A STRATEGY OF EXPLORATION FOR HIGH TEMPERATURE
HYDROTHERMAL SYSTEMS IN THE
BASIN AND RANGE PROVINCE

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December, 1979

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University of Utah Research Institute
Salt Lake City, Utah

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ABSTRACT

A fifteen phase strategy of exploration for high temperature convective hydrothermal resources in the Basin and Range province, recommended herein, features a balanced mix of geological, geochemical, geophysical, hydrological, and drilling activities. The strategy is based on a study of data submitted under the Department of Energy's Industry Coupled Case Study Program. Justification for inclusion in or exclusion from the strategy of all pertinent geoscientific methods is given. 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. Variations on the basic strategy are to be expected where the geology or hydrology requires it. 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 is expected to be particularly useful.

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1.0 INTRODUCTION

Geothermal energy is energy derived from the heat of the earth. The average heat flowing conductively out through the earth's surface is 0.08 watts per square meter. If we multiply this value by the total surface area of the earth (5.1×10^{14} square meters) we obtain the total heat flowing from the earth as 4.1×10^{13} watts or 41,000,000 megawatts. Only a small fraction of this energy can be extracted economically now or in the future. 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 the present time.

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. Cold meteoric water descends to the vicinity of a heat source via fractures and faults where it heats and convects upward through other structures to the upper portions of the system. Here it either discharges as hot springs, flows laterally along permeable horizons, or is prevented from escaping by a caprock of low permeability. In many cases these 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). These systems have relatively uniform temperature-pressure conditions which reflect the maximum enthalpy of saturated steam, which for pure water is 236°C and 31.8 kg/cm².

Hot water-dominated convective hydrothermal systems are generally classified as high temperature (>150°C), intermediate temperature (90°C to 150°C), and low temperature (<90°C) (White and Williams, 1975; Muffler, 1979). While some of these systems are considered to 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, Figure 1, are instructive for showing basic characteristics, these systems are much more complex than Figure 1 indicates. Indeed, the lower portions of the systems, and in particular the heat sources, are quite speculative. Figures

Figure 1 Generalized Model of a Convective Hydrothermal System

2, 3, and 4 show interpreted cross sections through the upper portions 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 Springs is thought to derive its heat from a cooling magma body at depth; the source of the heat for the other systems is unknown at this time.

It is clear through inspection of Figures 2 through 4 that hydrothermal systems within the Basin and Range province are structurally complex, and require three-dimensional modeling. Because they have all undergone several periods of faulting and repetitive igneous intrusion, 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 geologic picture. Clearly the structural picture must be understood early in the exploration process in order for an exploration program to be conducted efficiently (Nielson and Moore, 1979).

In addition to the geologic complexity of the Basin and Range province, a number of 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 that are commonly used in the exploration process. In addition, saline ground waters which are

EXPLANATION

	Qs	Siliceous sinter
	Qal	Alluvium
	Tmd	Microdiorite dikes
	Tg	Granite
TERTIARY	Ts	Syenite
	Tpg	Porphyritic granite
	Tqm	Quartz Monzonite
PRECAMBRIAN	PCgn	Hornblende Gneiss
	PCbg	Banded Gneiss

Figure 2 - Geologic cross section of the Roosevelt Hot Springs KGRA, Utah. (Nielson et. al., 1978)

EXPLANATION

	Qal	Alluvium
	Tj	Joe Lott Tuff
	To	Osiris Tuff
MIOCENE	Tbqm	Quartz Monzonite
	Tbl	Latite
	Tbc	White Tuff Member
	Tbr	Red Tuff Member
	Tbt	Three Creeks Tuff Member
OLIGOCENE	Tb	Lower Bullion Canyon Volcanics
	Tn	Needles Range Formation
PERMIAN	Pc	Coconino Sandstone

Figure 3 - Geologic cross section of the Cove Fort-Sulphurdale KGRA, Utah.
(Moore and Samberg, 1979)

Northwest

Southeast

EXPLANATION

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

Figure 4 - Geologic cross section of the Leach Hot Springs KGRA, Nevada. (Beyer et.al. 1976)

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.

3.0 NORTHERN NEVADA EXPERIENCE

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 front-end 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 is 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 the 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. Existing data are indicated by E while all new work items under the DOE/Company contracts are identified with an X.

Table 1

GEOTHERMAL INDUSTRY EXPLORATION STRATEGY AS INDICATED BY INDUSTRY COUPLED PROGRAM DATA PACKAGES

AREA	BALTAZOR	TUSCARORA	MC COY	LEACH H.S.	COLADO	BEOWAWE	BEOWAWE	SAN EMIDIO	SODA LAKE	STILLWATER	DIXIE VALLEY	DESERT PEAK	HUMBOLDT H.	COVE FORT - SULPHURDALE UTAH
COMPANY DATA	EPP	AM	AM	AO	G	G	C	C	C	U	SR	P	P	U
GRAVITY	E	X	X	E	E	X		E		E		E	E	E
GROUND MAG.					E	X						E		
AERO MAG.	E	X	X				E				E			E
ELEC. RES.					E	X	E	E	E	E				E
MAGNETO-TELLURIC		X	X	X	E		E		E	E	E	E	E	
AUDIO MAGNETO-TELLURIC					E									
SELF POTENTIAL		X	X				E	E						
SEISMIC EMISSIONS							E	E						E
MICRO-EARTHQUAKE	E	X	X				E							
SEISMIC REFL. (weight drop)							E		E					E
SEISMIC REFL. (CDPI2 or 24 fold)			X	X			X	E	E					
GEOLOGY	E			E				E			X	E	E	E
GEOCHEMISTRY	E			E							E			E
SHALLOW TEMPERATURE											X			
SHALLOW THERMAL GRADIENT	E	E	E	X	E	X		E	E	E	E			E
DEEP THERMAL GRADIENT	X	X	X	X	X	X			E		E	E		E
EXPLORATION WELL	X	X	X	X	X	X	E	E	E	E	X	X	X	E
FLOW TEST (if appropriate)	X	X	X	X	X	X	X			X	X	X	X	X

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

While one or more companies have not submitted all of the geoscience exploration data they obtained for a given area, we believe this summary reflects the methods used by the various companies. One is immediately impressed by the diversity of exploration strategies utilized. On the other hand, certain common denominators are evident as shown in Table 2.

4.0 PREVIOUS STUDIES

Ward (1977) summarized the exploration strategies existing in the literature up to the time of his writing. He referenced articles by Banwell (1970, 1974), Combs and Muffler (1973), Greider (1975), Dolan (1975), Furumoto (1975), Meidav and Tonani (1975), and McNitt (1975) 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.

McEuen et al (1979) provided analyses of exploration architectures required for each of twelve different physiographic provinces. Their report utilizes some interesting tables from an earlier report by the Mitre Corporation (1978). Table 3 (after Mitre Corporation) 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 from comparison of the two tables are:

- 1) Thermal methods rank universally highest.
- 2) Surface geologic mapping is generally but not always employed.
- 3) Gravimetry is usually employed.
- 4) Some form of electrical methods is usually employed.

TABLE 2
SUMMARY OF TECHNIQUE USE BY INDUSTRY,
CASE STUDY PROGRAM

METHOD	PERCENT OF CASES EMPLOYED	PRIORITY
MT	(71)	1
Shallow Thermal Gradient (100m)	(71)	1
Deep Thermal Gradient (600m)	(71)	2
Gravity	(71)	2
Magnetics	(57)	3
Geologic Mapping	(50)	3
Resistivity	(50)	3
Passive Seismic	(43)	4
Active Seismic	(43)	4
Self Potential	(29)	5
Geochemistry	(29)	6

TABLE 3

EVALUATION OF REGIONAL APPLICABILITY OF EXPLORATION/ASSESSMENT TECHNIQUE

Technique	Overall Regional Ranking Applicability	Ranking of Techniques According To Applicability In											
		Salton Trough	Basin And Range	Cas-cades	Basaltic Island Region	Snake River Plain	Wasatch Front	Rio Grande Rift	Geysers	Aleutian Arc Island	Appalachian	Eastern And SE Plutons	Geopres-sured
Thermal Method	1	1	1	1	2	1	1	1	1	1	1	1	2
Surface Geological 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 Infra-Red	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

LEGEND

1 = Most Applicable to 14 = Least Applicable

(After Mitre Corp., 1978)

- 5) Seismic, magnetic, and geochemical methods fall somewhat lower on the priority list.
- 6) Geology and fluid geochemistry, ranked 2 and 3 by the Mitre Corporation survey, 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 Corporation, 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 not far different from the above six conclusions with the exception that photographic imagery and geochemical methods are of high priority in the reconnaissance phase of exploration while active seismic methods are of high priority in the detailed phase of exploration.

5.0 CURRENT ASSESSMENT OF METHODS

Let us now consider the methods individually as listed in Table 1 and evaluate their applicability in the Basin and Range province.

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 stage, both regional and reconnaissance, of a program but then largely ignored until the drill cuttings return from the first exploration hole. Detailed (1:24,000) geologic mapping of a prospect size area, 20 to 60 square km, is not generally done. Instead short cuts are taken which include compilation of existing maps, photo geology, and perhaps the routine

application of several geophysical methods. Alteration and structural studies often are omitted.

Our observations to date reveal that inadequate geologic mapping by companies may result, for example, in geophysical survey lines being run 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 one's 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 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 portions of the area which seem to have the 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 (Truesdell, 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 was not submitted as a deliverable item. The low ranking could also represent the limited interest in soil geochemistry, and trace element surveys. As our case studies and technique development work proceed we find multi-element 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 (Kendall, 1976; Elders et al, 1978; Browne, 1970). 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 (Nielson, 1978; Capuano and Bamford, 1978).

Gravity Method: Gravity methods are often employed. A regional gravity map, with a station density of 1 station per 3 square km to 1 station per 25 square km, is generally available as the result of USGS regional studies, of the Department of Defense regional data compilation, or of university related geophysical studies. A compilation of these data has been accepted as adequate in many cases while 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 data aliasing, inadequate density information, relatively small density contrasts, and lack of precise elevation control.

Ground Magnetic Method: Ground magnetic data are often acquired as an addendum to the gravity survey at a modest additional 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 volcanics 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, reduce 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 two-to-four km flight line separation. These data, as at Baltazor and the 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 been flown at a one-half to one km line separation as draped flights 50 m 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 suffers from 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 complicate 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 Method: If one were to accept Tables 1 and 2 at face value, then the MT method would be recommended, strongly, for use in hydrothermal system exploration. The reason for this strong acceptance of the MT method is, we believe, 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 is necessarily a good conductor of electricity, when molten, must be conjectural since 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 only uses the standard one- or even two-dimensional MT interpretation methods, when indeed one is dealing with a three-dimensional earth, then one has no assurance that the method is capable of detecting a hot rock source via its assumed high conductivity. Means for surmounting this latter problem are evident (Wannamaker et al, 1979) 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.

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 for practical purposes is no more than twice the electrode separation, i.e., 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 quite 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 KGRAs in Utah, low (5-10 ohm-m) resistivity zones have been mapped which are probably related to hot, conductive fluids and large zones of wall rock alteration.

Self-Potential Method: Self-potential surveys are being used by a few of the major firms engaged in geothermal exploration. Recent papers by Hulse (1978), Fitterman (1979) and Corwin and Hoover (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 S. P. 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 its use for a late stage of exploration when resistivity data are also available and where any clue 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. 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) discuss these problems as evident in studies at Grass Valley, Nevada, while Douze and Laster (1979) discuss them in relation to studies at Roosevelt Hot Springs. The relative cost-effectiveness of the passive seismic methods 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 quite 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 data are cost-effective 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 in Utah, and Soda Lake, San Emidio and Grass Valley, in 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, but substantial structural information along the range front. At Beowawe, Nevada, 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. It is clear that the cost of this method and the mixed results observed to date 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, 2, and 3. Shallow temperature measurements in one-meter deep holes is 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 some 5 to 20 square km could be the best basis on which to plan a shallow (30-200 m) thermal gradient program.

Shallow thermal gradient holes varying 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 cases 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 cases data obtained but not submitted as part of the Industry Coupled Case Study Program. In the third case 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 vary from 300 m to more than 1,000 m deep, but generally fall in the 300 m to 600 m range. The ratio of shallow to deep thermal gradient holes varies but generally is between 1 to 5 and 1 to 10. Results from these holes will help determine the siting of exploration wells (Benoit, 1978).

6.0 THE STRATEGY

As indicated above, hydrothermal convection of fluids through structures is a phenomenon that occurs in high-, moderate-, and low-temperature environments. Although the 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 in most cases require some modification to fit the demands of individual exploration projects.

Philosophically, the approach we propose involves 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 geological, geochemical, geophysical and hydrological 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 for it; it is sufficient to understand the fundamental processes of a system and to understand its detection by various exploration tools.

Figure 5 portrays our recommended basic strategy for exploring for high temperature hydrothermal resources in the Basin and Range province. As noted earlier, modifications to this strategy may be required for specific prospects. The strategy assumes that one starts with a nominal 3,000 square km district 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 \$3.4 M if both seismic reflection and magnetotelluric surveys are included.

Where do these costs arise? Each box in the flow diagram of Figure 5 depicts a function or functions whose cost estimate is shown to the right of

SUGGESTED HIGH TEMPERATURE HYDROTHERMAL EXPLORATION STRATEGY

FIGURE 5

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, i.e. 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 in turn, by number.

Box 1 Literature and Data Search, Compilation, and Analysis

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 are important for defining the location of wells to be sampled during the district reconnaissance stage.

Box 2 Chemical and Isotopic Analyses of Waters

Where the chemistry and/or 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 wall-rock equilibration and hopefully, 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

carried out. While the water temperature predictions from such analyses are fraught with uncertainties due to fluid mixing and due 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.

Box 3 Initial Field Mapping

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 young volcanic and intrusive rocks should be performed at this time. Geologic maps at a scale of 1:62,500, or even more detailed, exist for portions 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 these in detail at an early stage to document the structural and lithological 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 in light of the data collected simultaneously in Boxes 2 and 4 provides an excellent data base for the definition of a prospect of greater interest.

Box 4 Thermal Gradients, Available Holes

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

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 cold water overflow.

Box 5 Prospect Mapping

The homework and district reconnaissance studies of Boxes 1 through 4 invariably lead to identification of a number of prospects. While not all hot spots are found in the district reconnaissance studies, those that are found are typically prioritized and 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 three square km per day. Thus several man-weeks of effort can generate a detailed geologic map which will be invaluable in planning and 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.

Boxes 6, 7, 8, and 9 Drill Gradient Holes, Lithology and Alteration, Temperature Measurements, Geochemistry

It is customary to drill about 20 holes of 30 m to 160 m depth in each high priority prospect as indicated earlier. The problem of cold water

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 (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.

Box 10 Conceptual Modeling

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 items 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 two man-months, at a cost of less than \$10,000, would be required for this activity.

Box 11 Obtain Color Air Photos and Base Map

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.

Box 12 Detailed Mapping 1:6,000

Mapping in greater detail than 1:24,000 may not be necessary, but in many instances added detail 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.

Box 13 Dipole-Dipole Resistivity Survey

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 vary between 150 m 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 to date is the recording of induced polarization data along key profiles of the survey (Chu et al, 1979). 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 this added data depends on the increased recording time and local noise levels. The routine inclusion of IP measurements is not advocated by the authors. A maximum of \$50,000 would be required for contract services for the basic resistivity survey, providing 60 line kilometers of control and numerical modeling of the data. A self-potential survey may be included for fluid flow information.

Box 14 Numerical and Conceptual Modeling

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.

A detailed modeling of the resistivity data can be completed using contract services or two- and three-dimensional computer programs now available to the public (Killpack and Hohmann, 1979). A definitive interpretation of resistivity structure to depths of about one-fifth the extreme electrode separation will often be possible. Especially useful output 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.

Box 15 Model Test Drilling and Logging

The Northern Nevada studies indicate that most companies drill two or more 500 m 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. While practice varies from company to company, we recommend temperature, resistivity, gamma and SP logging rather than acquisition of a full suite of logs.

Box 16 Isotopes, Chemistry, Hydrology

The model test drilling yields cuttings and fluids which permit one or more of 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) estimating the permeability of the reservoir via water/rock ratio analyses (Elders, et al 1978). One's understanding of the hydrology of the system can be improved by such inexpensive studies.

Box 17 Lithology and Alteration Studies

Lithologic logging is very important in determining the subsurface geologic relationships. 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 show up 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 relationships such as attenuation of units 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 geological, geochemical, and geophysical models be compatible. If discrepancies in interpretation are found, these should be rationalized or eliminated.

Box 18 Geophysical Logging

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 thus numerous low-cost logging units are available. However, most of these units are not designed to operate in high-temperature environments. Velocity and/or 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.

Box 19 Reflection Seismic and/or AMT/MT

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. Twenty-five kilometers of seismic reflection data at \$5,000 per line kilometer and 30 AMT/MT stations at \$2,000 per station are used in the estimate. In some instances one or both methods will be inapplicable and hence this box can be bypassed or limited to one method.

Box 20 Detailed Numerical and Conceptual Modeling

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/or seismic data. Two man-months and computer support may be required for this third update of the integrated numerical/conceptual model.

Box 21 Production Test Drilling and Logging

Known production test wells in the Basin and Range province have varied from 382 m at Thermal Power Co. Utah State 72-16 at Roosevelt Hot Springs to 2939 m at Phillips Petroleum Company's Desert Peak well B-23-1. Deeper drilling to 4000 m is rumored. If one assumes three production test wells of 1525 m at an average cost of \$850,000 (including Box 24, full suite logging and brief flow test), then the cost of Box 21 is \$2,550,000 and this seems to be a typical expenditure.

Box 22 Isotopes, Chemistry, and Hydrology

All of the 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.

Box 23 Lithology and Alteration Studies

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 relationships shown by surface mapping, deep and intermediate depth drill results, and numerical modeling of geophysical surveys completed to this point in time. Obviously, discrepancies in the interpretation of various data sets will exist and must be rationalized by re-modeling 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 (Burrass and Hollister, 1979).

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

Box 24 Geophysical Logs

A thorough study of the suite of geophysical logs, well coordinated with geochemical and lithological studies is mandatory. The results are an

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.

Box 25 Reservoir Modeling

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 here a rigorous multi-data 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.

7.0 CONCLUSIONS

In the previous section we have presented our recommended strategy for exploration for high temperature hydrothermal resources in the Basin and Range 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 typically cost about \$850,000.

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 hopefully will be updated by a more cost-effective one once new or improved technology becomes available and once 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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