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EXPLORATION STRATEGIES FOR REGIONAL ASSESSMENT OF HYDROTHERMAL RESOURCES

by

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ABSTRACT

This chapter briefly reviews the exploration strategies and techniques in general use for regional assessment of hydrothermal resources. The objective of regional assessment is to select from a large region those several areas that have highest potential for occurrence of a resource. Detailed exploration can then be carried on in these smaller areas. Most of the known hydrothermal resources and all those of high-temperature in the U. S. occur in the west including Hawaii and Alaska. There is diversity in the nature of and controls on hydrothermal resources that must be understood for the particular region under consideration before a specific assessment program, designed to optimize the ever-present trade-off between certainty of resource detection and cost, can be applied. Techniques from geology, geochemistry, geophysics and hydrology can then be applied in the most cost-effective combination during the assessment.

OBJECTIVE

It is our objective to describe exploration methodologies and their integration as applied to regional assessment of hydrothermal resources in the United States. Achieving this objective necessitates describing, briefly, our knowledge of regional geothermal resources in the U.S., outlining a basic exploration strategy suited to defining these resources in a regional context and, finally, discussing the geological, geochemical, and geophysical ingredients of the basic strategy. The basic strategy is expected to have variants suited to each region or even subsets of these regions. We must also clearly state that technology appropriate to the task of reliable regional assessment is in an early stage of development as evidenced by poor success ratios for new wildcat geothermal wells (Ehni, 1981). Development of better technology is needed but is probably not forthcoming from the private sector because of budget constraints brought about largely by the fact that geothermal development is only economic today at a few of the highest grade resources.

The exploration methodologies and philosophies which we outline in this paper have been formulated through our work with industry in The Department of Energy (DOE) Industry Coupled Program. In addition our work in exploration technique development has been supported under DOE's Exploration and Assessment Technology Program. This Federal support has greatly benefited geothermal exploration in recent years by placing exploration data in the public domain and by sponsoring research which is specifically directed toward improving the state-of-the-art of geothermal exploration.

BACKGROUND

Geothermal energy is derived from the heat of the earth.

> *"The Earth's interior is a gigantic but delicately balanced heat engine fueled by radioactivity, which has much to do with how the surface evolved. Were it running more slowly, geological activity would have proceeded at a slower pace.*
>
> *...if there had been more radioactive fuel and a faster running engine, volcanic gas and dust would have blotted out the Sun, the atmosphere would have been oppressively dense, and the surface would have been racked by daily earthquakes and volcanic explosions." (Press and Siever, 1974).*

The earth, fortunately, is a heat engine running at exactly the right speed for our survival. The average heat flowing out through the earth's surface is 0.08 watts per m^2. If we multiply this value by the total surface area of the earth (5.1×10^{14} m^2) we obtain the total heat flowing from the earth as 41,000,000 megawatts. Only a fraction of this energy can be extracted economically under current market conditions. However, the crust of the earth contains local hot spots from which extraction of energy, either for direct heat applications or for conversion to electricity, is economical at present. Geothermal hot spots are manifested as a continuum of seven accepted resource types: convective hydrothermal, geothermal gradient, deep sedimentary basin, geopressured, radiogenic, hot dry rock, and magma. We shall be concerned in this article only with the convective hydrothermal, geothermal gradient, and deep sedimentary basin types of resources; collectively they are usually referred to as *hydrothermal resources* and all involve movement of thermal water.

Hot-water-dominated convective hydrothermal systems are generally classified as high temperature (>150°C), intermediate temperature (90 to 150°C), and low temperature (<90°C) (White and Williams, 1975; Muffler, 1979). Although some of these systems may derive their heat from still molten or hot, crystallized plutonic masses (Smith and Shaw, 1975), others show no association with recent plutonic or volcanic activity but derive their heat from deep circulation along fault zones in areas of high thermal gradients. Any regional exploration program for hydrothermal resources should be based on the search for the components of hydrothermal systems, heat, water, and permeability, rather than the unlikely and obvious occurrence of these components together.

HYDROTHERMAL SYSTEMS IN THE U.S.

Introduction

The U.S. may be divided into two broad heat flow provinces which have much local and regional variation (Figure 1). The eastern U.S. is generally lower in heat flow with localized regions of higher heat flow occurring in areas of radiogenic plutons. The broader zones of higher heat flow in the West are due to higher thermal flux from the mantle (Simmons and Roy, 1969). This higher flux implies that the West, as a region, presents better opportunities to find hydrothermal systems. Indeed, the preponderance of known hydrothermal resources and all of the known high-temperature resources occur in the West, including Hawaii and Alaska. Young volcanic systems in the West form the thermal targets of potentially highest grade.

At the time of this writing, economically viable development of hydrothermal systems requires that adequate water be naturally present. This means a system must have both sufficient quantities of water available for recharge and adequate permeability, most commonly through fractures. Regional identification of fracture systems can help guide the explorationist to favorable terrains of fracture permeability.

The U.S. may be divided into hydrothermal provinces (Figure 2) based on regional heat-flow patterns, similarity of geologic environments and similarity of resource target models. The discussion below is based on these provinces, the margins of which, particularly west of the Great Plains, form attractive regional exploration targets in many places.

Alaska and Hawaii

Areas of young volcanic activity form the prime thermal targets in Alaska and Hawaii. In Alaska, most of the volcanos are found along the Alaska Peninsula and in the Aleutian Island Chain. Secondary Alaskan targets for hydrothermal resources are zones of high heat flow along regional strike-slip faults, areas of deep circulation, and deep sedimentary basins (Turner et al., 1980; Motyka et al., 1980; Motyka and Moorman, 1981). In Hawaii, volcanic rift zones around the margins of active volcanos form the best targets found to date (Thomas et al., 1980; Furumoto, 1978). Electric power development from the Puna rift resource is continuing and shows substantial promise (Chen et al., 1980).

Cascade Mountains

The young volcanos of the Cascade range of Washington, Oregon, and California have long been an attractive, but enigmatic, hydrothermal terrain. Although the resource potential is high (Brook et al., 1979; Youngquist, 1981), institutional barriers have slowed development (Bloomquist, 1981). Extensive resource investigations at Mt. Hood have failed to demonstrate an electric quality resource, although direct heat applications are planned (Riccio, 1979; Bowen, 1981). Recent U.S. Geological Survey drilling at Newberry caldera in central Oregon has demonstrated, however, that 265°C resources may be hidden beneath cold near-surface groundwater regimes (Sammel, 1981).

The recent eruption of Mt. St. Helens, the high-temperature fumeroles on Mt. Baker and Mt. Hood, the vapor-dominated hydrothermal system at Mt. Lassen, and the ongoing geothermal development at Meager Creek in British Columbia (Fairbanks et al., 1981) all suggest that there are extensive resources yet to be discovered and developed in the Cascades.

Plateaus

Isolated resources suitable for direct heat applications exist in the Plateaus terrain of Oregon and Washington. Unlike the large, young volcanos that serve as resource targets in Alaska, Hawaii, and the Cascades, most of the hydrothermal systems of the Plateaus will probably be discovered using target models that call for either deep circulation of water along faults or deep circulation along volcanic and interbedded sedimentary horizons. Electric-grade resources have not been documented from this terrain.

Snake River Plain

Zones of higher heat flow along the margins of the Snake River plain, and broader areas of resources in the western plain, form the most attractive resource targets (Mitchell et al., 1980). Electric development of a 150°C resource is proceeding at the Raft River, Idaho site and similar temperatures, without sufficient production, have been encountered in drill holes in both the eastern (Prestwich and Mink, 1979) and western (Austin, 1981) plain. The Yellowstone caldera, at the eastern end of the Snake River Plain, is the single largest concentration of geothermal energy in the U.S.; development in Yellowstone is prohibited, however, by its status as a National Park.

Rocky Mountains

Water heated in fault or fracture systems and flowing to the surface near drainage bottoms forms most of the known hydrothermal systems in the Rocky Mountains. Big Creek Hot Springs in Idaho and Paradise Hot Springs in Colorado are the only springs identified by Brook et al. (1979) as having potential reservoir temperatures above 150°C in this region. Systems such as Glenwood Springs in Colorado, however, have large flows and are very attractive targets for direct applications (Barrett and Pearl, 1978). Some systems, such as Thermopolis, Wyoming, apparently have water that circulates to depth in stratigraphic horizons and rises to the surface along the limbs of anticlines (Heasler, 1981). Exploration programs in the Rocky Mountains should be targeted to identify favorable deep circulation paths for water because local heat sources, such as very young volcanos, are rare.

Great Plains

Hydrothermal resources in the Great Plains are dominated by the Madison Group of Paleozoic carbonate rocks. These rocks are found predominantly in Montana, Wyoming, and the Dakotas. Temperatures are suitable for direct applications. In North Dakota, much of the water is of poor quality (Harris et al., 1980). In Nebraska, waters are found in the Cretaceous Dakota Formation which, although cooler than the deep waters in the Madison (Gosnold and Eversoll, 1981), typically have much better water quality.

Regional exploration in the Great Plains is based on a deep sedimentary basin model, where exploration is concerned with identification of appropriate stratigraphic horizons at suitable depths for the thermal gradient to provide sufficient temperatures. Areas of anomalously high heat flow within these basins can produce water several tens of degrees hotter than water elsewhere at the same depth.

Ouachita Belt

Hydrothermal resources in central Texas are principally found in Cretaceous sandstone and limestone aquifers along the buried Ouachita fold belt (Woodruff and McBride, 1979). Water heated in the thermal gradient of the earth circulates either downward from the west or upward from the deeper parts of the gulf basin to the east. Downward-circulating waters are typically fresh while upward-circulating waters are more saline. Woodruff and

McBride (1979) have identified a broad region favorable for geothermal resources. Exploration within this region is directed toward identifying suitable stratigraphic horizons at sufficient depth.

Rio Grande Rift

Non-volcanic related-hydrothermal systems in the Rio Grande rift are apparently the result of upward flow of waters from deep rift basins at groundwater constrictions (Harder et al., 1980; Morgan et al., 1981). These geothermal resources have potential for direct applications but one related to volcanic rocks is being explored for generation of electricity in the Valles Caldera in northern New Mexico (Dondanville, 1978). Also, a deep system suitable for electric generation may exist in the vicinity of Soccorro, New Mexico (Chapin et al., 1978).

Exploration for resources suitable for direct heat application should focus on identification of groundwater flow patterns in basins, particularly in areas where constrictions may cause water to flow to the surface, while exploration for resources suited to electric power generation should focus on local regions of young volcanic activity.

Colorado Plateau

Isolated, generally cool, and low-flow rate hydrothermal systems exist in the Colorado Plateau. Regional low heat flow (Figure 1) suggests that high-temperature hydrothermal systems are not likely to exist in this area.

Basin and Range

Young volcanic areas along the northern, eastern, and western margins of the Basin and Range Province, and the Butte Mountain heat flow high in northern Nevada (Figure 1) are the most favorable sites for the discovery of electric-quality hydrothermal systems in this region. Many hydrothermal systems exist along range-bounding faults throughout this area. Garside and Schilling (1979) list 298 thermal areas in Nevada alone; many more exist in California, Oregon, Utah, and Arizona. Although some of these are very hot, such as at Beowawe, electric-quality resources have not yet been demonstrated outside the area of high heat flow (Figure 1).

Smith and Shaw (1975) suggest that plutonic equivalents of rhyolites less than one m.y. old provide the heat for most electric-grade resources in the eastern Basin and Range. Unfortunately, the existence of such hot intrusions has yet to be established. Further, young rhyolites are not always associated with the higher-temperature resources already identified in the central and western Basin and Range of Nevada.. These observations lead us and other workers to conclude that the key ingredient of many Basin and Range hydrothermal systems is deep circulation (greater than 3 km) along major structures in a region of high heat flow where the crust is thin (less than 25 km). Siliceous melts may or may not be present at depth in proximity to these resources.

The Roosevelt Hot Springs system in Utah has produced small quantities of electricity and further development is planned. This system is discussed in more detail in sections below. High-temperature resources at Beowawe, Steamboat Springs, and Dixie Valley in Nevada and the Alvad desert of Oregon, are other hydrothermal systems that may be suitable for electric power generation.

Most of the resources in the Basin and Range are fault controlled; identification of zones of hydrothermal flow along faults thus becomes a prime task of the regional explorationist (Ward et al., 1981).

The Geysers

The Geysers area, California, is the premier hydrothermal production area in the world. Electric power generation began in 1960; nearly 1000 megawatts are now on line. The geology of this region has been summarized in McLaughlin and Donnelly-Nolan (1981). The Geysers is a vapor-dominated system (see discussion in following sections), with production of steam from fractured metamorphic rocks.

Vapor-dominated hydrothermal systems are rare, but they form the most attractive exploration targets, since production and fluid-handling characteristics are relatively simple. Larderello, Italy, is a vapor-dominated system that has been producing electricity since 1904.

The Geysers lies on the margin of the (primarily) Pleistocene Clear Lake volcanic field (Donnelly-Nolan et al., 1981). The heat source for The Geysers system is thought to be partially molten rock related to the young volcanic activity (Iyer and others, 1981). Geophysical studies reported in McLaughlin and Donnelly-Nolan (1981) support this conclusion. Present exploration in The Geysers area is emphasizing both the expansion of development of the steam field and regional identification of surrounding hot water systems.

Imperial Valley

Electricity is being produced from hydrothermal brines in the Imperial Valley and much additional development is planned. High-temperature resources have been identified in the Salton Sea, Westmoreland, Brawley, Heber, and East Mesa KGRAs; intensive industry effort suggests that other resources are likely to be discovered. At Cerro Prieto, just across the Mexican Border, electric power has been generated from a similar geologic environment since 1973.

Brook and others (1979) estimate that slightly less than 500 quads (10^{15} BTUs) may exist in the Salton Trough area. Numerous low- and moderate-temperature wells have also been drilled (Higgins and Martin, 1980). These resources are found in fractured stratigraphic horizons (Elders, 1979). The heat in these systems is apparently derived from local volcanic activity and high heat flow derived from a shallow mantle. Regional exploration in the Imperial Valley is based on identification of geophysical anomalies and extension of known systems.

Eastern United States

Several geological environments have been identified in the East in which geothermal resources may occur. Perhaps the best known to date is on the Atlantic coastal plain, portions of which are underlain by granitic intrusions in which the decay of naturally occurring radionuclides generates heat. Sediments of the plain that typically have low thermal conductivity blanket these intrusions, thereby causing thermal anomalies (Virginia Polytechnical Institute and State University, 1980; Costain et al., 1980). To date only one deep well has been drilled (at Chrisfield, MD) to prove the existence of such thermal anomalies and to determine the producibility of associated aquifers (Svetlichny and Lambiase, 1979). It is expected that water temperatures up to 100°C might be available at depths of perhaps 1500 m over fairly large areas defined by Costain and his co-workers.

Throughout the east there is some potential for occurrence of low-temperature thermal waters in basins and in permeable aquifers such as the basal sandstones. The potential for temperatures above 100°C seems to be quite limited, based on our present understanding of regional heat flow and sediment thermal conductivities.

EXPLORATION STRATEGY FOR REGIONAL RESOURCE ASSESSMENT

By now most major companies involved in geothermal exploration in the United States have addressed regional exploration in the high heat flow regions and in the most easily explored and highly favorable areas delineated in Figures 1 and 2. The USGS has conducted intensive intra- and extra-mural programs aimed at both geothermal resource assessment and the development of exploration technology. A great deal of geological, geochemical, geophysical and hydrological information of both a general nature and a specific geothermal nature has been published over the years. State agencies from at least 25 states, operating with federal (DOE) and state funds, have conducted resource inventories and have produced maps to aid the U.S. Geological Survey in geothermal resource assessment. DOE has funded much needed development of geothermal technology; especially pertinent to this discussion is the technology of geothermal exploration and geothermal reservoir engineering. The net result of all of this effort is that much resource data and data of a more general nature but pertinent to geothermal assessment have been placed in the public domain.

We visualize that the first major effort in regional hydrothermal resource assessment should be an integration of all available data, which we refer to as the "available data base", of box 1, Figure 3. Once these data have been integrated, critical items of missing information should be identified, and the data base should be supplemented and extended as required by acquisition of a first round of supplemental data as illustrated by boxes 2 through 5 of Figure 3. Data integration (box 6) is then performed to define the more promising prospect areas within the region. Thereafter a second round of supplemental data can meaningfully be collected (boxes 7 through 10) to evaluate each project area and to provide information to be used in selection of high priority hydrothermal targets. A final data integration (box 11) follows.

Data acquisition depicted in boxes 2 through 5 and 7 through 10 should allow considerable latitude in order to facilitate exploration of the variety of hydrothermal systems described earlier. Actual techniques shown in these boxes are in the nature of a shopping list, and the applicability of each technique or of others not indicated in Figure 3 must be assessed on a specific basis by experienced exploration personnel.

Data integration and interpretation depicted in boxes 1, 6, and 11 are based on a conceptual geological model of the resource type(s) known or expected to occur in the exploration area. These models are progressively refined with acquisition and incorporation of more data. Eventually firm conceptual models of each resource type within each region should be developed (box 12) and a prioritized inventory of all prospects based on these models should be prepared. Detailed exploration and assessment techniques can then be applied to these prospects to select suitable drill test sites or to make a decision to reject the prospect.

GEOLOGICAL TECHNIQUES

Introduction

Geological techniques for regional assessment of geothermal potential are used in conjunction with geochemical and geophysical techniques to narrow the search to a prospect area of less than 100 km^2 in size. Existing data are important, particularly geologic maps, but there will usually be a requirement for field checks and fill-in work. It is important at this stage to evaluate the tectonic and intrusive history of an area, understand the deposits and alteration produced by hydrothermal systems, and understand the effects of the regional hydrologic environment.

Tectonics

High-quality geothermal systems are located in areas of active tectonism as demonstrated earlier in this paper. This includes both faulting and young extrusive activity, although young intrusive activity may not be required for the occurrence of high-temperature systems. Faulting is necessary to maintain open fractures which are required to convey meteoric fluids to depth and return them to the surface. Permeable zones along these faults are the targets for much of the geothermal exploration that occurs today. Experience has shown that fault zones are not always permeable zones of upwelling hot fluids. Indeed, many faults exhibit lateral and vertical variability from permeable to impermeable. And, within the permeable parts, zones of cold water recharge and of thermal upwelling may be closely associated. These are problems which must be resolved using thermal and hydrological techniques.

Theories of the relationships between magmatic/volcanic areas and geothermal systems have been developed by Smith and Shaw (1975). Basically they have proposed that rhyolitic systems younger than 1 million years have the potential of providing the heat for high-temperature hydrothermal systems. Thus, the presence of these young rocks serves as a regional exploration tool.

The Roosevelt Hot Springs thermal area in Utah is a fault and fracture controlled hydrothermal system associated with young volcanism (Nielson et al., 1978). The geologic map (Fig. 4) shows the relationships which would be important to observe during regional geologic reconnaissance. In Figure 4, the geothermal system is defined by the production wells and dry holes. The Opal Mound fault has served as a fluid pathway as demonstrated by the siliceous sinter deposited along it. Although the Negro Mag fault does not have such an extensive development of siliceous sinter, production wells 54-3 and 14-2 and high heat flow values indicate that it is presently a zone of thermal fluid discharge. The Quaternary rhyolites exposed to the east and southeast of the field range in age from 800,000 to 500,000 years (Lipman et al., 1978). These rocks probably represent extrusive equivalents of an inferred granitic pluton which is sub-solidus and the heat source for the geothermal system.

Stratigraphy

Portions of stratigraphic sequences serve as geothermal reservoirs, as impermeable caps which confine the thermal system, and as cold water aquifers which may serve to mask the geothermal target. The controlling influences of the stratigraphy should be evaluated in the initial stages of an exploration program.

Large, stratigraphically controlled geothermal reservoirs are located in sedimentary basins in areas of normal and elevated heat flow. These resources are generally considered to be in the low- to intermediate-temperature range with the Paris Basin in France and the Pannonian Basin in Hungary being important examples which have been studied intensively. Ottlik et al. (1981) have studied the aquifer rocks of the Pannonian Basin and have found the aquifers to be in both carbonate and clastic rocks. The permeability in the carbonates is largely secondary with tectonic fracturing producing the permeability of some competent units while a solution porosity was developed in other units during a period of subaerial weathering.

In high-temperature environments, permeability is often considered to be principally fracture controlled with fractures at times localized within particular stratigraphic horizons. However, it is evident that the flow of geothermal fluids through stratigraphic units may increase permeability through the solution of mineral and/or glass phases. This is likely to happen where fluids are hot. On the other hand, precipitation of mineral phases and decrease in permeability will occur in areas of rapid temperature decrease.

Surface Deposits of Liquid- and Vapor-Dominated Systems

The surface deposits of both liquid- and vapor-dominated geothermal systems can include hot springs, sinters, and fumeroles. Although hot spring deposits are generally composed of calcium carbonate (travertine) or silica, manganese and iron deposits may also occur.

Hot spring waters that deposit siliceous sinters nearly always have been found to contain SiO_2 concentrations of at least 240 ppm. These concentrations of silica require subsurface temperatures of at least 180°C. Because of the high solubility of amporphous silica, these fluids then must cool to about 70°C to precipitate amorphous silica. These initial amorphous precipitates are very susceptible to weathering and their preservation is dependent on protection by subsequent deposits. Once the siliceous sinters have been deposited and protected, however, they undergo polymorphic transformations to more stable species. This transformation process generally follows the sequence:

opal → christobalite → chalcedony

The sequence is well documented at Roosevelt Hot Springs, Utah, and Steamboat Springs, Nevada, and may eventually be quantified in order to allow determination of the minimum age of hot spring deposits.

Travertine deposits are characteristic of many low- to intermediate-temperature geothermal systems. Although less conspicuous than siliceous sinters, travertine deposits also occur in high-temperature thermal fields. In these systems travertine deposits are most commonly found on the margins of the field or associated with secondary reservoirs.

Acid Alteration

The surface expressions of vapor-dominated reservoirs characteristically include chloride-poor acid sulfate springs with low discharges accompanied by sodium bicarbonate/sulfate springs, fumeroles, mudpots and acid-altered ground (White et al., 1971). These features are formed by steam and other volatile gases such as hydrogen sulfide, ammonia, and carbon dioxide which discharge at the surface or condense in meteoric water. Non-volatile components such as chloride remain in the underlying boiling brine and are not enriched in the surface discharges. Chloride-rich springs typical of hot-water systems are therefore conspicuously absent over the vapor-dominated portions of the reservoir but may occur on its margins in surrounding areas of lower elevation if the reservoir is relatively shallow.

Acid sulphate springs are typically a surficial feature produced by the oxidation of hydrogen sulfide to sulfuric acid. Altered ground surrounding the acid springs and fumeroles provide striking examples of reactivity of the waters. The altered areas are typically bleached and converted to a siliceous residue containing native sulfur, cinnabar, yellow sulfate minerals, and clay minerals including kaolinite and alunite. Similar acid alteration can also be formed at depth where steam heating of groundwaters occurs. At Matsukawa, Japan, alunite, quartz and pyrite appear to have formed from 250° to 280°C fluids with a pH near 3 (Sumi, 1969). Thus, mineral assemblages in acid-altered rocks may occur at both high and low temperatures.

Regional Hydrologic Considerations

Regional hydrologic data are viewed as being important from several standpoints. First, a sufficient amount of available water is necessary to ensure the life of a geothermal reservoir. Second, regional water quality data have been shown to be useful in pinpointing buried hydrothermal systems, and third, near-surface cold aquifers are able to distort or mask altogether the thermal signatures of underlying hydrothermal systems.

The quantity of water necessary to guarantee the recharge of the system is not generally regarded as a principal exploration factor but can be a supporting factor when combined with the probable presence of heat and fractures. In addition, it is often difficult to evaluate the recharge portion of the system until extensive exploration work has been completed, and often this remains a mystery even in fully developed fields.

Even in systems which crop out at the surface to form hot springs, it is thought that a large percentage of the thermal waters are lost to the near-surface hydrologic environment. For many buried systems, all the discharged water is thought to be lost to near-surface groundwater systems. Data from Roosevelt Hot Springs, Utah (Figure 5) have demonstrated that the system can be identified by using regional water quality data published by the USGS. Certain components such as boron, chlorine, and total dissolved solids define the discharge zones of the systems. Thus the analysis of available water quality data is a powerful and inexpensive geothermal exploration tool.

In addition to aiding in the exploration effort as described in the paragraph above, regional hydrologic systems often tend to distort or obscure entirely the discharge zones of active hydrothermal systems. Studies at Cerro Prieto, Mexico have shown that the flow of groundwater from the northeast has distorted the thermal plume rising from the system. Cold water overflow reaches an extreme condition in the Cascades Province of the U.S. where it is able to mask completely the near-surface thermal manifestations of buried systems (Sammel, 1981).

GEOCHEMICAL TECHNIQUES

Introduction

Geochemical investigations frequently play an important role in the regional evaluation of geothermal resources by providing information on sites of upwelling, the temperature and quality of the resource, and the type of resource present. This information can be obtained from careful evaluation of the chemical compositions of fluids discharged from springs and fumeroles, and from the mineral and trace element distributions in the altered rocks found at the surface and in the thermal gradient and deeper test wells. Geochemical data can also prove useful in that hydrothermal alteration effects may substantially affect the geophysical response of the rocks at depth, and the interpretation as a result.

Fluid Chemistry

Fluids discharged at the surface may differ chemically from the deeper reservoir fluids as a result of changes accompanying mixing, dilution, boiling, or conductive cooling. In addition, the chemistry of the fluid may be further modified as constituents partially or completely reequilibrate with the reservoir rocks during ascent of the fluids to the surface. The actual paths taken by the fluids may be complex and the fluid chemistry may be modified by more than one process. Despite this complexity, careful evaluation of fluid chemistry frequently provides diagnostic information about the subsurface characteristics of the geothermal system. As mentioned previously, geochemical and basic hydrologic data from springs and wells are an important source of information which can be used at an early stage in the exploration program to predict the kind of fluid that will be produced. Chemical analyses of many of the hot spring systems in the U.S. are tabulated in the literature and elsewhere (for example, U.S.G.S. computer file GEOTHERM; Teshin et al., 1979) and can be supplemented at relatively low cost during reconnaissance investigations.

The geothermal fluids of explored high-temperature liquid-dominated systems are sodium chloride brines which vary greatly in composition from field to field. These solutions may be as dilute as potable water or as concentrated as the 25 weight percent solutions characterizing some of the systems in the Imperial Valley. Systems with such extreme salinities are, however, rare. Most systems currently under evaluation in the Basin and Range Province contain less than 10,000 ppm total dissolved solids.

Bicarbonate-rich waters are commonly found in low-temperature geothermal systems and in secondary reservoirs in the shallow portions and margins of high-temperature fields. The origin of bicarbonate-rich fluids found in the secondary reservoirs of high-temperature systems was discussed by Mahon et al. (1980), who concluded that the fluids form by gas and steam heating of meteoric water. The final composition of the fluids is determined by the composition and volume of the gases and ground-water and the extent of water-rock interactions.

Subsurface Temperature -- Geothermometers

An understanding of the temperatures at depth in the geothermal reservoir rocks is crucial to the development and exploitation of the resource. Temperatures can be determined directly through downhole measurements or estimated indirectly from chemical and stable isotopic (O, H, S, C) analyses of the water, steam, gas and reservoir rocks themselves. Direct and indirect methods provide, however, different information about the reservoir.

The application of indirect methods plays a critical role in regional geothermal exploration. Indirect methods based on the chemistry of the thermal fluids can provide information on deep thermal regimes that are otherwise are inaccessible to shallow and even moderate-depth thermal gradient holes. Thus, indirect methods can be used to prioritize drilling targets and, when compared with thermal measurements made in shallow gradient wells, can be used to establish depth requirements for the deeper drilling program.

The quantitative geothermometer techniques currently available require chemical or isotopic analyses of thermal waters, steam and gas from wells and springs. These techniques can be categorized as follows: major element geothermometers, mixing geothermometers, and isotope geothermometers. The underlying premise for all three categories is that temperature-dependent reactions between either the reservoir rock and fluid or evolving gases and the fluid attain equilibrium. Furthermore, it is assumed that no reequilibration occurs after the fluid leaves the reservoir (see Fournier et al., 1974; Truesdell, 1976; Fournier, 1977; Ellis, 1979 for further details).

Several major element geothermometers have been proposed and have proven to be extremely valuable in accurately estimating subsurface temperatures. An extensive review of the use of these geothermometers was recently published by Fournier (1981).

Qualitative fluid geothermometers are used extensively during preliminary chemical surveys to locate zones of upwelling and determine the distribution of thermal waters and directions of groundwater flow. Fluid constituents that have proven to be particularly useful during these surveys include the soluble elements chlorine, boron, arsenic, cesium and bromine. Ellis and Mahon (1964, 1967) showed that the solubilities of these elements are controlled mainly by diffusion and extraction processes, and that once liberated they do not form stable secondary minerals. Changes in the concentrations of these elements as the fluids migrate from depth occur mainly from dilution or boiling. The use of atomic ratios (i.e., chloride/boron) can eliminate these effects. Other fluid constituents that are frequently used as qualitative geothermometers include lithum, trace metals (antimony, zinc, copper, uranium mercury), ammonia, hydrogen sulfide, and the ratios chloride/fluoride, chloride/sulfate, sodium/calcium, sodium/magnesium and chloride/(bicarbonate+carbonate). In general, the concentrations and ratios increase with increasing temperature, reflecting changes in constituent concentrations as a result of contamination with cold surface water, interaction between the fluids and rock at depth, and steam heating of waters (Mahon, 1970).

A map of the distribution of boron and chloride in waters in the region that includes Roosevelt Hot Springs is presented in Figure 5. It illustrates the use of one of these qualitative geothermometers. The data were compiled from published analyses of well and spring waters. The distribution suggests that the Roosevelt Hot Springs area is indeed a major center of upwelling thermal fluids and that exploration activities should be directed there. Changes in the concentration of boron and chloride occur as the thermal fluids are diluted with local groundwaters. Movement of the fluids appears to be first westward and then northward. A second source of thermal fluids is located at Thermo Hot Springs in the southwestern portion of the map and is marked by boron concentrations greater than 0.5 ppm.

The ratios of gases discharged from fumeroles have also been used as qualitative geothermometers. Mahon (1970) showed that fumeroles with the lowest ratios of carbon dioxide/hydrogen sulfide, carbon dioxide/ammonia and carbon dioxide/hydrogen were the most directly connected to the deep aquifers. The concentrations of these constituents are controlled by steam-rock reactions which can rapidly deplete the hydrogen sulfide, ammonia and hydrogen in the steam. The longer the steam path to the surface, the greater these depletions are likely to be.

Trace Element Analysis

Trace element analyses of hot spring deposits and altered rocks can supplement other data and help prioritize target areas. For example, mercury and sulphur are frequently enriched in rocks and altered ground over high-temperature thermal systems, (Matlick and Buseck, 1976; Capuano and Bamford, 1978).

GEOPHYSICAL TECHNIQUES

Introduction

Geophysics typically, and appropriately, plays a major role in the exploration for and delineation of geothermal systems by: 1) the identification of thermal provinces, and 2) geologic characterization on a regional or crustal scale. Several techniques have been applied in the geologic study and problem solving phases of detailed site-specific exploration (for example, Ward et al., 1981).

Thermal Methods

Regional heat flow characteristics on a province scale have been described in an earlier section. A prudent exploration program or regional assessment utilizes the existing heat flow or thermal gradient data base compiled by government agencies and academic workers over the years. It is often cost-effective to supplement this compilation with a regional-scale thermal gradient program which includes temperature measurement on all existing wells for which access can be gained. Several papers and texts describe details and refinements of the method and the results of regional or detailed heat flow studies (Lachenbruch, 1978; Sass et al., 1971; Chapman and Pollack, 1977; Sass et al., 1980; Ryback and Muffler, 1981).

The limitations on the use of the thermal methods are generally imposed by the drilling program. The main factor is drilling cost, but environmental restrictions, land control, permitting, and time involved are other considerations. One reconnaissance method to determine near-surface temperatures is a shallow temperature survey. With a hand-held or truck-mounted power auger a large number of holes are bored to depths of 1 to 2 meters (LeShack, 1977; Olmsted, 1977). Plastic (PVC) pipe with a sealed bottom is inserted, the hole is back filled, and temperature measurements are made after the hole temperature has stabilized. The advantage of the method is that a large number of holes can be drilled to cover a fairly large area at low or moderate cost.

The use of shallow temperature surveys has been limited because of the uncertainty that these temperatures are related to the temperature distribution at depth. The principal unknowns and disturbing factors are near-surface hydrology, soil thermal properties, topographic and slope corrections, and short-term variations. At Long Valley and Coso Hot Springs areas in California, and Soda Lakes in Nevada, however, shallow temperature measurements (Olmstead, 1977; LeShack, 1977) seem to delineate the area of anomalous heat flow in a low-cost manner. In the absence of substantial surface thermal manifestations and without obvious near-surface cold-water flow, a shallow temperature survey could be the best basis on which to plan a shallow (30-200 m) thermal gradient program. There does seem to be a limited acceptance by industry of this technique (Ward et al., 1981).

Aeromagnetic Methods

Aeromagnetic data can play a major role in the regional assessment of geothermal resources. Two major areas in which the magnetic data contribute are Curie point isotherm determinations and interpretation for subsurface geologic information.

Curie point isotherm interpretations have been reported in the literature by Bhattacharyya and Leu (1975), Shuey et al. (1977), Aiken et al. (1981) and many others. These interpretations are dependent on many assumptions and limitations. It is assumed that long wavelength negative anomalies due to lithologic changes, e.g., alluvial basins in the Basin and Range, do not significantly perturb the interpretation, and that the bottom determination of a magnetized crustal block is due to temperatures above Curie point rather than to deep-seated lithologic changes. Numerous other limitations apply to the interpretational algorithms and the data themselves. Our present judgment is that a) Curie point depth anomalies have been determined with unknown accuracy in some cases, b) Curie point studies can be a regional exploration guide especially in active volcanic provinces, c) many interpreted Curie point highs may, in fact, be due to lithologic changes at depth or lateral geologic changes, and d) because the bottom of a magnetized prism is not accurately determined from magnetic data, accuracy of Curie point depth as determined by these techniques can be poor.

Aeromagnetic surveys are widely used by industry in petroleum and mineral exploration in attempting to map subsurface structure and lithologic changes. The use in geothermal exploration should closely follow that of mineral exploration, for most geothermal resources are located in active tectonic environments characterized by a broad range of volcanic and intrusive rocks and often by active structural movement. Magnetic susceptibility often varies substantially in these rock types and provides major magnetization changes which delineate geologic units. The scale of many geothermal systems is also similar to porphyry-type mineral occurrences.

Regional aeromagnetic data are often available as part of State, (Cook et al., 1975) USGS, (Zietz et al., 1976) or NURE (Tinnel and Hinze, 1981) magnetic survey programs. These data, as at the Baltazor and Carson Sink areas in Nevada, often show major structural features and aid in forming a generalized geologic model for areas otherwise covered. These regional data are generally too widely spaced and/or too high to warrant detailed quantitative model interpretation.

The locations of faults, fracture zones, intrusives, silicic domes and possibly major alteration areas (speculative) are apparent on data we have examined from the Coso Hot Springs KGRA in California, from Baltazor, Tuscarora, McCoy, and Beowawe in Nevada, from Cove Fort-Sulphurdale and Roosevelt Hot Springs, in Utah, and from a moderate-temperature prospect near Alamosa, Colorado along the northern extension of the Rio Grande Rift. Figure 6 shows a portion of the Aeromagnetic Map of Utah (Zietz et al., 1976). The Monroe Hot Springs, Chief Joseph, Cove Fort-Sulphurdale, and Roosevelt Hot Springs KGRAs are all located in close proximity to a major magnetic discontinuity which trends east-west for a distance exceeding 150 km. This trend reflects the northern margin of the Pioche-Beaver-Tushar mineral trend with many intrusive and volcanic rocks to the south, and thin volcanics overlying thick Paleozoic through Tertiary sediments and few intrusions to the north. The magnetic trend clearly indicates a major tectonic-geologic feature important to geothermal resource localization.

Mabey (1980) has reported on the use of aeromagnetic data for the Raft River area of the Snake River Plain. Bacon (1981) interprets major structural trends and fault zones from aeromagnetic data in the Cascades. Couch et al. (1981) report Curie point isotherm minima of 5 to 9 km for several areas within the Cascade Mountains area. Costain et al. (1977;1980) have used aeromagnetic data to search for radiogenic granitic rocks beneath the insulating sediments of the Atlantic coastal plain.

The general utility of the method, the applicability to numerical modeling, the low unit costs, all argue strongly for inclusion of aeromagnetic studies in the regional assessment of geothermal resources.

Gravity Methods

Regional gravity data, with station densities of 1 station per sq km to 1 station per 25 sq km, may be available as the result of USGS studies, the Department of Defense (DOD) regional data compilation, or of university or state geophysical studies. These data are often suitable for regional-scale interpretations and are often the starting point for detailed survey design rather than the basis for detailed interpretation.

The contribution from gravity data is much the same as from aeromagnetics, that is, structural and lithologic information. The location of Basin and Range faults, thickness of alluvial fill and thickness of volcanic cover are problems addressed by gravity surveys for both the mining and geothermal industry. The delineation of low-density silicic intrusives, magma chambers in the Cascades, or major structural zones of crustal significance are other applications of the method. Gravity data may also contribute to the definition of deep sedimentary basins which are a different geothermal resource type. Costain et al. (1977;1980) have made extensive use of regional gravity data in defining radioactive granitic rocks, generally expressed as negative Bouguer anomalies, beneath the Atlantic Coastal Plain.

Regional gravity data (Cook et al., 1975) provide evidence for some of the major tectonic elements present in the main geothermal province of southwestern Utah (Fig. 7). A prominent north-trending 35-50 milligal gradient links these areas, bending eastward at Cove Fort, then trending northeast along the margin of the Colorado Plateau. Using detailed gravity data, Cook et al. (1980) mapped the many faults which define the Beaver-Cove Fort graben and add substantially to the geologic model for the Cove Fort area. In a similar manner the gravity data have delineated major faults that probably control the geothermal fluid flow at Alamosa, Colorado (Mackelprang, in prep.) and at Baltazor Hot Springs in Nevada (Edquist, 1981).

Regional gravity studies and their interpretation play a major role in understanding the tectonic framework of geothermal systems in the Cascade Range. Bacon (1981) reports a contiguous zone of gravity lows west of the High Cascades in central Oregon and notes that these define major structural trends and delineate fault zones which may localize the movement of geothermal fluids. The zone of gravity lows coincides with (1) an abrupt east-to-west decrease in heat flow from High Cascades values of 100 to 40 mW/m^2, and (2) a substantial east-to-west increase in depth to the lower crustal conductor defined by magnetotelluric soundings. Couch et al. (1981) report similar interpretations. Williams and Finn (1981) have described complexities in reduction of gravity data especially important to the Cascade Province. They report that the large silicic volcanos, calderas exceeding 10 km diameter, produce gravity lows when proper densities of 2.15 to 2.35 g/cm^3 are used for the Bouguer reduction. All other volcanos produce gravity highs as a result of higher-density subvolcanic intrusive complexes.

It would appear that gravity data contribute to a regional exploration program in most geothermal environments.

Passive Seismic Methods

Passive seismic data, which can contribute to a regional geothermal assessment, include long-term historical records of major earthquake activity and microearthquake surveys. On a regional scale, areas of high seismicity, as indicated by earthquake recording networks, define active tectonic provinces which include most areas of geothermal potential in the western

United States. Unfortunately many seismic zones have little geothermal potential.

Microearthquake surveys have been completed in several geothermal areas including Coso Hot Springs and The Geysers, California; Tuscarora and McCoy, Nevada; Roosevelt Hot Springs and Cove Fort-Sulphurdale, Utah and Raft River, Idaho. Some general observations may apply to the seismic behavior of these systems. Earthquake activity is generally episodic rather than continuous. Earthquake swarms, sometimes including tens to hundreds of events over a few days, may be typical. Earthquake magnitudes are small, generally $-0.5 < M < 2.0$, with shallow focal depths generally less than 5 km. The data are interpreted in terms of P-wave delay, S-wave attenuation, and position and alignment of epicenters.

Microearthquake surveys may play a more important role in exploration for deeper, blind geothermal systems where cold water overflow masks near-surface thermal and electrical characteristics, such as the Snake River Plain and the Cascade Province.

Seismic Refraction

Seismic refraction profiles have been recorded at The Geysers, Yellowstone National Park, Roosevelt Hot Springs, and other geothermal areas. These studies may be appropriate for regional-scale structural or crustal studies (attenuation by magma chambers, etc.), but they do not have the spatial resolution or signal averaging appropriate for prospect-scale delineation. Hill et al. (1981) recently reported on a 270-km profile from Mount Hood to Crater Lake in the Cascades and presented results in terms of crustal velocity structure. These data contribute to a better understanding of regional geology and are indirectly used in geothermal exploration.

Regional seismic reflection data such as the COCORP profiles may be useful in the same sense but are rarely available.

Electrical Methods

Thermal waters become increasingly conductive with increasing salinity and with increasing temperature up to 300°C above which conductivity decreases, and the long-term interaction between thermal fluids and the subsurface environment gives rise to extensive wall rock alteration (Moskowitz and Norton, 1977). The alteration produces conductive mineral assemblages such as clays and may develop additional porosity. This environment of low-resistivity pore fluids and conductive mineral assemblages is often a good target for the electrical exploration techniques.

The magnetotelluric (MT) method is routinely used in both the reconnaissance and detailed stages of geothermal exploration. Through precise measurements of the frequency-dependent electric and magnetic field components made at the earth's surface, one may obtain information relating to the impedance distribution (i.e., electrical resistivity) to depths greater than 100 km within the earth's crust, although reliable interpretations to these depths are rarely achieved in routine contract surveys.

Ward et al. (1981) noted that MT was used in most of the Basin and Range exploration programs which they reviewed. They attribute this to its advertised great depth of exploration and a common assumption that it is able to detect the hot rock source of heat at depths on the order of tens of kilometers. Neither of these attributes is necessarily correct. Only if a carefully selected two- or three-dimensional modeling of the earth is used in interpreting the survey results may one predict accurately the distribution of resistivities at depths of several to several tens of kilometers. Predictions of resistivities at depth are limited by the influence of surficial conductors such as alluvial fill or shallow alteration zones unless these are included in the model (Wannamaker et al., 1980). In addition the conductivity of magma at elevated temperatures is strongly dependent upon the partial pressure of water (Lebedev and Khitarov, 1964) and so hot, dry partial melt is more difficult to detect by MT than hot, wet partial melt.

Stanley (1981) described a regional, 97 station MT survey for the Cascades volcanos region. In addition to generalizing the resistivity structure for 0 to 10 km depth, he interpreted a lower crustal conductor ($\rho <$ 5 ohm-m) at 10-22 km depth which he suggests may be due in part to a partial melt associated with Cascade volcanoes. Perhaps the most important application of MT in regional geothermal exploration will lie in detecting regions of partial melt in the deep crust or upper mantle (Wannamaker et al., 1980).

Electrical resistivity data are routinely acquired in geothermal exploration on the detailed, site-specific scale but are less frequently used in regional or reconnaissance exploration. Schlumberger soundings are often conducted at many scattered sites within a large region, and depth to a given conductive horizon is contoured from these data. Although the array is efficient for data acquisition, the assumption of one-dimensional environments must be evaluated, particularly as current and potential electrodes expand across structures or other lateral resistivity contrasts in complex geologic environments. Thus the results are often misleading even for a regional assessment.

The USGS and some survey contractors have promoted the bipole-dipole or roving dipole array for reconnaissance resistivity surveys. In this array current is introduced through a long (one- to two-km) transmitting dipole and voltage drops are observed at two short (0.2 to 0.5 km) orthogonal receiving dipoles two to ten km distant. The reduced resistivity values are contoured and then considered to represent large-scale resistivity variations at substantial (one to five km) depths. Although the generalization is often valid, the reduced resistivity values are strongly dependent on the local resistivity distribution in the vicinity of the transmitting dipole (Frangos and Ward, 1980). The data are difficult to interpret accurately and are, in general, only appropriate for regional-scale interpretation. In view of these complications for reconnaissance resistivity arrays, the resistivity method plays a relatively minor role in regional assessment in contrast to a key role in detailed site-specific exploration.

CONCLUSIONS

Hydrothermal resources occur worldwide in specific geologic environments. In the U.S., the bulk of known resources and all known high-temperature resources occur in the west, including Hawaii and Alaska. Although the hydrothermal potential of a given region can often be qualitatively assessed based on knowledge of the geologic environment, reconnaissance exploration is usually required to locate and assess sub-regions having higher potential for resource occurrence. Thereafter more detailed exploration is performed in these sub-regions for the purpose of locating sites to drill test wells. Geological, geochemical, geophysical and hydrological surveys and evaluations are used jointly for all of this work.

The specific techniques used in a given region are ideally selected by considering the expected causes and manifestations of hydrothermal resources in that region. This requires an understanding of the regional geology including stratigraphy and structure. For example, in the mid-continental U.S. one would use techniques capable of providing information on occurrence of aquifers at depth, areas of highest heat flow and areas of best water quality, whereas in the Basin and Range Province one would select techniques that reveal previously overlooked surface manifestation of once-active thermal springs and techniques that detect faults carrying circulating thermal waters. Compilation of available relevant data allows gaps in the data base to be identified, and these gaps are filled in by field and laboratory work.

Several successive cycles of field surveys and data integration are used with progressive refinement of understanding and elimination of areas having low potential for occurrence of a resource. An attempt is made to use techniques having lower unit cost during early stages of the regional assessment program, when a large area is being considered, and to apply those techniques that have higher unit cost to a small, carefully selected portion of the whole region.

Geological techniques are used to study the stratigraphy, structure and tectonics of a region and to locate and evaluate surface manifestations such as thermal springs and spring deposits. The objective at this stage is to identify geologic environments where the three basic elements of a geothermal resource, a source of heat, permeable rocks and water to carry the heat to the surface where it can be extracted, are present together. The geologist may thus search for volcanic rocks that are young enough to indicate a still-cooling intrusion at depth to provide heat, and for indications that thermal waters are now or recently were active in the area. Alternatively an environment may be found that has high regional heat flow and active faulting that may provide pathways for deep water circulation and subsequent heating in the geothermal gradient. In any case, it is required that the geologist be experienced enough to recognize potential hydrothermal environments and to recognize in the field even subtle indications of present or former geothermal activity.

Hydrologic considerations can be important at this stage both in assessing potential of specific areas and in helping to guide other exploration work. For example, flow of cold water in near-surface aquifers invalidates use of heat flow and thermal gradient studies in holes that do not penetrate the cold aquifers.

Geochemistry finds important application to regional hydrothermal assessment. Traditionally in geothermal work geochemistry as a term has meant fluid geochemistry, mostly because of excellent, pioneering work by the U.S.

Geological Survey and others. In recent years it has become evident that geochemical study of rocks and of hydrothermal alteration products is equally important.

Upwelling thermal water can sometimes be detected by rather simple studies of the chemistry of springs and wells. Often these chemical data are available and, whenever they are not, they are relatively fast and inexpensive to collect. Potential chemical indications of hydrothermal waters include anomalous boron or chloride concentrations in ground water. Another important application of fluid geochemistry is in predicting reservoir temperatures. Although chemical geothermometry is based on many seemingly limiting assumptions, it has proven successful in predicting subsurface temperature in most high-temperature systems. Application to resources whose temperature is below, perhaps, 130°C is questionable at present. New work in application of light stable isotope studies to geochemistry shows promise but needs further development.

Once a potential resource area is located, certain predictions about the reservoir fluids are possible through geochemistry. For example, chloride-rich waters are usually associated with water-dominated hydrothermal systems whereas acid-sulfate waters often occur in association with vapor-dominated systems or portions of systems. In addition, it is practical to study trace element distribution in rocks and hydrothermal alteration products over specific areas but probably not over the whole region under assessment. Mercury, sulfur, antimony, arsenic, gold, silver and thallium are often concentrated in rocks and/or soil over high-temperature geothermal systems.

Geophysical methods can be used directly to detect a hydrothermal resource through heat flow and downhole temperature surveys and also to contribute to a better geological picture of the reconnaissance area and of selected subareas of high resource potential. It is important to remember that one is looking not for high heat flow per se but for anomalous temperature. Temperature and, if possible, heat flow measurements should be made in available wells in the region, especially those within subareas of expected high resource potential. Great care must be exercised in interpreting these data, and, if cold water overflow is suspected, an area should not be casually downgraded simply because of low temperature or heat flow values. Data from available wells is usually fairly inexpensive but collection of gradient and heat flow information can become very expensive when new drilling is required. Techniques under development for using temperature measurements made in shallow (3 m) holes promise to cut costs substantially in specific areas where this technique may apply.

Aeromagnetic and gravity methods are primarily valuable in helping to determine regional and detailed structure, locating deeply buried radiogenic granites, and in extending geologic information into areas of little or no outcrop. Gravity surveys have been used to detect silicified zones over hydrothermal systems in the less dense sediments of the Imperial Valley, California, but this use probably has restricted application. Curie point isotherm interpretations may make a major contribution to regional evaluation in certain geological provinces.

Electrical geophysical methods are often used to detect the greater electrical conductivity, or lower resistivity, often associated with hydrothermal systems due to elevated temperature, fracturing and deposition of clay and other minerals through alteration of reservoir rocks by thermal fluids. Magnetotelluric (MT) surveys are also used to attempt to detect hot rocks or magma at depth. Some recent studies (Wannamaker et al., 1980) indicate that MT has the potential to detect partial melts in the lower crust or upper mantle. To do so, however, requires an extensive MT data base throughout the region. Galvanic resistivity is not often used in a reconnaissance mode, but has proved to be very helpful in evaluation of specific prospect sites.

Experience with regional hydrothermal assessment will convince even the most optimistic that a great deal of improvement is needed in many techniques. Geothermal exploration has not had the benefit of the decades of development and refinement in techniques common to petroleum and mining exploration. Wildcat well success ratios are very low in hydrothermal exploration, and this has had a negative impact on the economics of hydrothermal development for a fledgling industry struggling with economics for even the highest grade resources.

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FIGURE 1
HEAT FLOW IN THE U.S.

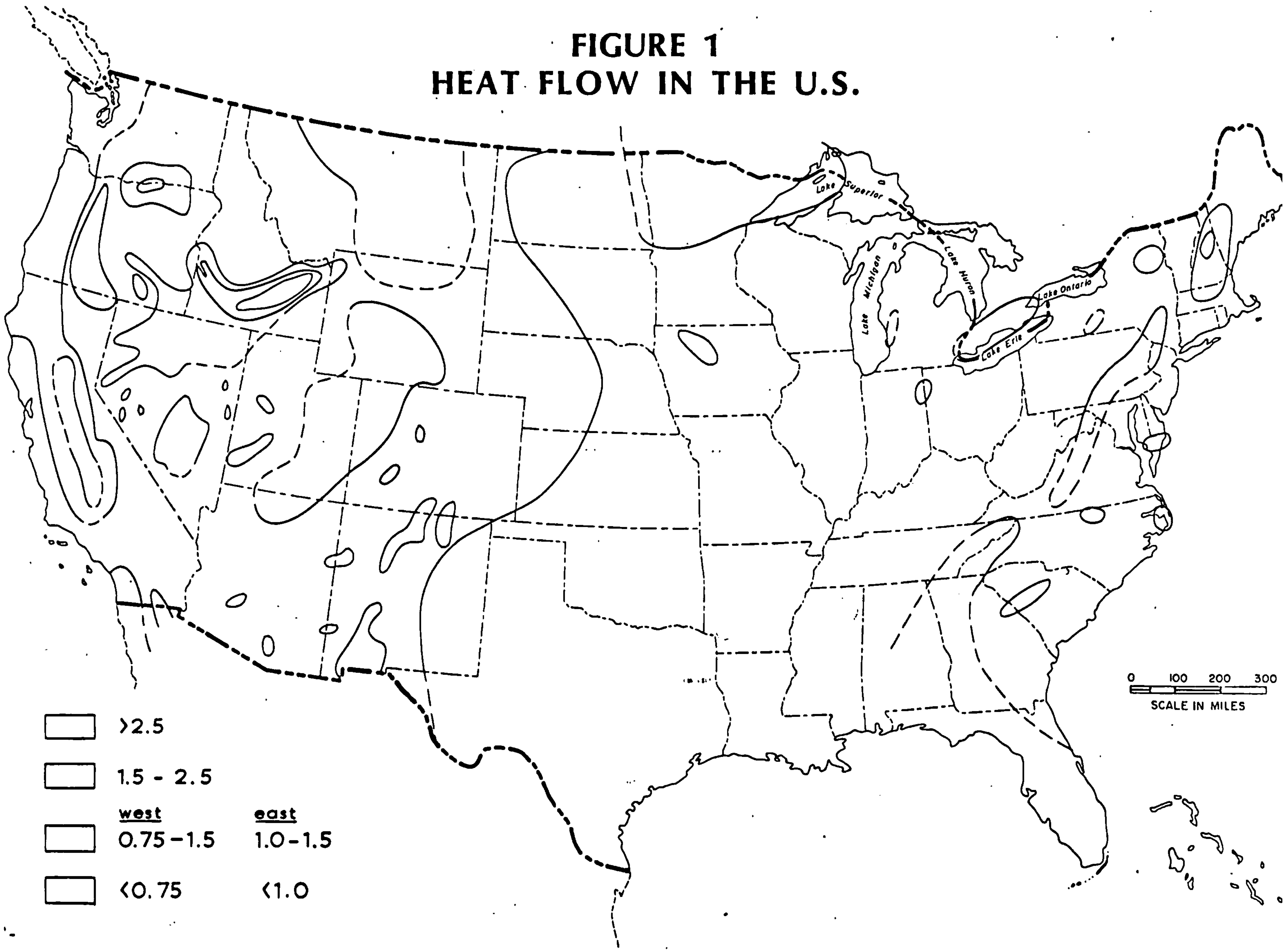
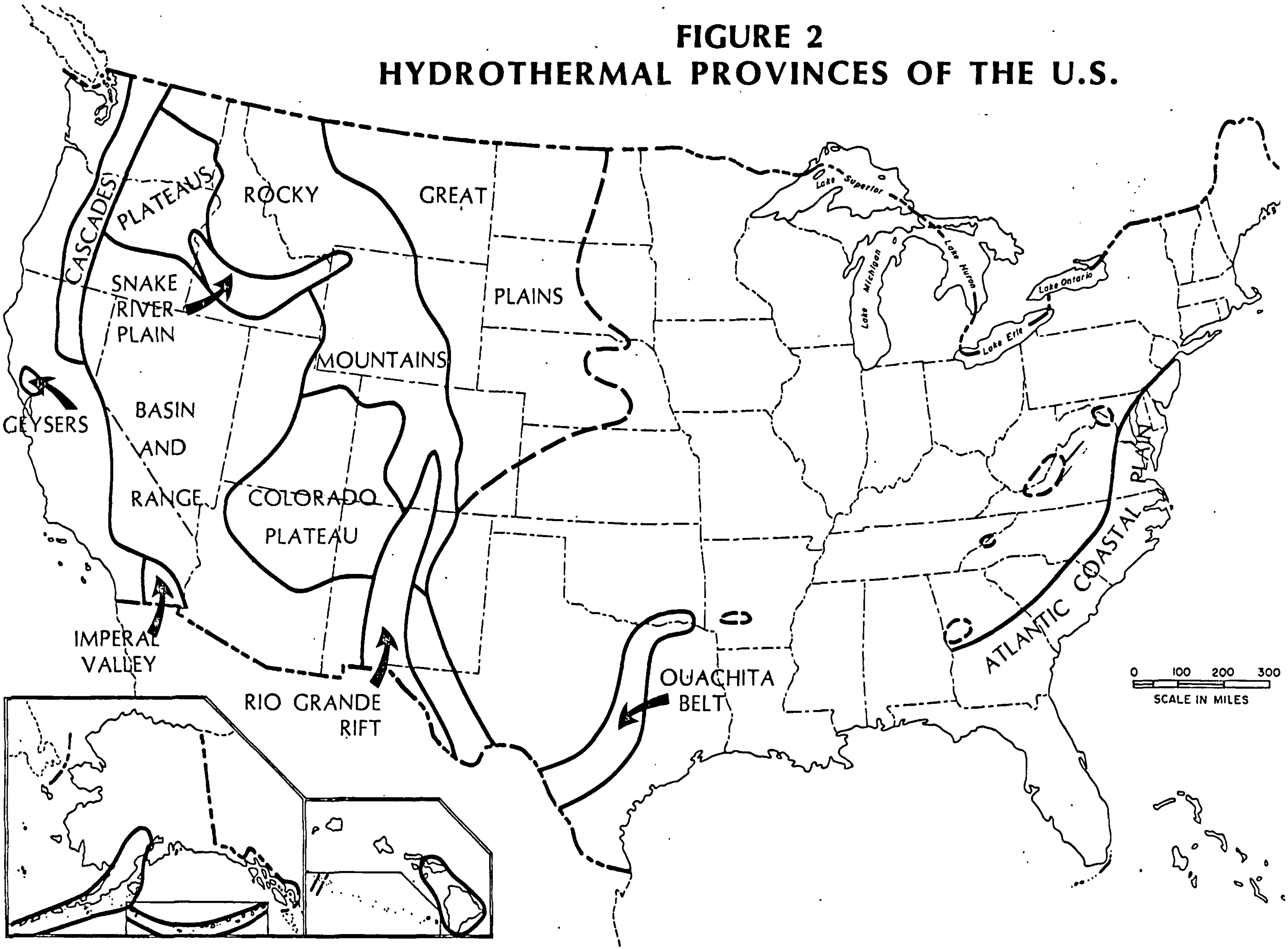
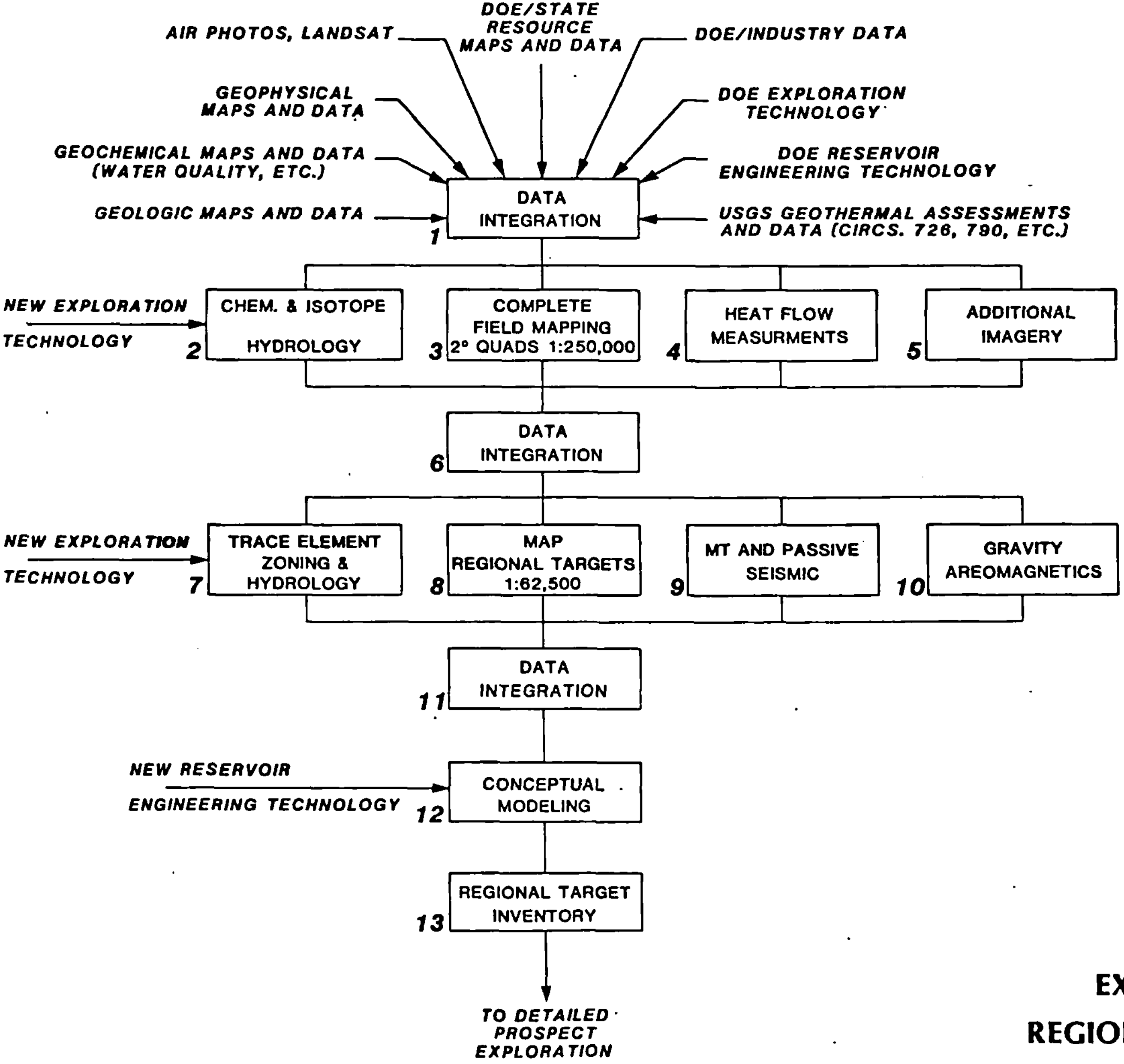


FIGURE 2
HYDROTHERMAL PROVINCES OF THE U.S.





- *AVAILABLE DATA BASE*
- *FIRST ROUND SUPPLEMENTAL DATA*
- *REGIONAL TARGET DEFINITION AND PRELIMINARY RESOURCE TEMPERATURE AND TYPE ASSESSMENT*
- *SECOND ROUND SUPPLEMENTAL DATA*
- *REGIONAL TARGET REFINEMENT AND FINAL RESOURCE TEMPERATURE AND TYPE ASSESSMENT*

FIGURE 3
EXPLORATION STRATEGY
REGIONAL RESOURCE ASSESSMENT

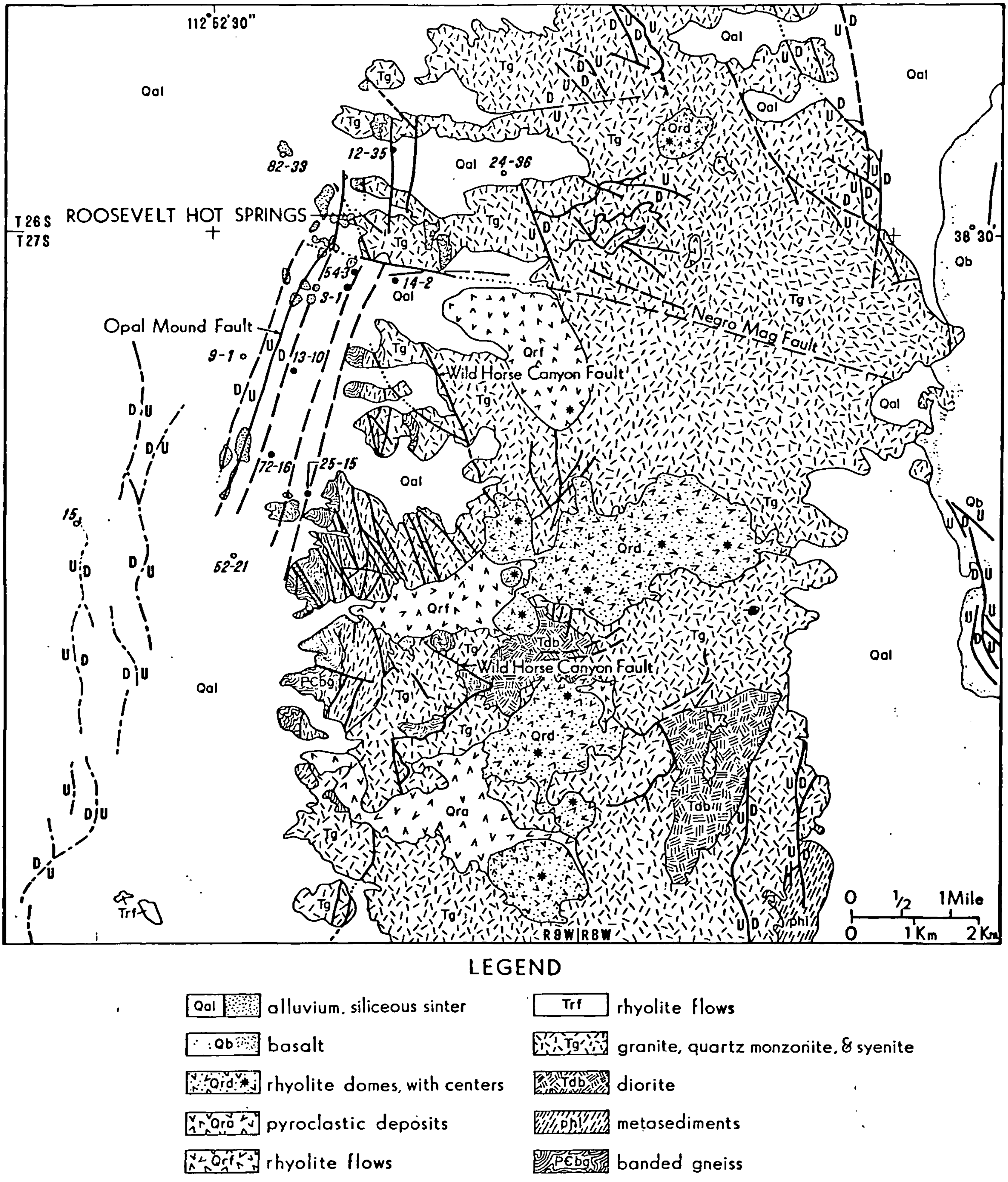


Figure 4. Geologic map of the Roosevelt Hot Springs geothermal area and the adjacent Mineral Mountains. Closed circles indicate producing geothermal wells and dry holes are shown by the open circles. (Ross et al., 1982)

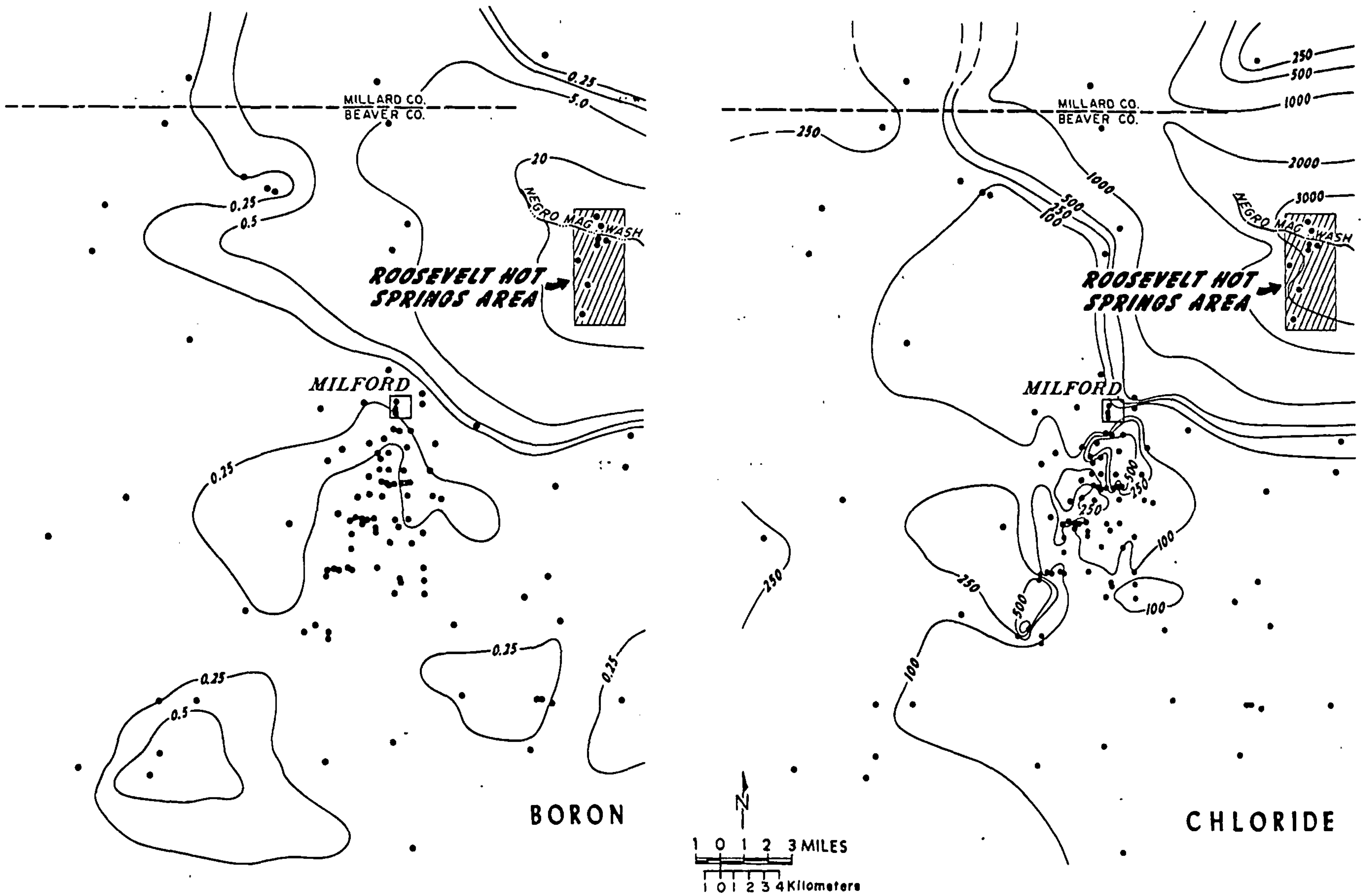


Figure 5 Boron and cloride in wells and sqrings in the Milford, Utah area.

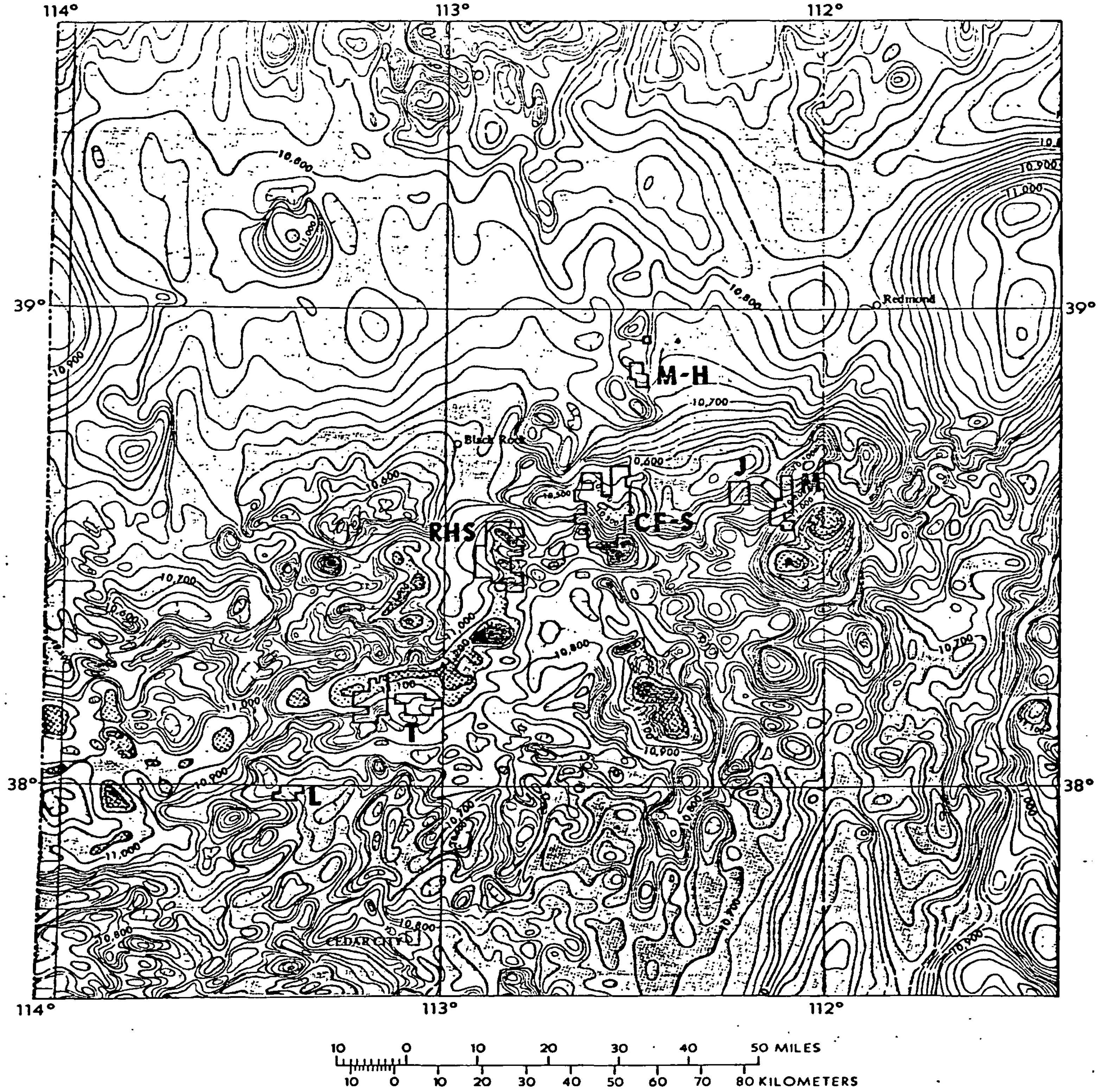


Figure 6. A portion of the Aeromagnetic Map of Utah (after Zietz, Shuey, Kirby)

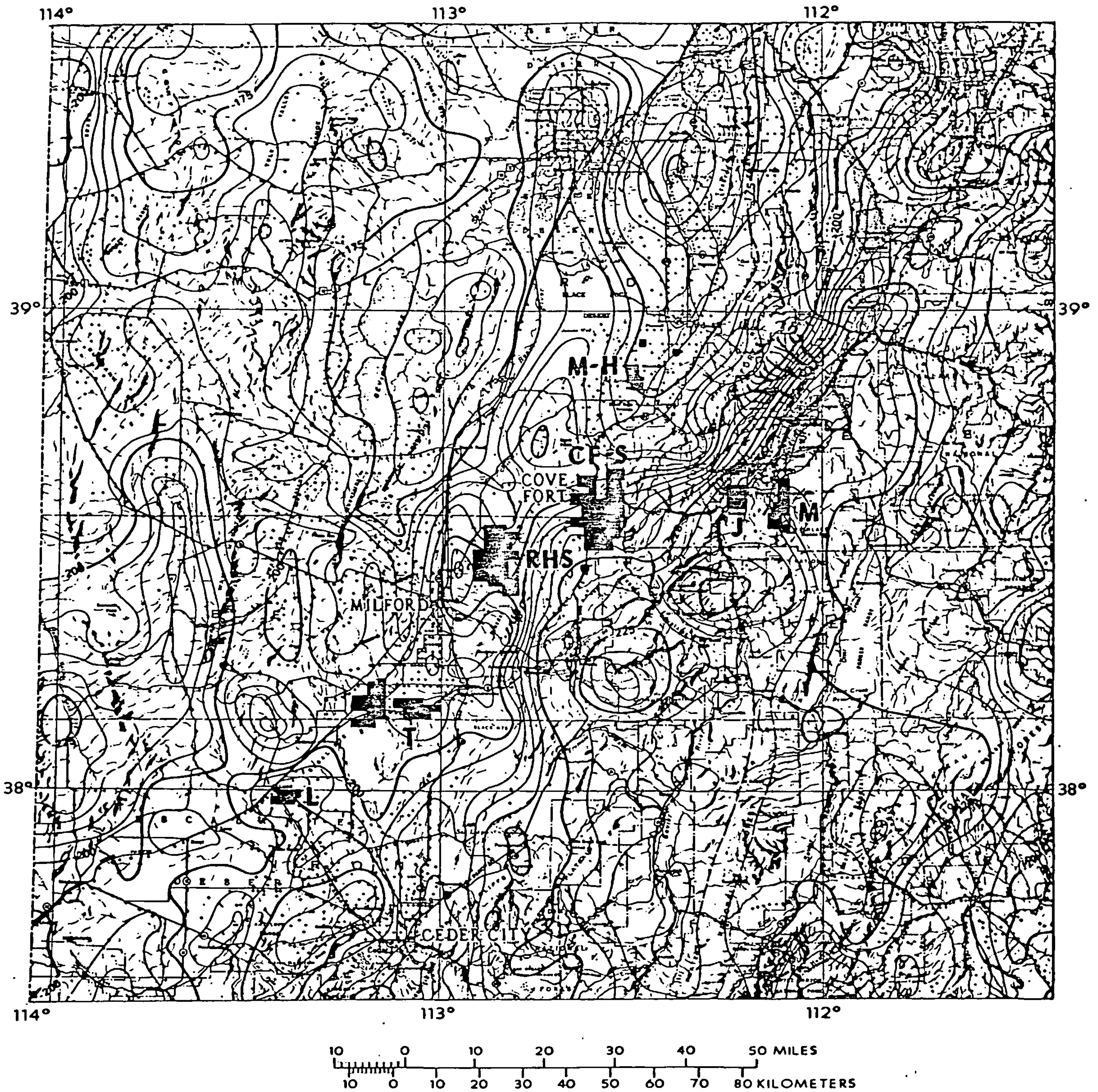


Figure 7. A portion of the Simple Bouguer Gravity Anomaly Map of Utah (after Cook et al.)

AN EXPLORATION STRATEGY FOR REGIONAL ASSESSMENT OF HYDROTHERMAL RESOURCES

by

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1.0 OBJECTIVE

A reasonable assumption which one might make today is that sometime in the near future the United States will face a national emergency which demands that all available domestic energy resources be activated because one or more external conventional supplies shall not be available. If one believes this assumption, and we do, then some level of Federal effort ought to be spent on developing technology of exploration for and/or exploitation of alternate energy resources. Presumably this will be performed largely as a part of a regional assessment if Federal funds are to be expended in an expansion of the USGS and DOE State/Federal cooperative programs of the past. Alternatively, it may develop as expansions of the DOE Industry Coupled and User-Coupled Drilling programs currently in termination phases. It is not our objective here to discuss what the format or what the dollar level of the appropriate Federal effort ought to be. Rather it is our objective to describe how exploration methodologies are best applied to regional assessment of geothermal energy, independent of the mix of Federal, State, and Industrial funds, ought to proceed in the future.

2.0 BACKGROUND

Geothermal energy is derived from the heat of the earth.

> "The Earth's interior is a gigantic but delicately balanced heat engine fueled by radioactivity, which has much to do with how the surface evolved. Were it running more slowly, geological activity would have proceeded at a slower pace. The continents might not have evolved to their present form, and volcanoes might not have spewed out the water and gases that became the oceans and atmosphere. Iron might not have melted and sunk to form the liquid core, and the magnetic field would never have developed. The Earth would then have evolved as a cratered, dead planet similar to the Moon.
>
> ...if there had been more radioactive fuel and a

> faster running engine, volcanic gas and dust would have blotted out the Sun, the atmosphere would have been oppressively dense, and the surface would have been racked by daily earthquakes and volcanic explosions." (Press and Siever 1974).

The earth, fortunately, is a heat engine running at exactly the right speed for our survival. Let us catch a glimpse of how much heat it produces.

The average heat flowing <u>conductively</u> out through the earth's surface is 0.08 watts per m^2. If we multiply this value by the total surface area of the earth (5.1×10^{14} m^2) we obtain the total heat flowing from the earth as 4.1×10^{13} watts or 41,000,000 megawatts.

Only a fraction of this energy can be extracted economically under current market conditions.—However, the crust of the earth contains local hot spots from which extraction of energy, either for direct heat applications or for conversion to electricity, is economical at present.

Geothermal hot spots are manifested as a continuum of seven accepted resource types: magma, hot dry rock, convective hydrothermal, geothermal gradient, deep sedimentary basin, geopressured, and radiogenic.

We shall be concerned in this article only with the convective hydrothermal, geothermal gradient, and deep sedimentary basin types of resources; collectively they are usually referred to as <u>hydrothermal resources</u> and all involve convection.

Hot-water-dominated convective hydrothermal systems are generally classified as high temperature (>150°C), intermediate temperature (90 to 150°C), and low temperature (<90°C; White and Williams, 1975; Muffler, 1979). Although some of these systems may derive their heat from still molten or hot, crystallized plutonic masses (Smith and Shaw, 1975), others show no association with recent plutonic activity but derive their heat from deep circulation along fault zones in areas of high thermal gradients.

A regional exploration program for hydrothermal resources should be based on the search for the components of hydrothermal systems: heat, water, permeability, and, in some cases, impermeable caps. The major target of a regional exploration program is heat, which is measured as either thermal gradients or heat flow. Other indirect indicators of hydrothermal resources are also employed in regional assessments as shall be described subsequently.

3.0 HYDROTHERMAL SYSTEMS IN THE U.S.

Introduction

The U.S. may be divided into two broad heat flow provinces, which have much local and regional variation (Figure 1). The eastern U.S. is generally lower in heat flow, with regions apparently localized, often in areas of radiogenic plutons. The broader zones of higher heat flow in the west are due to higher thermal flux from the mantle (Simmons and Roy, 1969). This higher flux implies that the west, as a region, presents better opportunities to find hydrothermal systems. Young volcanic systems in the west form the highest grade thermal targets.

At the time of this writing, economically viable development of hydrothermal systems requires that adequate water be naturally present. This means a system must have both sufficient quantities of water available for recharge, and adequate permeability, either through fractures, which is most common, or through intergranular pores. Regional identification of fracture systems can help guide the explorationist to favorable terrains of fracture permeability.

A hydrologically impermeable, and often low thermal conductivity, cap, may be associated with attractive hydrothermal targets. This cap, however, is not a primary target for regional exploration programs.

The U.S. may be divided into hydrothermal provinces, (Figure 1), which are based on regional heat-flow patterns, similarity of geologic environments and similarity of resource target models. The discussion below is based on the hydrothermal provinces illustrated on Figure 1. The margins of the provinces, particularly west of the Great Plains, form attractive regional exploration targets.

ALASKA AND HAWAII

Areas of young volcanic activity form the prime thermal targets in Alaska and Hawaii. In Alaska, most of these volcanos are found along the Alaska Peninsula and and the Aleutian Island Chain. Secondary Alaskan targets for hydrothermal resources are zones of high heat flow along regional strike-slip faults, areas of deep circulation, and deep sedimentary basins (Turner and others, 1980; Motyka and others, 1980; Motyka and Moorman, 1981).

In Hawaii, volcanic rift zones around the margins of active volcanos form the best targets (Thomas and others, 1980; Furumoto, 1978). Electric development of the Puna rift resource is continuing (Chen and others, 1980).

CASCADE MOUNTAINS

The young volcanos of the Cascade range of Washington, Oregon, and California have long been an attractive, but enigmatic, hydrothermal terrain. Although the resource potential is high (Brook and others, 1979; Younquist, 1981), institutional barriers have slowed development (Bloomquist, 1981).

Extensive resource investigations at Mt. Hood have failed to demonstrate an electric quality resource, although direct heat applications are planned (Riccio, 1979, Bowen, 1981). Recent U.S. Geological Survey drilling at Newberry caldera in central Oregon has demonstrated, however, that attractive resources may be hidden beneath cold near-surface groundwater regimes (Sammel, 1981).

The recent eruption of Mt. St. Helens, the high temperature fumeroles on Mt. Baker and Mt. Hood, the vapor-dominated hydrothermal system at Mt. Lassen, and the ongoing development at Meager Creek in British Columbia, all suggest that there are extensive resources yet to be discovered and developed in the Cascades.

PLATEAUS-SNAKE RIVER PLAIN

Isolated direct-applications quality resource hydrothermal resources exist in the Plateaus terrain of Oregon and Washington. Unlike the large young volcanos that serve as resource targets in Alaska, Hawaii, and the Cascades, most of the plateaus systems will probably be discovered using target models that call for either deep circulation of water along faults, or deep circulation along volcanic and interbedded sedimentary horizons. Electric grade resources have not been documented from this terrain.

SNAKE RIVER PLAIN

Higher heat flow zones along the margins of the Snake River Plain, and broader areas of resources in the western Plain form the most attractive resource targets (Mitchell and others, 1980). Electric development of a 150°C resource is proceeding at the Raft River Idaho site and similar temperatures, without sufficient production have been encountered in drill holes in both the eastern (Prestwich and Mink, 1979) and western plain (Austin, 1981).

The Yellowstone Caldera, at the eastern end of the Snake River Plain, is the single largest concentration of geothermal energy in the U.S.; development in Yellowstone is prohibited, however, by its National Park status.

ROCKY MOUNTAINS

Water heated in fault or fracture systems, flowing to the surface near drainage bottoms, forms most of the known hydrothermal systems in the Rocky Mountains. Big Creek Hot Springs in Idaho and Paradise Hot Springs in Colorado are the only springs identified by Brook and others (1979) as having reservoir temperatures above 150°C in this region. Systems such as Glenwood Springs, in Colorado, however, have large flows and are very attractive targets for direct applications (Barrett and Pearl, 1978). Some systems, such as Thermopolis, Wyoming, apparently have water that circulates to depth in stratigraphic horizons, and circulates to the surface along the limbs of anticlines (Heasler, 1981).

Exploration programs in the Rocky Mountains should be targeted to identify favorable circulation paths for water, as local heat sources such as very young volcanos are rare.

GREAT PLAINS

Hydrothermal resources in the Great Plains are dominated by the Madison Group of Paleozoic limestones. These rocks are found predominantely in Montana, Wyoming, and the Dakotas. Temperatures are suitable for direct applications. In North Dakota, much of the water is poor quality (Harris and others, 1980). In Nebraska, waters are found in the Cretaceous Dakota

Formation, which, although colder than the deep waters in the Madison (Gosnold and Eversoll, 1981) typically have much better water quality.

Regional exploration in the Great Plains is based on identification of appropriate stratigraphic horizons at suitable depths for the thermal gradient to provide sufficient temperatures.

OUACHITA BELT

Hydrothermal resources in central Texas are found primarily in Cretaceous sandstone and limestone aquifers, along the buried Ouachita fold belt (Woodruff and McBride, 1979). These waters are heated in the thermal gradient of the earth, either by downward circulation from the west, or they rise from the deeper parts of the gulf basin to the east. Downward circulating waters are typically fresh, upward circulating waters are more saline. Woodruff and McBride (1979) have identified the broad region favorable for resources; exploration within this region is directed toward identifying suitable stratigraphic horizons at sufficient depth.

RIO GRANDE RIFT

Non-volcanic related hydrothermal systems in the Rio Grande Rift are apparently the result of upward flow of waters from deep rift basins at groundwater constrictions (Harder and others, 1980; Morgan and others, 1981). These geothermal resources primarily have potential for direct applications. A volcanic related geothermal system is being developed for generation of electricity in the Valles Caldera in northern New Mexico (Dondanville, 1978). A deep system, suitable for electric generation, may exist in the vicinity of Soccorro (Chapin and others, 1978).

Exploration for direct applications resources should focus on identification of groundwater flow patterns in basins and at constrictions, while young volcanic activity seems required for the existence of electric quality resources.

COLORADO PLATEAU

Isolated, generally cool and low-flow hydrothermal systems exist in the Colorado Plateau. Regional low heat flow (Figure 2) suggests that major hydrothermal systems are not likely to exist in this area.

BASIN AND RANGE

Young volcanic areas along the Northern, eastern, and western margins of the basin and range, and the high heat flow zone in northern Nevada (Figure 2) are the most favorable sites for the discovery of electric-quality hydrothermal systems in the Basin and Range. Many hydrothermal systems exist along range-bounding faults throughout this area, although some of these are very hot, electric quality resources have not yet been demonstrated outside the area outlined above. The Roosevelt Hot Springs system in Utah has produced small quantities of electricity; further development is planned. This system is discussed in detail below.

Most of the resources in the basin and range are fault controlled; identification of zone of hydrothermal flow along these faults becomes a prime task of the regional explorationist.

GEYSERS

The Geysers area, with the production of nearly 1000 megawatts of electricity, is the premier hydrothermal production area in the U.S. The geology of this region has been summarized in McLaughlin and Donnelly-Nolan (1981). Production of dry steam is from fractured metamorphic rocks.

Exploration in The Geysers is directed toward both further development of the steam field and identification of a hot water system. Magma is postulated to exist in the vicinity of the young volcanic rocks at The Geysers (Iyer and others, 1981). This magma provides the heat to the system.

IMPERIAL VALLEY

Small amounts of electricity are being produced from hydrothermal brines in the Imperial Valley; much further development is planned. These resources are found in fractued stratigraphic horizons (Elders, 1979). The heat in these systems is derived from local volcanic activity and high heat flow derived from a shallow mantle.

Regional exploration in the Imperial Valley is based on identification of geochemical and geophysical anomalies, and extension of known systems.

4.0 EXPLORATION STRATEGY FOR REGIONAL ASSESSMENT

By now most major companies involved in geothermal exploration in the United States have addressed regional exploration in the high heat flow areas delineated in Figure 2. The USGS has conducted intensive intra- and entramural programs designed at both resource assessment and development of exploration technology. State agencies from at least 25 states, operating with Federal (DOE) and state funds, have conducted resource inventories and have produced maps of the same to aid the USGS in its geothermal resource assessment. The net result of all of this effort is much data has been placed in the public domain.

We visualize that the next major effort ought to be an integration of all such data, which we refer to as the initial data base, as shown in box 1 of Figure 3. Once this data has been integrated, then completion of the required exploration information ought to be completed via acquisition of a secondary data base as illustrated by boxes 2 through 5 of Figure 3. Once again the total data integration of box 6 must be performed in an attempt to sharpen focus on the most worthwhile regional targets and to eliminate areas devoid of promise. The data integration of box 6 should be followed by the tertiary data base acquisition of boxes 7 through 10; the final data integration of box 11 follows. considerable latitude in application of the data acquisition of boxes 2 through 5 and 7 through 10 ought to be allowed in order to facilitate the variety of primary exploration features of section 3.0 above. Eventually, however, firm conceptual models of each regional resource type ought to be developed in box 12 and an inventory of all such regional resource targets ought to be prepared for assimilation by industry. This, logically, could occur in the second successor to USGS Circular 790. Industry is unlikely to have the financial resources to prepare this inventory, and, traditionally this role has been left to the USGS working in concert with industry and the states. Throughout this effort, direct expenditures on improving exploration and reservoir engineering technology must be made since the U.S. is short of reliable technology in these fields at the present time.

5.0 GEOLOGICAL TECHNIQUES FOR REGIONAL ASSESSMENT

Introduction

The geological technqiues for regional assessment of geothermal potential are used to narrow the search for a geothermal system down to a prospect which would be on the order of less than 100 km^2 in size. These techniques will largely use existing data, particularly geologic maps, but will include field checks and fill-in work where required. It is important at this stage to evaluate the tectonic and intrusive history of an area, understand the deposits and alteration produced by hydrothermal systems, and understand the effects of the regional hydrologic environment.

Tectonics

High quality geothermal systems are located in areas of active tectonism. This includes both faulting and young extrusive activity, although the young intrusive activity may not be required for the occurrence of high-temperature systems. Faulting is necessary to maintain open fractures which are required to convey meteoric fluids to depth and return them to the surface. It is permeable zones along these faults which are the target for much of the geothermal exploration which is ongoing today. Experience has shown that fault zones are not always permeable zones of upwelling hot fluids. Indeed, many faults have lateral variability from permeable to impermeable areas. And, within permeable areas, zones of cold water recharge and thermal upwelling may be closely associated. These are problems which must be resolved using thermal techniques.

Theories of the relationships of magmatic/volcanic and geothermal systems have been developed by Smith and Shaw (1976). Basically they have proposed that basaltic systems of less than 30,000 years and rhyolitic systems which are younger than 1 million years have the potential of providing the heat for high-temperature hydrothermal systems. Thus, the presence of these young rocks serves as a regional exploration tool.

Hot Spring Deposits

The presence of hot springs or lithologies deposited by thermal fluids is of course an excellent indication of the presence of a hydrothermal system. Hot spring deposits are termed sinters and are generally composed of calcium carbonate (Travertine) or silica. The resource implications of such deposits are somewhat different.

Calcite has a retrograde solubility, i.e., it is more soluble at low temperatures than at high temperatures. However, the solubility does increase rapidly with an increase in the partial pressure of carbon dioxide. Thus, as fluids which are saturated with calcium carbonate approach the surface, $CaCO_3$ is deposited as a result of the loss of CO_2 rather than from cooling. Other carbonate species such as witherite ($BaCO_3$) and dolomite ($MgCO_3$), as well as sulfates such an anhydrite ($CaSO_4$), show solubility relationships similar to those of calcite (Holland and Malinin, 1979).

Hot spring waters which deposit siliceous sinters have been found to contain (nearly always), SiO_2 concentrations of at least 240 ppm. These concentrations of silica require subsurface temperatures of at least 180°C. because of the high solubility of amporphous silica, these fluids then must cool to about 70°C to precipitate amorphous silica. These initial amorphous precipitates are very susceptible to weathering and their preservation is dependent on protection by subsequent deposits. Once the siliceous sinters have been deposited and protected, however, they undergo polymorphic transformations to more stable species. This transformation process generally follows the sequence:

opal → christobalite → chalcedony

The sequence is well documented at Yellowstone and at Roosevelt Hot Springs and may eventually be quantified in order to allow determination of the minimum age of hot spring deposits. The transformation process does seem to require a minor amount of burial and elevated temperatures as well as time.

Acid Alteration

The surface expressions of vapor-dominated reservoirs characteristically include chloride-poor acid sulfate springs with low discharges accompanied by sodium bicarbonate/sulfate springs, fumeroles, mudpots and acid altered ground (White et al., 1971). These features are formed by steam and other volatile gases such as hydrogen sulfide, ammonia, and carbon dioxide which discharge at the surface or condense in meteoric water. Non-volatile components such as chloride remain in the underlying boiling brine and are not enriched in the surface discharges. Chloride-rich springs typical of hot water systems are therefore conspicuously absent over the vapor-dominated portions of the reservoir but may occur on its margins in surrounding topographically low areas if the reservoir is relatively shallow.

Acid sulphate springs are typically a surficial feature produced by the oxidation of hydrogen sulfide to sulfuric acid. Altered ground surrounding the acid springs and fumeroles provides a striking example of reactivity of the waters. The altered areas are typically bleached and converted to a siliceous residue containing native sulfur, cinnabar, yellow sulfate minerals, and clay minerals including kaolinite and alunite. Similar acid alteration can, however, also be formed at depths where steam heating of groundwaters occurs. At Matsukawa, Japan, alunite, quartz and pyrite appear to have formed from 250° to 280°C fluids with a pH near 3 (Sumi, 1969). Thus, mineral assemblages in acid-altered rocks may occur at both high and low temperatures.

Regional Hydrologic Considerations

Regional hydrologic data is viewed as being important from several standpoints. First, a sufficient amount of available water is necessary to insure the life of a geothermal reservoir. Second, regional water quality data has been shown to be useful in pinpointing buried hydrothermal systems, and third, near surface cold aquifers are able to distort or mask altogether the thermal signatures of underlying hydrothermal systems.

A quantity of water necessary to guarantee the recharge of the system is not generally regarded as a principal exploration factor, but can be a supporting factor when combined with the probable presence of heat and fractures. In addition, it is often difficult to evaluate the recharge portion of the system until extensive exploration work has been completed, and often this remains a mystery even in fully developed fields.

Even in systems which crop out at the surface to form hot springs it is thought that a large percentage of the thermal waters are lost to the near-surface hydrologic environment. For many buried systems, all the discharged water is thought to be lost to near-surface groundwater systems. Data from Roosevelt Hot Springs (Ross et al., 1982) has demonstrated that the system can be identified by using regional water quality data published by the USGS. Certain components such as boron, chlorine, and total dissolved solids define the discharge zones of the systems. Thus the analysis of available water quality data is a powerful and inexpensive geothermal exploration tool.

In addition to aiding in the exploration effort as described in the paragraph above, regional hydrologic systems often tend to distort or obscure entirely the discharge zones of active hydrothermal systems. Studies at Cerro Prieto have shown that the flow of groundwater from the northeast has distorted the thermal plume rising from the system. Cold water overflow reaches an extreme condition in the Cascades province of the U.S. where it is able to completely mask the near-surface thermal manifestations of buried systems.

6.0 GEOCHEMICAL TECHNIQUES FOR REGIONAL ASSESSMENT

Introduction

Geochemical investigations frequently play an important role in the regional evaluation of geothermal resources by providing information on sites of upwelling, the temperature and quality of the resource, and the type of resource present. This information can be obtained from careful evaluation of the chemical compositions of fluids discharged from springs and fumeroles, and from the mineral and trace element distributions in the altered rocks found at the surface and in the thermal gradient and deeper test wells.

The physical properties of the geothermal reservoir rocks are also strongly dependent on the extent of hydrothermal alteration and can be significantly altered as a result of mineral deposition in fractures and by the formations of clays. These changes may substantially affect the geophysical response of the rocks at depth. Thus an estimate of the extent and character of the hydrothermal alteration is needed to quantitatively interpret the geophysical data.

System Classification

The surface manifestations of both liquid- and vapor-dominated geothermal systems commonly include hot springs and fumeroles. The discharged fluids may differ chemically from the deeper reservoir fluids as a result of changes accompanying mixing, dilution, boiling, or conductive cooling. In addition, the chemistry of the fluid may be further modified as constituents partially or completely reequilibrate with the reservoir rocks during the fluids' ascent to the surface. The actual path taken by the fluids may be complex and the chemistry modified by more than one process. Despite this complexity, careful evaluation of fluid chemistry frequently provides diagnostic information about the subsurface characteristics of the geothermal system. Geochemical and basic hydrologic data from springs and wells is an important source of information which can be used at an early stage in the exploration program to predict the kind of fluid that will be produced. Chemical analyses of many of the hot spring systems in the U.S. are tabulated in the literature and can be supplemented at relatively low cost during reconnaissance investigations.

The geothermal fluids of the explored high-temperature liquid-dominated systems are sodium chloride brines which vary greatly in composition from field to field. These solutions may be as dilute as potable water or can be as concentrated as the 25 weight percent solutions characterizing some of the systems in the Imperial Valley. Systems with such extreme salinities are, however, rare. Most systems currently under evaluation in the Basin and Range contain less than 10,000 ppm total dissolved solids.

Bicarbonate-rich waters are commonly found in low-temperature geothermal systems and in secondary reservoirs in the shallow portions and margins of high-temperature field.

The origin of bicarbonate-rich fluids found in the secondary reservoirs of high-temperature systems was discussed by Mahon et al. (1980 a, b). They concluded that the bicarbonate-rich fluids form by gas and steam heating of meteoric water. The final composition of the fluids is determined by the composition and volume of the gases and ground-water and the extent of water-rock interactions that occur.

The surface expressions of vapor-dominated reservoirs characteristically include chloride-poor acid sulfate springs with low discharges accompanied by sodium bicarbonate/sulfate springs, fumeroles, mudpots and acid altered ground (White et al., 1971). These features are formed by steam and other volatile gases such as hydrogen sulfide, ammonia, and carbon dioxide which discharge at the surface or condense in meteoric water. Non-volatile components such as chloride remain in the underlying boiling brine and are not enriched in the surface discharges. Chloride-rich springs typical of hot water systems are therefore conspicuously absent over the vapor-dominated portions of the reservoir but may occur on its margins in surrounding topographically low areas if the reservoir is relatively shallow.

Acid sulphate springs are typically a surficial feature produced by the oxidation of hydrogen sulfide to sulfuric acid. Altered ground surrounding the acid springs and fumeroles provides a striking example of reactivity of the waters. The altered areas are typically bleached and converted to a siliceous residue containing native sulfur, cinnabar, yellow sulfate minerals, and clay minerals including kaolinite and alunite. Similar acid alteration can, however, also be formed at depths where steam heating of groundwaters occurs. At Matsukawa, Japan, alunite, quartz and pyrite appear to have formed from 250°-280°C fluids with a pH near 3 (Sumi, 1969). Thus mineral assemblages in acid-altered rocks may occur at both high and low temperatures.

Subsurface Temperature

An understanding of the temperatures at depth in the geothermal reservoir rocks is crucial to the development and exploitation of the resource. Temperatures can be determined directly through downhole measurements or estimated indirectly from the chemistry and stable isotopes (O, H, S, C) of the water, steam, gas and reservoir rocks themselves. Direct and indirect methods provide, however, different information about the reservoir.

The application of indirect methods plays a critical role in the initial assessment of a thermal field. Indirect methods based on the chemistry of the thermal fluids can provide information on deep thermal regimes within the high temperature parts of the reservoir that otherwise are unaccessible to shallow and even moderate-depth thermal gradient wells. Thus, indirect methods can be used to prioritize drilling targets and, when compared with thermal measurements made in shallow gradient wells, can be used to establish depth requirements for the deeper drilling program.

The quantitative geothermometer techniques currently available require chemical or isotopic analyses of thermal waters, steam and gas from wells and springs. These techniques can be categorized into the following groups:

1) Major element geothermometers
2) Mixing geothermometers
3) Isotope geothermometers

The underlying premise for all three categories is that temperature-dependent reactions between either the reservoir rock and fluid or evolving gases and the fluid attain equilibrium. Furthermore, no reequilibration occurs after the fluid leaves the reservoir (Fournier et al., 1974; Truesdell, 1976; Fournier, 1977; Ellis, 1979 for further details).

Several major element geothermometers have been proposed and have proven extremely valuable in accurately estimating subsurface temperatures. The relationships between the major element concentrations and temperature are given in Table II-1. An extensive review of the use of these geothermometers was recently published (Fournier 1981).

Qualitative fluid geothermometers are used extensively during the preliminary chemical surveys to locate zones of upwelling, determine the distribution of thermal waters and directions of groundwater flow, and to determine the lithologies of the reservoir rocks. Fluid constituents that have proven to be particularly useful during these surveys include the soluble elements chlorine, boron, arsenic, cesium and bromine. Ellis and Mahon (1964, 1967) showed that the solubilities of these elements are controlled mainly by diffusion and extraction processes, and that once liberated they do not form stable secondary minerals. Changes in the concentrations of these elements as the fluids migrate from depth occur mainly from dilution or boiling. The use of atomic ratios (i.e., chloride/boron) can eliminate these effects.

Other fluid constituents that are frequently used as qualitative geothermometers include lithum, trace metals (antimony, zinc, copper, uranium mercury), ammonia, hydrogen sulfide, and the ratios chloride/fluoride, chloride/sulfate, sodium/calcium, sodium/magnesium and chloride/bicarbonate+carbonate. In general, the concentrations and ratios increase with increasing temperature reflecting changes in constituent concentrations as a result of contamination with cold surface water, interaction between the fluids and rock at depth, and steam heating of waters (Mahon, 1970).

A map of the distribution of boron in waters in the region containing Roosevelt Hot Springs is presented in Figures (unpub. data, Cole,) and illustrate the use of one of these qualitative geothermometers. The data was compiled from published analyses of well and spring waters. This distribution boron suggested that the Roosevelt Hot Springs area is indeed a major center of upwelling thermal fluids and that exploration activities should be concentrated in this area. Changes in the concentrations of boron occur as the thermal fluids are diluted with local groundwaters. Movement of the fluids appears to be first westward and then northward. The plume of westward-migrating thermal waters provides an explanation both for the relatively high thermal gradients encountered in the shallow wells and for anomalous concentrations of soil mercury which extends westward from the thermal area.

A second source of thermal fluids located at Thermo Hot Springs in the southwestern portion of the map and is marked by concentrations greater than .5 ppm.

The ratios of gases discharged from fumeroles have also been used as qualitative geothermometers. Mahon (1970) showed that fumeroles with the lowest ratios of carbon dioxide/hydrogen sulfide, carbon dioxide/ammonia and carbon dioxide/hydrogen were the most directly connected to the deep aquifers. The concentrations of these constituents are controlled by steam-rock reactions which can rapidly deplete the contents of hydrogen sulfide, ammonia and hydrogen in the steam. The longer the steam path to the surface is, the greater these depletions are likely to be.

Reconnaissance

Trace element analyses of hot spring depoints and altered rocks can supplement other data and further help prioritize target areas. For example, mercury and sulphur are frequently enriched in rocks and altered ground over high temperature thermal systems, (Matlick and Buzech, 1976, Capuano and Bamford, 1978) hot spring deposits in high temperature fields may contain significant concentrations of antimony, arsenic, gold, silver, and thallium, in addition to mercury.

7.0 GEOPHYSICAL TECHNIQUES FOR REGIONAL ASSESSMENT

Introduction

Geophysics typically, and appropriately, plays a major role in the exploration for and delineation of geothermal systems. Several techniques have been applied in the geologic study and problem solving phases of detailed site-specific exploration (i.e. Ward et al., 1981). The role of geophysics in regional assessment, or reconnaissance geothermal exploration is twofold: the identification of thermal provinces, and geologic characterization on a regional or crustal scale.

Thermal Methods

Regional heat flow characteristics on a national province scale have been described in an earlier section. A prudent exploration program or regional assessment utilizes the existing heat flow or thermal gradient data base compiled by government agencies and academic workers over the years. It is often cost effective to supplement this compilation with a regional scale thermal gradient program which includes temperature measurement on all exising wells for which access can be gained.

Several papers and texts describe details and refinements of the method and the results of regional or detailed heat flow studies, for instance: Lachenbruch, 1978; Sass, et al., 1971; Chapman and Pollack, 1977; Ryback and Muffler, 1981.

The limitations on the use of the thermal methods are generally imposed by the drilling program. The main factor is drilling cost, but environmental restrictions, land control, permitting, and time involved are other considerations.

One reconnaissance method to determine near-surface temperatures is a shallow temperature survey. With a hand-held or truck-mounted power auger a large number of holes are bored to depths of 1 to 2 meters (LeShack, 1977;

Olmsted, 1977). Plastic (PVC) pipe with a sealed bottom is inserted into the hole, the hole is back filled, and temperature measurements are made after the hole temperature has stabilized.

The advantage of the method is that a large number of holes can be drilled to cover a fairly large area at low or moderate cost.

The use of shallow temperature surveys has been limited because of the uncertainty that these temperatures are related to the temperature distribution at depth. The principal unknowns and disturbing factors are near-surface hydrology, soil thermal properties, topographic and slope corrections, and short-term variations. At Long Valley and Coso Hot Springs areas in California, and Soda Lakes in Nevada, however, shallow temperature measurements (LeShack, 1977; Olmstead, 1977) seem to delineate the area of anomalous heat flow in a low-cost manner. In the absence of substantial surface thermal manifestations and without obvious near-surface cold-water flow, a shallow temperature survey could be the best basis on which to plan a shallow (30-200 m) thermal gradient program. Thus there does seem to be a limited acceptance by industry of this technique (Ward et al., 1981), however.

Aeromagnetic Surveys

Aeromagnetic data can play a major role in the regional assessment of geothermal resources. Two major areas in which the magnetic data contribute are: curie point isothermal determinations; and interpretation for subsurface geologic information.

Curie point isotherm interpretations have been reported in the literature by Battacharyya (1978), Shuey et al. (1977), Aiken et al. (1981) and many others. These interpretations are dependent on many assumptions and limitations. It is assumed that long wavelength negative anomalies due to lithologic changes (i.e., alluvial basins in the Basin and Range) do not significantly perturb the interpretation, and that the bottom of a magnetized crustal block is due to temperatures above Curie point rather than to deep-seated lithologic changes. Numerous other limitations apply to the interpretational algorithms and the data themselves. Our present judgement is that: Curie point depth anomalies have been determined with unknown accuracy in some cases; it is a regional exploration guide except perhaps inactive volcanic provinces; many interpreted Curie point highs may well be lithologic changes at depth or lateral geologic changes.

Aeromagnetic surveys are widely used by industry in petroleum and mineral exploration in attempting to map subsurface structure and lithologic changes. The use in geothermal exploration should closely follow that of mineral exploration, for most geothermal resources are located in active tectonic environments characterized by a broad range of volcanic and intrusive rocks and often by active structural movement. Magnetic susceptibility often varies substantially in these rock types and provides major magnetization changes which delinate geologic units. The scale of many geothermal systems is also similar to porphyry-type mineral occurrences.

Regional aeromagnetic data are often available as part of states sponsored, USGS, (Zietz et al., 1976) or NURE (Tinnel and Hinze, 1981) magnetic survey programs. These data, as at the Baltazor and Carson Sink areas, often show major structural features and aid in forming a generalized geologic model for otherwise covered geology prospect areas. These regional data are generally too widely spaced and/or too high to warrant detailed quantitative model interpretation.

The locations of geologic structures (faults, fracture zones), intrusives, silicic domes and possibly major alteration areas (speculative) are apparent on data we have examined from: the Coso Hot Springs KGRA, CA, from Baltazor, Tuscarora, McCoy, Beowawe, Nevada from Cove Fort-Sulphurdale and Roosevelt Hot Springs, UT, and from a moderate-temperature prospect near Alamosa, CO along the northern extension of the Rio Grande Rift. Figure Gp-1 shows a portion of the Aeromagnetic Map of Utah (Zietz et al., 1976). The Monroe Hot Springs, Chief Joseph, Cove Fort-Sulphurdale, and Roosevelt Hot Springs KGRA's are all located in close proximity to a major magnetic discontinuity which trends east-west for a distance exceeding 150 km. This trend reflects the northern margin of the Pioche-Beaver Mineral trend with many intrusive and volcanic rocks to the south, and thin volcanics, Paleozoic through Tertiary sediments and few intrusives to the north. The magnetic trend clearly indicates a major tectonic-geologic feature important to geothermal resource localization.

Mabey (1980) has reported on the use of aeromagnetic data for the Raft River area of the Snake River Plain. Bacon (1981) interprets major structural trends and fault zones from aeromagnetic data in the Cascades. Couch et al. (1981) report Curie point isotherm minima of 5 to 9 km for several areas within the Cascade Mountains area, again based upon magnetic interpretation.

The general utility of the method, the applicability to numerical modeling, the low unit costs, all argue strongly for inclusion of aeromagnetic studies in the regional assessment of geothermal resources.

Gravity Methods

Regional gravity data, with station densities of 1 station per sq km to 1 station per 25 sq km, may be available as the result of USGS studies, the

Department of Defense (DOD) regional data compilation, or of university or state supported geophysical studies.

These data are often suitable for regional scale interpretations and are often the starting point for detailed survey design rather than the basis for detailed interpretation.

The contribution from gravity data is much the same as from aeromagnetics, that is, structural and lithologic information. The location of Basin and Range faults, thickness of alluvial fill and thickness of volcanic cover are problems addressed by gravity surveys for both the mining and geothermal industry. The delineation of low-density silicic intrusives, magma chambers in the Cascades, or major structural zones of crustal significance are other applications of the method. Gravity data may also contribute to the definition of deep sedimentary basins which are a different geothermal resource type.

Regional gravity data (Cook et al., 1975) provides evidence for some of the major tectonic elements present in the major geothermal province of southwestern Utah (Fig. Gp-2). A prominent north-trending 35-50 milligal gradient links these areas, bending eastward at Cove Fort, then trending northeast along the margin of the Colorado Plateau. More detailed gravity data (Cook et al., 1980) map the many faults which define the Beaver-Cove Fort graben and add substantially to the geologic model for the area. In a similar manner the gravity data have delineated major faults which probably control the geothermal fluid flow at Alamosa, CO (Mackelprang, in prep.) and at Baltazor Hot Springs (Edquist, 1980).

Regional gravity studies and their interpretation play a major role in understanding the tectonic framework of geothermal systems in the Cascade Range. Bacon (1981) reports a contiguous zone of gravity lows west of the High Cascades in central Oregon and notes that these define major structural trends and delineate fault zones which may localize the movement of geothermal fluids. The zone of gravity lows coincides with 91) an abrupt east-to-west decrease in heat flow from High Cascades values of 100 to 40 mW/m^2, and (2) a substantial east-to-west increase in depth to the lower crustal conductor defined by magnetotelluric soudings. Couch et al. (1981) report similar interpretations. Williams and Finn (1981) have described complexities in gravity data reduction especially important to the Cascade Province. They report that the large silicic volcanos (calderas exceeding 10 km diameter) produce gravity lows when proper densities (2.15 to 2.35 g/cm^3) are used for the Bouguer reduction. All other volcanos produce gravity highs as a result of higher-density subvolcanic intrusive complexes.

It would appear that gravity data contribute to a regional exploration program in most geothermal environments.

Seismic Methods

Passive seismic data which can contribute to a regional geothermal assessment include long-term historical records of major earthquake activity and microearthquake surveys.

On a regional scale, areas of high seismicity, as indicated by earthquake recording networks, define active tectonic provinces which include most areas of geothermal potential in the western United States. Unfortunately many seismic zones have little geothermal potential.

Microearthquake surveys have been completed in several geothermal areas including Coso Hot Springs and The Geysers, CA; Tuscarora and McCoy, NV; Roosevelt Hot Springs and Cove Fort-Sulphurdale, Utah and Raft River, ID. Some general observations may apply to the seismic behavior of these systems. Earthquake activity is generally episodic rather than continuous. Earthquake swarms, sometimes including tens to hundreds of events over a few days, may be typical. Earthquake magnitudes are small generally $-0.5 < M < 2.0$, with shallow focal depths generally less than 5 km. The data are interpreted in terms of P-wave delsy, S-wave attenuation, and position and alignment of epicenters.

Microearthquake surveys may lay a more important role in exploration for deeper, blind geothermal systems where cold water overflow masks near surface thermal and electrical characteristics, such as the Snake River Plain and the Cascade Province.

Seismic refraction

Seismic refraction profiles have been recorded at The Geysers, Yellowstone National park, Roosevelt Hot Springs, and probably several other geothermal areas. These studies may be appropriate for regional-scale structural or crustal studies (attenuation by magma chambers, etc.), but they do not have the spatial resolution or signal averaging appropriate for prospect-scale delineation. Hill et al. (1981) recently reported on a 270 km long profile from Mount Hood to Crater Lake in the Cascades and presented their results in terms of crustal velocity structure. These data contribute to a better understanding of regional geology and are indirectly used in geothermal exploration.

Electrical Methods

Thermal waters become increasingly conductive with increasing salinity and with increasing temperature and the long-term interaction between thermal fluids and the subsurface environment gives rise to extensive wall rock alteration (Moskowitz and Norton, 1977). The alteration produces conductive mineral assemblages such as clays and may develop additional porosity. This environment of low-resistivity pore fluids and conductive mineral assemblages is often a good target for the electrical exploration techniques.

Magnetotelluric (MT) Studies

The magnetotelluric (MT) method is routinely used in both the reconnaissance and detailed stages of geothermal exploration. The earth's electric and magnetic fields vary as a function of frequency in response to natural electrical (telluric) currents flowing within the earth's crust. Through precise measurements of the electric and magnetic field components made at the surface, one may obtain information relating to the impedance distribution (i.e., electrical resistivity) to depths greater than 40 km within the earth's crust. The reader is referred to an excellent paper by Vozoff (1972) for a detailed description of the method.

Ward et al. (1981) noted that MT was used in most of the Basin and Range exploration programs which they reviewed. They attribute this to its adverstised great depth of exploration and ability to detect the hot rock source of heat at depths of several tens of kilometers. Neither of these attributes is necessarily correct. For a three-dimensionally inhomogeneous earth, one's ability to predict the distribution of resistivities at depth is severely limited by the influence of surficial conductors such as alluvial fill or shallow alteration zones (Wannamaker et al., 1980). The conductivity of magma at elevated temperatures is strongly dependent upon the partial pressure of water (Duba, 1974).

Stanley (1981) described a regional, 97 station, MT survey for the Cascades Volcanos region. In addition to generalizing the resistivity structure for 0 to 10 km depth, he interprets a lower crustal conductor ($\rho < 5$ ohm-m) at 10-22 km depth, which may be due in part to a partial melt associated with Cascade volcanoes. The MT method does seem applicable to regional, academic-oriented studies and jointly funded reconnaissance surveys.

Electrical Resisitivity

Electrical resistivity data are routinely acquired in geothermal exploration on the detailed, site specific scale but are less frequently used in regional or reconnaissance exploration. Schlumberger soundings are often conducted at many scattered sites within a large region and depth to a given (conductiveπ) horizon contoured from these data. Although the array is efficient for data acquisition the assumption of one-dimensional environments, as current electrodes expand across structures or other lateral resistivity contrasts. Thus the results are often misleading even for a regional assessment.

The USGS and some survey contractors have promoted the bipole-dipole or roving dipole array for reconnaissance resistivity surveys. In this array current is introduced through a long (one to two km) transmitting dipole and voltage drops are observed at two short (0.2 to 0.5 km) orthogonal receiving dipoles two to ten km distant. The reduced resistivity values are contoured and then considered to represent large scale resistivity variations at substantial (one to five km) depths. Although the generalization is often valid, the reduced resistivity values are strongly dependent on the local resistivity distribution in the vicinity of the transmitting dipole. The data are difficult to interpret accurately and are in general only appropriate for regional scale interpretation. In view of these complications for reconnaissance resistivity arrays, the resistivity method plays a relatively minor role in regional assessment in contrast to a key role in detailed site-specific exploration.

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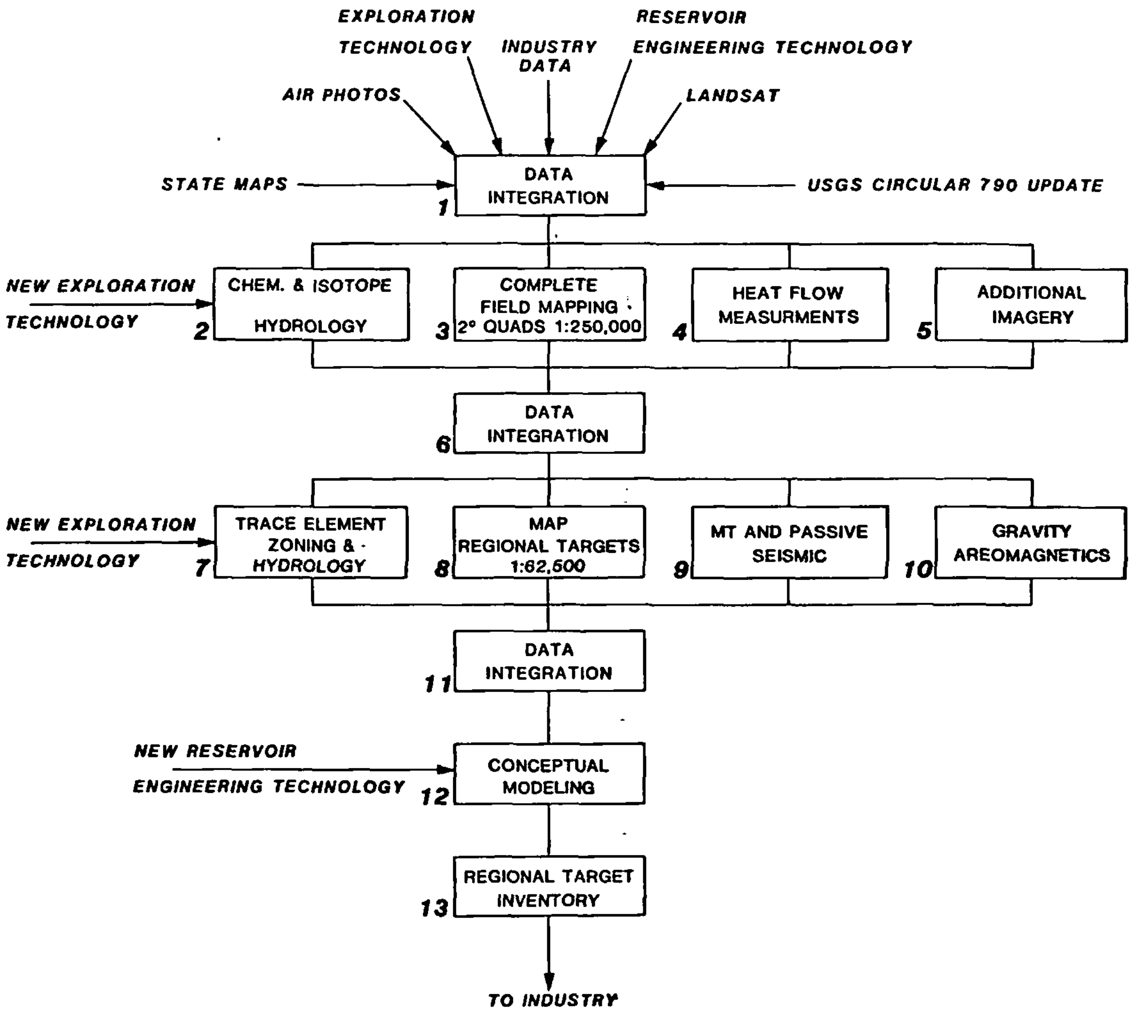

- *FIRST DATA BASE*
- *SECOND DATA BASE*
- *REGIONAL TARGET DEFINITION AND PRELIMINARY RESOURCE TEMPERATURE AND TYPE ASSESSMENT*
- *THIRD DATA BASE*
- *REGIONAL TARGET REFINEMENT AND FINAL RESOURCE TEMPERATURE AND TYPE ASSESSMENT*