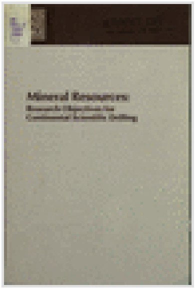

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Mineral Resources:
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PREFACE

The importance of a scientific drilling program to study mineralized hydrothermal systems has been emphasized in numerous workshops and symposia, including the 1978 Los Alamos, New Mexico, Workshop on Continental Drilling for Scientific Purposes (U.S. Geodynamics Committee, 1979) and the 1974 Workshop on Continental Drilling held at Ghost Ranch, New Mexico (Shoemaker, 1975). To some degree the present report, prepared by the Panel on Mineral Resources of the Continental Scientific Drilling Committee, both reinforces and expands upon earlier recommendations.

The report of the Los Alamos workshop, Continental Scientific Drilling Program, placed a 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 added on to current, mission-oriented drilling activities, the Panel on Mineral Resources recognized that such opportunities are limited and thus focused on holes dedicated to broad scientific objectives.

In the present report, the panel has developed a program that will provide answers to many scientific questions that have existed for almost 100 years concerning mineralized hydrothermal systems. The committee notes that research drilling may lead to results in addition to those anticipated, results that will provide new directions and ideas of equal or greater value that those basic ones originally posed. The Continental Scientific Drilling Committee endorses this report and the recommendations put forth by the Panel on Mineral Resources. The committee welcomes comment from the scientific community and encourages participation in the implementation of research drilling projects to investigate the roots of fossil mineralized hydrothermal systems.

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1. SUMMARY AND RECOMMENDATIONS

Many important metals, including gold, silver, copper, cobalt, molybdenum, tin, and tungsten, are concentrated in mineral deposits formed by hydrothermal activity driven by heat from subvolcanic intrusions. The geological evolution of such deposits involves a complex of spatial physical and chemical changes whose duration is a function of the magnitude and timing of magmatic events and the interactions of water with hot rock and magma. Hydrothermal deposits formed at different depths in the earth's crust have ultimately been exposed at the earth's surface by a combination of uplift and erosion. Through geological and geochemical reconstruction of the environments of mineral deposition, time-dependent hydrothermal models have been developed that include intervals of early growth, maturity, and dissipation, each correlative with events in an evolving hydrothermal system. Thus, intensive research over the last century has developed sophisticated understanding of ore-forming processes in different crustal environments.

However, information on such systems is still fragmentary because the overall spatial dimensions--particularly the depth dimension--of ore-generating hydrothermal systems are invariably larger than those parts of the systems exposed at the surface or accessible at current mining and exploration drilling depths. In a given geographic location, research has been restricted to small, accessible parts of large hydrothermal systems. For example, scientists now have advanced knowledge of mineralization processes and vertical zonations in shallow environments (such as epithermal precious- metal volcanic settings) and in deeper crustal environments (such as porphyry copper and molybdenum subvolcanic settings). However, they cannot resolve completely the basic question of whether these processes and zonations are genetically unrelated products of hydrothermal systems that originated at different crustal depths, or genetically related but vertically separated parts of a single hydrothermal system that have not been examined through the system's full vertical dimension.

The possibility of subjacent ore deposit systems also has obvious economic and resource implications because it is not known today whether epithermal ore deposits are genetic entities in themselves or near-surface manifestations of mineralogically different but economically important ore deposits at depth. Many other scientific problems in ore genesis require improved access to marginal parts, both lateral and vertical, of mineral deposits. The question of vertical chemical transition in large hydrothermal systems is fundamental and will provide the central theme of this report.

A program of basic research leading to a better understanding of mineralized hydrothermal systems will be of value to many areas of geological study that provide benefits to society. Results of the program will be applied to such subjects as enhanced exploration techniques, inventory of national mineral resources, geothermal energy development, and underground radioactive and chemical waste isolation.

MINERALIZED HYDROTHERMAL SYSTEMS

We recommend that the United States initiate a new, highly focused scientific drilling program to investigate the roots of mineralized hydrothermal systems. Research should focus on heat and metal sources, fluid composition and evolution, circulation patterns, rock permeability, and metasomatism, and on relating features observed at various depths in the systems. Ideally, the proposed program should involve investigation of each type of epithermal system over a wide range of tectonic environments and over chemical environments ranging from the adularia-rich precious-metal deposits such as are found at Cripple Creek, Colorado, through intermediate types such as are found at Creede, Colorado, and Tonopah, Nevada, to the kaolinite- and alunite-rich alteration at Goldfield, Nevada. A summary of the major research objectives for the fossil and active hydrothermal systems discussed in this report is shown in Table 1.

Epithermal Systems

In applying the drilling target selection criteria defined herein to establish priorities, the mining districts of Creede and Tonopah (Figure 1) are recognized as containing epithermal systems most likely to produce new scientific information through research drilling. These epithermal systems may be near-surface parts of larger hydrothermal

TABLE 1 Mineral Resources Research Drilling Summary

Location	Major Mineral Resource Research Objectives	Anticipated Drilling: Number of Holes	Anticipated Drilling: Depth per Hole, km
Fossil Systems			
Creede, CO (Epithermal precious metal deposit)	1) Test Creede formation as source of water, sulfur, and salinity of mineral fluids.	2	1
	2) Quantify physical and chemical nature of source rock system; investigate rock-hydrothermal interactions at depth; determine nature of heat source driving the hydrothermal system; construct comprehensive model of epithermal mineral-forming system.	2	5
Red Mountain, AZ (Porphyry copper system)	1) Examine zone between shallow epithermal(?) silver-gold and top of porphyry copper mineralization; continue to bottom of potash alteration zone.	1	3 - 5
	2) Test relationship of mineralized breccia to main porphyry body and related alteration zones.	1	3 - 5
Tonopah, NV (Epithermal precious metal deposit)	1) Refine epithermal and breccia geometries; confirm molybdenum- and base-metal-bearing character of epithermal mineralization; detect low-dipping faults.	1 - 3	1 - 2
	2) General objectives similar to those for Creede, applied to intermediate complex; describe intrusive complex and investigate molybdenum source.	1 - 2	2 - 5
Butte, MT (Base-metal vein system roots superimposed on porphyry copper system)	1) Determine extent of mineralized breccia and relation to mineralized porphyry.	2	3 - 4
	2) Examine roots of copper-molybdenum deposit; probe for postulated large intrusive heat source.	2	3 - 4
Active Geothermal Systems			
Valles Caldera, NM Yellowstone, WY Long Valley, CA Salton Sea, CA The Geysers/ Clear Lake, CA	For all active mineral systems: 1) Understand temperature, composition, and source of fluids as a function of depth. 2) Define source of high salinity. 3) Study role of boiling in mineral deposition. 4) Determine permeability variations and extent of self-sealing processes.		

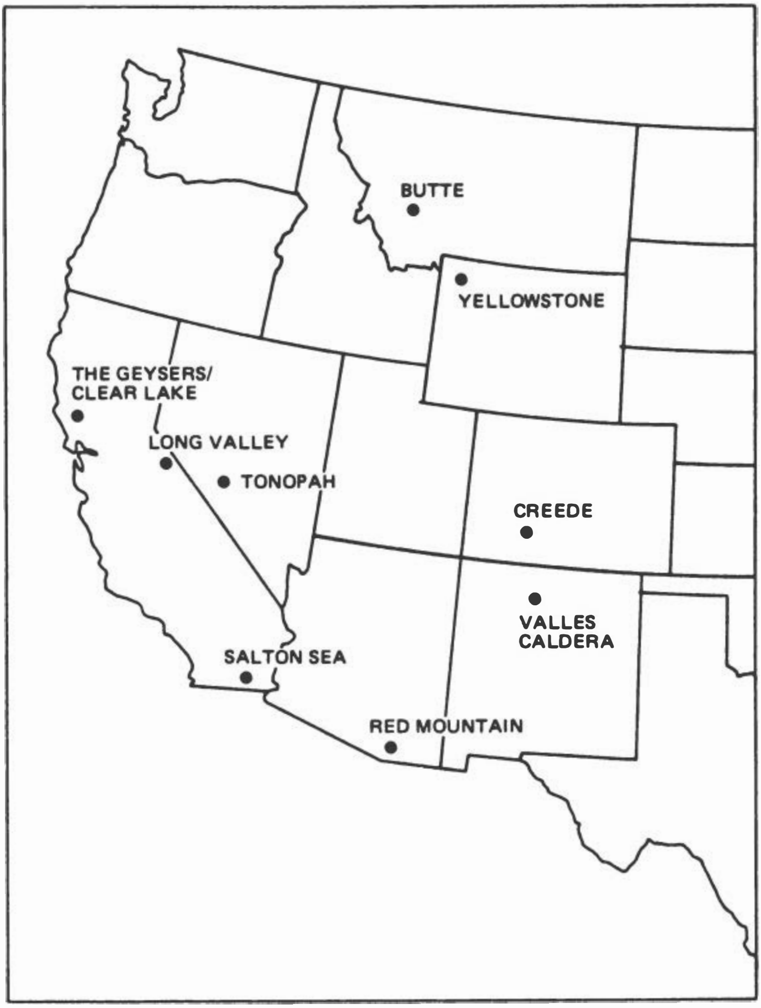

FIGURE 1 Map of the western United States showing locations of the scientific research drilling targets identified in the text.

systems that evolved from disseminated and stockwork mineralization of copper and/or molybdenum at depth. Testing of this hypothesis by deep drilling is critical to the evaluation of partially exposed epithermal mineralized systems of a similar type elsewhere. Such epithermal districts are numerous in the western United States (including Alaska); their potential application to the discovery of ore from deeper zones could become a substantial contribution to the American mining economy.

Porphyry Systems

The Red Mountain, Arizona, and Butte, Montana, mining districts (Figure 1) contain zones of disseminated and stockwork copper-molybdenum mineralization at depth. Superimposed vein systems contain increasing proportions of silver (and gold?) outward and upward from a central zone richer in base metals. Red Mountain may offer an opportunity to investigate the entire range of mineralization in a porphyry copper system of moderate size and vertical extent. Butte offers a potential opportunity to drill the root zone of a well-defined copper-molybdenum stockwork in a much larger granodiorite/base-metal system.

Research Drilling Priorities

The Creede mining district is recommended as the highest priority target. A research drilling project should be undertaken at Creede in order to examine a caldera-related silver- and base-metal-bearing hydrothermal mineral system. Selection of this target is based primarily on the availability of an extensive data base that includes industry drill hole data, on the existence of a comprehensive and well-documented geological-geochemical model, and on the economic importance of epithermal mineral deposits. The proposed program includes two shallow, 1-km-deep drill holes plus one or two 3- to 5-km-deep holes, supplemented with information from research drilling in active, caldera-related geothermal systems (Continental Scientific Drilling Committee, 1984). New data gained from this program would be integrated into existing models for enhanced interpretations of the Creede system.

Red Mountain, Tonopah, and Butte are lower priority targets that offer opportunities for future research drilling. Much like Creede, the Red Mountain and Tonopah targets would test the vertical and possible genetic relationships between epithermal and subjacent deposits, whereas drilling at Butte would address the separate question of what may lie at the very roots of a hydrothermal system that may have formed initially at depths of at least several kilometers. Additional data are required for each of these systems in order to define specific drilling requirements and sites. Geological surveys and related studies at Red Mountain, Tonopah, and Butte should be continued toward a goal of defining future research drilling targets in these important mineral systems.

ACTIVE HYDROTHERMAL SYSTEMS

Available data indicate that the Creede system represents a mineralized fossil analog of certain active geothermal systems associated with silicic calderas such as the Yellowstone, Wyoming, and Valles, New Mexico, caldera complexes (Figure 1). A major research objective that requires drilling of active geothermal systems is to develop the ability for proper interpretation of the individual stages of hydrothermal development of fossil mineral systems that are rarely well preserved in ore deposits. Typical hydrothermal mineral deposits exhibit features that formed during late-stage thermal collapse and fracture, followed by vein-filling events producing major overprinting of early zonations and obscuring critical field relationships of earlier mineralization. Recognizing whether diverse types of mineral deposition in subjacent parts of the system occurred simultaneously in separate convection cells or sequentially in a single cell is made difficult by this overprinting.

Because of the similarities between active and fossil hydrothermal systems, information obtainable from the deeper portions of currently active systems should be directly applicable to the construction of more accurate models for epithermal mineralization in the Creede system and other volcanic settings. A research drilling program complementary to that proposed at Creede should be initiated in an active hydrothermal system in a silicic caldera complex (Continental Scientific Drilling Committee, 1984). At this time, the Valles geothermal system in New Mexico is the best available target. The feasibility of future research drilling at Yellowstone is being studied by the Continental Scientific Drilling Committee.

ADD-ON INVESTIGATIONS

Many critical aspects of mineral deposits and related geothermal activity can be addressed by investigations added on to current and planned government and industry drilling activities. Experiments addressing significant problems of mineral deposits should be designed for opportunities that may arise for such add-on investigations. These investigations would involve sampling and measurements in host rocks which, though peripheral to mineral concentrations, have played an essential role in the evolution of the deposit. However, mining and exploration drilling in mining areas normally do not provide information on unproductive, distal portions of mineral systems, so few opportunities may be available for add-on investigations. High priority problems are discussed herein; input from the scientific community is necessary to identify specific projects and targets.

DRILLING, DIAGNOSTICS, AND DATA NEEDS

Scientific drilling and diagnostic requirements should be defined for sampling of solids and fluids, logging, and in situ measurements from slim holes (diameters of 13 cm or less). For planning purposes, information on the capabilities and costs of slim hole and rotary drilling and downhole logging should be compiled, and technology developments needed to acquire the downhole measurements and samples required by scientists for this research should be identified.

A major problem that must be faced in a national continental scientific drilling program is the management of samples and other relevant data. Careful handling of and accounting for these materials is necessary to ensure that maximum benefit is gained from the effort for the greatest number of interested scientists. Careful attention should be given to developing a plan for the appropriate curation and management of all data relevant to the national Continental Scientific Drilling Program.

2. MINERAL RESOURCE PROBLEMS TO BE ADDRESSED

Only those small portions of mineral-deposit-forming systems exposed in mines are available for detailed study. Little information is available from the exploration or mining of the margins of such systems, which include the eroded tops, laterally adjacent areas, and roots. The source of important metals may be remote from or immediate to an ore deposit. Commonly, the source and transport mechanisms of metals are unknown, as are the reasons why many significant concentrations of metals have precipitated where they are found. The major purpose of this report is to identify and describe as high priority targets for research drilling specific mineral deposit systems that are both suitably accessible and geometrically complete in the sense that no portion of the deposit has been removed by faulting or erosion.

SELECTION OF HIGH PRIORITY MINERAL DEPOSIT TARGETS

The following classes of mineral deposits are among those that occur within the continental United States:

- Porphyry copper and molybdenum,
- Epithermal gold-silver (antimony, mercury),
- Volcanogenic massive sulfides (lead, zinc, copper, silver),
- Magmatic nickel-copper-platinum,
- Granite-related tin and tungsten,
- Mississippi Valley-type (carbonate-hosted) lead, zinc, copper, silver,
- Clastic-hosted copper, lead, zinc, uranium,
- Sedimentary iron,
- Sedimentary phosphate,
- Lateritic nickel,
- Evaporite minerals and elemental sulfur, and
- Chromite.

Emphasis on research drilling should be directed toward epithermal gold- silver and porphyry-type deposits for the following reasons:

1. Sources of metals and heat for generation of epithermal systems need to be identified to determine if they are genetically related to deeper, porphyry-type mineralization.

2. Such research will provide important data for understanding of (a) how fluids, derived from and/or mobilized by the magmatic source, evolve in different portions of a vertically extensive hydrothermal system, (b) how and where in the systems these fluids mix with heated, convecting meteoric waters, and (c) the effects of different degrees of mixing on the wallrock alteration, metal transport, and deposition.

3. Epithermal gold-silver and porphyry-type fossil geothermal systems, which represent end-stage examples for comparison with active geothermal systems, provide an opportunity for study of the chemical, thermal, and hydrological evolution of geothermal systems, whereas active geothermal systems provide an opportunity for study of a fossil system at a specific instant in its evolution.

4. Successful exploration for both epithermal gold-silver and porphyry-type deposits requires a better understanding of the origin, evolution, and geometry of the deposits in order to maintain an ability to discover unexposed or poorly exposed reserves.

5. A wide variety of each type of mineral deposit occurs in the United States, comprising a major part of the mineral industry and providing opportunity for selection of good study sites.

6. Technology for core drilling, sampling, and logging can be tested in a mineralized hydrothermal system for future use in the more hostile environments of active geothermal systems.

Critical preliminary data can be acquired in many cases by the acquisition and study of existing drill samples and by further scientific investigations added on to government and industry drilling activities. The study of spatial and genetic relationships involving base-metal veins and epithermal precious- metal mineralization and the underlying igneous intrusive rocks, however, requires specially designed research drilling projects to depths of 2 to 5 km. This report thus addresses two methods of access to drilling samples and measurements, exploratory drill holes dedicated to broad scientific objectives and investigations added on to other drilling activities.

GEOMETRY OF INDIVIDUAL MINERAL DEPOSIT SYSTEMS

The recognition and proper interpretation of the geometric relations found in exposed portions of mineralized and altered zones or halos depend on careful observations and accurate three-dimensional models of complete mineral deposit systems. Response to a questionnaire regarding needs for mineral exploration research, distributed and compiled by the Society of Economic Geologists Research Committee (Eidel, 1981), identified a need for bulk and trace element analytical data on the margins of ore deposit systems. The most common suggestion as to useful methods needed in future research efforts included comprehensive geological mapping and sampling, followed by correlation of that data with detailed geochemical data. The most common criticism of published alteration-zoning studies referred to their limited geographic scope and their focus on spatially limited "ore grade" metal concentrations, thereby precluding extrapolation to poorly exposed exploration targets. This limited understanding of mineralogical and associated chemical effects at the margins of ore deposits also hinders recognition of ore-forming signatures as distinct from background regional variations in barren terrane. Drilling into the margins of mineral deposit systems can provide critical data for relating deep mineralization/ alteration patterns with the better understood shallow patterns, allowing more accurate interpretation of unexposed or partially exposed lower portions of mineral deposit systems.

RELATIONSHIPS AMONG MINERAL DEPOSIT SYSTEMS

Thermal energy drives convection within hydrothermal systems. In many locations this thermal energy is transferred from subcrustal depths to shallow crustal regions by upward extruding magma. Various types of mineral deposition may occur simultaneously within different, subjacent parts of hydrothermal systems and sequentially during different stages in their development. Superposition of hydrothermal activity and mineral deposition also may occur as a result of successive pulses of igneous intrusions.

Near-surface epithermal mineral deposits may be linked to deeper, magma-related hydrothermal deposits containing base metals. Stacking of one type of mineral deposit above another has been inferred from partially exposed systems that commonly exhibit barren intermediate levels. No examples of complete or nearly complete mineralized systems that show the expected transition from porphyry mineralization to epithermal vein and hot spring deposits have been continuously exposed through mining and drilling. Knowledge of the relationships between subjacent and vertically zoned mineral deposits would be useful for the design of future exploration programs. Responses to the Society of Economic Geologists' research questionnaire mentioned above indicated considerable interest in the investigation of hydrothermal systems below epithermal deposits.

PROBLEMS CONCERNING METAL SOURCE, TRANSPORT, AND DEPOSITION

While much is known about the geometric and mineralogical relationships within mineral deposits, the mechanisms of metal transport and deposition are largely conjectural. For many classes of mineral deposits, metal sources remain unknown. Chloride-rich solutions are widely recognized as important for the extraction of many metals from their sources and for their transport in hydrothermal systems; these solutions may not be essential in the case of metals such as gold, molybdenum, and tungsten. How and where natural fluids acquire their chlorinities are important unanswered questions. The source of the fluids themselves is an unresolved question in many cases, since the chemical and isotopic evidence is commonly lacking or ambiguous.

The oxidation state in hydrothermal systems also is recognized as an important parameter in the transport and deposition of metals, especially as sulfides. Little is known of the precise manner in which oxidation interrelates to the chloride and sulfur contents of the fluids in effecting metal transport and deposition. The association in space and time of certain metals with distinctive types of intrusive igneous rocks suggests a magmatic source for these metals, but how the magmas themselves acquired their metal-rich character is not fully understood. For example, the source of the metal-bearing brines that produced Mississippi Valley and clastic-hosted types of deposits and various uranium deposits is still actively debated by the scientific community.

RECENT REPORTS ON MINERAL RESOURCE RESEARCH NEEDS

The genesis and distribution of mineral resources, recognition of the need for research that benefits society, and a better understanding of continental mineral resources have been addressed by several important studies.

In 1976, scientists involved in research and exploration for mineral deposits met at Pennsylvania State University, sponsored by the National Science Foundation, to consider research that could lead to the discovery of new mineral deposits. In the report of this meeting, Research Frontiers in Exploration for Non-Renewable Resources (Rose et al., 1977), the participants recommended the following requirements for the improvement of mineral exploration:

1. Intensive study of representative mineral districts,
2. Expanded basic research on ore genesis concepts,
3. Increased coverage of the United States by geological maps and geophysical surveys, and
4. Frequent interchanges between exploration and research personnel.

The report recognized that the most productive new direction for research should consist of an integrated program of comprehensive geological, geochemical, and geophysical research that would focus on specific regions containing representative major ore types. Drilling techniques should be improved to allow cheaper, faster, and deeper drilling, and logging methods should be developed to maximize the information from drill holes.

The Frontiers of Mining Geophysics (Ward et al., 1977) was a report of two workshops held by the National Science Foundation in 1976 to identify subjects in the field of mining geophysics that require additional research effort. The participants of these workshops concluded that there was a need for research into both surface geophysical and downhole measurements for mineral exploration. A recommendation that received strong support from the participants was the design of a program to drill holes to depths of 15,000 to 25,000 ft (4.6 to 7.6 km) to explore and characterize the roots of porphyry copper systems.

The National Research Council's Workshop on Continental Drilling for Scientific Purposes, held in Los Alamos, New Mexico, in 1978, concluded with the principal recommendation that a continental scientific drilling program be initiated to achieve expanded knowledge and understanding of the uppermost part of the crust of the earth in the United States. The report of that workshop, Continental Scientific Drilling Program (U.S. Geodynamics Committee, 1979), identified three general areas of interest related to mineral resources that would benefit from data provided by a continental drilling program; (1) the fundamental geological structure and composition of the continental crust, (2) active geothermal systems of the kind that have formed mineral deposits in the past, and (3) past mineral deposits. In the chapter on mineral resources of the report (pp. 106-130), the authors noted that although some deep holes will be needed for mineral resource studies, many vital scientific questions may be answered by relatively shallow drilling to depths of about 1.5 km, provided the holes are properly located. The essential goal of the program is to provide an opportunity to study mineral-depositing processes in three dimensions to achieve better understanding of how mineral deposits form.

A National Research Council report, Mineral Resources: Genetic Understanding for Practical Applications (Geophysics Study Committee, 1981), pointed out that understanding of ore deposits may be two or three decades behind that of the interpretation of global geology. The report contained the recommendation that future research on mineral deposits should focus on the acquisition of a genetic understanding of mineralization to increase the efficiency of exploration and the accuracy of resource assessment. A significant portion of this research should consist of large, multidisciplinary studies, requiring coordination and collaboration among industry, academia, and government. Burnham and Ohmoto (pp. 62-72 of the report) described the current deficiencies in understanding magmatic hydrothermal processes and concluded that there is need for focused research efforts on the numerous interrelated geological, petrological, and geochemical aspects of mineral-forming processes. Cathles (pp. 105-110) stated that a strategy is necessary for increasing knowledge of the factors controlling mineral genesis. Such a strategy would increase exploration effectiveness by quantitative modeling of the ore-forming processes of individual mineral deposit systems. Bailly, in the same report (pp. 21-32), pointed out that cost-effective improvements in drilling, sampling, and analytical techniques are needed in order to decrease the costs of drilling and drill-sample analyses.

CRITERIA FOR SELECTION OF DEDICATED RESEARCH TARGETS

The panel reevaluated the mineral resource objectives formulated at the 1978 Los Alamos Workshop on Continental Drilling for Scientific Purposes. Achievement of scientific goals proposed in the mineral resources chapter of the report of the workshop, Continental Scientific Drilling Program, was evaluated from a point of view of drilling holes dedicated to broad scientific objectives (dedicated drilling) and investigations added on to holes drilled for specific missions by government agencies and industry (add-on investigations). Dedicated drilling for present research needs in mineral resources represents the only viable approach to study of targets in active and fossil hydrothermal-magma systems for the near future. However, objectives for add-on investigations may be addressed by defining research priorities and recognizing and coordinating research in identified industry and government "holes of opportunity".

Ten criteria were established for use in assuring that the dedicated drill hole targets selected would maximize scientific and technological returns in the 1980s.

Criterion 1: Scientific Impact--The research objectives must address fundamental scientific problems with potentially broad impact on the understanding of mineral deposits.

Criterion 2: National Needs--The objectives should be sufficiently broad to address research relevant to national needs (e.g., mineral resource inventory, enhanced exploration techniques, geothermal energy development, and radioactive and chemical waste isolation).

Criterion 3: Broad Representative Examples--The targets should represent broad classes of mineral deposits so that the scientific results may be applied to exploration for mineral deposits in other areas.

Criterion 4: Background Data Available--Previous studies of the area should be in an advanced stage, allowing selection of specific research drill sites within a reasonable time frame.

Criterion 5: Scientific Efficiency--Targets should be as specific as possible to maximize the value of data obtained and to ensure achievement of the scientific objectives with minimum expenditure of time and funds.

Criterion 6: Target Uniqueness--The target should be unique in the sense that data sought are rarely available from continuous, uninterrupted rock sequences in the United States.

Criterion 7: Well-Defined Models--Geological models should be well defined, using near-surface data to derive substantiated geometric relationships.

Criterion 8: Data Integration--Results of geophysical field studies should be integrated with surface and near-surface geological and geochemical data.

Criterion 9: Site Accessibility--The location should be accessible to scientists and suitable for surface geological, geochemical, and geophysical studies. If the site is in a mining district, workings should be accessible and required subsurface data should be available.

Criterion 10: Environmental Impact--The site should be on property providing no insurmountable environmental difficulties, and studies on the site should be compatible with the interests of land and mineral-rights owners.

It should be noted that Criteria 9 and 10, although not generally scientific in nature, do influence the establishment of priorities for selected research drilling targets because of practical matters that must be addressed on a case-by-case basis.

PRIORITIES FOR DEDICATED RESEARCH TARGETS

The highest priority for dedicated research is given to determining the complete range in hydrothermal activity related to relatively shallow (less than 5 km) silicic magmatic intrusions in both space and time. This requires studies in both fossil and active hydrothermal systems. Based on the criteria described previously, the recommended target area for determining the relationships of shallow epithermal mineralization and possible deep silicic igneous activity is at Creede, Colorado. Other hydrothermal systems of significant merit as potential research targets include: Red Mountain, Arizona; Tonopah, Nevada; and Butte, Montana.

The deeper portions of an active hydrothermal system in a silicic volcanic complex should be drilled to bridge the gaps in knowledge about the interactions of shallow hydrothermal activity with igneous intrusives at or near-magmatic temperatures. The Valles caldera in New Mexico is given a high priority for research drilling because it represents an environment geologically similar to Creede. Each system should provide information useful for interpreting the other. Active hydrothermal systems that should also be considered for research include Yellowstone, Wyoming, and The Geysers/Clear Lake, Salton Sea, and Long Valley, all in California (Figure 1).

3. MINERALIZED HYDROTHERMAL SYSTEMS

There are many critically important scientific problems with societal and potential economic benefits in mineral deposits that have not been drilled because the holes are difficult to justify as economically sound risks for private capital. Such holes, however, are highly appropriate research goals for government support because of the significant new opportunity for ore deposit insight that they afford. The earth science community is prepared with ideas for excellent drilling projects for research in mineral deposits.

Many important types of mineral deposits were formed by circulation of hydrothermal solutions through the continental crust. Most of the energy for hydrothermal systems is supplied by cooling of igneous rocks at various crustal levels. Magma invasion into cooler crustal rocks initiates fluid convection. The-near surface expression of such convection is observed in currently active hot springs and steam vents. A few such active geothermal areas have ore minerals directly associated with them, including some important gold and mercury deposits associated with ancient hot springs. Interesting but currently subeconomic concentrations of gold, silver, and lead are known in hot spring areas, and subaerial and subaqueous brine emanations contain many metals.

In western North America there are hundreds of shallow veins and disseminations of gold and silver in volcanic and subvolcanic environments that have the appearance of "fossil" hot springs or the roots of hot springs. The direct evidence for surface sinter is only rarely present, presumably having been eroded away. These epithermal deposits are again making significant contributions of gold and silver in the United States, and their restudy is currently a major effort in mineral exploration.

Historically, most epithermal gold-silver veins were discovered and mined in the late nineteenth and twentieth centuries, when bonanzas like Tonopah, Goldfield, Cripple Creek, and Comstock contributed immensely to the westward expansion of the United States. The precious metal ores in these deposits gave out at relatively shallow depths; few contained economic ore below about 700 m beneath the surface. However, there were a few cases such as Butte, Montana, where lateral development of the initial silver mines encountered base metals nearer the core of the district. The recognition of these zoning patterns encouraged speculation that silver originally projected over the top of base metals for the district as a whole, prior to being removed by erosion.

Consideration of the possible transition in depth between epithermal veins and deeper porphyry copper or molybdenum stockwork ores is not new. European geologists including Stelzner, Elie de Beaumont, Franz Posepny, and others began postulating such a relationship late in the nineteenth century. In the early 1900s American geologists including Waldemar Lindgren and S. F. Emmons argued that it was possible that base metal and related ore types underlay epithermal or volcanic precious-metal veins. But then, as evidence accumulated during the extensive mining of the epithermal ores in the United States, many geologists including Lindgren himself began to doubt the "stacking" hypothesis as applied generally between epithermal gold-silver deposits and subjacent porphyry-related subvolcanic base-metal ore systems. This critical relationship cannot be established until there is deep drilling under selected epithermal gold-silver districts, aided by research drilling of active hydrothermal systems.

The fundamental mineral deposit research objective is understanding the vertical relationship between continental ore deposit systems, in particular testing the hypothesis that porphyry copper-molybdenum systems underlie epithermal systems.

CREEDE MINING DISTRICT, COLORADO

The Creede mining district in the San Juan Mountains, Colorado, has been in almost continuous production for over 90 years. More than a billion dollars (at 1983 prices) worth of silver, gold, lead, zinc, and copper has been produced. It is the most intensively studied epithermal district in the world as a result of over 25 years of comprehensive, multidisciplinary investigations, primarily by the U.S. Geological Survey (USGS). The USGS selected the Creede district in 1959 for the establishment of a "natural laboratory" wherein to study processes of hydrothermal mineralization as a complement to experimental and theoretical studies of mechanisms of metal transport and deposition. As a result of these ongoing investigations a comprehensive model integrating the hydrology, geology, and chemistry of the ore-depositing environment has been developed that represents the best documented model of its kind currently available. The most important papers describing the studies on which the model is based include Steven and Ratte (1965), Steven and Eaton (1975), Steven and Lipman (1976), Barton, Bethke, and Roedder (1977), Bethke et al. (1976), Bethke and Rye (1979), and Roedder (1965, 1977).

The Creede district lies near the center of the San Juan Mountains, the largest erosional remnant of a mid-Tertiary volcanic field that once covered most of the Southern Rocky Mountains. Volcanism began about 40 million years ago with the eruption of a series of andesites and basaltic andesites from a number of scattered centers. The aprons from these stratavolcanoes coalesced to form a pile of intermediate composition rocks from 1 to 2 km thick that makes up approximately two-thirds of the volume of the San Juan volcanic field. About 30 million years ago the character of the volcanism changed and a series of silicic ash flows were erupted from 18 known or inferred calderas. These ash flows covered the earlier intermediate rocks and formed a broad volcanic plateau that has since been dissected to form the present rugged topography of the San Juan Mountains. About 25 million years ago the character of the volcanism again changed and a thin veneer of basalt-dominated, bimodal basalt-rhyolite volcanics was deposited on top of the silicic ash flows. The inception of bimodal volcanism appears to have corresponded with the change from compressional to extensional tectonics in the Southern Rocky Mountains.

The ores of the Creede district were deposited along the top of a deeply circulating hydrothermal cell analogous to modern geothermal systems active in silicic volcanic terranes. The ores are localized in fractures slightly younger than, and radiating northward from, the Creede caldera, the youngest of six silicic calderas that make up the central San Juan caldera complex. The rocks that host the veins are part of a thick sequence of rhyolitic ash flows that are the intercaldera fill of the older Bachelor caldera (older than the Creede caldera by about 2 million years). The ore-forming hydrothermal system represents the youngest recognized thermal event within the district, although bimodal basalt-rhyolite volcanism has been active elsewhere throughout the San Juans and adjacent areas up until at least 5 million years ago.

Oxygen, hydrogen, carbon, and sulfur isotope studies have suggested that the deeply circulating brines responsible for metal transport and deposition had their origin as partially evaporated lake waters contained in the interstices of the lacustrine sediments that filled the moat between the resurgent dome and the wall of the Creede caldera. Detailed mineral assemblege studies indicate that the redox state, pH, and sulfur fugacity were buffered by the mineral assemblege in the ore zone, and except for brief perturbations the ore fluids closely approached chemical (but not sulfur isotopic) equilibrium with the assemblege. Fluid inclusion studies show that the fluids were sodium-chloride-dominant brines ranging in concentration from one to three times that of seawater. These studies further indicate that these deep brines boiled near the top of the system and mixed with overlying low-salinity waters. Both boiling and mixing were important processes leading to base- and precious-metal deposition. Within the ore zone this model can be verified by quantitative calculations, but the ore zone represents only a small fraction of the hydrothermal system (perhaps 10 percent by volume). Conditions in the marginal and deeper parts of the system can only be inferred from extrapolation of the known parameters of the ore zone, through comparison to well-studied root zones of hydrothermal systems in other areas, and from comparison to modern geothermal systems. Evidence from studies of exposed root zones and of active systems shows that there is considerable variation in the chemistry, hydrology, and physical conditions between the various areas studied. Which root zones may be near-complements of the Creede ore zone can only be conjectured.

The Creede district has been selected by the Panel on Mineral Resources as the highest priority target for a program of scientific drilling for mineral resource objectives. This selection has been based on the following factors.

1. The Creede system will provide a test of the hypothesis that shallow epithermal systems of this type are the near-surface manifestations of underlying porphyry molybdenum or porphyry copper-molybdenum systems.

2. The extensive available background data on the geology, geochemistry, geophysics, and ore-fluid chemistry and isotopy and the exceptionally well-documented quantitative model of the upper part of the hydrothermal system.

3. The importance of Creede as representative of hydrothermal ore deposits formed at the top of deeply circulating hydrothermal systems.

4. The relative simplicity of the geometry and geological setting of the Creede district, which maximizes the chances of successful drilling.

5. The similarity of the Creede fossil hydrothermal system to active geothermal systems in silicic volcanic terranes, which makes possible a coupled, comparative, and mutually supportive program of scientific drilling in analogous modern and fossil hydrothermal systems.

Research Objectives

The ultimate objective of a program of scientific drilling in the Creede district is to develop a comprehensive, quantitatively verifiable model for the origin, transport, and deposition of base and precious metals of the Creede hydrothermal system. Such a model would provide a much more advanced basis for our understanding of hydrothermal ore deposits in general, and in particular, those related to silicic volcanic centers and calderas. Understanding is needed to improve the efficiency and effectiveness of exploration and evaluation for both mineral and geothermal resources. In order to develop such a model it is necessary to establish a physical connection between a well-understood ore zone such as is found in the Creede district and the roots of the hydrothermal system that formed it. Specific information is sought about:

1. The nature of the heat source for the ore-forming hydrothermal system,

2. The nature of the source rocks from which the metals and chemical and isotopic components of the hydrothermal fluids were derived, and

3. The physical and chemical conditions and nature of the rock-water interactions in the roots of the hydrothermal system.

Proposed Program

It is proposed that four, continuously cored slim holes be drilled, two to depths of approximately 1 km to test the caldera moat-filling lake sediments as a source of water, salinity, and sulfur, and two to depths of approximately 5 km, sited in the central part of the Creede district, to study the roots of the hydrothermal system. These holes would provide data regarding the three subjects mentioned above: heat source, source rocks, and the roots of the hydrothermal system.

Heat Source   Steven and Eaton (1975) postulated the existence of a stock emplaced some 3 to 5 km below the present mineral deposits in the center of the Creede district. Their main evidence was that the maximum displacement on the mineralized faults defining the Creede graben was located in the center of the district, and diminished to the north and south. Supporting evidence is derived from subtle gravity and magnetic anomalies based on regional-scale geophysical studies. This conclusion is widely accepted; however, other geothermal systems in the western United States appear to be related to abnormally high regional thermal gradients rather than to local magmatic heat sources. Bethke et al. (1976) have shown that mineralization followed the last known igneous event in the central San Juan caldera complex by 1 to 2 million years. This observation presents the question as to whether the postulated stock is part of the eruptive cycle of the Creede caldera and, therefore, caldera-related, or a high-silica rhyolitic stock of the younger bimodal basalt-rhyolite sequence and therefore unrelated to the caldera evolution. This question is of fundamental importance in evaluating the role of calderas in epithermal mineral formation.

Extensive age dating in the Creede district has closely bracketed the age of the Creede mineralization. Age dating of the rocks encountered at depth in the Creede drill hole will indicate whether or not the intrusives penetrated are potential heat sources that drove the hydrothermal system.

Source Rocks   Doe et al. (1979) showed that the lead isotopic composition of Creede minerals is more radiogenic than any of the volcanic rocks in the San Juan Mountains. They suggested that this is due to substantial additions of radiogenic lead from the Precambrian basement. Steven and Friedman (1968) postulated that the isotopic composition of the travertine mounds in the moat of the Creede caldera indicates that the carbon dioxide was derived by decarbonation reactions of Mesozoic limestones at depth below the Creede district. The high salinity (4 to 12 wt % NaCl equivalent) of fluid inclusions in the Creede minerals suggests that the chloride content may be due to mechanisms other than leaching of the underlying volcanics. Bethke and Rye (1979) suggested that, based on the oxygen and hydrogen isotopic composition of the Creede mineral fluids, these fluids were of meteoric origin and were derived from the interstitial waters in the lacustrine sediments filling the moat of the Creede caldera.

Rye, Barton, and Bethke (U.S. Geological Survey, unpublished data) suggest that the oxygen and sulfur isotopic composition of the barite requires that the sulfate gained its isotopic signature by biogenic sulfate reduction in a lacustrine environment. They also conclude that the sulfur isotopic data on barite and sulfide minerals imply that approximately 10 times as much sulfur exists elsewhere in the system as in the known ores. This sulfur may exist as pyrite or pyrrhotite disseminated in the underlying volcanics. Alternatively, the sulfide may reside in a deep, porphyry-type system from which mineral concentrations were derived by hypogene leaching at depth and redeposition at the top of the system, as suggested for Creede by Barton et al. (1977) and postulated for Butte by Brimhall (1979, 1980). All of these hypotheses have bearing on the present concept of the Creede system and can be investigated by drilling the mineralized portion of the moat-filling sediments.

<u>Roots of the Hydrothermal System</u> The final objective of the Creede research program is to gain a quantitative knowledge of the physical and chemical conditions in the roots of a hydrothermal system. Specifically, temperatures and salinities of fluids from fluid inclusions trapped deep in the system are needed, together with estimates of the controlling chemical parameters based on mineral assemblages and of metasomatism analogous to alteration at the top of the system. Estimates of both the nature and the magnitude of the permeability at the bottom of the system are essential for quantitative definition of the hydrologic parameters of the ore-forming system.

RED MOUNTAIN, ARIZONA

The Red Mountain mineral deposit, located in southeastern Arizona, is suggested as a research site to examine a complete porphyry copper system. The Patagonia Mountains, of which Red Mountain is a part, offer an environment in which a series of epithermal deposits may be spatially and genetically related to the Red Mountain porphyry copper system. Additional geological, geochemical, and geophysical studies supplementing the proposed drilling program could add to the knowledge of epithermal and porphyry copper-molybdenum system relationships.

The proposed study of the Red Mountain district represents an unusual opportunity for increasing scientific understanding of important criteria in hydrothermal mineral genesis, geochemistry, and paleohydrology. The district presents a number of unique features that are scientifically attractive, including the simple geological setting of an apparently vertical and structurally undisturbed porphyry copper system encompassing an extensive vertical interval assumed to be as great or greater than all major, extensively mined porphyry copper systems. The deposit is unmined; because of its undisturbed nature, sampling of an essentially complete vertical system is possible.

Drilling by Kerr-McGee Corporation from 1961 to the present explored the porphyry copper system over a vertical range of 2 km. Existing data are derived from 71 drill holes, totaling approximately 55 km of penetration and including 24 holes each deeper than 1.5 km. The deposit is interpreted to consist of at least three distinct zones representing a broad spectrum of hydrothermal mineralization and alteration. The upper portion of the deposit consists of (1) a relatively thin chalcocite-enriched blanket developed from chalcopyrite-enargite-bearing material within high level phyllic and argillic alteration patterns, (2) a deeper porphyry copper sulfide deposit 1.1 km below the chalcocite blanket, and (3) a copper-molybdenum breccia pipe near the center of the sulfide deposit.

The major purpose of the research program would be to define the limits of the hydrothermal system in terms of geological and mineralogical features of porphyry copper deposits. Transitions in physical rock properties at depth would be of prime interest. Collectively, these factors relate to the understanding of the vertical and horizontal limits of hydrothermal fluid circulation and paleopermeability variations over a 4.3-km interval. Because of economic limitations, these depths are not commonly explored, but they represent regions critical to the complete understanding of porphyry copper-molybdenum systems. Root zones exposed in other districts may not be recognized as being the lower portions of eroded porphyry copper systems.

A research program at Red Mountain would also provide an opportunity to acquire basic data regarding mineral deposition and metasomatic zoning. Although recent advances in isotope geochemistry have provided insight into various water sources, the specific source of metals and sulfur and the controlling transport processes remain targets for scientific pursuit.

The geology and base metal occurrences at Red Mountain have been intermittently studied since 1915 (Schrader, 1915; Drewes, 1971a,b, 1972a,b; Simons, 1971, 1974). More recent efforts have focused on data provided by the Kerr-McGee drilling program (Corn, 1975; Bodnar and Beane, 1980; Quinlan, 1981) and comparisons with postulated genetic models of porphyry copper deposits (Lowell and Guilbert, 1970; Rose, 1970). Surface geological sampling by the U.S. Geological Survey surrounding Red Mountain was summarized by Chaffee et al. (1981).

The geological setting of Red Mountain consists of an altered complex of flat-lying volcanic and intrusive rocks of Cretaceous and early Tertiary age. Three layered volcanic units have been described, including an upper rhyolite and dacite tuff unit of 730-m maximum thickness, an underlying andesite 900 m thick, overlying a basal felsite-latite unit. Porphyritic rocks ranging in composition from granodiorite to quartz monzonite cut the layered volcanic rocks.

Silicate alteration, described in detail by Quinlan (1981) and Corn (1975), varies with rock types and depth. Alteration assemblages (i.e., argillic, phyllic, and potassic) typical of porphyry copper deposits are present. The alteration zoning pattern can be explained by a deep ore stage alteration system superimposed on an earlier, larger, and essentially copper-barren alteration system. Argillic and phyllic alteration at the surface is a part of the large, early stage system. Strong potassic and phyllic alteration at depth is a part of the deep-level porphyry copper stage alteration.

Mineral zoning appears to be related to the deep-level porphyry copper stage alteration. Lead and zinc generally occur in the upper portions of the deposit, and small amounts of molybdenum are present throughout. Chalcopyrite is the predominant copper mineral. Enargite occurs in the upper levels, and minor amounts of bornite are present at depth in the potassic core of the deposit. The proportion of bornite increases with depth.

The formation of intrusive breccias has been interpreted to be the youngest hypogene mineralization event. Breccia pipes crop out at the surface and are recognized in the deep drill holes. A breccia pipe within the potassic core area of the deposit may be the deepest copper-molybdenum breccia pipe known in the world. Strong phyllic alteration is recognized at the top of this pipe, and to a lesser extent at its margins. A zone of copper, molybdenum, and silver enrichment is situated near the margins of the pipe. This pipe presents a unique environment permitting insight into vertically zoned mineral deposits in relation to other major elements of such deposits and providing an opportunity to compare high-level and deep-level breccia pipes in a porphyry copper environment. Understanding of the structural evolution of this district could aid in the interpretation of other mineral deposits that represent single phases of the multi-staged process at Red Mountain.

Research Objectives

The prime purpose of the research program would be to explore the root systems of the deposit, particularly the extent to which metals have been leached from lower portions. Deep alteration of fresh wall rock may have liberated trace elements that are not included in the primary ores. Additional research would provide mineralogical zoning data relating to the vertical interval over which metals and particular alteration processes have been concentrated. Studies of the alteration and mineralization patterns at Red Mountain have not been as intensive as those at other mining districts in the western United States. Geochronology research to determine the ages of alteration assemblages is also recommended.

Proposed Program

Although coring at Red Mountain has provided samples over a considerable vertical interval within the porphyry copper deposit, additional geological work in the district is needed to refine the understanding of mineralization and alteration relationships of the Red Mountain system with the spatially associated epithermal deposits. Geological mapping, geochemical sampling, and comprehensive analysis of existing drill core for cross-cutting relationships, alteration products, and fluid inclusions should precede selection of specific scientific objectives and drilling sites. Existing geophysical data require supplemental gravity and aeromagnetic surveys. These predrilling studies will provide a better three-dimensional model for validation and/or refinement from data obtained by the proposed research drilling. At present it is too early to consider research drilling at Red Mountain.

A minimum of two research drill holes is proposed, based on the known geometry of the district zonation (i.e., the breccia pipe and bulk sulfide deposit). One drill hole should be located specifically to test the breccia pipe and its downward extension, and a second hole should test depths below the known sulfide body at 2.4 to 3.0 km. Both holes may be drilled to depths of up to 5 km to explore the bottom of the potassic alteration zone. These holes should penetrate the lower limit of fluid circulation, where a test of the nature of fluid transport could be conducted and paleopermeability estimates could be made. Paleotemperature isotherms would be generated through fluid inclusion and mineralogical studies. Gradients in permeability, paleotemperature, and fluid composition would improve the present understanding of the relationship of magmatic heat supply, fluid convection, and hydrothermal fluid composition. Research drill holes in these environments would also provide data regarding the existing hypotheses of metal remobilization and alteration in root systems.

TONOPAH, NEVADA

The Tonopah mining district is located in west-central Nevada. Almost 2 million ounces of gold and 175 million ounces of silver have been produced from epithermal precious-metal veins within a complex of igneous flows, tuffs, intrusions, and breccias, ranging in composition from andesite to rhyolite. Mineralization at Tonopah has been dated at 17-20 million years (Silberman et al., 1979).

The epithermal mineralization at Tonopah may be related to a porphyry molybdenum system at depth. In the western part of the Tonopah district, intrusive breccias may represent the uppermost parts of a shallow hypabyssal molybdenum-bearing porphyry complex. Although molybdenum is not abundant in Tonopah precious-metal ores, molybdenum values increase in the western and deeper parts of the district. Indications that the Tonopah district may be the top of a porphyry molybdenum system include

(1) changes from gold-silver to copper-lead-zinc to lead-zinc-molybdenum mineralization with depth, (2) presence of a host igneous complex of nearly contemporaneous andesitic, dacitic, and rhyolitic rocks, and (3) presence of intrusive breccia bodies.

Tonopah was selected as a research target for the following reasons:

1. Considerable production of silver and gold in the western United States has come from epithermal deposits in volcanic rocks. Exploration groups are interested in applying new conceptual models and exploration techniques in the search for additional deposits of this type in the United States.
2. The epithermal system at Tonopah, as at Creede, is similar to active geothermal systems in many ways.
3. The district is compact in size, intensely mineralized, relatively undisrupted by faults in the mineralized interval, and simple in overall geometry.
4. Intrusive breccias and molybdenum-bearing outcrops in the district suggest the likelihood of intersecting a contemporaneous underlying system of porphyry mineralization or, alternately, of observing results of remobilization of an earlier mineralization in the roots of an epithermal system.

Research Objectives

One to three preliminary shallow holes (to depths of 1 to 2 km) and one or two deeper holes (to depths of 2 to 5 km) are proposed to explore the possibility that another mineralization environment may exist below the epithermal precious-metal deposits. The sequence might include epithermal mineralization overlying anomously high molybdenum with tungsten values, in turn overlying porphyry molybdenum mineralization in an intrusive complex. Research drilling at Tonopah would test the hypothesis that epithermal deposits, intrusive breccias, and geochemical anomalies may be upward extensions of porphyry molybdenum systems.

Proposed Program

The regional geology and detailed geochronology of the Tonopah district are described by Bonham and Garside (1979) and Silberman et al. (1979). The distribution of veins, orebodies, and structures observed underground during exploration of the district was well documented by Nolan (1935). A museum collection assembled by Nolan has been used for fluid inclusion and stable isotope studies (Fahley, 1981; Taylor, 1973). Additional unpublished data pertinent to this drilling program have been acquired by mining companies in recent years, particularly by Houston International Minerals Corporation. In order to site drill holes effectively, the following studies are needed.

1. Analysis of existing data and samples, including core, core logs, and geochemical data from industry drilling in the western part of the district, geochemical data from surface and underground samples, and low-level aeromagnetic data. The main objective of this step is to confirm that the increase in molybdenum values with depth in the western part of the district is coincident with the occurrence of intrusive breccias. The industry drill core would also provide material for chemical analyses to determine whether the possible intrusive complex has alkaline affinities, as is typical of major known fluorine-rich porphyry molybdenum systems. Existing geochemical data and additional analyses of unoxidized mineralized material will better define the minor element suite associated with molybdenum. This information may also make it possible to predict whether the anomalous molybdenum is related to a deeper molybdenum system or was mobilized from older mineralized rocks.

2. Examination of samples available from core, surface exposures, and existing collections to see if recent fluid inclusion work of Fahley (1981) can be extended spatially. This information could provide a better understanding of the paleohydrology of the mineralizing system needed for drill hole site selection.

3. Detailed study of oxygen and hydrogen isotopic variations should be undertaken to extend the earlier study of Taylor (1973), which established that the mineralizing hydrothermal system was meteoric-water dominated.

4. Detailed gravity and magnetic studies to help establish the existence of an intrusive mass at depth that gave rise to the intrusive breccias.

5. Detailed seismic reflection work over the entire Tonopah area to detect any low-dipping faults or detachment surfaces.

The proposed research program would begin with one to three 1- to 2-km- deep drill holes to confirm the molybdenum- and other base-metal-bearing character of epithermal mineralization at depth, to refine further the known geometry of the epithermal system and the breccia bodies, and to detect any low-dipping faults that may offset the lower parts of the system.

Geometry of the Epithermal System The work of Nolan (1935) revealed that the productive zone at Tonopah is an approximately symmetrical elongate shell 60 to 180 m thick, concave downward. Taylor's (1973) oxygen data for whole rocks show maximum shift over the highest part of the productive zone. The symmetrical productive zone and coincident isotopic pattern could be explained by upward fluid flow beneath the center of the district, giving way to dominantly lateral flow away from this upwelling center at about the level of the productive zone. Fahley (1981), however, found the highest fluid inclusion temperatures (260°C) in the western part of the district; evidence of boiling was found in the center. Fluids thus may have come up the Tonopah fault, a major low-dipping mineral-controlling structure that forms the west side of the shell, and discharged above the center of the district. Taylor's data are also consistent with the idea that the center of the district was a high-discharge area. A 1- to 2-km hole should be drilled west of the westernmost productive veins to intersect the area through which upward-flowing hydrothermal fluids may have entered the Tonopah fault zone.

Geometry of the Intrusive Complex Intrusive breccias in the district, the West End Rhyolite and the Extension Breccia, are exposed only in mine workings as sills that intrude along the Tonopah fault. Where the Tonopah fault is occupied by intrusive rock, ore bodies occur at the intrusive contacts, indicating that hydrothermal fluids moved up along these contacts and into the fault zone. Both units contain abundant fragments, largely from the Tonopah formation rhyolitic extrusives and intrusives. The units appear just west of the center of the district and thicken to the west, indicating that the dikes or plugs that fed the sills from a deeper, multiple-phase stock are probably located just west of the district. The first hole proposed above may locate these feeders, which should overlie the inferred molybdenum-bearing stock. An additional 1- to 2-km hole somewhat farther west might be required.

Low-Dipping Faults Low-dipping or detachment faults were not recognized by Bonham and Garside (1979) in their mapping of the Tonopah district and surrounding area. Such faults have been recognized in several other parts of western Nevada. Horizontal distension and associated shingle faulting was recognized by Ashley (1974) at Goldfield, 40 km south of Tonopah. Faulting similar in age to that at Goldfield would predate mineralization at Tonopah. The Tonopah fault may be part of a low-dipping fault system of premineralization age. If a detachment fault is found, the project would have to be reevaluated, depending upon the depth at which the detachment fault is encountered and the displacement involved.

Drilling Proposed The shallower holes proposed for this program should be cored continuously. If the shallower holes successfully intercept the downward pipe- or dike-like portions of the breccia bodies, confirm anomalous molybdenum and other base metals, and confirm the absence of major faults, one or two deeper holes (2 to 5 km) should be drilled. A deep hole could penetrate the bottom of the epithermal system, the deeper parts of the intrusive complex, and the possible source of the molybdenum.

The research drilling would provide information to address fundamental uncertainties similar to those being addressed in the Creede district: nature of the heat source; nature of the source rocks that supplied the mineral components; and conditions in the roots of the system. Comparison of the results of drilling projects in these two districts would explain the fundamental influences of intermediate versus silicic rock systems on related mineral systems, leading to more accurate models of epithermal-hypothermal deposits.

BUTTE, MONTANA

Scientific research studies of the mineral deposits at Butte, Montana, could provide additional data regarding mineral deposition/metasomatism, including the possibility of subjacent mineral systems. Although recent advances in isotope geochemistry have provided insight into water sources in mineral deposits, direct sources of metals and sulfur and transport mechanisms remain frontiers for scientific pursuit.

Large copper-silver-zinc veins at Butte are superimposed upon an extensive copper-molybdenum stockwork. The zoning may have been generated in a one- or two-stage cycle. Extensions of the Butte base-metal veins above the present surface may have included higher precious-metal concentrations if zoning upward had been similar to the silver-zinc concentrations surrounding the copper deposits. One of the principal objectives of research drilling at Butte would be to determine the extent to which the metals may have been leached from the lower portions of the deposit, to be reprecipitated in veins at higher elevations.

It is possible that new holes would not have to be drilled in a research program at Butte. In the past 5 years, the Anaconda Minerals Company has drilled a series of holes up to depths of 2.1 km, and it may be possible to reenter and deepen one or more of these holes. Sampling requirements, because of the possibility of hole reentry, could be satisfied by slim hole coring. The core would be studied petrographically for vein and alteration types, fluid inclusions (including pressure corrections), veinlet inclinations and intersections, and stable isotopes.

Although published information describing the Butte deposit indicates that it should be considered as a possible site for future research drilling, limited access to the mining properties and the proprietary nature of existing data preclude consideration of this target at the present time, at least until new information about the zoning at Butte is published.

4. ACTIVE HYDROTHERMAL SYSTEMS

Present knowledge of hydrothermal mineral deposits and active geothermal systems demonstrates the importance of interaction of shallow, dilute meteoric water and deeper brines. The origin and character of these deep brines are poorly understood. Fluid inclusions in mineralized porphyry copper-molybdenum systems contain both high salinity and moderate to dilute fluids. Highly concentrated brines thus far encountered in active hydrothermal systems have come from environments in which the waters may have interacted with evaporites. Such environments include the Salton Sea in California (White, 1968), El Tatio in Chile (Ellis and Mahon, 1977), and Cesasano in Italy (Calamai et al., 1976). Highly saline, as well as moderately concentrated brines may evolve from a magma, depending on the initial water and chloride contents and depth of crystallization (Burnham and Ohmoto, 1980; Fournier, 1977; Burnham, 1967, 1979). Highly concentrated brines may also develop from dilute meteoric waters as a result of boiling, for example, at the bottom of a vapor-dominated system (White, Muffler, and Truesdell, 1971). The primary objective of the proposed research drilling as related to the objectives of mineral resources research is to investigate the origin, evolution, and geometric relations of brines in an active silicic volcanic center, uncomplicated by a sedimentary section containing evaporites.

RESEARCH OBJECTIVES

Specific elements of the objective are summarized in the following set of questions.

1. What are the sources of the waters deep in the hydrothermal system and how did they acquire their salinities?
2. What is the variation in temperature and chemical/isotopic composition from the top to the bottom of an active hydrothermal system at a given time? Do less saline waters form separate convecting cells above more saline convecting cells? If so, mineral deposition of

different types and intensities might occur simultaneously in various parts of the system at interfaces where different fluids mix.

3. What is the origin and concentration of metals and sulfur in hydrothermal systems, how are they transported, and how and where are they deposited?

4. How do porosity and permeability change with depth in an active hydrothermal system?

5. To what extent does self-sealing take place at tops, lateral extensions, and roots of hydrothermal convection cells? If more than one convection cell is present, will each tend to be self-sealed? In subjacent mineralized zones, barren silicified rock might represent the separation of mineral concentrations formed from different brines (Bodvarsson, 1964; Facca and Tonani, 1967; White et al., 1971; Grindley and Brown, 1976; Fournier, 1977 and in preparation).

6. Is there a change from hydrostatic to lithostatic fluid pressures in the vicinity of shallow magmatic intrusives, possibly caused by self-sealing through deposition of minerals from an evolved magmatic fluid? If so, drastic changes in fluid pressure may occur from time to time if the seal is broken by tectonic movements or pressure buildup derived from magmatic fluid, with major implications for mineral deposition (Phillips, 1973; Henley and McNabb, 1978; Fournier, in preparation).

7. How do partial pressures of gases and oxidation states of the system change with depth? What is the origin of the gases in active systems? What are the relative contributions from the mantle, shallow magmatic bodies, and metamorphic reactions?

The general objective for studying an active hydrothermal system is to gain information about the evolution of hydrothermal systems and mineral genesis. Study of the solid and fluid samples obtained in a hole drilled into an active system could answer some of the questions enumerated above. It is equally important to understand why many shallow hydrothermal-magma systems apparently have no associated economic mineral deposits.

PROPOSED TARGETS

With the above questions in mind, it is concluded that important concepts relating to mineral deposit formation could be developed through research of active hydrothermal systems. A deep hole should be drilled into a currently active system within a silicic caldera complex in which rock temperatures of 500°C at depths of about 5 to 7 km are likely to exist. Many hydrothermal ore deposits are spatially and genetically related to such caldera complexes, and an investigation of an active system would relate directly to a study of a fossil system in a similar geological environment. The above factors and those outlined in the report A National Drilling Program to Study the Roots of Active Hydrothermal Systems Related to Young Magmatic Intrusions (Continental Scientific Drilling Committee, 1984) indicate several active hydrothermal system candidates for drilling to address the research objectives listed above.

Yellowstone, Wyoming

Extensive studies of the Yellowstone silicic caldera complex have provided abundant geological, geophysical, and geochemical data with which models can be formulated. However, the deepest drill holes are relatively shallow (maximum of 332 m), so there are few subsurface data that can be used to test models. Judging by the currently available geophysical data, there probably is an extensive body of high temperature rock (possibly partial melt or magma) within 3 to 10 km of the surface beneath much of the Yellowstone caldera. This hot rock may come closest to the surface (within 3 km) beneath the northeast part of the caldera, where a research drill hole would provide scientific information about the roots of hydrothermal systems. Before attempting any research involving drilling in an environmentally sensitive area such as Yellowstone National Park, drilling techniques into rocks approaching magmatic temperature and possibly with high fluid pressures should be in an advanced stage.

Valles Caldera, New Mexico

Because accessibility of the Yellowstone caldera as a drill site is uncertain because of environmental considerations, the Valles caldera system is recommended as an alternative site for research drilling. The Valles caldera system also has been extensively studied and has the advantage of 25 existing industry-financed intermediate-depth holes down to depths of 3.2 km that provide information about the chemical and physical nature of the upper parts of the hydrothermal system. At present there is no direct evidence for the existence of magma beneath the Valles system at a depth accessible by drilling. However, the geological evidence indicates that the system is still hot, the heat source is large, and the hydrothermal system is well developed. The Valles caldera is considered to be an excellent target to gain information about depth-temperature-pressure-salinity conditions in a relatively simple hydrothermal system that has evolved above a shallow silicic magma. The similarities between the geological environments at the Valles caldera and at Creede are striking. A comparison between the active system at Valles and the fossil hydrothermal system at Creede will yield interpretations that are beneficial to the understanding of both systems.

Long Valley, California

The Long Valley silicic caldera system is geologically similar to the Valles caldera system, but it has been investigated only by a limited number of intermediate-depth drill holes. A major drawback to research at Long Valley is the distinct possibility that the underground thermal regime and hydrothermal system are changing at a rapid rate owing to upward movement of magma. Recent uplift of the caldera floor, local seismic activity (spasmodic tremors), and increased hot spring and fumarole activity prompted the U.S. Geological Survey to issue in May 1982 a notice of potential volcanic hazard. If magma is currently rising within or near the Long Valley caldera, it should greatly perturb the subsurface thermal regime and could alter the chemical and physical nature of the hydrothermal system. This would make it difficult to interpret drilling data. Research at Long Valley might be more appropriately directed toward answering questions about the early stages of development of a hydrothermal system related to a younger magmatic intrusion. While the early stages of development of a hydrothermal system related to a magmatic intrusion are of great interest, the later "mature" stage is likely to provide more useful information for modeling hydrothermal ore-depositing systems.

The Geysers/Clear Lake, California

The Geysers/Clear Lake geothermal system appears to be related to a moderately well-defined magmatic body present at a shallow depth that could serve as a source of sulfur as well as heat. The evolution of any brine in the deep part of the system could be related to factors other than interaction with evaporite deposits because there are no known or inferred halide deposits in the sedimentary rocks in the immediate area. However, hot spring waters flowing from the Great Valley sequence rocks in the region generally do contain much more chloride than do hot spring waters flowing from Franciscan rocks. A boiling brine may exist beneath the vapor-dominated zone at The Geysers. If so, present-day mineral deposition could be occurring there. From the point of view of relating an active system to studies of similar fossil systems, The Geysers/ Clear Lake system is ranked lower in priority than the Valles caldera. Current industry interest in drilling deeper and closer to the inferred magmatic body at The Geysers should be monitored for possibilities of add-on investigations in holes of opportunity.

Salton Sea, California

The Salton Trough is one of the best onshore targets for add-on investigations that address the problems of mineral concentration related to spreading centers. The Salton Sea geothermal field represents a class of hydrothermal systems where the salinity and dissolved metal concentrations in the brines are very high, the result of interaction with the evaporites in the geological section. Considerable information is available concerning the rocks and high-temperature fluids in the upper parts of this system. By deeper drilling into the hydrothermal system in the Salton Sea, information would be obtained about the metamorphism of an initially relatively uniform pile of sediments and the consequent changes in porosity and permeability. Information might also be obtained concerning how deeply the brine circulates and whether there are changes in salinity, sulfur, and metal content of the brine with depth. The above information might be obtained through add-on investigations, including deepening of existing or planned industry drill holes, rather than by a program of drilling dedicated holes.

5. EXAMPLES OF OBJECTIVES TO BE ADDRESSED BY ADD-ON INVESTIGATIONS

Numerous scientific objectives, considered to be of importance equal to the specific objectives of the proposed dedicated drilling projects, can be accomplished by scientific investigations in holes and on drilling samples and measurements available from drilling activities of industry or government agencies in and adjacent to mineralized fossil and active geothermal regions. Existing holes may be deepened or otherwise used to provide access to untested lower horizons and peripheral portions of mineralized systems normally inaccessible to sampling. The concept of add-on investigations to such holes of opportunity requires establishment of a dialogue between industry, government, and the scientific community, such as through the Continental Scientific Drilling Committee's DEW (Drilling Early Warning) Newsletter, in which both specific research needs and the availability of pertinent mission-oriented holes can be described.

The acquisition, maintenance, and deepening of selected holes will allow studies of mineral deposits and related active hydrothermal systems for which available data relate only to the immediate vicinity of "ore" grade mineralization. The exploration of peripheral relationships, the reactions of ore deposit systems with marginal facies, and the interpretation of zonal relationships that may be guides to ore would also require access to holes of opportunity. As mentioned previously, geological and geochemical studies of the margins (both lateral and vertical) of ore deposit systems constitute the principal area of recommended research by those who responded to the Society of Economic Geologists' Research Committee questionnaire. The potential scientific benefits of add-on investigations are high in comparison with their costs.

Specific add-on investigations, including deepening holes beyond the proposed depth, additional coring and logging, and additional analyses of samples, could be used for:

1. Whole rock and mineralogical sampling for petrologic, bulk and trace element geochemistry, fluid inclusions, and isotopic and geochronological studies,

2. Geophysical experimentation to establish response and continuity of mineralization and/or mineral-related facies, and

3. Determination of micropore and microfracture densities.

The following ore deposit types are cited as examples that should be considered in selecting areas of existing drill holes for further study.

PORPHYRY COPPER SYSTEMS

There are few porphyry copper systems for which the marginal or lateral characteristics associated with mineralization have been adequately studied. The definition and study of the margins of these systems may not require deep holes such are as proposed for the dedicated research drilling. Research on abandoned holes in the margins of such systems could define lateral dimensions of porphyry copper systems, hydrologic systems associated with porphyry copper and molybdenum concentrating processes, related skarn processes, and basic elemental abundance based on comparisons of selective metal contents within and outside of the producing areas. Cores from the margins of porphyry copper systems are needed for bulk and trace metal geochemistry, fluid inclusion, and isotopic studies.

The Yerington granodiorite batholith in west-central Nevada provides opportunities for add-on investigation. It includes three well-drilled porphyry copper systems with attendant skarn development in adjacent metasedimentary rocks. The Ann Mason, Yerington, and Bear/Lagomarsino systems are rotated in a near-horizontal position, providing both vertical and lateral access from the paleovolcanic surface to batholithic depths of up to 8 km (Proffett and Dilles, 1983).

Approximately 400,000 ft (120 km) of drill core samples are available for study, assuming suitable storage and curation facilities are provided. The Yerington mine has been best studied through 1978 via open pit exposure; however, its margins are accessible only via drill core because of a Quaternary cover. The Ann Mason system, on the other hand, is characterized by 4.5 km of uninterrupted vertical exposure largely in the propylitized margins and albitized root zone of the system.

Further, the following work is recommended.

1. Detailed petrographic and analytical studies to define the geochemical environment of potassic and sericitic alteration zones already mapped in the Yerington mine. Such studies have been completed for the deep albitic zones in the Yerington mine (Carten, 1981). The Ann Mason surface studies (Dilles, 1983) should be extended to include the core from the Ann Mason deposit.

2. Documentation of vein-fill mineralogy and vein alteration envelopes, including phase abundances and compositions, fluid inclusions, and phase composition.

3. Bulk composition and specific gravity data in sufficient detail to attempt to characterize gains and losses on the scale of the hydrothermal system.

The core also represents extensive source material for light stable isotopic study that should include oxygen-18 and deuterium analysis of both hydrothermal and igneous mineral separates to document the source and timing of the ore fluids, the use of quartz-magnetite pairs for oxygen isotope fractionation geothermometry and sulfur-34 analysis to document the source of sulfur and define the geochemical environment. Space-time constraints extended from field investigations by this research and fluid inclusion studies should allow quantitative estimates of the pressure-temperature and component activity gradients over several kilometers of vertical and lateral exposure. These data will facilitate the construction of a quantitative three-dimensional model of the Yerington and Ann Mason systems, including empirical estimates of mass transfer between alteration zones and comparison with theoretical mass transfer calculations.

PRECIOUS METAL ENVIRONMENTS

The current exploration effort directed toward the discovery of epithermal vein gold-silver deposits and related "invisible" gold-silver disseminated in carbon- and/or sulfide-bearing host rocks includes many drill holes that are candidates for add-on investigations. The spatial and temporal relationships of these gold-silver-bearing systems to silicic caldera systems and to deeper seated base-metal-bearing systems should be better understood. For instance, at Creede there still is not a thorough understanding of the "invisible" disseminated silver mineralization in the lake sediments that may represent a leakage of the vein fluids upward into the sedimentary cover. Add-on investigations are recommended to study the vertical relationship of mineral systems that have undergone multiple boiling episodes.

MASSIVE SULFIDE DEPOSITS

Many of the key questions pertaining to the origin of massive sulfide deposits can be answered only by study of wall rocks beyond the limits of ore grade mineralization. There is increasing interest in the comparison of wall rock alteration patterns associated with massive sulfide deposits and those associated with sulfide-forming vents in active rift systems on the modern sea floor. A current line of investigation is directed at the interaction of massive sulfides with host rocks during regional metamorphism, involving sulfide-silicate reactions that tend to obscure primary mineral assemblages. In both of the cases cited, the research requires access to samples that may be barren but are nevertheless scientifically informative. Once the opportunities for extension of drill holes planned by industry are identified by the scientific community, add-on investigations would provide a cost-effective means for probing these mineral-forming systems. The success of an add-on program will depend upon development of an efficient mechanism for communication of the scientific needs to industry and the coordinated development of drilling programs that might satisfy those needs.

PLATINUM GROUP METAL (PGM) DEPOSITS

Recent research on the layered mafic complexes of the world has advanced understanding of the thermodynamic concentration and temperature control of sulfur saturation in gabbroic magmas, which in turn has led to various models for the generation of PGM-enriched sulfide layers in the Bushveld and Stillwater complexes. Further evaluation of such models will require continued research aimed at development of criteria for recognition of spatial and temporal sulfur saturation in the magma chamber, and a better understanding of melt-solid and solid-solid partitioning of the PGM elements as crystallization proceeds. Even given an improved understanding of the experimental systems, the recognition of the concentration processes that were operative, as opposed to merely possible, will require access to samples that can only be provided by drilling. In the Stillwater complex, for example, it becomes essential to determine the actual solid-melt partitioning of the PGM elements in the basal sulfide-free cumulate zone if mechanisms for generation of the PGM-enriched zones are to be defined. For the Stillwater complex, this research might be accomplished by add-on studies of existing holes and cores.

MISSISSIPPI VALLEY-TYPE DEPOSITS

Mississippi Valley-type ore deposit systems are considered in an add-on investigation category because many of the genetic problems associated with these systems can be addressed by experiments added on to industry drilling in intracratonic basins. Although this important type of mineralization has been intensely studied for decades, many of the basic questions such as the age of mineralization and the source, mode of transport, and precipitation mechanisms for the metals remain unsolved. As with all of the mineral deposits considered in this report, it is essential to study the entire mineral-forming system of which the ore deposit itself may make up an economically important, but volumetrically trivial part. In the case of Mississippi Valley-type deposits, this requires access to the deeper parts of the basins where the metallizing brines were probably generated. One can visualize numerous situations in which add-on investigations would permit studies of water-rock reactions and isotopic exchange, shale filtration mechanisms, diagenetic versus mineral-related carbonate facies and their possible relations to fluid interfaces or mixing zones, and metal partitioning between brines and host rocks at various depths. In some instances, it would be essential to extend existing drill holes into genetically significant but economically unrewarding ground. For example, studies of solution collapse mechanisms and of the relationships between rock matrix (karst) and superimposed mineral matrix (hydrothermal) breccias are often hindered or precluded by inaccessibility to the full stratigraphic section involved.

SEDIMENTARY ENVIRONMENTS

The question of why more economically significant metal concentrations have not been found in black shale or "red bed" environments within the United States has been raised by both industry and academic groups. A number of university and U.S. Geological Survey scientists have studied these carbonate and clastic environments, and a few industry research programs are oriented toward discovery of base metals in sedimentary environments. Add-on investigations to holes of opportunity represented by present and future drilling activities should be conducted to acquire samples and measurements from sedimentary basins. In addition, an examination of drilling sample repositories should be made to determine the availability of existing samples and measurements.

As one example, further investigation of sedimentary iron-manganese facies is required in the Animikie Basin of Minnesota. Studies of down-dip manganese distributions, iron-manganese ratios, and iron-manganese formations in the Animikie Basin in general, and in the Cuyuna Range specifically, are recommended. Such projects could possibly be considered as add-on investigations to holes proposed in the future concerning research drilling to study basement structures and deep continental basins. Precambrian sedimentary basins contain a large portion of the world's mineral resources; they are poorly studied in this country.

CHEMISTRY OF THE CRUST

Significant subsurface data relating to metallogenic provinces could be obtained from a series of deep drill holes in the southwestern United States porphyry copper province. Such holes would provide a cross-section of a significant crustal region that characterizes critical features of the copper belt. It is unlikely that the question of whether a metallogenic province represents an inheritance of metals from an anomalous crustal section would be answered in a few drill holes. However, the information produced would supplement existing downhole logs and core descriptions.

The geochemical setting of Mid-Continent basement magnetic and gravity anomalies is of considerable interest to investigators of the Mississippi Valley-type base-metal sources. These metallogenic considerations could also be addressed as add-on investigations to holes identified by scientists involved in research on basement structures and deep continental basins. Given the current level of petroleum exploration, it may also be possible to identify future oil company test sites for cooperative add-on geochemical experiments.

6. DRILLING, DIAGNOSTICS, AND DATA NEEDS

Scientific objectives for research investigations in drill holes will present unique requirements and constraints on drilling, logging, and downhole measurements. Although using current state-of-the-art equipment can provide much of the information needed, needs for accurate determination of physical and chemical parameters may require the development of special tools and sensors. Each research activity, whether an add-on investigation or a carefully planned drill hole dedicated to broad scientific objectives, will evolve specific requirements to attain its desired goal.

Table 1 summarizes the research objectives and proposed drill holes for research on mineral resources. Although the focus of this report is on the scientific aspects of mineral deposit systems, technology development in drilling and diagnostics will also affect other aspects of the mineral resource base of the nation. Any new technologies developed to explore deep, crystalline, and possibly hot formations could result in lower exploration costs. Knowledge generated on fluid pressures and formation permeability in deep holes will be critical for technological development in hydrofracturing and solution mining, both new methods that are developing for mineral extraction. Technological requirements for scientific studies of fossil mineralized systems at depth will be less demanding than requirements for studying hot, overpressurized or underpressurized, active hydrothermal-magma systems.

DRILLING

Continental scientific research drilling requirements include such factors as (1) recovering extensive core and fluid samples, (2) using completion techniques that allow in situ experiments, and (3) maintaining an open hole for a number of years for continuous monitoring and future scientific research. Current drilling techniques need refinement to improve sample recovery and downhole studies. Advanced technology is also needed for systems involving excessively hot, active hydrothermal formations.

Geothermal drilling has provided wells and completions at temperatures to 300°C, with limited capabilities to 400°C. Coring and sampling equipment is currently limited to environments below about 200°C.

Continuous coring, needed for most of the research holes, may include the use of specialized wireline deep-coring rigs that can bore holes up to 11 cm in diameter and cut cores up to 5.4 cm in diameter. Current wireline rigs have the capability to drill to depths of about 4.6 km; conventional rotary rigs would probably be required for deeper or significantly larger diameter drill holes.

DIAGNOSTICS

Scientific data from holes will be obtained from cores, fluid samples, and well logs and other downhole measurements. Parameters such as the following need to be collected:

1. Orientation, spacing, and apertures of fractures,
2. Fluid inclusions in vein fillings,
3. Structures and/or textures indicative of hydrothermal leaching and precipitation,
4. Vein and alteration mineral assemblage studies for estimates of chemical parameters,
5. Isotopic (stable--sulfur, oxygen, carbon, hydrogen--and radiogenic) studies of solid and fluid phases,
6. Brine zones and compositions,
7. Distribution of in situ temperature, pressure, and geophysical properties (magnetic, electrical, seismic, gravity, mechanical) with depth, and
8. Near-hole properties (determined by hole-to-hole and hole-to-surface measurements).

Samples of fluids from various depths, as localized and uncontaminated as possible, must be obtained to define the origins of potential fossil ore fluids or contributors to the ore fluid system. Equipment development will be needed for research by individual scientists as specific experiments are proposed. A limited but effective analytical capability at the drill site is required to provide real-time research input to the drilling and field logistics. Analyses needed (e.g., fluids and solids, petrographic, scanning electron microscopy with X-ray fluoresence) are currently available. Operational facilities will be defined when research requirements are specified.

Geophysical and geochemical, downhole, hole-to-hole, and hole-to-surface measurements are needed to extrapolate data from core and log analyses out into the surrounding rocks, to aid interpretation of surface geophysical exploration techniques, to identify major structural changes, and to study temporal chemical and physical changes. Specific downhole experiments include measurements of in situ stress, petrochemical analysis, application of seismic and electrical techniques for formation studies by frequency sweeps, effect of potential fields on chemical processes, identification of permeation routes via tracer studies, and isotopic or fluid chemistry changes with time.

Hole-to-hole seismic, electrical, and tracer studies will help determine structural and stratigraphic discontinuities and anomalies, identify permeable paths, evaluate the uniformity of a given volume with respect to the surface geophysical data, and confirm mineral deposit models. Hole-to-surface measurements are critical to separate the effects of near-surface geology in the interpretation of geophysical exploration data. Specific experiments would include hole-to-surface or surface-to-hole seismic studies to understand quantitatively the effect of weathering, faults, and fractured structures on refraction and reflection seismic data. Similar electrical resistivity data are needed to confirm theoretical analyses on the effect of layered conductors on geophysical data interpretations.

Long-term experiments are required to identify permeabilities and permeable paths by injection of tracers into a formation and monitoring appearance of the tracer in the drill hole. In situ teleseismic measurements would be used to distinguish deep crustal structure without the effects of signal loss by attenuation and dispersion caused by the fractured upper crust. In situ temperature measurements are needed to define undisturbed thermal gradients and fluid motion in the formation. Equilibrium thermal properties of the formation are required to validate models of the heat sources and transport. Electrical measurements, hole-to-hole or hole-to-surface, would be used to evaluate the effect of climatic cycles on the formation response to geophysical measurements.

Geophysical logs will be run in all boreholes, whether or not core is recovered. Such logs provide vital quantitative information on intervals where core recovery is incomplete due to fracturing or dissolution, identify specific regions for detailed coring or repeat logging analysis, and provide information on variations near the drill hole. Geophysical logs also provide essential ancillary information on continuity of rock properties that is difficult or impossible to obtain from core by laboratory measurement. Drill logs may indicate which core sections and which laboratory measurements should be analyzed in greater detail, and which may be omitted. Geophysical logs of a properly sited borehole may also be used to calibrate and thereby substantially improve the precision of interpretation of regional geophysical work. Analyses are expected to suggest new geophysical strategies to address scientific questions raised by the research drilling project.

Many of the experimental and developmental logging tools afforded by university, government, and industry laboratories have been designed specifically for small-diameter holes. For example, the U.S. Geological Survey (USGS) Branch of Petrophysics and Remote Sensing has developed a suite of experimental and developmental logging tools designed specifically for small-diameter holes (7 to 11 cm) in crystalline rock. However, new tools may need to be developed as scientists define the parameters that must be measured in each research drilling project.

Logging tools for hot, active hydrothermal systems are limited by insulation capabilities and cable degradation. New commercial tools with cable are useable to about 300°C. Special systems could be developed for high temperature use when specific scientific needs are identified. Diagnostics and technologies needed for logging in such hostile environments must also be identified as drilling projects evolve.

PRELIMINARY INFORMATION REQUIREMENTS

Drilling and diagnostic technology requirements will be modified to meet the scientific goals as specific sites are selected and as details of experiments are developed. Issues that need to be addressed include:

1. Development of models of the downhole environments by each group of scientists planning a dedicated drilling project,

2. Identification of specific geological data requirements, and

3. Definition of downhole experiment requirements, including in situ chemistry and property measurements, data and operational constraints, and hole-to-hole experiments.

Logistics and costs for research operations obviously will be determined by the specific sites and experiments. The following information should be acquired to support research planning:

1. Compilation of contract drilling, costs, and limitations,

2. Estimation of costs of staging, workover rigs, and other field-related operations,

3. Comparison of types, dimensions, and capabilities of slim hole logging tools, and

4. Investigation of required insurance for personnel and equipment involved in the research and provisions to keep selected holes open.

DATA MANAGEMENT

The management of mineral resource research drilling data, including proper collection, handling, analysis, and archiving, is vital to the success of the proposed program. These data will include not only solid and fluid samples and measurements from the drilling activity, but also surface geological, geochemical, geophysical, and hydrologic measurements, analyses, and compilations that are necessary for the comprehensive study of each selected research target. Additional data may become available from industry and government drilling and surface surveys that represent important background materials for siting of drill holes and filling in data gaps. Some of the factors that must be considered include development of policies for collection, evaluation, and indexing of samples and other data, location of and financial support for sample repositories, dissemination of data to interested scientists, and centralization of data banks for efficient access and processing.

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