibria can provide useful information on site selection.

Geothermal Energy

The most obvious application of the drilling program to society's needs is the fact that, with the exception of Yellowstone National Park, the areas suggested in this report for research drilling are potential sites for the exploitation of geothermal energy. For optimum development of any such site it is necessary to understand the workings of the entire hydrothermal system, including portions that are inaccessible with present drilling and logging technology. There is no question that the expected technological improvements in drilling and logging as well as the new scientific knowledge to be gained will be important in enabling development of geothermal resources to the fullest degree possible.

Fundamental Understanding of the Earth's Crust

The intrusion of magma into the upper crust, the release of heat and volatiles from the intrusions, and the development of associated hydrothermal systems are problems central to understanding the evolution of continental crust and its resources (Luth and Hardee, 1980; U.S. Geodynamics Committee, 1979; Varnado and Colp, 1978; Shoemaker, 1975).

OBJECTIVE OF THE PROGRAM

The objective of the thermal regimes component of a national Continental Scientific Drilling Program should thus be to understand the dynamic evolution in space and time of actively coupled hydrothermal-magma systems in sufficient detail to choose among predictive physical models of this phenomenon. This would involve, within a 5- to 10-year time frame, an iterative approach that closely integrates the drilling results with two other essential elements of the program: (1) ongoing field studies using geological, geochemical, geophysical, and hydrologic observations at the surface and (2) ongoing theoretical studies that simulate physiochemical processess associated with mass and thermal energy transport within these systems.

The program seeks to map one or more hydrothermal-magma system in three dimensions and to measure as many geophysical, geochemical, and petrologic parameters as possible by direct observation at known positions in the subsurface. This requires close integration of deep drilling with surface geological, geochemical, hydrologic, and geophysical studies. In working out the dynamics of the hydrothermal flow regime in such systems, it is extremely important to identify (if possible) different stages of evolution of a given type of hydrothermal system. However, even complete drilling of a single system gives us only a single snapshot of the three-dimensional state of that particular system. For such a system, one would like to know its earliest history and its subsequent history to the time of final decay of the hydrothermal convective flow.

The type of information described above probably can be obtained only by drilling several systems of the same general type that are at different stages in their development. The identification of these different stages will not be easy, and this will undoubtedly be done only by an iterative procedure involving drilling and careful geological and geophysical studies of a number of potential sites. However, it is believed that by focusing on a single type of system for which a conceptual model is relatively well developed, evolutionary studies should be possible. If such studies do come to fruition, there can be no doubt that in the future the research drilling studies of hydrothermal-magma systems will be recalled as one of the truly foresighted programs in the history of earth sciences.

5. SELECTION OF HYDROTHERMAL-MAGMA RESEARCH PRIORITIES

Within the United States, there are five main classes of active hydrothermal-magma systems:

1. Dominantly andesitic centers,
2. Spreading centers,
3. Basaltic fields,
4. Evolved basaltic centers, and
5. Silicic caldera complexes.

Each class occurs in different tectonic provinces yielding important differences in their igneous "plumbing" systems and volcanic histories. Dominantly andesitic centers are characteristic of volcanism along active convergent plate boundaries and yield magma products that range continuously in composition from basalt to dacite. Continental examples of spreading centers result in bimodal basalt-rhyolite volcanic activity along a complex network of rapidly evolving dikes, sills, and surface flows. Basaltic fields are spatially distinct and are dominated by tholeiitic flows; some larger basaltic centers have evolved to late-phase silicic differentiates. Silicic caldera complexes are characteristic of zones of regional tensional tectonics; the dominant magmatism consists of bimodal basalt-rhyolite sequences extruded from centralized craters that evolve into caldera structures.

SCIENTIFIC SELECTION CRITERIA

Scientifically based selection criteria that may be used to rate candidate sites for drilling programs include the following considerations:

Criterion 1: Location--The location should be easily accessible and amenable to surface geological, geochemical, geophysical, and hydrologic studies.

Criterion 2: Presence of Magma--The surface studies should lead to a strong suggestion of active near-surface magma bodies, or at least well-defined regions with anomalous physical properties that may be reasonably interpreted as magma chambers.

Criterion 3: Stage of Model Development--Previous studies should have progressed to such a stage that well-developed conceptual models have been constructed that are particularly amenable to testing by drilling.

Criterion 4: Geological Complexity--Initial focus should be on geologically simple examples, preferably on magma bodies that can be reasonably modeled with simple geometries.

Criterion 5: Integration of Data--It is necessary to closely integrate drilling results with geophysical models and surface geology to facilitate the iteration of refined models with the accumulating data.

Criterion 6: Well-Defined Magmatic Evolution--Geological studies indicate that the different hydrothermal-magma systems evolve through successive stages of magmatic activity. Thus it is important to examine cases where evolutionary sequences are clearly defined by the surface geology so that a drilling program may focus on distinct stages in the maturation of a magmatic system.

Criterion 7: Phenomena Represented--Selected examples should be characteristic of a wide class of phenomena, so that results may be generalized.

Criterion 8: Applicability to Ore Deposits--A number of mineral districts are centered on fossil hydrothermal-magma systems. Thus the study of active centers could yield valuable insights into the dynamics of the concentration processes that lead to the formation of ore deposits. Complexes that yield this added insight would be preferred.

APPLICATION OF CRITERIA

All five classes of active hydrothermal-magma systems satisfy Criterion 1 (ready accessibility and availability of adequate geological, geophysical, geochemical, and hydrologic data). However, application of the next seven selection criteria leads to the following observations (keyed to the criterion number listed previously).

Dominantly Andesitic Centers (Components of the Cascade and Aleutian Ranges)

Criterion 2--Near-surface magma chambers do exist, although perhaps not continuously throughout the life of a given volcano.

Criterion 3--Generalized models of the magmatic processes and hydrothermal systems exist.

Criterion 4--Neither the magma bodies nor the hydrothermal systems are areally constrained; both are likely to be complex.

Criterion 5--Surface geology is typically very complex with little surface expression of hydrothermal systems; geophysical models of subsurface conditions are crude.

Criterion 6--Both magmatic and hydrothermal systems evolve rapidly and complexly, with the youngest volcanic rocks commonly obscuring earlier phases.

Criterion 7--Young centers have abundant analogs in the geological record.

Criterion 8--The relationship of young centers to ore deposition is not clear.

Spreading Centers (Salton Trough)

Criterion 2--Basaltic (and some rhyolitic) magma likely do exist.

Criterion 3--There are well-developed tectonic and hydrothermal models.

Criterion 4--Although the upper parts of the hydrothermal systems in the Salton Trough are well known, the geometry of underlying intrusive bodies is poorly known and likely to be complex, diffuse, or both.

Criterion 5--Models of spreading centers (e.g., mid-ocean ridges) are very well developed; however, in the Salton Trough (which contains the only active examples of this class within the continental United States), knowledge of the relevant surface geology is limited because of a thick cover of Quaternary sediments of the Colorado River delta.

Criterion 6--The evolutionary stages of magmatic activity are poorly defined and poorly discriminated.

Criterion 7--The spreading-center environment represents an important class of hydrothermal-magma systems, and some of the largest hydrothermal systems in the world are of this class; some workers have suggested fossil analogs in the ancient geological record of the United States.

Criterion 8--Within the Salton Trough is the Salton Sea geothermal system, one of the world's best examples of a metal-rich, potentially ore-depositing fluid that can be sampled directly.

Basaltic Fields (e.g., Craters of the Moon; Pisgah Crater)

Criterion 2--Basalts are likely to be generated in the mantle or lower crust and come quickly to the surface, without producing well-developed near-surface magma chambers or hydrothermal systems.

Criterion 3--Well-developed tectonic and magmatic models exist but are not particularly amenable to drilling.

Criterion 4--Geometry of near-surface magma chambers (if they exist) is not readily inferred from surface information.

Criterion 5--Volcanic geology is well understood, but surface expression of hydrothermal systems is minimal.

Criterion 6--Stages of petrologic evolution are subtle and difficult to discriminate.

Criterion 7--Analogs in the geological record of the United States are abundant.

Criterion 8--The relationship (if any) to ore deposition is unknown.

Evolved Basaltic Centers (e.g., Newberry, Medicine Lake Highlands, San Francisco volcanic field)

Criterion 2--High-level silicic magma chambers may be present.

Criterion 3--Tectonic and magmatic models are well developed, but the nature of associated hydrothermal circulation needs further refinement.

Criterion 4--The geometric configurations of the hydrothermal systems and the magmatic bodies are essentially unknown.

Criterion 5--Surface volcanic geology is well known but commonly complex; the surface expression of hydrothermal systems is limited.

Criterion 6--Newberry and Medicine Lake Highlands have documented petrologic evolution, and the San Francisco volcanic field displays a complex spatial separation of evolutionary stages.

Criterion 7--Some analogs do exist in the geological record of the United States.

Criterion 8--The relationship to ore deposition is unknown.

Silicic Caldera Complexes (e.g., Yellowstone, Valles, Long Valley-Inyo-Mono and Coso)

Criterion 2--Silicic magma chambers of substantial size are likely.

Criterion 3--Models of tectonic setting, magma systems, and hydrothermal systems are all highly developed.

Criterion 4--The magma chamber appears to be relatively simple geometrically.

Criterion 5--Surface geology is well known, and geophysical models of deep structure often indicate a good correspondence to surface features.

Criterion 6--Several examples show distinct evolutionary patterns with clear spatial separation.

Criterion 7--Many well-documented analogs exist in the geological record of the United States.

Criterion 8--Analogous systems from the geological record are known to have epithermal and base-metal ore deposits.

Table 1 gives a qualitative summary of the panel's evaluation of each group in relation to the selection criteria and suggests that silicic caldera complexes have the highest priority, closely followed by the spreading-center environments. All other groups have much lower priority, particularly the basaltic fields.

RELEVANT STUDIES SELECTION CRITERIA

A further set of criteria includes the potential for improved understanding in connection with predicting volcanic and earthquake hazards and resource-relevant issues such as associated geothermal energy potential and mineral deposits. Analysis of these issues is summarized in Table 2, which lends support to the conclusion that caldera complexes are of highest priority, followed closely by spreading centers and andesitic centers. Basaltic fields clearly are of lowest priority.

TABLE 1 Qualitative Summary of Scientific Selection Criteria for the Main Classes of Active Hydrothermal-Magma Systems

System Class	Selection Criterion [a,b] 1	2	3	4	5	6	7	8
Dominantly andesitic centers	H	M	M	L	L	L	H	H
Spreading centers	H	H	H	M	M	L	H	H
Basaltic fields	H	L	M	L	M	L	H	L
Evolved basaltic fields	H	M	M	L	M	H	M	L
Silicic caldera complexes	H	H	H	H	H	H	H	H

[a] Selection Criteria (see text):
1, accessible location;
2, presence of magma;
3, stage of model development;
4, geological simplicity;
5, integration of data;
6, well-defined magmatic evolution;
7, representative of wide class of phenomena;
8, applicability to ore deposits.

[b] Relation to criterion:
H, high;
M, medium;
L, low.

TABLE 2 Qualitative Summary of Relevant Studies Selection Criteria for the Main Classes of Active Hydrothermal-Magma Systems

System Class	Selection Criterion [a] Volcanic and Earthquake Hazards	Geothermal Resources	Mineral Deposits
Dominantly andesitic centers	H	M	H
Spreading centers	M	H	H
Basaltic fields	L	L	L
Evolved basaltic fields	M	M	M
Silicic caldera complexes	H	H	H

[a] Relation to criterion:
H, high;
M, medium;
L, low.

ANALYSIS OF SILICIC CALDERA COMPLEXES

Within the western conterminous United States, there are three young, large silicic caldera complexes: Yellowstone, Wyoming; Valles, New Mexico; and Long Valley, California. Each of these caldera complexes has associated hydrothermal systems and already has been subjected to a wide variety of earth-science investigations, including drilling. However, in none of the three areas is direct drill-hole knowledge of the roots of the hydrothermal systems available.

Major criteria for choosing one or more of these caldera complexes for deep drilling under the auspices of a national Continental Scientific Drilling Program are as follows:

1. Reasonable certainty of encountering temperatures of at least 400°C at depths of 5 km.
2. Representative (or typical) of fossil caldera systems.
3. Presence of a well-defined magma body.
4. Available to drilling in terms of both geographical accessibility over a significant portion of the target area and environmental sensitivity.
5. Potential for add-on experiments during commercial or mission-oriented drilling.
6. Clearly defined, geographical separation of evolutionary stages.
7. A complete, compatible set of geological, geophysical, and intermediate-depth drilling data.
8. Technical feasibility of drilling and maintaining the drill hole.

A preliminary evaluation of the three candidate caldera systems in terms of these eight criteria is given in Table 3. No single caldera system meets all the criteria.

On the basis of available data, the Valles caldera appears to be reasonably favorable, primarily because of the already demonstrated high-temperature geothermal system, the large amount of intermediate-depth industry drilling, and good access logistically. However, the Panel recognizes that drilling the required hole may be extremely difficult because of the underpressured nature of the principal hydrothermal reservoir. This can result in poor borehole stability, making open-hole scientific experiments difficult and possibly leading to loss of the

TABLE 3 Preliminary Evaluation of Young Silicic Caldera Systems for Drilling to the Roots of their Associated Hydrothermal Systems

	Caldera Complex Systems		
Selection Criterion	Yellowstone	Valles	Long Valley (including Inyo and Mono areas) and Coso
1. At least 400°C at 5 km	Very likely	Likely	Unknown
2. Representative of fossil calderas	Likely	Likely	Likely
3. Presence of a well-defined magma body	Very likely	Unlikely in large amounts	Probable beneath western part of Long Valley
4. Availability	Low--owing to environmental sensitivity of National Park	Good	Good
5. Potential for using holes of opportunity	None	High because of large industry and government activity	Moderate; low level of industrial activity
6. Geographical separation of evolutionary stages	Yes--on a time scale of 5 Ma; no--on finer scale with overlap of 3 calderas in 1.8 Ma	Poor; geographical overlap of 2 calderas and subsequent volcanism	Likely, if target includes Mono, Inyo, and Coso areas
7. Availability of site-selection data	Good	Good	Good for Long Valley and Coso; poor for Inyo-Mono
8. Feasibility of deep drilling	Good to fair, depending on location	Poor in the principal hydrothermal reservoir because of under-pressured hydrologic regime; good in other areas	Good on the basis of present evidence, but a high-temperature reservoir has not yet been penetrated

hole while drilling. The need to use air or aerated drilling fluids in such drilling increases corrosion and limits the ability to cool downhole equipment with the circulating fluid. Massive invasion of cement into the underpressured formation during cementing operations could preclude successful perforation in zones of interest. These problems will cause higher costs and risks for these wells than for similar wells drilled into hydrostatically pressured formations.

Yellowstone clearly represents a more intense magmatic and geothermal anomaly but has no opportunity for add-on commercial drilling; indeed, even for dedicated scientific holes it might be difficult and time consuming to gain National Park Service approval because of the environmental sensitivity of the area. The CSDC has recently established a task group to identify unique scientific questions that can be addressed only through a drilling project in Yellowstone.

The hydrothermal system at Long Valley does not appear to have the high temperatures at shallow levels that are present in the other two caldera systems, although geological and geophysical field evidence indicates the presence of a magma system at depths of 8-10 km. Recent tectonic deformation, seismicity patterns, and the reactivation of furmarolic activity caused the U.S. Geological Survey to issue in May 1982 a notice that a potential volcanic hazard exists for the southwestern segment of Long Valley caldera. Moreover, the eastern Sierra front may contain several systems (Inyo, Mono, and Coso) in the precaldera stage, thus giving the opportunity to sample and study a set of geologically related but geographically separated caldera systems at various stages in their evolution.

As a prelude to a deep-drilling (greater than 2.5 km) program at any site, sufficient intermediate-depth drilling as well as geological, geochemical, geophysical, and hydrologic field studies need to be carried out in conjunction with theoretical modeling of physical and chemical processes to define more closely the long-term drilling objectives. For example, it is not completely clear what phase of the evolutionary history of a hydrothermal-magma system needs to be drilled for greatest understanding. Does one drill a system in an early stage of development to determine the initial evolutionary conditions, or does one drill a system in a late stage of development?

The major problem in designing a long-term drilling program is that the site-selection data sets for the three areas considered to be of greatest potential are not now comparable. There are ongoing studies in both the Valles and Long Valley calderas. In addition, geophysical studies and intermediate-depth drilling of the Inyo and Mono areas should be intensified in order to determine whether these systems have identifiable magma chambers and whether they represent hydrothermal-magma systems in a precaldera stage of evolution. If this can be demonstrated, then the importance of multihole drilling in the Long Valley-Inyo-Mono region will be underscored.

Accordingly, it is recommended that a deep-drilling program be carried out in one or more of the young, silicic caldera complexes but that no specific complex be chosen until the requisite geological, geochemical, geophysical, and hydrologic studies and intermediate-depth drilling are carried out. To this end, scientific investigators should acquire the necessary data and develop conceptual models as soon as possible.

Whichever site is finally chosen for the first dedicated drilling project, the drilling plan should be designed in such a way that the data and conclusions can be applied to the many fossil hydrothermal systems associated with silicic calderas in older geological terranes, of which there are literally scores of examples in the United States alone, many of them associated with important ore deposits. Enhanced general knowledge of water-rock interactions and hydrothermal phenomena will, of course, be applicable to and increase understanding of all hydrothermal phenomena in nature.

ANALYSIS OF SPREADING-CENTER ENVIRONMENTS

The Salton Trough is one of the most impressive examples of active hydrothermal-magma systems associated with major spreading centers on a continent in the world. It is the only such example in the United States. Therefore, for this class of targets there is no problem associated with general site selection, and the only difficulty is in delineating the specific drilling sites within this broad geothermal region. There are many reasons for including the Salton Trough within the thermal regimes component of a national Continental Scientific Drilling Program:

1. There are a large number of present drill holes, and there will very likely be an increased level of drilling activity in the future; thus, there is considerable potential for add-on experiments associated with this high level of industrial drilling.

2. Because of the large number of previous drill holes, the system is already very well explored to depths of about 3.5 km, but below that depth the area is relatively unknown.

3. The drilling technology is already sufficient to extend the drilling in this area to considerably greater depths. Because of the high salinity of the fluids, this area is slightly overpressured (relative to hydrostatic pressures) and will be less difficult to drill than underpressured reservoirs found in other systems.

4. Very high temperatures (greater than 340°C) have already been measured in a variety of drill holes at moderate depths; thus, there is a good likelihood of reaching considerably higher temperatures without carrying out inordinately deep drilling.

5. The Salton Trough is located in the rift zone where the East-Pacific Rise impinges on the North American continent. Therefore, the geothermal systems in the Salton Trough are related to an important class of hydrothermal systems associated with the worldwide mid-ocean ridges, and several types of important ore deposits are known to form in these environments.

6. This is an unsurpassed natural laboratory for studying water-rock interactions involving highly saline fields at high temperatures because of the extremely high-salinity, metal-rich brines in this area. In that sense, this locality will provide an instructive contrast with the water-rock interactions produced in the silicic caldera systems, where the fluids are typically meteoric waters with low salinities.

Although the major recommentation put forth in this report is the study of silicic caldera systems, it is strongly recommended that a program also be developed to take advantage of all available opportunities to conduct research drilling investigations in the Salton Trough. A broadly based program of geophysical, geological, geochemical, and hydrologic studies should be developed and closely integrated with scientific drilling in this region.

6. RATIONALE FOR SCIENTIFIC EXPERIMENTS IN A DEEP DRILL HOLE

The report Continental Tectonics (Geophysics Study Committee, 1980) recommended that an important goal of earth-science research in the next decade is toward the exploration and understanding of the dynamics, structure, evolution, and genesis of continents. One important aspect of this goal is to obtain a three-dimensional understanding of the dynamics of hydrothermal-magma systems in the Earth's crust. This understanding can be approached by iterative use of various direct and indirect measurements to refine conceptual and mathematical models. Approaches used to date include extrapolation of surface geology, interpretation of surface geophysics, direct measurements in shallow and intermediate-depth drill holes, inferences from fluid geochemistry, and comparison with fossil hydrothermal systems.

Geothermal wells have been drilled to depths greater than 4 km and temperatures greater than 400°C, although most meaningful measurements are at present restricted to downhole environments having temperatures less than 250°C. Ideally, one would like to drill and carry out observations in the entire hydrothermal-magma system, to magmatic temperatures and to depths well within the crust. Such an objective would require major advances in technology. It seems realistic to restrict the present objective to temperatures of less than 500°C at depths of less than 7 km, i.e., the "roots" of the hydrothermal systems. Even with this restriction, direct sampling of this environment would represent a quantum jump in understanding of such a system and would provide important knowledge not obtainable in any other way.

The ways in which information from a deep drill hole to a temperature of 500°C in a hydrothermal system could be used can be categorized according to four broad purposes:

1. Characterization of the natural hydrothermal systems to the depth penetrated,
2. Constraints on conceptual models of the overall hydrothermal-magma system in space and time,

3. Validation and refinement of interpretive methods for surface geophysics, and

4. Determination of parameters that bear on the regional tectonic setting.

Many of the measurements that can be made in a deep drill hole bear on more than one of these broad purposes, as outlined in Table 4 and discussed in detail below.

CHARACTERIZATION OF THE NATURAL HYDROTHERMAL SYSTEM TO THE DEPTH PENETRATED

Without direct determination of the various properties of the hydrothermal system, both conceptual and mathematical models of the system are necessarily speculative. A variety of parameters need to be known as a function of depth. Temperature, fluid pressure, and transport properties (thermal conductivity, porosity, permeability, and fracture geometry) determine the balance of conductive versus convective heat transport, the proportion of vapor to liquid, and the horizontal and vertical rates of fluid flow. The fluid properties (chemistry, isotopic relations, and phases) lead to determination of flow paths, source of fluids, number and nature of circulation cells, extent of mixing of fluids from different sources, and age of the circulation system. The solid properties (mineralogy, petrology, geochemistry, and isotopic relations) lead to the determination of the extent and duration of water-rock interaction, source of dissolved constituents, history of fracturing, and paragenesis of ore and alteration minerals (for comparison with fossil geothermal systems). Synthesis of all of these observations constrains the conceptual and mathematical models of this specific geothermal system and thus determines those models that best fit the natural situation.

CONSTRAINTS ON CONCEPTUAL MODELS OF THE OVERALL HYDROTHERMAL-MAGMA SYSTEM IN SPACE AND TIME

Many experiments and observations that might be made in a deep drill hole to 500°C are necessary not only to constrain the hydrothermal model to that depth but also to provide important constraints on the model of the overall hydrothermal-magma system. Studies of the isotopic relations of solids, liquids, and gases allow inference

TABLE 4 Scientific Requirements for Drill-Hole Measurements to be Made in Hydrothermal-Magma Systems

Parameter	Specific Hydrothermal System	Overall Hydrothermal-Magma System	Calibration of Surface Measurements	Regional Tectonic Setting
Temperature	X		X	
Fluid pressure	X			X
Thermal conductivity	X	X	X	
Porosity	X	X	X	
Permeability	X	X	X	
Rock chemistry/mineralogy	X		X	X
Fluid composition	X	X	X	
Isotopes	X	X		
Seismic properties			X	
Electrical properties	X		X	
Fission tracks		X		X
Stratigraphic data	X	X	X	X
Stress tensor				X
Rock strength				X

of the source of fluids, the extent of magmatic contribution, the depth of circulation, and the age of the fluids. Determination of the composition of pore fluids and fluid inclusions as a function of depth constrains models of ore deposition, particularily in providing direct determination of any chemical discontinuities that would require stacked hydrothermal cells of differing salinity. Determination of mineralogy, paragenesis, and fluid-inclusion compositions also serve to refine models of ore deposition and the sources of ore constituents, including magmatic contributions.

VALIDATION AND REFINEMENT OF INTERPRETIVE METHODS FOR SURFACE GEOPHYSICS

A variety of in-hole experiments are essential to evaluate and calibrate surface geophysical techniques. Direct determinations of density, magnetic susceptibility and remanence, electrical conductivity, and seismic velocity and attenuation (for both compressional and shear waves) can be integrated with surface gravity, magnetic, electrical, and seismic surveys to give greatly increased ability to infer structures and properties at depths greater than those penetrated by the drill holes and to extrapolate information laterally from the drill hole into the adjacent environment. Furthermore, the increased precision of geophysical interpretation would allow the various surface geophysical techniques to be used much more effectively and confidently at the sites of other hydrothermal-magma systems.

DETERMINATION OF PARAMETERS THAT BEAR ON THE REGIONAL TECTONIC SETTING

Deep drill holes in a hydrothermal system also provide information that bears critically on the regional tectonic setting. Stratigraphic data are essential for determination of the geological history of the system. The hydrothermal mineral zonation patterns and the characteristics of fission tracks elucidate the history of the thermal anomaly. And finally, deep drill holes provide a unique environment for the determination of the variation of stress, fluid pressure, and rock strength with depth and the comparison of these parameters with their counterparts in nearby holes that are not thermally anomalous.

7. FURTHER CONSIDERATIONS

ACCOMPLISHMENT OF THE PROGRAM

To meet the program objectives outlined by this report in a 10-year period, two major activities should be initiated. These activities are (a) communication and coordination between the Continental Scientific Drilling Committee (CSDC) and the scientific community and (b) organization by the CSDC and the scientific community of the framework needed to finance and manage the program.

A summary of this program report should be published in a CSDC DEW (Drilling Early Warning) NEWSLETTER for broad distribution to scientists in universities, government agencies and laboratories, and industry. In this summary, comments should be solicited from interested persons to identify potential active participants and to determine research and manpower needs to accomplish this program. A group needs to be established and funded to carry out the functions of management, research planning, coordination, and fiscal procurement for this program. This group would eventually require some full-time staff support perhaps along the lines of the Joint Oceanographic Institutions, Incorporated.

The Panel on Thermal Regimes notes the important relationship between hydrothermal-magma systems and mineral resources. The panel will coordinate its activities with those of the CSDC Panel on Mineral Resources to ensure that maximum scientific benefit can be achieved in this program.

MULTIPLE HOLES

The goals of scientific drilling into thermal regimes can be achieved most effectively by drilling several holes of varying depths into prospective targets, rather than by drilling a single very deep hole. Several categories of holes are envisaged:

Category	Depth Range (m)
Shallow	0- 300
Intermediate	300-3000
Deep	3000-5000
Very deep	5000+

Most of the holes should be dedicated to the intermediate-depth range for the purpose of exploring the geometry, properties, dynamics, and geological framework of the hydrothermal systems. Only a limited number of holes should be allocated to the 0- to 300-m depth range category, and these for specific, well-defined purposes. The shallower holes will permit site selection for the remaining deeper holes in such a way as to optimize scientific payoff.

The panel underscores the value of drilling at least two very deep holes adjacent to each other as opposed to a single hole. This concept has been stated in previous workshop reports and is worth restating here. Several scientific objectives are best achieved by two closely spaced holes, tens of meters apart. In-situ flow properties such as permeability, flow porosity, diffusion porosity, and fracture geometry can be most unambiguously obtained in flow tests using a two-hole geometry. Horizontal gradients in rock, fluid, and geophysical properties and the correlation of dikes, sills, veins, fracture zones, and other geological features also require two holes. Furthermore, several technical drilling considerations indicate that one of the most efficient methods of penetrating deeply into hydrothermal systems involves drilling an initial reconnaissance slim hole in which the sole objective is to drill as deeply as possible. Information obtained from this hole would allow for careful planning of a second, larger diameter hole in which extensive sampling could be conducted and downhole measurements are made.

DEDICATED HOLES vis-à-vis ADD-ON EXPERIMENTS

Information relevant to various thermal regimes often can be obtained from drilling programs designed for other purposes. The panel recognizes the value of existing holes and the multiple-use potential of drill holes, and the panel supports strongly an effort to alert the scientific community to current and proposed drill holes with multiple-use potential for add-on experiments pertinent to thermal regimes. The thermal regimes drilling program, however, cannot be based entirely or even primarily on add-on holes. Funding agencies should recognize the value of add-on opportunities in conjunction with the overall goals of their programs, but the division of a large program into too many small projects must be avoided. In its initial stages the program should be flexible and respond to opportunities as they arise; but if the overall objective stated above for scientific drilling into hydrothermal-magma systems is to be met, a series of dedicated drill holes must ultimately be the centerpiece of future long-range activities.

DATA REQUIREMENTS AND TECHNOLOGY REQUIREMENTS

Current forecasts suggest that drilling technology, if a development program including drilling, completion, and measuring instrumentation can be undertaken agressively, can realistically be expected to function at the 500°C range by the end of this decade. At present, logging and coring equipment dependent on silicon chips, elastomeric seals, and electrical cables cannot be relied on in temperature regimes that exceed 250 to 275°C (Cooper and Traeger, 1984).

Few if any instruments can withstand fluids rich in hydrogen sulfide. The minimum data requirements for scientific objectives demand that representative samples of rocks and formation fluids be obtained and measurements of temperatures and fluid pressures be made in hydrothermal environments at temperatures up to 500°C. Provision also should be made for preservation of the in-situ chemical and mechanical properties of core, especially from the deeper parts of the system. Prevention of core oxidation and fracturing are especially important. In addition, provision must be made for preservation of the in-situ chemical properties for formation fluids (aqueous solutions, supercritical fluids, gases) during and after sampling. Attaining these goals at temperatures up to 500°C constitutes a considerable challenge to technical capabilities.

Planning for sample curation and data-management activities and policies should be initiated (Continental Scientific Drilling Committee, in preparation). The samples and other data that will be collected as part of this research drilling program must be handled, indexed, stored, and disseminated to interested scientists in the most careful and expeditious manner possible to preserve the integrity and maximum scientific value of each drilling project.

The hazards and risks of drilling into such a high-temperature environment have not been thoroughly identified. One might anticipate, for example, dangers from "blow-outs" when overpressured steam zones are unexpectedy encountered, as well as dangers from explosive interaction between downhole fluids and high-temperature magmatic intrusions. These hazards must be evaluated at an early stage in a program of scientific drilling. A somewhat related problem concerns drill-hole stability and integrity--can the drill hole be successfully completed and maintained in a sufficiently pristine state to support the type of long-term experiments that are anticipated in the research program? Technology development will be needed to address the above problems; such development should begin immediately.

PRACTICAL CONSIDERATIONS FOR SCIENTIFIC DRILLING

Even with the most careful, thorough, thoughtful, and intensive site selection and predrilling activities, it is highly probable that many of the observations made during drilling will be unforeseen. Consequently, the drilling plan must be flexible and directed by an on-site scientific team. The drilling program should allow for resolution of scientific questions and for the possibility to take advantage of opportunities that evolve during drilling. Funding agencies should recognize that at some stage of the drilling it might become imperative to support surface geological or geophysical studies that must be mobilized quickly to address particular concepts as they evolve. To ensure that the proper attitude toward drilling is maintained, careful attention should be given to the experiences of other groups recently involved in scientific drilling; the benefit of these experiences should be incorporated into plans for drilling thermal regimes. Careful consideration should also be given to the development of a facility for the rapid, on-site analysis of core to provide a data base for decision making by the on-site scientific team. The scientific information from expensive drill holes will be optimized if cores are immediately examined and results periodically reviewed during drilling.

SUPPORTIVE RESEARCH ON RELATED PROBLEMS

Over the past 5 years, significant advances have been made in the acquisition and interpretation of geochemical and geophysical data from surface measurements, from in-situ borehole measurements, and from measurements on drill cores in the laboratory. Many of these advances have not yet been applied to the targets outlined in this report. Integrated studies of this kind need to be performed, however, in order to establish constraints on conceptual models that currently exist for the target areas.

Ongoing research investigations are currently being carried out on problems that are important to the national Continental Scientific Drilling Program. For example, geophysical, drilling, petrologic, and thermal modeling studies on Kilauea Iki Lava Lake in Hawaii offer not only an example of the value of the close integration of field, laboratory, and theoretical studies but are providing, thorough in-situ observations, new constraints on the differentiation and segregation of magma.

The scientific deep drilling program in Iceland should be monitored closely for the following reasons: first, such experiments will contribute significantly to understanding the nature of thermal and material transport mechanisms associated with crustal stretching, magmatic intrusion, and crustal underplating in an active environment that may have analogs in the areas of crustal extension and thinning in the western United States such as the Basin and Range Province, the Rio Grande Rift, the Snake River Plain, and the Salton Trough; second, a clearer understanding may be obtained of the relationship between the genesis of basaltic magma, its emplacement at intermediate levels in the crust, and its relation to shallow thermal processes (e.g., remelting of the crust, hydrothermal circulation, and the redistribution of minerals at shallow depths); and third, this activity will ultimately address in a relatively predictable environment the technological problems associated with drilling, core recovery, and drill-hole stability in a region of high geothermal gradient (bottom-hole temperatures greater than 400°C expected at depths less than 4-5 km) and thus offers a valuable opportunity for testing and evaluating technologies that may be important to the national Continental Scientific Drilling Program.

The new Ocean Drilling Program has identified studies of the configuration, chemistry, and dynamics of ocean-floor hydrothermal systems and of the processes of magma generation at mid-ocean ridges as two of its top priority objectives (JOIDES, 1982). The studies will include drilling to determine the geochemical properties of the hot water and hydrothermal precipitates and to study the petrology and geochemistry of the basalt and glass samples obtained from mid-ocean ridges. To accomplish the studies, development of logging and sampling tools that can withstand temperatures above 350°C is required. This research is particularly relevant to continental scientific drilling in the Salton Trough geothermal fields discussed earlier.

Under the International Lithosphere Program of the 1980s, several countries are initiating programs of drilling on continents for scientific purposes. The Coordinating Committee on Continental Drilling of the Inter-Union Commission of the Lithosphere (ICL) was established to provide a forum for discussion of national research program and to encourage international collaboration (ICL, 1981). Drilling into geothermal systems for both scientific investigations and energy extraction is planned or taking place in a number of countries. Through the ICL it is anticipated that opportunities will arise for research cooperation and data exchange internationally.

PERIODIC PROGRAM REVIEW

Recognizing that no single advisory group can forecast the emergence of scientific concepts and developments over an extended time, the panel recommends that a periodic reassessment be made of the overall activity in research related to characterizing the thermal regime of the Earth's interior. It is the panel's intention to draw into a national Continental Scientific Drilling Program exciting new research initiatives that might emerge as the program matures.

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