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Exploration Strategy for High-Temperature Hydrothermal Systems in Basin and Range Province[1]

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ABSTRACT

A 15-phase strategy of exploration for high-temperature convective hydrothermal resources in the Basin and Range province features a balanced mix of geologic, geochemical, geophysical, hydrologic, and drilling activities. The strategy, based on a study of data submitted under the Department of Energy's Industry Coupled Case Study Program, provides justification for inclusion or exclusion of all pertinent exploration methods. With continuing research on methods of exploration for, and modeling of, convective hydrothermal systems, this strategy is expected to change and become more cost-effective with time. The basic strategy may vary with the geology or hydrology. Personal preferences, budgetary constraints, time and land position constraints, and varied experience may cause industrial geothermal exploration managers to differ with our strategy. For those just entering geothermal exploration, the strategy should be particularly useful; many of its elements may apply in other geologic settings.

INTRODUCTION

Geothermal energy is derived from the heat of the earth. The average heat flowing conductively to the earth's surface is 0.08 W/sq m. If we multiply this value by the total surface area of the earth (5.1×10^{14} sq m), we obtain the total heat flowing from the earth as 4.1×10^{13} W or 41,000,000 MW. 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. Within the Basin and Range province the most important high-temperature resource type, and the one with which this paper will be specifically concerned, is the convective hydrothermal system.

A generalized model of a convective hydrothermal system is shown in Figure 1. By way of fractures and faults, cold meteoric water descends to the vicinity of a heat source where it heats and convects upward through other structures to the upper parts of the system. Here it is discharged as hot springs, flows laterally along permeable horizons, or is prevented from escaping by a cap rock of low permeability. Many systems may reach temperatures of over 350°C, although temperatures of 275°C and less are more common. In relatively rare instances, boiling at the upper surface of a water table may produce a vapor-dominated hydrothermal system (White et al, 1971).

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.

CHARACTERISTICS OF CONVECTIVE HYDROTHERMAL SYSTEMS

Although generalized cross sections of convective hydrothermal systems (Fig. 1) are instructive for showing basic characteristics, these systems are much more complex than the figure indicates. Indeed, the lower parts of the systems, and in particular the heat sources, are speculative. In this paper we shall refer to specific hydrothermal systems in Nevada and Utah (Fig. 2). Figures 3, 4, and 5, as examples, show interpreted cross sections through the upper parts of geothermal systems at Roosevelt Hot Springs, Utah, Cove Fort–Sulphurdale, Utah, and Leach Hot Springs, Nevada. These figures emphasize the structural geology of these areas; unfortunately insufficient work has been done to document the fluid-flow paths within them. Roosevelt Hot

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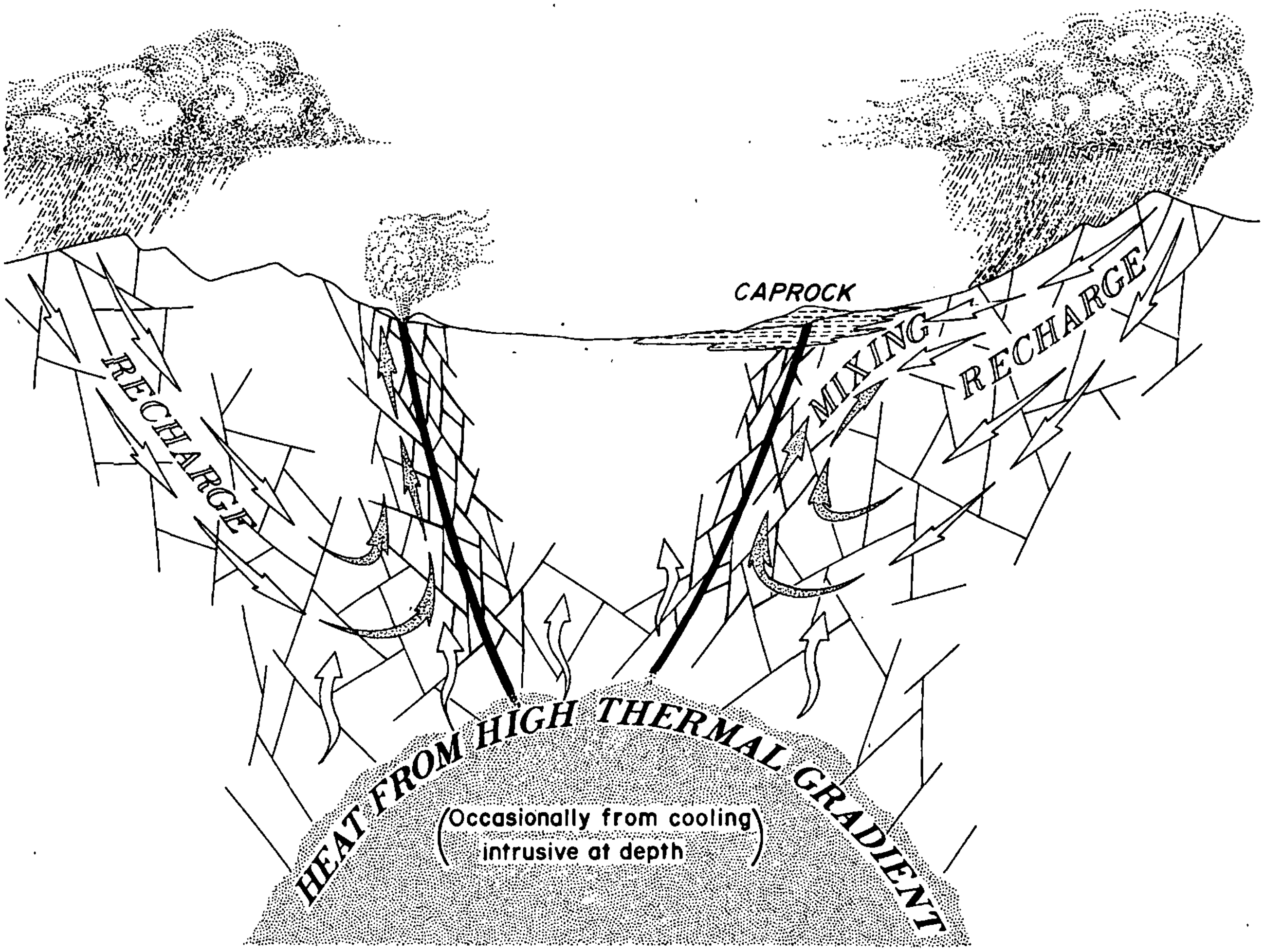


FIG. 1—Generalized model of convective hydrothermal system.

Springs is thought to derive its heat from a cooling magma body at depth; sources of heat for the other systems are unknown, but it is speculated that these systems derive their heat from deep circulation along faults in zones of high thermal gradients.

Figures 3 through 5 show that hydrothermal systems within the Basin and Range province are structurally complex and require two- and three-dimensional modeling. All have undergone several periods of faulting and some have undergone repetitive igneous intrusion. Therefore, it is crucial for the explorationist to understand which of the structures in such areas controls the hydrothermal system and to separate the latter from structures which do not channel fluids but only complicate the geology. Clearly the structure must be understood early in the exploration process for an exploration program to be conducted efficiently (Nielson and Moore, 1979).

In addition to the geologic complexity of the Basin and Range province, practical considerations must be taken into account in defining individual exploration strategies. Extreme topography in some areas complicates not only the performance of geophysical surveys but also the modeling of the results of those surveys (Fox et al, 1978). The presence of playas may negate the usefulness of some of the electrical surveys commonly used in the exploration process. In addition, saline ground waters common in this environment can produce misleading interpretations if the common chemical geothermometers are not correctly applied. The complexity of the basin fill in this province can result in stacked aquifers separated by impermeable horizons. This clearly presents problems for the interpretation of thermal measurements. The basin-fill alluvium and volcanic rocks often negate the usefulness of the seismic techniques. Our experience with the limitations of individual methods is discussed in a subsequent section.

NORTHERN NEVADA PROGRAM

In an attempt to accelerate the development of high-temperature geothermal resources by private industry, the Department of Energy, Division of Geothermal Energy, initiated the Industry Coupled Case Study Program in 1977. The program is designed to offset high initial costs and reduce exploration risk through cost-sharing with industrial partners. In exchange for the government funding, all technical data obtained as part of the agreed-upon exploration program are released to the Department of Energy and made public. In addition, a substantial amount and a variety of existing data generally emphasizing early stage exploration are acquired as part of the DOE/Company contract.

Phase I of the Industry Coupled Case Study Program resulted in contracts for work at two major geothermal systems in southern Utah. Phase II includes work at 12 high-temperature systems in northern Nevada. A summary of the data packages already submitted or forthcoming under Phase II, supplemented by a coherent program from one Phase I area, is presented in Table 1.

Although one or more companies have not submitted all of the geoscience exploration data they obtained for a given area, and hence the data reported may not be a complete list of exploration techniques used, we believe this summary reflects a representative sample of the methods used by the various companies. One is immediately impressed by the diversity of exploration strategies, although certain common denominators are evident as shown in Table 2.

PREVIOUS STUDIES

Ward (1977) summarized the exploration strategies from the literature up to the time of his writing. He referenced articles by Banwell (1970, 1974), Combs and Muffler (1973), Dolan (1975), Furumoto (1976), B. Greider (1975, unpub. ms.), McNitt (1976), and Meidav and Tonani (1976), and showed a strategy containing elements common to his own analysis for the eastern Basin and Range province and to those of the other referenced authors for the areas with which they were then familiar.

McEuen et al (1979) provided analyses of exploration architectures required for each of 12 different physiographic provinces. Their report used tables from an earlier report by Dhillon et al (1978). Table 3 (after Dhillon et al, 1978) lists the applicability of various methods obtained from sampling 35 opinions from individuals and companies. The differences between Tables 2 and 3 are numerous. The common conclusions

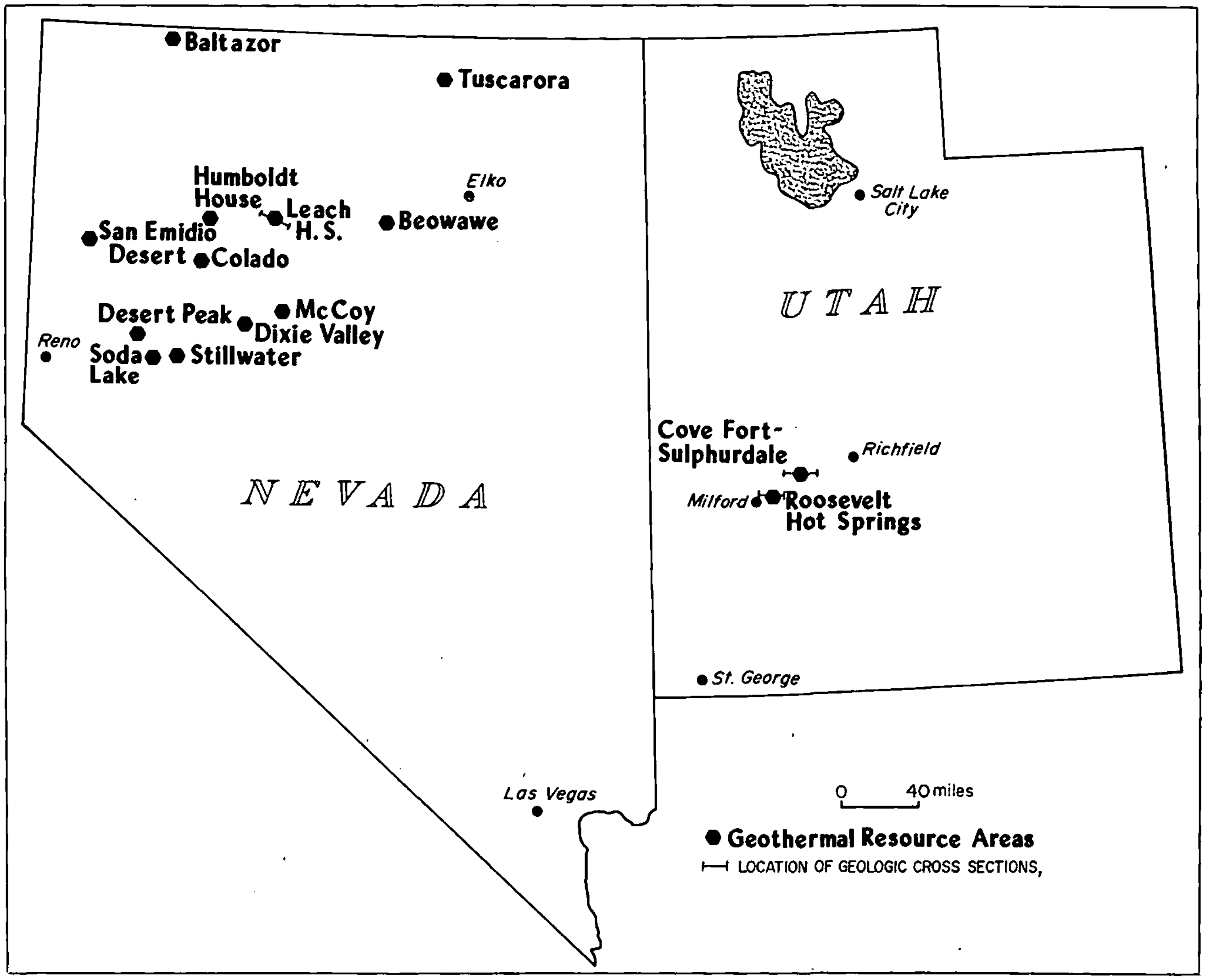


FIG. 2—Index map of Industry Coupled Program hydrothermal systems. Indicated cross sections shown on Figures 3, 4, and 5.

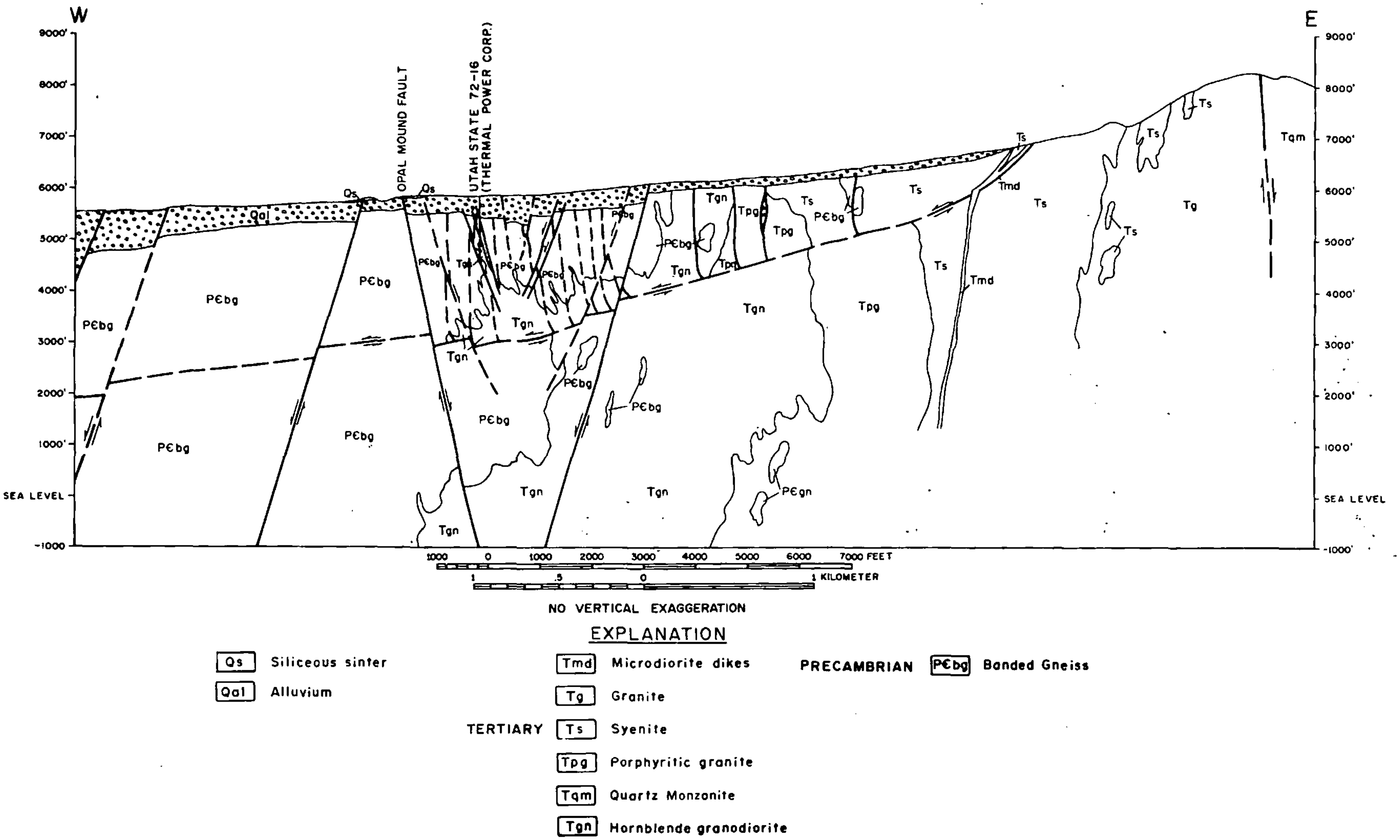


FIG. 3—Geologic cross section of Roosevelt Hot Springs KGRA, Utah (Nielson et al, 1978). Depths are in feet. For location, see Figure 2.

from comparison of the two tables are: (1) thermal methods rank universally highest; (2) surface geology mapping is usually but not always employed; (3) gravimetry is usually employed; (4) some form of electrical method is usually employed; (5) seismic, magnetic, and geochemical methods fall somewhat lower on the priority list; (6) geology and fluid geochemistry, ranked 2 and 3 by Dhillon et al (1978) are poorly represented in the deliverables from the Industry Coupled Case Study Program.

Goldstein (1977) earlier had made an analysis similar to that of the MITRE Corp., but he restricted his attention to northern Nevada. Ball et al (1979) presented an exploration, assessment, and confirmation strategy for the high-temperature resources in the eastern part of the Basin and Range province. Their conclusions are similar to the preceding six conclusions with the exception that photographic imagery and geochemical methods are of high priority in the reconnaissance phase of exploration whereas active seismic methods are of high priority in the detailed phase.

CURRENT ASSESSMENT OF METHODS

We will now consider the methods individually as listed in Table 1 and evaluate their applicability in the

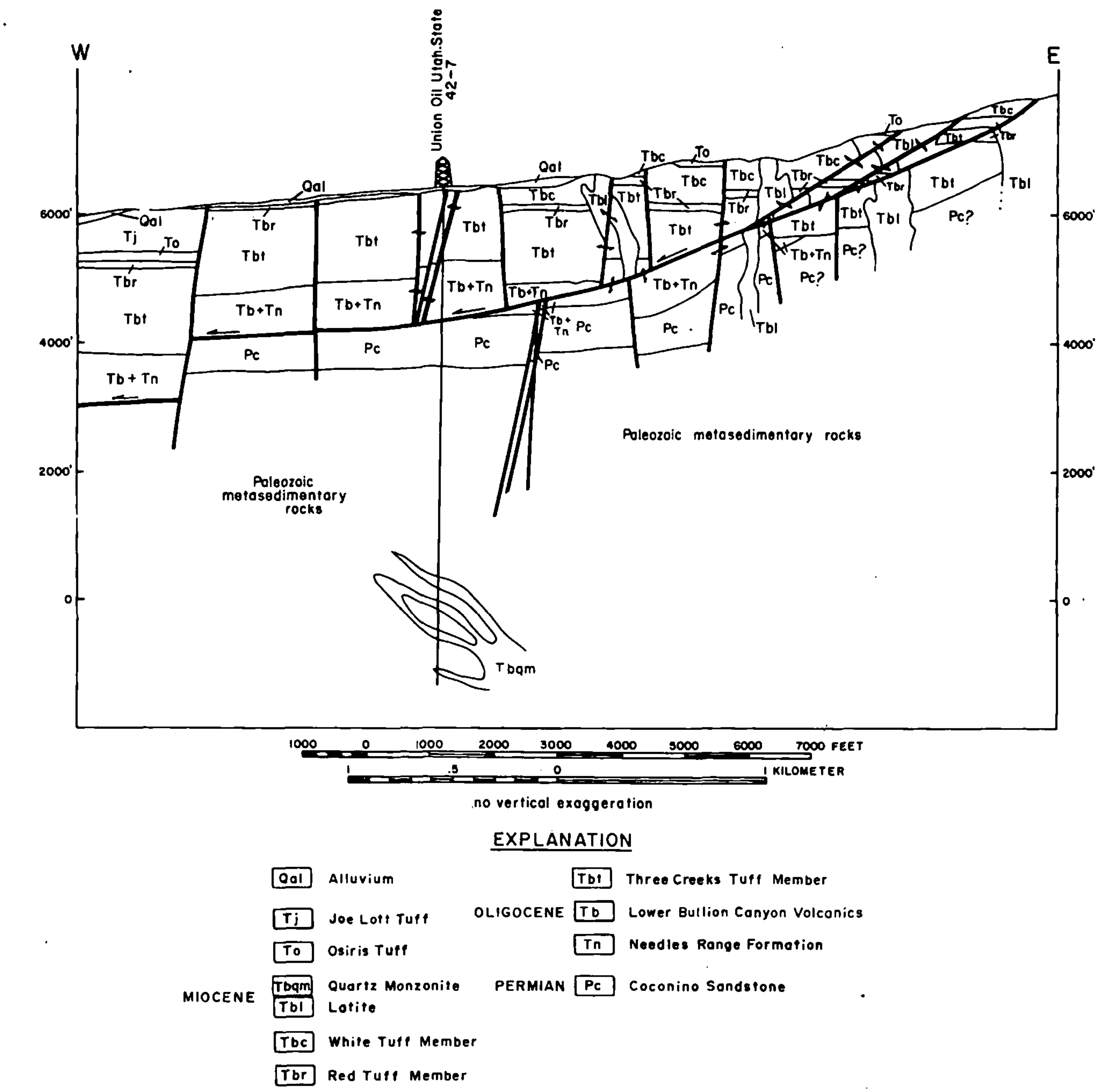
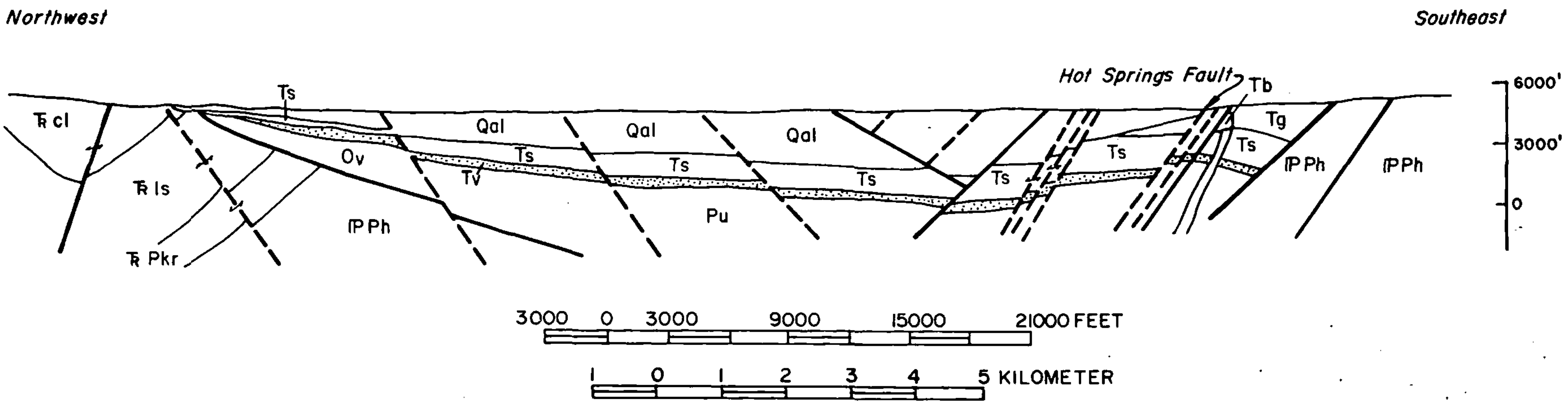


FIG. 4—Geologic cross section of Cove Fort-Sulphurdale KGRA, Utah (Moore and Samberg, 1979). Depths are in feet. For location, see Figure 2.



EXPLANATION

QUATERNARY	Qal	Alluvium		TR cl	Triassic clastic rocks
	Tb	Basalt	MESOZOIC	TR ls	Triassic calcareous rocks
	Tg	Gravel		TR Pkr	Koipato formation
TERTIARY	Ts	Sediments and tuffaceous rocks		IP Ph	Havallah sequence
	Tv	Intermediate to acidic volcanic rocks	PALEOZOIC	Ov	Valmy formation
				Pu	Undifferentiated Paleozoic rocks-complexly folded and faulted

FIG. 5—Geologic cross section of Leach Hot Springs KGRA, Nevada (Beyer et al, 1976). Depths are in feet. For location, see Figure 2.

Basin and Range province for areas of some surface expression.

Geologic Mapping

Our evaluation of the exploration efforts included in the Industry Coupled Case Study Program is that geologic mapping is always used in the early program stages, both regional and reconnaissance, but is then largely ignored until drill cuttings return from the first exploration hole. Detailed (1:24,000) geologic mapping of a prospect-size area, 20 to 60 sq km, is not generally done. Instead shortcuts are taken which include compilation of existing maps, photogeology, and perhaps only routine application of several geophysical methods. Complete alteration and structural studies often are omitted or are underfunded.

Our observations reveal that inadequate geologic

Table 1. Geothermal Exploration Strategy Indicated by Industry Coupled Program Data Packages

Data	Baltazor (EPP)	Tuscarora (AM)	McCoy (AM)	Leach H.S. (AO)	Colado (G)	Beowawe (G)	Beowawe (C)	San Emidio (C)	Soda Lake (C)	Stillwater (U)	Dixie Valley (SR)	Desert Peak (P)	Humboldt H. (P)	Cove Fort-Sulphurdale (U)
Gravity	E	X	X	E	E	X		E		E		E	E	E
Ground Mag.					E	X						E		
Aeromag.	E	X	X				E				E			E
Elec. Res.					E	X	E	E	E	E				E
Magnetotelluric		X	X	X	E		E		E	E	E	E	E	
Audio Magnetotelluric					E									
Self Potential		X	X				E	E						
Seismic Emissions							E	E						E
Microearthquake	E	X	X				E							
Seismic Refl. (weight drop)							E		E					E
Seismic Refl. (CDP12 or 24 fold)			X	X			X	E	E					
Geology	E			E				E			E X	E	E	E
Geochemistry	E			E							E			E
Shallow Temperature											X			
Shallow Thermal Gradient	E	E X	E X	X	E X	X		E	E	E	E			E
Deep Thermal Gradient	X	X	X	X	X	X			E X		E X	E		E
Exploration Well	X	X	X	X	X	X	E	E	E	E	X	X	X	E X
Flow Test (if appropriate	X	X	X	X	X	X	X			X	X	X	X	X

*See Figure 2 for locations.

Company Explanation:

EPP — Earth Power Production
AM — Amax Exploration Inc.
AO — Aminoil USA, Inc.
G — Getty Oil Co.
C — Chevron Resources Co.
U — Union Oil Co. of Ca.
SR — Southland Royalty Co.
P — Phillips Petroleum Co.

E = EXISTING DATA

X = NEW PROGRAM

Table 2. Technique Use by Industry Coupled Case Study Program

Method	Cases (%)	Priority
Shallow Thermal Gradient (~100 m)	71	1
Deep Thermal Gradient (~600 m)	71	1
Magnetotelluric (MT)	71	1
Gravity	71	1
Magnetics	57	2
Geologic Mapping	50	3
Resistivity	50	3
Passive Seismic	43	4
Active Seismic	43	4
Self Potential	29	5
Geochemistry	29	5

mapping by companies may result, for example, in geophysical survey lines along major structures and thermal gradient holes being drilled inadvertently on structural intersections. Without proper recognition of these geologic features, and the bias they interject into the geophysical measurements, the survey or temperature data can be misinterpreted. We believe that detailed geologic mapping would be cost-effective as soon as a commitment is made to acquire land. This commitment would imply intent to carry out a shallow thermal gradient survey and supportive geophysics, as a minimum effort.

We do not naively ignore the possibilities of alluvial or even volcanic cover which may not warrant detailed mapping. This must be assessed as the project proceeds. Neither are we unaware of problems of land acquisition and needs for preliminary encouragement to sell an area to management. We recognize that these considerations may prevent a systematic geologic program.

We presume that detailed mapping is often omitted because it takes longer, requires an experienced and well-trained staff, and is generally still in progress when the geophysical results are obtained. We envision a continuing mapping program, depending on existing maps and outcrop availability, which would allow 1:24,000-scale mapping prior to drilling thermal gradient holes and completing detailed electrical or seismic surveys. Subsequently the base could be refined to include fracture and alteration mapping at 1:12,000 or 1:6,000 for those parts of the area which seem to have most potential. This level of mapping would be completed prior to siting deep thermal-gradient tests or exploration wells.

In conjunction with geologic mapping, it is often desirable to collect suites of samples for petrographic analysis, physical property measurements, geochemical orientation surveys, and potassium-argon and fission-track dating. The locations of these samples should be documented carefully to aid in interpretation of results.

Geochemistry

Aqueous geochemistry ranks third in usage in Table 3, and is probably not correctly represented by the deliverables in Tables 1 and 2. Chemical geothermometry and aqueous geochemistry of available springs and wells is common to most regional and reconnaissance efforts (Truesdall, 1976; Fournier, 1977). It is certainly practiced in the thermal-gradient and exploration-well stage also. The low ranking of geochemistry in Table 2 indicates that geochemical data were not submitted as a deliverable item. The low ranking could also represent the limited interest in soil geochemistry and trace-element surveys. Ewers and Keays (1977) reported well-developed zoning of volatile elements and precious metals in the Broadlands geothermal field, New Zealand. As our case studies and technique development work proceed, we find multielement zoning patterns have developed about high-temperature geothermal systems and about high-temperature fluid entries in geothermal wells (Bamford, 1978). Fluid entries have also been effectively delineated by oxygen isotopes and hydrothermal mineralogy (Browne, 1970; Kendall, 1976; Elders et al, 1978). To a large extent the distribution of radon and mercury can be used to locate zones of past and present permeability and as such can be an aid in mapping and siting of drill holes (Capuano and Bamford, 1978; Nielson, 1978).

Hydrology

No hydrologic data packages were submitted under the Industry Coupled Case Study Program, although we are aware that most companies do not neglect this fundamental data set. Regional hydrologic data are available for many of the basins in the Basin and Range, and this is undoubtedly considered in the initial compilation stages of the project. Such information as number of aquifers, elevation of water table, regional-flow patterns, and water chemistry can be extremely valuable in the initial stages of the exploration program. In addition, hydrologic information is often collected in conjunction with thermal-gradient drilling.

Gravity Method

Gravity methods are often employed. A regional gravity map, with a station density of 1 station per 3 sq km to 1 station per 25 sq km, is generally available as the result of U.S. Geological Survey (USGS) regional studies, of the Department of Defense regional data compilation, or of university-related geophysical studies. Many compilations of these data have been accepted as adequate and several companies supplement this base with detailed profiles. The method offers a relatively low-cost delineation of shallow Basin and Range faults and of alluvial thicknesses. The resolution of these features improves with quantitative numerical modeling but the method is often limited by spatial wavelength aliasing, inadequate density information, relatively small density contrasts, and lack of precise elevation control.

Ground Magnetic Method

Ground magnetic data are sometimes acquired as an addendum to the gravity survey at a modest additional

Table 3. Regional Applicability of Exploration/Assessment Technique*

Technique	Overall	Salton Trough	Basin And Range	Cascades	Basaltic Island Region	Snake River Plain	Wasatch Front	Rio Grande Rift	Geysers	Aleutian Arc Island	Appalachian	Eastern And SE Plutons	Geopressured
Thermal Method	1	1	1	1	2	1	1	1	1	1	1	1	2
Surface Geologic Mapping	2	9	2	2	1	2	2	2	2	2	3	5	9
Gravimetry	3	2	7	5	4	3	7	7	3	4	2	2	5
Electrical Methods	4	3	4	3	3	8	4	3	8	5	8	6	7
Borehole Logging	5	5	8	10	10	4	8	9	7	3	15	4	1
Seismic Methods	6	4	5	8	6	6	5	5	6	6	9	7	3
Liquid Geochemistry	7	6	3	4	5	9	3	4	5	7	6	8	4
Air Photogeology	8	7	6	7	8	5	9	8	4	9	7	9	12
Age Dating	9	10	9	6	7	7	6	6	9	8	10	10	14
Magnetics	10	8	10	9	9	10	10	10	10	11	4	3	6
Gas Geochemistry	11	11	13	13	11	13	13	13	11	12	11	12	8
Remote Sensing	12	12	12	12	13	11	11	11	12	13	12	11	10
Thermal Infrared	13	13	11	11	12	12	12	12	13	10	13	13	11
Other	14	14	14	14	14	14	14	14	14	14	14	14	13

*After Dhillon et al (1978).
1 = Most Applicable to 14 = Least Applicable

charge. The typical station spacing for a gravity survey may severely limit the spatial frequency content of the magnetic survey and considerably reduce its utility. Near-surface magnetic contrasts, arising mainly from Tertiary volcanic rocks within a mountain range or at shallow depth in the alluvium often dominate the ground magnetic survey and this, coupled with a limited survey area, reduces the interpretative value of the survey data. As expected, and as Table 1 demonstrates, airborne magnetic surveys are favored by most of the geothermal companies.

Aeromagnetic Method

Regional aeromagnetic data are generally available for the Basin and Range province as part of the USGS regional mapping programs. These data are normally obtained as high-altitude barometric flights with a 2 to 4-km flight-line separation. These data, as at the Baltazor and Carson Sink areas, often show major structural features and aid in forming a generalized geologic model for the prospect area. The data are not sufficiently detailed to warrant quantitative model interpretations or accurate delineation of structural or intrusive features. Follow-up surveys have often been flown at a 0.5 to 1-km line separation as draped flights 50 to 300 m above the mean topographic surface.

Data packages submitted as part of the Industry Coupled Case Study Program and discussions with companies and contractors indicate some interest in Curie point isotherm interpretation of magnetic data. Selected profiles have been flown at several altitudes in an attempt to refine these interpretations. The Curie point interpretation as applied to most known Basin and Range target areas has several problems: (1) the lateral extent of the Curie isotherm high is several times the size of a typical deep fault circulation system; (2) interference at this scale of reversely polarized volcanic units and widely varying susceptibilities complicates the interpretation; (3) there is uncertainty in determining the depth to the bottom of a prism model. Shuey et al (1977) have discussed these and other problems with Curie depth determinations. Yet another problem is multilevel data interpretations which assume two-dimensional geology in far more complex settings.

Magnetotelluric (MT) Method

If one were to accept Tables 1 and 2 at face value, then the MT method would be recommended for use in hydrothermal system exploration due to its advertised attributes of great depth of exploration and ability to detect the hot rock source of heat at depths of several tens of kilometers. Unfortunately, neither of these attributes is necessarily correct. In 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, 1978). That a hot rock, when molten, is necessarily a good conductor of electricity must be conjectural, for conductivity in magma at elevated temperature is dependent upon the partial pressure of water (Duba, 1974). Hot dry rocks are good insulators almost by definition. If one uses only the standard one- or even two-dimensional MT interpretation methods when dealing with a three-dimensional earth, then one has no assurance that the method is capable of detecting a hot rock source by means of its assumed high conductivity. Means for surmounting this latter problem are evident (Wannamaker et al, 1980) but are seldom applied. Accordingly, we do not recommend using the MT method until late in the exploration sequence when one is justified in applying the higher cost techniques. The poor lateral resolution of MT interpretation does not make the method well-suited for siting a drill hole to intersect a given structure in the advanced stage of exploration, but it may be used effectively by a consortium of companies for early reconnaissance evaluation of a region.

Electrical Resistivity Method

Resistivity surveys, particularly with the dipole-dipole array, have been used by many companies. A major limitation is the sensitivity to geologic changes at depth which is no more than twice the electrode separation, that is, generally in the range of 600 m for a 300-m dipole using dipole spacings to $n = 6$ (Roy and Apparao, 1971; Ward et al, 1978). The survey data are sensitive to lateral variations in resistivity, and hence are generally well suited to delineation of high-angle structures, but are not sensitive to dip. Through detailed numerical modeling (Beyer, 1977), a useful map of intrinsic resistivity distributions to depths of 500 m can be generated. At Roosevelt Hot Springs and Cove Fort–Sulphurdale, Known Geothermal Resource Areas (KGRAs) in Utah, low (5 to 10 ohm-m) resistivity zones have been mapped which are probably related to hot, conductive fluids and large zones of wall-rock alteration. Similar results have been obtained for several prospects in northern Nevada.

Self-Potential (SP) Method

Self-potential surveys are being used by a few of the major firms engaged in geothermal exploration. Recent papers by Corwin and Hoover (1979), Fitterman (1979), and Hulse (1979) present a theoretical basis and observed data showing the utility of the method for geologic mapping and geothermal exploration. Our observations are that either polar or dipolar patterns of self-potential anomalies can occur in the Basin and Range province. Sometimes the two patterns are superimposed. Ambiguity in interpretation must therefore be expected. Anomalous patterns often relate to known geologic structures, suggesting a dominant role for the electrokinetic as opposed to the thermoelectric coupling models. Some geophysicists have stated, off the record, that SP surveys are their most cost-effective exploration method, but this may be in part a commentary on the relatively low cost of field surveys. We would reserve their use for a late stage of exploration when resistivity data are also available and where any clue to fluid flow is helpful and justifiable to offset high drilling costs.

Passive Seismic Methods

Within this category fall all the earthquake, microearthquake, and seismic noise or emissions thought to relate to hot-spring or deep-reservoir activity and to active structural deformation. Areas of thick alluvial cover often manifest high noise levels which may obscure the reservoir signature sought in many seismic-noise surveys, if such signature exists (Katz, 1976). Liaw and McEvilly (1979) discussed these problems as evident in studies at Grass Valley, Nevada, and Douze and Laster (1979) discussed them in relation to studies at Roosevelt Hot Springs. The relative cost-effectiveness of the passive seismic methods in locating hidden reservoirs is still very much in doubt, as indicated by limited acceptance (Tables 1, 3) and the conclusions of a recent workshop devoted to these methods (Ward, 1978).

Reflection Seismic Methods

We have inspected reflection seismic data for several Basin and Range geothermal areas including Roosevelt Hot Springs KGRA, Utah, and San Emidio, Soda Lake, and Beowawe in Nevada. The data are generally of two types: shallow penetration weight-drop-type seismic surveys and conventional 12- or 24-fold CDP surveys with various types of processing. The data from the shallow surveys are ambiguous in interpretation and are best evaluated in terms of outcropping geology and other geophysical data. Although the cost is relatively low, it is not apparent that these latter data are cost-effective in structural and bedding delineation in the typical Basin and Range geothermal areas.

Conventional seismic surveys appear to give good definition of Basin and Range border faulting and depths to the base of alluvial fill at Roosevelt Hot Springs KGRA, Utah, and Soda Lake, San Emidio, and Grass Valley, Nevada. In an area of limited outcrop, such as the Carson Sink region, the reflection seismic method would appear to be cost-effective in the delineation of structures and bedding to depths of about 1,000 m. One seismic line which crosses the Mineral Mountains at Roosevelt Hot Springs KGRA shows little obvious lithologic or structural information within the range itself, or within the reservoir, but substantial structural information along the range front. At Beowawe, extensive and varied digital processing was ineffective in eliminating the ringing due to a complex near-surface volcanic section. Majer (1978) found reflection data extremely useful in delineating structure in Grass Valley, Nevada. The cost of this method and the mixed results observed argue against its routine inclusion in a geothermal exploration program. However, where the geology appears to be permissive for reasonable reflection quality, and where predictable acoustic contrasts exist, this may be the most cost-effective way to site exploration wells.

Thermal Methods

The thermal methods are clearly recognized as the most direct indicator of the geothermal resource as indicated in Tables 1-3. Shallow temperature measurements in holes 1 m deep are seldom used because of unknowns in near-surface hydrology, soil thermal properties, topographic corrections, and short-term variations. At the Long Valley and Coso Hot Spring areas in California, and Soda Lakes, Nevada, however, shallow temperature measurements (Le Shack, 1977; Olmsted, 1977) seem to delineate the area of anomalous heat flow in a low-cost manner. In the absence of substantial surface thermal manifestations or favorable geology and without obvious near-surface cold-water flow, a shallow temperature survey of about 5 to 20 sq km could be the best basis on which to plan a shallow (30 to 200 m) thermal gradient program.

Shallow thermal gradient holes ranging from 30 to 200 m deep are almost always used. The holes are logged for temperature and the chips can be used in stratigraphic, alteration, and geochemical studies. In many places it is advisable to measure thermal conductivities and determine heat-flow values. The thermal gradients and observed temperatures still may be influenced by shallow ground-water flow which may obscure or offset the deep thermal anomaly. The omissions of a shallow thermal gradient program in Table 1 probably reflect in two examples data obtained but not submitted as part of the Industry Coupled Case Study Program. In the third example, an exploration well was drilled directly on surface geothermal features and previous high-temperature drilling results. The need for a more systematic thermal gradient data base has since been recognized and was recently completed as a supplemental part of the DOE/Company program.

Deep thermal gradient holes may range in depth from 300 to more than 1,000 m, but generally are in the 300 to 600-m range. The ratio of shallow to deep thermal gradient holes varies but typically is between 1 to 5 and 1 to 10. Results from these holes will help determine the siting of exploration wells (Benoit, 1978).

STRATEGY

As indicated in the foregoing, hydrothermal convection of fluids through structures is a phenomenon that occurs in high-, moderate-, and low-temperature environments. Although systems are basically similar, each has its own unique characteristics. Thus, although a general exploration strategy for hydrothermal systems can be proposed, the strategy will require some modification to fit the demands of most individual exploration projects.

We propose the formulation of exploration models and the constant updating of these models as exploration proceeds. We feel that the most efficient exploration programs are based on a knowledge of the physical/chemical processes within a convection system and interpretation of the geologic, geochemical, geophysical, and hydrologic manifestations of these processes. For each increment of exploration dollars, these models should be updated and the important controlling parameters of systems should be documented, analyzed, and understood. A genetic model is the end point of the entire process with the exploration model approaching the genetic model with each new increment of data. In short, it is not necessary to understand fully a system to explore it; it is sufficient to understand the fundamental processes of a system and to understand its detection by various exploration tools.

Figure 6 portrays our recommended basic strategy for exploring for high-temperature hydrothermal resources in the Basin and Range province in areas of surface thermal manifestations. As noted earlier, modifications to this strategy may be required for specific prospects. The strategy assumes that one starts with a nominal district of 3,000 sq km and finds one high-priority prospect in this area which eventually demands a production test. If other prospects are found in the district, they are herein considered of lower priority than the one drilled for production. We consider that the strategy recommended is a minimum one, yet its cost through drilling and logging and subsequent reservoir modeling is estimated to be $4.6 million if both seismic reflection and magnetotelluric surveys are included.

Where do these costs arise? Each box in the flow diagram of Figure 6 depicts a function or functions whose cost estimate is shown on the right of the box. The sequence of events in the flow diagram has been carefully considered to provide the most cost-effective data gathering consistent with the risk involved. By design, the risk of failure should become less as one moves downward in the diagram, that is, forward in time, so that higher cost or less demonstrated, yet promising, exploration techniques can be justified late but not early. Let us discuss each box, by number.

Literature and Data Search, Compilation, and Analysis (Fig. 6, Box 1)

Invariably, aerial photography, satellite imagery, regional geologic maps, water chemistry, regional gravity data, regional aeromagnetic data, plus relevant geologic reports are available prior to a company's entry into a district. The functions of box 1 dictate that these data must be located, compiled, analyzed, and integrated as a basis for designing the rest of the exploration strategy.

Subsurface information is often available from water wells and oil tests. This material is of use in defining basin stratigraphy, regional hydrologic patterns, and occasionally subsurface temperatures. Compilation of well locations and depths is important for defining the location of wells to be sampled during the district reconnaissance stage.

Chemical and Isotopic Analyses of Waters (Fig. 6, Box 2)

Where the chemistry and light stable isotope analyses of spring and well waters are available in a district, these data are utilized in empirical geothermometric formulae to predict the temperature of last water-rock equilibration, hoping thereby to predict the temperature of the hydrothermal fluid in the reservoir. If the analyses are not available or are of uncertain reliability, the collection and analyses of spring and well waters are usually made. Although the water-temperature predictions from such analyses have uncertainties due to fluid mixing and to the effects of soluble components in wall rocks unrelated to the thermal event, they are nevertheless extremely useful in locating prospects.

During sampling of available wells, pertinent hydrologic data, such as depth to the water table, should be collected.

Initial Field Mapping (Fig. 6, Box 3)

With air photos, imagery, and geologic maps in hand, initial field mapping can be designed to coincide with the initial geochemical sampling and thermal-gradient measurements. Collection of samples of young volcanic and intrusive rocks should be performed at this time. Geologic maps at a scale of 1:62,500, or even more detailed, are available for parts of the Basin and Range province, but these maps are of variable quality and usefulness for the geothermal explorationist. If the area under consideration contains known geothermal resources, it is often advisable to map it in detail at an early stage to document the structural and lithologic controls. Reconnaissance mapping at this stage will also confirm the quality of existing maps and will be valuable in interpreting features defined by the aerial photography. Analysis of these results and the data collected simultaneously in boxes 2 and 4 provide an excellent data base for the definition of a prospect of greater interest.

Thermal Gradients, Available Holes (Fig. 6, Box 4)

Many companies concerned with exploration for high-temperature hydrothermal resources have vigorous programs of measuring temperatures versus depth in all available water wells, oil and gas wells, and mining drill holes. This reconnaissance data collection can be extremely valuable in pinpointing hot spots, but care must be taken to evaluate such effects as cold-water mixing and overflow.

Prospect Mapping (Fig. 6, Box 5)

The homework and district-reconnaissance studies of boxes 1 through 4 invariably lead to identification of a number of prospects. Although not all hot spots are found in the district reconnaissance studies, those that are found are typically given priority and are mapped. We consider it important that, providing exposures are suitable, geologic mapping at a scale of approximately 1:24,000 be done early in the prospect-evaluation stage. Depending on the complexity of an area, a geologist can generally cover a minimum of 3 sq km per day. Thus several man-weeks of effort can generate a detailed geologic map which will be invaluable in planning and

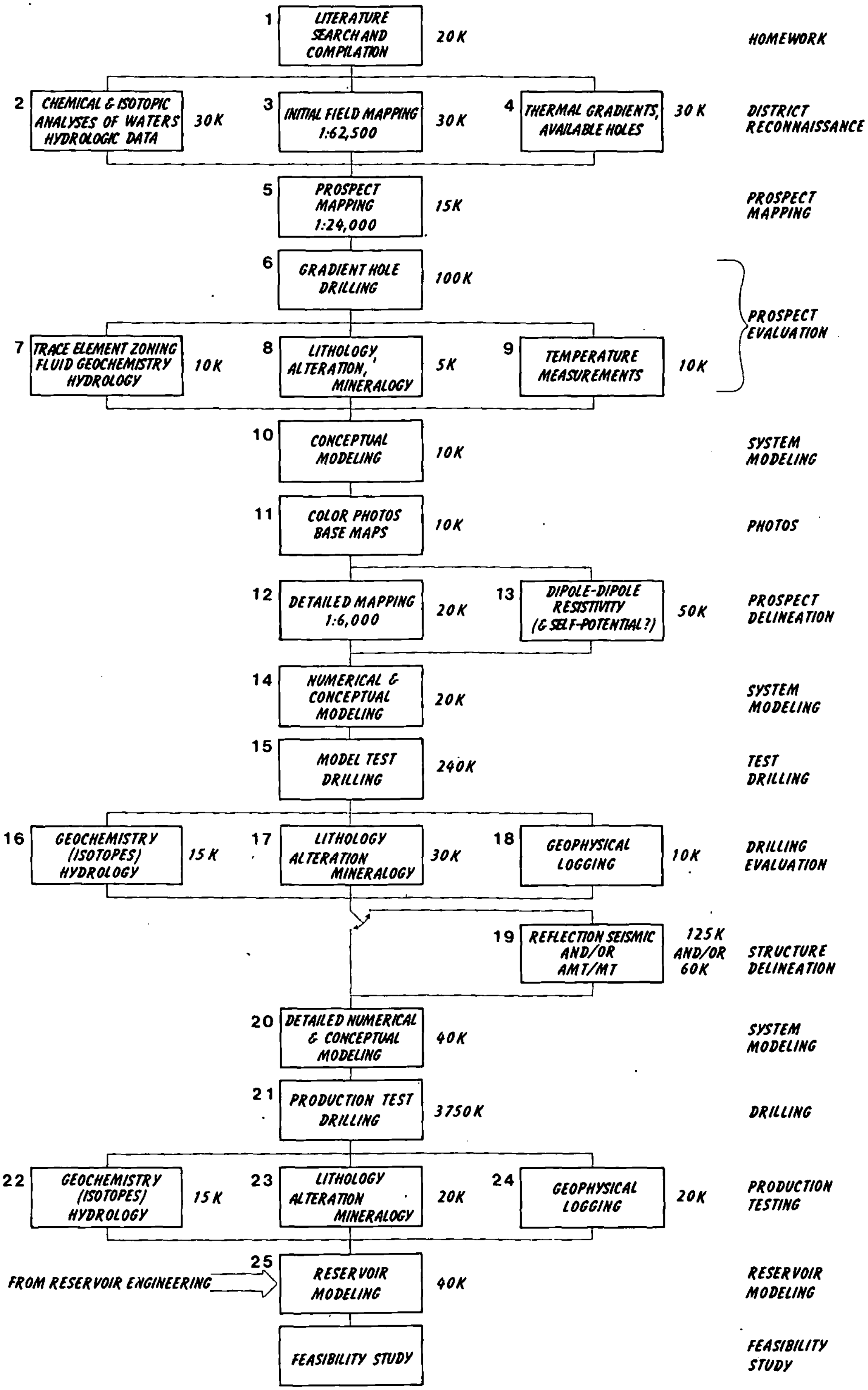


FIG. 6—Suggested high-temperature hydrothermal exploration strategy. Numbers at left of blocks indicate operating sequence. *K* numbers at right of blocks indicate estimated dollar cost in thousands.

interpreting subsequent drilling and geophysical and geochemical surveys. Our experience with data collected by companies participating in DOE's Industry Coupled Case Study Program has been that the completion of a detailed map at this early stage in the exploration program might have suggested to some companies that they not drill thermal-gradient holes at structural intersections or run resistivity lines along major structures; topographic access may dictate otherwise. We shall assume, for the purposes of the subsequent discussion, that only the top-priority prospect will initially warrant detailed investigation.

Drill Gradient Holes, Lithology and Alteration, Temperature Measurements, Geochemistry (Fig. 6, Boxes 6-9)

It is customary to drill about 20 holes 30 to 160 m deep in each high-priority prospect indicated earlier. The problem of cold-water overflow reducing near-surface gradients is generally recognized and is serious. Nevertheless, the gradient measurements in these specifically drilled holes are, perhaps, the most fundamental data to be acquired in the early stages of hydrothermal exploration.

Although temperature measurements are the principal product of these drill holes, additional data can be acquired at relatively low cost. Thermal-conductivity measurements on cores or chips will permit the gradient measurements to be converted to heat flow. Lithologic logging of the holes may give important information concerning hydrothermal alteration and mineral deposition, and can be tied with the surface mapping to give valuable insight into the structural geology. Trace-element analyses of cuttings can be done at small cost to investigate the possibility of geochemical zoning (Ewers and Keays, 1977; Bamford, 1978). Determination of depth to the water table and chemistry of waters encountered will begin to develop a hydrologic data base which will prove to be of great value in subsequent stages of exploration.

Conceptual Modeling (Fig. 6, Box 10)

Completion of the shallow-temperature measurement program is a major milestone in the history of a prospect. This is the appropriate time for the explorationists to formalize their target concepts with the development of a conceptual model. The process should integrate the prospect-specific geologic mapping, geochemical, alteration, and thermal-gradient information and relate these to the broader reconnaissance data base. The output of the process is a target model consistent with the data; some contradictory information will now become apparent. Parameters identified may include lateral extent, depth, heat-source types, and temperature. The options for testing the model in the most efficient manner should be evaluated prior to proceeding. A maximum of 2 man-months, at a cost of less than $10,000, would be required for this activity.

Obtain Color Air Photos and Base Map (Fig. 6, Box 11)

In areas where adequate stereo air-photo coverage and good base maps are available this step will be unnecessary. However, when dealing with an area with complex structural and alteration patterns, it is often most efficient to obtain low-altitude, color aerial photography. These photos provide an excellent base for detailed geologic mapping and can be used to generate detailed topographic base maps.

Detailed Mapping 1:6,000 (Fig. 6, Box 12)

Mapping in greater detail than 1:24,000 may not be necessary, but many added details may be required to answer specific structural questions or to unravel complex alteration patterns. In general, the purpose of this step is to understand the geologic setting as completely as possible prior to initiating the expensive surveys and drilling indicated in the latter half of the exploration process.

Dipole-Dipole Resistivity Survey (Fig. 6, Box 13)

A dipole-dipole resistivity survey should be planned to extend the results of surface geologic mapping to depth. Typically, survey lines are oriented as nearly perpendicular to geologic strike and structures as possible. The dipole length may range between 150 and 600 m to reach the appropriate compromise between lateral resolution and the increased response to features at depth. A dipole separation of 300 m seems to be preferred by the industry in the Basin and Range province. The data should be recorded to at least $n = 6$ (sixth separation) to allow confidence in subsequent interpretation to depth.

An option not generally exercised is the recording of induced polarization (IP) data along key profiles of the survey (Chu et al, 1980). This may be warranted if trace-element or lithologic studies suggest sulfide zoning which may be related to the geothermal system, or if this parameter can further discriminate between geologic units at depth. The cost of these added data depends on the increased recording time and local noise levels. We do not advocate routine inclusion of IP measurements. A maximum of $50,000 would be required for contract services for the basic resistivity survey, providing 60 line-km of control and numerical modeling of the data. A self-potential survey may be included for fluid-flow information.

Numerical and Conceptual Modeling (Fig. 6, Box 14)

Numerical modeling should be applied to two data sets to test and subsequently modify the conceptual model. The shallow-temperature hole data should be combined with measured or assumed thermal conductivity to produce a heat-flow map. A better definition of the heat source may be apparent after attempts to model this distribution of heat flow by means of forward calculations, or inversion.

A detailed modeling of the resistivity data can be completed using contract services or two- and three-dimensional computer programs now available (Killpack and Hohmann, 1979). A definitive intepretation of resistivity structure to depths of about one-fifth the extreme electrode separation will often be possible. Especially useful outputs from the process are the location of Basin and Range faults and areas of low resistivity associated with hot conductive fluids and altered rock. Although the reservoir itself may be too deep to detect, zones of leakage to the surface may be delineated. These geometric models place new constraints on the conceptual model, as does the more detailed geologic mapping. The model is updated, and serves as the basis for siting intermediate-depth drill testing. The cost, suggested at $20,000, is justified by the commitment of the subsequent drilling.

Model Test Drilling and Logging (Fig. 6, Box 15)

The northern Nevada studies indicate that most companies drill two or more 500 to 800-m slim holes which are referred to variously as deep geothermal-gradient holes, stratigraphic-test wells, or as model test-drill holes. These holes serve to evaluate (a) shallow cold-water overflow or mixing and (b) shallow thermal aquifers as at Desert Peak, Nevada (Benoit, 1978). They also serve to provide a preliminary test of the conceptual model of the geothermal system. We recommend three such holes at an estimated cost of $80,000 each. Although practice varies from company to company, we recommend temperature, resistivity, gamma, and SP logging rather than acquisition of a full suite of logs.

Isotopes, Chemistry, Hydrology (Fig. 6, Box 16)

The model test drilling yields cuttings and fluids which permit one or more of the following: (a) isotopic and chemical geothermometric predictions of temperature in the reservoir, (b) the possibility of identifying the source of recharge to the system, and (c) estimation of the permeability of the reservoir by water/rock ratio analyses (Elders et al, 1978). An understanding of the hydrology of the system can be improved by such inexpensive studies.

Lithology and Alteration Studies (Fig. 6, Box 17)

Lithologic logging is important in determining the subsurface geologic relations. Logging should emphasize the correlation of cuttings with units delineated during the geologic mapping. With this information, geologic cross sections can be drawn and conceptual models of the geometry of the system refined. By relating the cuttings to the surface geology, the three-dimensional structural setting can be defined. Fault zones may appear as areas of gouge or mylonite. Often faults are the focus of areas of hydrothermal alteration. However, many times the fault zones are unspectacular in cuttings and must be delineated on the basis of known geologic relations, such as attenuation and juxtaposition of units, which can only be explained by faulting.

The geologic cross sections drawn at this time should integrate all of the data sets accumulated. It is particularly important that the geologic, geochemical, and geophysical models be compatible. Discrepancies in interpretation should be rationalized or eliminated.

Geophysical Logging (Fig. 6, Box 18)

Thermal measurements will be made in the model test drilling. For a small additional investment, SP, resistivity, and gamma logs can be run to provide additional stratigraphic control. This type of logging is commonly done in the uranium exploration industry and numerous low-cost logging units are available. However, most of these units are not designed to operate in high-temperature environments. Velocity and density logs could also be obtained, at a significant increase in cost, to assist in the design or interpretation of any subsequent reflection seismic survey.

Reflection Seismic and Audio Magnetotelluric/Magnetotelluric (AMT/MT; Fig. 6, Box 19)

In our strategy we have allowed for the possibility of using either or both of the reflection seismic and AMT/MT methods to assist in mapping structures or fracture systems; 25 km of seismic reflection data of $5,000 per line-kilometer and 30 AMT/MT stations at $2,000 per station are used in the estimate. In some places one or both methods will be inapplicable and hence this box can be bypassed or limited to one method.

Detailed Numerical and Conceptual Modeling (Fig. 6, Box 20)

The target concept is again updated prior to deep drilling in our strategy. Refinements in the numerical models may be possible through hydrology and chemical geothermometry, and through stratigraphic drilling and seismic data; 2 man-months and computer support may be required for this third-update of the integrated numerical and conceptual model.

Production Test Drilling and Logging (Fig. 6, Box 21)

Known production test wells in the Basin and Range province have ranged from 382 m at Thermal Power Co. Utah State 72-16 at Roosevelt Hot Springs to 2,939 m at Phillips Petroleum Co. Desert Peak well B-23-1. Deeper drilling to 4,000 m is rumored. If one assumes three production test wells of 1,525 m at an average cost of $1,250,000 (including box 24, full suite logging and brief flow test), then the cost of box 21 is $3,750,000 and this seems to be a typical expenditure.

Isotopes, Chemistry, and Hydrology (Fig. 6, Box 22)

All activities of box 16 are repeated here. Additionally, down-hole temperatures and pressures and their variations during the brief (24 hour nominal) flow test are available to provide further assessment of the reservoir.

Lithology and Alteration Studies (Fig. 6, Box 23)

Lithologic logging of the cuttings from deep drilling should again concentrate on correlating the lithologies with the surface mapping, identifying structures, and characterizing alteration assemblages. The results will provide data needed to draw geologic cross sections through the prospect area and may define small-scale structures that control fluid flow. These cross sections must now be compatible with relations shown by surface mapping, deep- and intermediate-depth drill results, and numerical modeling of geophysical surveys completed. Obviously, discrepancies in the interpretation of various data sets will be present and must be rationalized by remodeling or collection of additional data.

Characterization of alteration assemblages has been shown to yield important information on the location of production zones and the permeabilities of individual units (Browne, 1970, 1978). In addition it is often possible to document the chemical and thermal history of the system by using alteration assemblages (Browne, 1978) and fluid inclusion results (Burruss and Hollister, 1979).

Characterization of the mineralogy of test holes is crucial in facilitating the interpretation of geophysical well logs (Glenn and Hulen, 1979).

Geophysical Logs (Fig. 6, Box 24)

A thorough study of the suite of geophysical logs, well-coordinated with geochemical and lithologic studies, is mandatory. The results are an improved assessment of reservoir temperatures, fracture porosity and permeability, location of hot and cold fluid entries, and the identification of various reservoir-rock properties. For $20,000 we envision digitizing and replotting the various logs to a common depth scale with lithology and cross plots for unit discrimination and physical property evaluation. One man-month of interpretation time by an experienced well log analyst for each of three well tests is expected.

Reservoir Modeling (Fig. 6, Box 25)

The last update of the model considered here is a product consistent with the drilling results, the physical properties determined from the geophysical logs, and the surface geophysical and geochemical data. We do not necessarily imply a rigorous multidata-set numerical-model solution, but rather models from individual different data bases which are now internally consistent, or largely so.

Through flow testing and geometric modeling a preliminary reservoir model is available as the main input to the feasibility study. A decision to enter production implies continued monitoring of key variables and the modification of the reservoir model.

CONCLUSIONS

In the previous section we have presented our recommended strategy for exploration for high-temperature hydrothermal resources in the Basin and Range province and our justification for this choice of strategy. It is an expensive strategy, costing between $680,000 and $865,000 per prospect prior to production test drilling. We justify such large expenditures on the basis that we wish to minimize the risk of a poorly placed production test well when such wells often cost $1,000,000 to $1,800,000. The ratio of predrilling costs to the cost of the first hole therefore is approximately 0.5 under this strategy.

Research in exploration and assessment technology is expected to lead to introduction of new methods (e.g., controlled source electromagnetic methods), reintroduction of old methods, and more cost-effective use of some methods. Hence the strategy we recommend will be updated by a more cost-effective one when new or improved technology becomes available and when we make the next major step in developing conceptual models of high-temperature convective hydrothermal systems. Further, the strategy may evolve from the current one which is primarily directed to convective hydrothermal systems with surface manifestations to one primarily directed toward blind systems.

The broadly experienced geothermal exploration manager may wish to differ with our recommended strategy for various reasons including personal preference, budgetary constraints, time and land position constraints, and environmental or legal constraints. Our intent is not to force uniformity in exploration but to offer our recommendations based upon our collective experience and observations. The newcomer to geothermal exploration is expected to benefit more from this manuscript than the veteran geothermal explorationist.

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