Title:
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Publication Date:
01-18-2011

Publication Info:
Lawrence Berkeley National Laboratory

Permalink:
http://escholarship.org/uc/item/3zk7d1w0

Local Identifier:
LBNL Paper LBL-7012

605
3-17-78

Lh. 1937

LBL-7012
UC-66b
TID-4500-R66

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December 1977

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

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LBL-7012

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NORTHERN NEVADA GEOTHERMAL EXPLORATION

STRATEGY ANALYSIS*

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* Work supported by the U. S. Department of Energy (DOE).

ABSTRACT

The results of exploration techniques applied to geothermal resource investigations in northern Nevada were evaluated and rated by seven investigators involved in the work. A quantitative rating scheme was used to obtain estimates of technique effectiveness. From survey cost information we also obtained and compared cost-effectiveness estimates for the various techniques. Effectiveness estimates were used to develop an exploration strategy for the area. However, because no deep confirmatory drilling has been done yet, the technique evaluations and exploration strategy must be considered as preliminary. The strategy was further studied by means of a decision tree analysis, merging the strategy with the timing of land acquisition and deep drilling to find the scenario that gives the highest cost-effectiveness values for drilling sucess, overall project success, and maximum expected returns on exploration investment. Based on assumed probabilities we show through this exercise that land acquisition should be deferred until after the basic detail-phase exploration is completed. The cost effectiveness of the initial confirmatory drill hole will be a maximum when land acquisition is followed by a supplemental detail-phase program, but this approach does not lead to the highest expected return on investment.

INTRODUCTION

In the Spring of 1973 the Lawrence Berkeley Laboratory (LBL) under the auspices of the U. S. Atomic Energy Commission (AEC), later the U. S. Energy Research and Development Administration (ERDA), commenced exploration operations in north-central Nevada to locate a geothermal resource capable of supporting a 10 MWe electrical power plant. The search was confined to federal lands in a region of high crustal heat flow and numerous hot springs, some of which suggested temperatures at depth in excess of 150°C (Sass et al, 1971; Olmsted et al, 1975). By 1975 the goal of a demonstration plant was dropped but LBL was asked to continue its evaluation of techniques for exploration and assessment of the Basin and Range geothermal resource.

This work was conducted in a study area of approximately 2500 square miles (Fig. 1), encompassing parts of Buena Vista Valley (Kyle Hot Springs), Grass Valley (Leach Hot Springs), Buffalo Valley, and Whirlwind Valley (Beowawe). To a lesser extent, parts of the intervening ranges were also covered in the study: East, Sonoma, Tobin Ranges, Fish Creek Mountains and the northern end of the Shoshone Range.

As part of the program summarization, results of investigations were reviewed and quantified in terms of effectiveness and cost-effectiveness factors as perceived by the LBL and U. C. Berkeley geologists, geophysicists, and geochemists who were involved in the studies. The purpose of this exercise was to evaluate the various techniques used and to develop a geothermal exploration strategy applicable to northern Nevada. Studies of a similar nature appear in the geothermal exploration literature. For example, Ward (1977) presented a geothermal exploration architecture for the eastern Basin-and-Range (southwestern Utah) and included, for comparison, strategies and costs developed by others. Discussions of geothermal exploration costs and risks have also been presented by Sacarto (date unknown), Duprat and Omnes (1975), among others.

A technical summary report containing survey results and interpretations is in preparation and partial results have already been given in Open File Reports (Wollenberg et al, 1975; Beyer et al, 1976; Goldstein et al, 1976) and in topical reports (Beyer, 1977a, b, and c; Liaw and McEvilly, 1977; Morrison et al, 1977; Goldstein and Paulsson, 1977; Wollenberg et al, 1977).

Ideally, a geothermal exploration evaluation and strategy developed for a specific area should be referenced to and supported by the results from deep confirmatory drill holes. However, in the northern Nevada program no deep confirmatory holes were drilled at the time of writing, and thus our assessments and strategy are preliminary. These might properly be viewed as pertaining to the choice of drill targets as yet untested.

METHOD OF APPROACH

For initial simplicity, exploration methods applied during the study, plus some that were not applied here but have been used by others, were listed and grouped into two categories: reconnaissance-phase and detail-phase investigations (Table 1). The exploration project is assumed to consist of these two phases, each phase with a specific objective, and project leading ultimately to drill tests. In keeping with the LBL activity sequence during the northern Nevada

Table 1. Northern Nevada geothermal exploration plan outline.

	Reconnaissance Phase	Detail Phase	Drill Tests
Study Area:	2500 square miles	<100 square miles	2 to 4 square miles
Objective:	Reduce study area to one or more subareas of <100 square miles for detailed exploration	Reduce study area to one or more subareas of 2 to 4 square miles for drill tests	Verify the presence of geothermal resource
Methods:	A. <u>Airborne</u> ** Aeromagnetics ** Infrared imagery ** Photography • Low-medium altitude color and color IR • High altitude black & white	A. <u>Airborne</u> High sensitivity aeromagnetics	Test drilling to depths of 1 to 2 km and well logging.
	B. <u>Surface</u> * Geological studies * Geochemical studies * Regional gravity ** Rock age-dating * Passive seismic • Regional Seismotectonic • Studies • Microearthquake and ground noise studies ** Hydrologic studies Regional magnetic variometry * Heat flow	B. <u>Surface</u> * Geological studies * Magnetics * Gravity * Active seismic * Passive seismic • Microearthquake • Teleseismic P-wave studies • Ground noise * Resistivity studies * Self-potential * Heat Flow	

* Denotes data acquired directly by LBL or with the assistance of the U. S. Geological Survey.

** Denotes data made available to LBL from other sources or from previous scientific studies in northern Nevada.

program, we considered first a reconnaissance phase directed at an initial study area of 2500 square miles (about 70 townships), the exploration designed to identify one or more promising areas of no more than 100 square miles (about three townships) for more detailed exploration. The objective of the subsequent detailed exploration phase is to identify smaller areas of two to four square miles where deep drill tests are to be made.

EFFECTIVENESS FACTORS

For each technique listed in Table 1, each of seven investigators* provided quantitative estimates for two rating factors, R and F, defined as follows:

1. The R factor, on a scale of 0 to 10, is a judgment of the scientific value of the method, i.e., the amount of useful geological information that can be derived from a proper interpretation of the data.
2. The F factor, on a scale of 0 to 100, is a measure of the practical value of the method in meeting the stated objective.

In assigning the two rating factors, the investigators were asked to disregard costs. However, by means of discussions between investigators, scopes of work from which cost estimates could be made were developed and refined. Scopes of work and associated costs for each method in Table 1 are given in Appendices B and C. The product R x F, ranging in value from 0 to 1000, is taken as a quantitative measure of the effectiveness of each method as it applies to geothermal exploration

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* The seven investigators whose views were solicited all held responsible scientific roles in the program, many since the inception of the program in 1973. The investigators are listed in Appendix A.

in northern Nevada. These values, together with the averaged R x F product, are shown in the scatter diagrams of Figures 2 and 3 for reconnaissance and detail phases, respectively. While these values have no meaning in absolute terms, their relative values serve to differentiate the effective from the less effective methods. In this sense, an average R x F value of 500 seems to designate a mandatory method, 100 to 500 a desirable method, and less than 100 a method of little value.

The various methods are listed in descending order of average R x F in Tables 2 and 3. A cost estimate for each method is also given, based on current contractor prices for the survey specifications, discussed in Appendices B and C. The quotient of average R x F and data acquisition cost (in $ thousands) is a cost-effectiveness factor by which the various methods may be compared. Although this factor also has no meaning in absolute terms, we find that values of ≥ 10 seem to be associated with cost-effectiveness methods and values of ≤ 1 clearly denote cost-ineffective methods. For the reconnaisance phase, exploration methods that have a high effectiveness (R x F) also tend to be cost-effective. However, for the detail phase there is no correlation between effectiveness and cost-effectiveness. Self-potential and ground magnetics are rated near the bottom in terms of effectiveness, yet are both near the top in terms of cost effectiveness. On the other hand, resistivity studies were rated reasonably effective but did not fare well in terms of cost effectiveness. Therefore, an exploration planner for the detail phase might include the magnetic and self-potential

Table 2. Averaged effectiveness and cost effectiveness ratings. Geothermal exploration reconnaissance phase (2,500 square miles).

Technique	Effectiveness Rank	Cost ($000)	(R x F) Average	Cost Effectiveness Factor (R x F/$C)
Geologic Studies	1	60	663	11
Heat Flow	2	60	622	10
Air Color, Color IR Photography	3	16	556	35
Rock Age Dating	4	5	544	109
Geochemical Studies	5	20	500	25
High Altitude B&W, Near IR Photography	6	8	460	58
Regional Seismotectonic Studies	7	70	372	5
Infrared Imagery 8-14 μm Band	8	21	138	7
Microearthquake-Ground Noise	9	100	119	1.2
Aeromagnetics	10	33	41	1.2
Regional Magnetic Variometry	11	50	30	0.8
Regional Gravity	12	20	20	1
Hydrologic Studies	13	40	Very Low	Very Low

Table 3. Averaged effectiveness and cost effectiveness ratings. Geothermal exploration detail phase (100 square miles).

Technique	Effectiveness Rank	Cost ($000)	(R x F) Average	Cost Effectiveness Factor (R x F/$C)
Heat Flow	1	60	770	13
Active Seismic	2	50	688	14
Geologic Studies	3	15	619	41
Gravity	4	15	506	34
Electrical Resistivity	5	59	497	8
Microearthquake and Teleseismic P-Wave Studies	6	50	496	10
Microearthquake Studies	7	30	337	11
Ground Noise	8	50	204	4
Self Potential	9	3.4	140	41
Ground Magnetics	10	3.4	122	36
High Sensitivity Aeromagnetics	11	9	101	11

methods because of their low cost, and might reduce the amount of electrical resistivity coverage because of the high costs involved.

RECONNAISSANCE PHASE PROGRAM

The analysis reveals that geologic studies, rock age-dating, geochemical studies, air color/color IR photography and heat flow drilling constitute the core or mandatory elements of the reconnaissance program, the total cost of which is estimated to be $161,000 ($0.10 per acre). To this one might easily add high-altitude, low sun-angle, black and white photography, which is relatively inexpensive, has a high cost-effectiveness factor, and provides good information on minor faults in valley-filled areas. Regional seismotectonic studies might also be considered for a supplementary method. A program chart is shown in Fig. 4.

The respondents uniformly rejected aeromagnetic, regional gravity, and hydrologic surveys, classifying these as not effective for providing information that would help meet the program objective. Aeromagnetic, regional gravity, and hydrologic information exist for much of the northern Nevada study area. These data were reviewed during the program but no attempt was made to analyze them in any rigorous or systematic fashion or to utilize them for selecting areas for detail surveys.

The geochemical studies in the reconnaissance phase include sampling and analysis of cold- and hot-spring waters for inputs to calculate the proportions of near-surface cold-water mixing with deeply circulating hot water, and the temperature of the unmixed hot water (Fournier and Truesdell, 1974). Opinions differed markedly on the subject of geochemical studies; two respondents (both seismologists) stated that the geochemical surveys in Nevada gave little new information, and they could not place any reliance on the accuracy of chemical geothermometers because of uncertainties due to mixing of thermal and meteoric waters. Ratings for geochemical studies varied by respondent much as the hydrologic ratings did, indicating that those who rated geochemistry highly also saw the need of hydrologic studies to interpret the geochemistry data. Those who saw no value to geochemistry were similarly disposed toward hydrologic studies.

Opinions differed most considerably on the usefulness of thermal IR imagery. A single predawn flight was completed by NASA/Ames over the northern Nevada areas, and the data indicated the known thermal manifestations plus one previously unrecorded warm spring in Buffalo Valley, approximately 5 km northwest of the known hot springs. The imagery also detected moist ground related to a fault zone. The majority of respondents gave a marginal to very low rating to the effectiveness of thermal IR because no previously unknown thermal area was revealed, and they felt that this would probably be the case elsewhere in the region. This belief is supported by the independent results of a thermal IR survey in the Black Rock Desert area near Gerlach, Nevada (Grose and Keller, 1975).

Regional magnetic variometry and regional MT for determining regions of thinner, hence hotter, crust were rated low, but neither method was specifically evaluated during the Nevada program. There is evidence from the amplitude of the long-period vertical magnetic (24 hour) variation and the magnetotelluric depth soundings that an anomalously shallow conductor occurs beneath the Basin and Range

(Hermance and Pedersen, 1976). At one station near Leach Hot Springs, Grass Valley, we obtained good quality MT data to 1000 seconds period which showed a high conductivity zone at approximately 14 km depth. A conductive zone, also determined by means of MT surveys (Stanley et al, 1976), was found at depths of 4-7 km in the Carson Sink area of Nevada.

Both seismotectonic and microearthquake (MEQ) ground noise studies were rated marginally effective as reconnaissance methods, but because of the high costs involved, neither method fared well in cost-effective terms. However, a regional seismotectonic study was clearly preferred over a MEQ/ground noise study and could be considered a possible supplemental method.

Although it received a high average rating, heat flow drilling did not receive uniformly high ratings, due in part to differing perceptions of how this work would fit into the overall program. Those rating heat flow lowest did so with the idea that the holes would be drilled on a low-density, wide-spread basis to obtain two or three values per valley. On the other hand, those rating heat flow highest, stipulated that the drilling had to be thought of as a transition phase between reconnaissance and detailed exploration, and that the drilling had to be of a semi-detailed nature to assist with the final selection of one or two areas for detailed exploration. It was recommended that the heat flow work begin late in the reconnaissance phase with the drilling of a few relatively deep (~150 m) holes from which the linear portion of the geothermal gradient can be determined. Based on these results, two or three times as many shallow holes (15 to 30 m) are drilled in the detail phase.

DETAIL PHASE PROGRAM

The analysis showed that geologic studies, gravimetry, active seismic and temperature gradient/heat-flow drilling constitute the mandatory portion of the detail phase exploration (Fig. 5). Together, these methods would require a per-study area cost of $140,000, or approximately $2.20 per acre. Following close behind, in terms of effectiveness, were (a) microearthquake (MEQ) studies coupled with teleseismic P-wave delay and amplitude variations, and (b) electrical resistivity studies. Either or both could be considered as valid supplemental techniques, and, if applied, would bring the total cost to $249,000 or approximately $3.89 per acre*.

Geologic studies and shallow drilling received predictably high ratings. Based on the results of the transition phase heat flow drilling, 20 to 30 shallow holes (~ 50 m) would be drilled in a tighter pattern, followed if necessary by a dense pattern of shallow holes (~ 15 m) for detailing the heat flow anomalies.

Active seismic and gravimetry also received high effectiveness ratings, but there is a question of how site-dependent these ratings are. In the one area (Grass Valley) where we applied both methods, they provided consistent and useful information on faults and valley

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* When we include the $161,000 to $169,000 cost involved in the reconnaisance phase, the per acre exploration cost of $6.00 is consistent with large-area estimates reported by Sacarto (date unknown), but far more than the ~ $1.00/acre exploration costs estimated by Ward (1977).

structure. Active seismic (Vibroseis* reflection and refraction) received uniformly high R x F values because all respondents considered it best for defining basement configuration and the bounding faults, which are believed to provide the fracture permeability for the ascending hydrothermal fluids (Majer, 1977). Gravimetry received approval for the structural information derived from a two-layer inversion, which gave an apparent depth to basement and inferred fault locations which agree well with the seismic results (Goldstein and Paulsson, 1977). Gravimetry also indicated what appear to be hydrothermally altered and densified "pipes" within the valley fill and underlying sediments. These gravity highs correlate with surface manifestations of present and/or past hydrothermal activity, and in Grass Valley also correlated with P-wave advances and heat-flow highs. Based on our interpretation of various geophysical data for Grass Valley, we have questioned whether active seismic can be eliminated on the grounds that a combination of gravity, passive seismic and d.c. resistivity provide almost the same information regarding valley structure. However, because of the high degree of resolution possible with a combined refraction-reflection survey, we will retain active seismic in the mandatory portion of the detail phase exploration.

Among the passive seismic methods, MEQ alone was not rated as highly as MEQ combined with teleseismic P-wave studies. While no evidence could be found for a significant body wave component in the microseismic background noise in Grass Valley (Liaw and McEvilly,

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*Registered name, Continental Oil Company.

1977), many respondents felt that the teleseismic results showed that the P-wave advances (i.e., negative P-wave delays) delineated a vertical "cylinder" of silicified sediments centered over the Leach Hot Springs area (Majer, 1977).

Respondents, in general, judged resistivity studies to be only moderately effective for selecting an area for confirmatory drilling. However, Beyer's (1977c) careful and detailed two-dimensional model studies of dipole-dipole data, supported by telluric surveys and other geophysical data, resulted in drilling recommendations to test several low-resistivity zones within the valley fill of Grass Valley.

Because so much of the northern Nevada program involved the use of natural field and controlled-source electrical resistivity methods, the subject of electrical resistivity deserves special elaboration at this point.

Geophysicists closely connected with the resistivity work tended to assign higher effectiveness ratings but qualified their ratings by recommending a stricter approach than was followed in the field work. For example, they would exclude roving dipole (bipole-dipole) because of ambiguities in interpretation and lack of depth discrimination (Dey and Morrison, 1977), and would concentrate on the following plan:

1. E-field-ratio tellurics at two frequencies, with scalar MT for resistivity control at two or three stations per line, followed by
2. dipole-dipole sections along selected lines, dipole lengths of 250, 500, and 1000 meters, depending on depth of exploration/ resolution factors and dipole separations up to N = 10.

Dipole-dipole pseudo-sections were interpretable in terms of two-dimensional models from which subsurface geology could be inferred (Beyer, 1977c), but the modeling effort was aided and supported by the results from active seismic, gravity, and E-field-ratio telluric surveys. These data often indicate where vertical boundaries should be located in the resistivity model. The electrical surveys resolved vertical and horizontal lithologic/resistivity changes within the more conductive, near-surface environment. However, because of the large resistivity contrast between shallow rocks ($\rho \sim 10\ \Omega \cdot m$) and "basement" ($\rho \sim 200\ \Omega \cdot m$), it is not possible for dipole-dipole to provide information on changes below this interface. For example, a conductive region buried within the Paleozoic rocks flooring a valley probably would not be detectable. Hot springs areas have a small but recognizable electrical response, a resistivity increase due to silification or calcification of Quaternary valley sediments around the springs.

Applied in the manner recommended above, electrical resistivity studies nevertheless have one of the lowest cost-effectiveness factors, 8, of the detail phase exploration methods. This low factor can be attributed to the inherently high cost of electrical resistivity surveys and to the often difficult and frequently time-consuming problem of finding a reasonably close fit between observed data and a two-dimensional resistivity model. The interpretation difficulties persist even though an experienced geophysicist assisted by an efficient computer program attempts the analysis. The problem worsens as geology departs from two-dimensionality, or if the survey line is highly oblique to the geologic strike (J. H. Beyer, personal communication).

Schlumberger soundings, widely used in geothermal exploration, were not used during the Nevada program. However, using interpreted results, it was shown by means of direct calculations that Schlumberger soundings followed by 1-D inversion lead to significant errors introduced by lateral changes in resistivity (H. F. Morrison, personal communication).

A controlled-source EM experiment was conducted along one long line in Grass Valley, and the interpreted results compare well with the dipole-dipole interpretation (Jain, 1977). Although the results are encouraging, and this method holds the promise of improving the cost-effectiveness of electrical resistivity studies, we did not specifically consider the method in the effectiveness study because too little was known about it at the time the investigators reviewed and evaluated the exploration results.

Tensor magnetotellurics can provide useful information beyond the depth of the valley fill, but it is difficult to recommend this resistivity method for detail phase exploration because it presents a number of unresolved problems that must be addressed in future research. Standard TE interpretations based on a layered earth model gave valley thickness 50% less than found from dipole-dipole and controlled-source EM interpretations (Morrison et al, 1977). This is explained by bias introduced by the strongly two-dimensional geometry of the valley, the errors verified by means of two-dimensional model studies. It was also found that impedances are strongly influenced by local, near-surface inhomogeneities. This is manifested by the dependence of the fields on electric dipole length and the influence that shallow inhomogeneities can have on impedances over a wide range of periods. It was also found that uncorrelated electromagnetic noise was biasing impedance estimates at certain stations (Gamble et al, 1977).

Only seismic ground noise is rated lower in cost-effectiveness terms than resistivity studies. It received a low rating because of the time and complexity involved in post-field processing needed for a proper interpretation of the data. Passive seismic techniques, in general, could be much more cost effective if partial or complete in-field processing were available.

Marginally effective techniques, such as magnetics and self-potential, are rated high in cost-effectiveness terms and could be recommended on this basis. We cannot point to anything particularly diagnostic in the magnetic data in the areas studied, but the SP method may be helpful when applied carefully over a large area. The Leach Hot Springs area gave a clear SP anomaly and another anomaly was picked up over an area of high heat flow near Panther Canyon (Corwin, 1976; Corwin and Hoover, 1977). On the other hand, a major SP anomaly was traced for many miles along the west flank of the East Range (Buena Vista Valley), but shallow heat-flow holes showed the SP source is probably caused by near-surface graphitic and pyritic sediments (Beyer et al, 1976). Thus, the effectiveness of SP in northern Nevada is degraded by major anomalies that may have no relationship to geothermal systems.

AN OVERALL PROGRAM PLAN

Based on the effectiveness and cost-effectiveness results, an exploration plan for northern Nevada can be formulated, and one is shown in Table 4 which meets the following criteria:

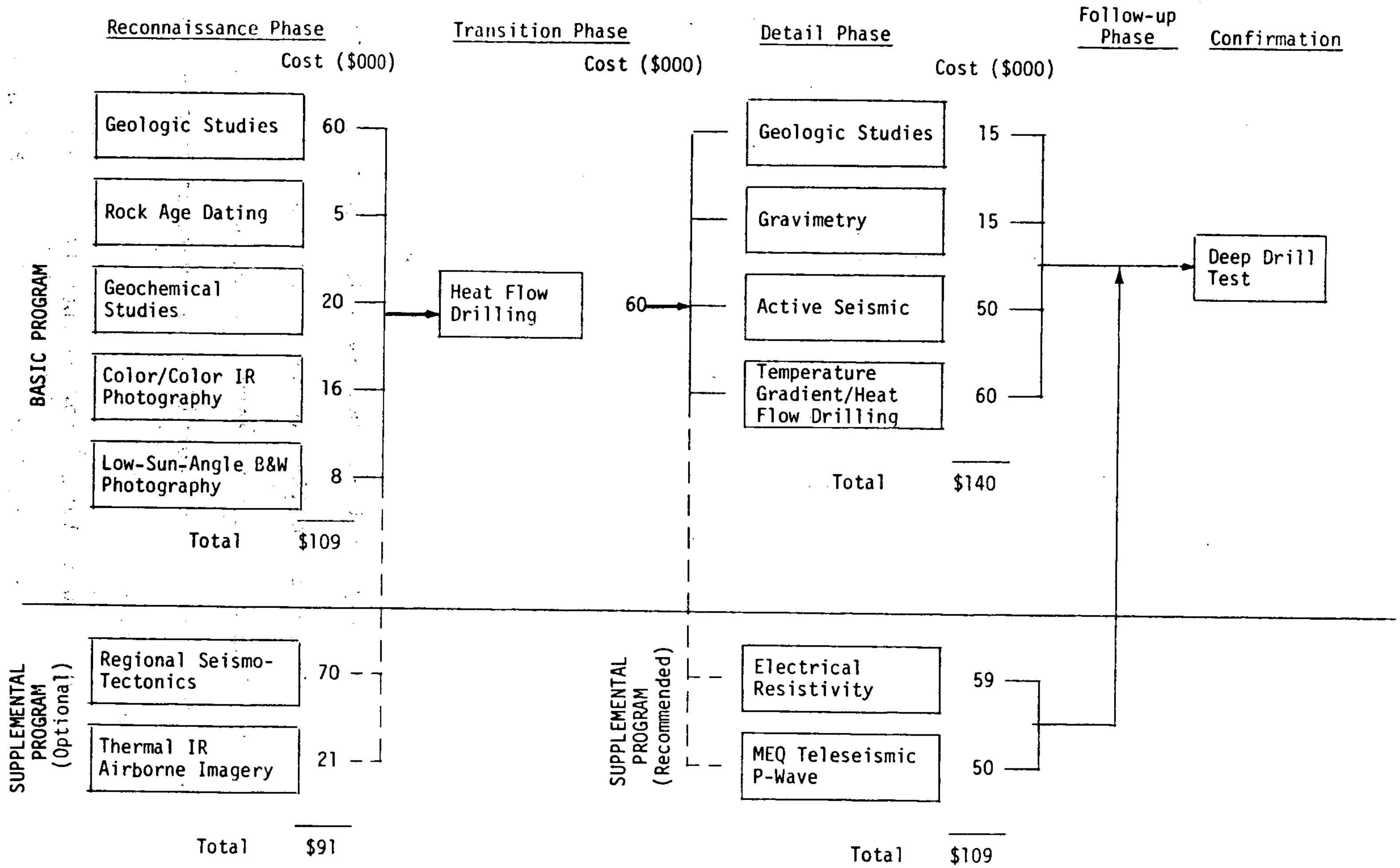
1. The number of phases is held to a minimum; the strategy is to reduce a large area to a drill target in the briefest sequence of operations.
2. Exploration costs are minimized by choosing only the more effective methods. Cost-effectiveness is not a primary consideration, although it often turns out that effective methods are also among the more cost-effective ones.

A comparison of Tables 1 and 4 shows that one result of the analysis was to expand the exploration sequence from three to four or possibly five phases. A separate heat flow drilling phase is inserted between the reconnaissance and detail phases, and the detail phase could either be expanded to include or be followed-up by a supplemental program consisting of electrical resistivity and passive seismic investigations.

Table 4 ignores land acquisition and where this activity fits into the strategy. This subject and the question of possibly eliminating certain portions of the exploration plan are discussed in the next section, where, by the use of a decision-tree analysis, it is shown that drill success and cost-effectiveness on a project scale are keyed to certain choices at decision points between phases.

TABLE 4

NORTHERN NEVADA GEOTHERMAL EXPLORATION STRATEGY



DECISION TREE ANALYSIS

The exploration strategy shown in Table 4 can be expanded into a decision tree, a pictorial representation of the decision sequence and the possible results from each decision. When the cost at each decision point and the probabilities of the resulting outcomes are posted, the decision tree can become an effective planning and management tool for analyzing exploration strategy and selecting the optimum approach to complex problems.

In the typical decision process there are three or more choices at the initial or time-zero decision point, and the objective is to identify which initial course leads to the best final result in terms of some specified value, e.g., minimum financial risk, maximum expected value profit, etc. Examples of decision tree analysis in exploration were given by Newendorp (1976) and parts of his methodologies are applied here to geothermal exploration in northern Nevada.

A segment of a decision tree that might be considered for northern Nevada is shown in Fig. 6. It is not a complete decision tree because the time-zero decision involves only whether to (a) conduct a reconnaissance program over a large initial area, or (b) to pass up the exploration opportunity (a trivial matter in this discussion). Other unspecified options are indicated at time zero, and for a thorough analysis all of these would have to be identified and carried through a decision sequence to termination.

The tree shown in Fig. 6 corresponds to the exploration strategy and associated costs summarized in Table 4. The broken vertical lines are drawn through decision points (or nodes) and separate the tree into four regions or time segments corresponding to the following exploration phases:

(a) The first phase or reconnaissance exploration of a 2500 square-mile area;

(b) A transition phase consisting only of temperature gradient or heat flow holes to assist in the selection of areas for more careful study;

(c) Second-phase or detailed exploration conducted either prior to or after land acquisition; and

(d) Third-phase exploration for drilling of a single confirmatory well. Drilling may follow supplemental detail exploration or proceed without it.

The decision tree illustrates a number of possible scenarios. Each scenario is a branch of the tree, terminating eventually in either a successful drill test which gives evidence for a high-temperature, hot-water geothermal field, or in any one of several possible failure situations. In actuality, scenarios could terminate for reasons other than shown; the explorers might be unable to obtain leases or to continue because of financial constraints such as the scenario exceeding the project budget level. Each scenario is determined by the choices at the decision nodes (squares) and controlled by the probabilities of ensuing results at the chance nodes (circles). The sum of the probabilities at each chance node must equal unity.

The exploration costs shown are derived from our effectiveness and cost effectiveness study and from published costs for land acquisition and drilling. The probabilities are based in part on experience, but some are only reasonable guesses where experience is lacking. The probabilities at nodes A, C, and F, for example, are predicated by experience. Beyond these, the probabilities are much less certain and should be viewed as tentative, semi-educated guesses.

Two numbers are given at the end of each scenario: the total dollars (in thousands) spent to the end-point, and the cumulative probability, expressed as the product of the many dependent probabilities along the branches of the scenario. The sum of all cumulative probabilities exceed unity and therefore a cumulative probability number is not, with few exceptions, the probability of reaching that end-point from time zero. These numbers can be viewed in a relative sense, however, and the ratios may provide revealing information, as shown later.

The particular decision tree presented here is derived from the exploration strategy and costs discussed earlier. At time zero the decision is either to embark on a reconnaissance of the 2500 square-mile study area or to pass up the area entirely. A positive decision would call for an estimated expenditure of $109K. As previously stated, we show a very limited range of options at time zero, and in practice other options should be present. The nature of these would depend on an assortment of institutional and financial considerations as well as the level of accumulated technical knowledge. Based on the latter, for example, the time-zero decision options might include one or more of the subsequent decisions thereby by-passing an early exploration phase(s). Here, however, we illustrate the decision sequence based on the exploration strategy developed in the previous section.

After the first chance node, A, experience indicates the probability of encouraging indications will be high, .95 in this example, and therefore the upper main branch B, C, etc., is the one of principal interest to us. For completeness, and because it is always within the realm of possibility, a similar decision sequence is also shown for the lower main branch, Z, Y, etc. In practice, it seems unlikely that the decision process would proceed very far along the lower main branch and we therefore concentrate attention on the upper branch.

In this simplified decision tree the first significant decision occurs at node D where the choice is either to acquire 10,000 to 20,000 acres under lease and then proceed to the detail exploration phase, or to defer land acquisition until after the basic detail-phase exploration work is conducted on a larger study area. Practical considerations might unequivocally dictate the choice here, but in any case, it is also important to examine and compare the resulting outcomes from the choices. If a basic detail-phase program is conducted over an area of ~100 square miles prior to land acquisition (path D, F, G, etc.), cummulative costs to a terminal point will be higher. Not only would one spend more for the second stage exploration because of the larger area size, but land acquisition costs might subsequently be greater. The latter cost increment is ignored here, however. Further, as this choice is more likely to produce encouraging exploration results (chance node F), there is a better chance that additional money will be spent on a supplemental exploration program (decision node G) prior to drilling. Compensating for these heavier costs are improved probability ratios at subsequent chance nodes, thus leading to a more favorable drill success ratio at comparable termination points. For example, by deferring land acquisition at D, the drill success ratio ($P_3:P_4$) is 2.2 times better than the comparable ratio ($P_1:P_2$) obtained when leases are acquired prior to the detail exploration phase.

Other important decision points occur at G and H and these scenarios are expanded and illustrated in Figs. 7 and 8. Figure 7 is an expansion of the decision tree from node H and corresponds to the general scenario in which acreage is acquired relatively early in the exploration sequence (node D). Subsequent work, then, is concentrated in the smaller study area of some 10,000 to 20,000 acres (15 to 30 square miles). We have no historical basis for the probabilities shown in this figure. The probabilities may or may not be appropriate for northern Nevada; they do, however, illustrate evaluation techniques which are now discussed.

Relative to node H, the drill success/failure ratio differs depending on whether a deep test hole is drilled immediately or whether a supplemental exploration program is first conducted in order to help confirm the exploration concept and/or to help select a more promising drill hole location. An additional expenditure of $55K for electrical resistivity and passive seismic studies increases the drill success/failure ratio from .1 to .15. The latter number is derived from the following expression:

$$\frac{\text{drill success}}{\text{drill failure}} = \frac{\Sigma \text{ cumulative probabilities for success}}{\Sigma \text{ cumulative probabilities for failure}}$$

$$\frac{DS}{DF} = \frac{.04 + .02 + .01}{.23 + .09 + .15} = .15$$

We notice that this risk improvement applies only when exploration reaches the drilling stage after the supplemental exploration work is performed. Should that work produce negative results and no hole is drilled, the project success/failure ratio is .11. This is roughly the same as the ratio when a hole is drilled at H, but the project cost is less ($349K vs. $429K). Therefore, we see an example of cost effectiveness improvement by deferring a commitment to a deep drill hole until supplemental exploration is performed.

For other comparisons, Fig. 8 is an expansion from node G, and corresponds to the scenarios in which land acquisition is deferred. Here the basic segment of the detail-phase exploration program would be conducted over an area of ~100 square miles, leading to the following choice of decisions at G:

(a) to conduct the supplemental exploration program over promising portions of the area ($109K),

(b) to acquire acreage* and perform a limited supplemental exploration program over the leased land ($130K), or

(c) to acquire acreage* and proceed immediately to a deep drill test ($190K).

For the probabilities assumed, each choice leads to a different terminal drill success/failure ratio. The ratios improve incrementally as a function of exploration extensiveness and intensiveness prior to drilling. For example, looking at the most extensive and intensive

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* Federal regulations currently limit private companies to hold under lease no more than 20,000 acres per State at any one time. However, exploration can be done over unlimited Federal acreage with appropriate exploration permits from the Bureau of Land Management.

exploration scenario, the upper branch from G (Fig. 8), we see that the probabilities lead to a drill success/failure ratio of .3 and an overall project success ratio of .21. That is, if this scenario is carried to termination and a confirmatory hole is drilled, approximately one project out of three will yield a successful hole. However, as it is possible that the area will be downgraded after the supplemental exploration program and no hole will be drilled, the overall project success drops to one chance in five. This project success is nearly equal to the other two shown in Fig. 8 but this is mainly a fortuitous result caused by the probabilities assumed at the various chance nodes.

Accepting the probabilities shown, one observation that can be made from Fig. 8 is that the most expensive exploration program may not be the optimum one in cost-effective terms. The middle branch from G results in only slightly lower success ratios than the most extensive and intensive program and the total cost is \$54K less. Therefore, it would appear that the middle branch may offer the best approach. To examine this quantitatively we can calculate and examine a cost-effectiveness parameter as follows:

$$\text{Cost Effectiveness} = \frac{\text{Drill Success Ratio or Project Success Ratio}}{\text{Maximum Financial Risk (\$000)}} \times 1000$$

The 1000 factor is introduced to obtain numbers near unity. Cost-effectiveness parameters derived from the above expression are shown in the following table.

Table 5. Cost-effectiveness values for exploration scenarios.

Branch	Maximum Financial Risk ($000)	Drill Success	Project Success	Cost-Effectiveness Confirmatory Hole	Cost-Effectiveness Overall Project	EV ($000)
G-Upper	608	0.30	0.21	0.49	0.35*	3085
G-Middle	554	0.29	0.19	0.52*	0.34	2705
G-Lower	499	0.17	0.17	0.34	0.34	2576
H-Upper	429	0.10	0.10	0.23	0.23	1614
H-Lower	484	0.15	0.11	0.31	0.23	2056

* Best values for probabilities assumed.

For the probabilities assumed, the G branch (i.e., deferring land acquisition until after the basic detail-phase exploration is completed) gives higher cost-effectiveness in overall project success. Of the three choices at the G node, the middle branch is more cost-effective whenever the project is taken to the drilling stage. However, the G-upper branch gives a slightly better cost-effectiveness in overall project terms.

Another way of evaluating the decision choices is to calculate the expected values (EVs) according to the procedures given by Newendorp (1976) to find which branch offers the maximum expected return on investment. To do this we begin at the terminal points and work backward toward the time-zero decision, one node at a time. At a chance node we calculate an expected value using the probabilities and the values received at each of the chance node branches. The EV represents an equivalent value of everything to the right of the chance node. To obtain this value one must specify a value for the geothermal resource when the confirmatory hole is successful. In this example we will assume that the resource, if discovered, will have a discounted value of $20 million over the life of the field. An accurate estimate of discounted value is unimportant for this calculation unless one is using the analysis to compare EVs for different areas or different exploration opportunities.

Here, we would need to work backward to the D decision point because it is the first point on the tree where a clear decision is explicated. However, as it turns out, working backward only as far as the G and H decision points is sufficient to show which method of approach leads to the higher EVs. The EV calculations are presented below. Values and costs are expressed in $ thousands.

1. H-upper: Acquire land prior to detail-phase exploration and drill without doing the recommended supplemental detail-phase work.

$$EV_{HU} = .1 \times \$20{,}000 + .9 \times -\$429 = \$1{,}614$$

2. H-lower: Acquire land prior to detail-phase exploration but defer drilling until after recommended supplemental work is completed.

$$\begin{aligned} EV_{HL} = {} & .5(.15 \times \$20{,}000 + .85 \times -\$484) \\ & + .2(.17 \times \$20{,}000 + .83 \times -\$484) \\ & + .3(\text{Max of } -\$369 \text{ or } .05 \times \$20{,}000 - .95 \times 484) \\ = {} & \$1{,}294 + 600 + 162 = \$2{,}056 \end{aligned}$$

3. G-upper: Defer land acquisition and drilling until after both basic and supplemental detail-phase exploration is completed.

$$\begin{aligned} EV_{GU} = {} & .22(.25 \times \$20{,}000 + .75 \times -\$608) \\ & + .53(.23 \times \$20{,}000 + .77 \times \$608) \\ & - .25(\$418) \\ = {} & \$1{,}000 + 2190 - 105 = \$3{,}085 \end{aligned}$$

4. G-middle: Acquire acreage after basic detail phase and conduct supplemental phase on the smaller area acquired prior to drilling.

$$\begin{aligned} EV_{GM} = {} & .20(.23 \times \$20{,}000 + .77 \times \$554) \\ & + .50(.22 \times \$20{,}000 + .78 \times -\$554) \\ & - .30(-\$379) \\ = {} & 835 + 1984 - 114 = \$2{,}705 \end{aligned}$$

5. G-lower: Defer land acquisition until basic detail phase is completed and drill without doing supplemental work.

$$EV_{GL} = .15 \times \$20,000 + .85 \times -\$499 = \$2,576$$

Because the probability values strongly effect the EVs, it is not surprising that there is a good correlation between EVs and the success ratios and cost-effectiveness parameters discussed above. The G-branch yields the higher EVs, the highest going to G-upper which also gave the largest cost-effectiveness on a project level.

For the sake of completeness, the EV analysis can be continued backward to the D decision point in the following steps:

1. H branch. The EV at the E chance node is

$$EV_E = .6 \times EV_{HL} + .4 \times -\$314$$
$$= .6 \times \$2056 + .4 \times -\$314$$
$$= \$1108$$

2. G branch. The EV at the F chance node is

$$EV_F = .9 \times EV_{GU} + .1 \times -\$309$$
$$= .9 \times 3085 - 31$$
$$= \$2746$$

Because $EV_F > EV_E$, the choice at decision point D should be to defer land acquisition, and conduct a detail-phase program on a larger area than would have been leased.

SUMMARY

An evaluation process was used to rank the exploration techniques applied in northern Nevada on the basis of (a) the amount of useful geological information derivable from a proper interpretation of the data and (b) the practical value of that information in meeting the exploration objectives. Rating factors were provided by each of seven investigators involved in the interpretation of survey results, and the average ratings were used to differentiate the effective from the less effective methods. Discussions among the investigators were useful for outlining a scope of work for each exploration technique. From each scope of work a survey cost was calculated, and these costs were combined with the effectiveness ratings to yield cost-effectiveness ratings. Discussions were also useful in developing an exploration sequence, which consists of the following four phases (Table 4):

1. Reconnaissance phase - directed at an initial study area of approximately 2500 square miles. This phase would have a basic program of:
   a. Geologic studies
   b. Rock age dating
   c. Geochemical studies
   d. Color/color IR photography
   e. Low-sun-angle black and white photography and an optional supplemental program of:
   f. Regional seismotectonic studies
   g. Thermal IR imaging
2. Transitional phase of 12 heat flow holes drilled to about 500 feet; the data to supplement existing regional data.
3. Detail phase directed at a study area of approximately 100 square miles. This phase would have a basic program of:
   a. Geologic studies
   b. Gravimetry
   c. Seismic reflection and refraction

d. Temperature gradient/heat flow drilling and a recommended supplemental program of:

e. Electrical resistivity

f. Microearthquake, teleseismic P-wave delay and amplitude variation studies.

4. Confirmation phase of deep drilling to test the targets outlined from previous work.

The strategy developed was further exercised by means of a decision tree analysis in which several variable factors were considered: (a) the timing of land acquisition and (b) the elimination of either or both the basic and recommended segments of the detail-phase exploration prior to confirmatory drilling. Many scenarios were outlined, each terminating eventually in either a successful drill test or in any one of several possible failure situations. Among the possible scenarios, several of the more interesting ones were studied in detail. On the basis of assumed probabilities, many of which are only semieducated guesses, we were able to derive quantitatively several important exploration guidelines. These can be refined when more reliable probabilities are known for decision outcomes at the many chance nodes in the decision tree. However, for the assumed probabilities we found the following:

(a) Conducting the detail-phase exploration prior to land acquisition will result in a higher cumulative exploration cost, but will result in a 2.2 times better chance for a favorable drill hole if the project gets to the final drilling stage.

(b) Project cost-effectiveness is found to increase as exploration thoroughness increases. Deferring land acquisition until after the basic detail-phase exploration is completed gives higher cost-effectiveness values for both the general project and for those projects that ultimately reach the confirmatory drilling stage.

(c) An expected value (EV) analysis shows that the maximum return on drilling investment can also be expected if land acquisition is deferred until after the detail-phase exploration is completed. Conducting the recommended supplemental detail exploration prior to land acquisition entails the highest financial risk, but also gives the highest EV. Acquiring land before doing a more limited version of the supplemental detail exploration results in less financial risk and slightly higher cost effectiveness but gives a lower EV.

APPENDIX A

LIST OF CONTRIBUTORS TO EXPLORATION STRATEGY ANALYSIS

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APPENDIX B

BASIS OF SURVEY COSTS

RECONNAISSANCE PHASE

Aeromagnetics: The aeromagnetic survey would consist of approximately 3000 line-miles at a survey altitude 2000 feet above terrain (A.T.), line separation one mile, flown with a fixed winged aircraft carrying a proton magnetometer and standard navigation equipment. Based on mobilization and demobilization from and to Salt Lake City, Utah, line-mile cost is approximately $11 or $33,000 for the entire survey. Structural and a Curie-point-isotherm analysis could be made at additional cost.

Airborne IR Imagery: A single predawn flight, at 6000 feet A.T., will be flown to obtain imagery in the 8-14 micron band. With a 77° field of view and a 30% side-lap between adjacent scans, a line separation of 1.25 miles is required. Based on cost of about $21 per line mile, which buys the B&W paper tape prints and recorded data with no enhancement, the total survey cost would be approximately $41,500. However, assuming that 50% of the area can be eliminated on the basis of geological screening, a cost of $21,000 is a more reasonable estimate of the total survey cost.

Color and Color IR Photography: Air photos at a scale of 1:24,000 with 30% overlap between adjacent frames are acquired with a Super-wide Zeiss RMK-A, 85mm focal length. Assuming two separate flights have to be made, the combined cost for both sets of photographic prints is $25 per line mile, or approximately $16,250 for the entire area.

High Altitude B&W Photography: B&W air photos at a scale of 1:100,000 are obtained at a flight altitude of 40,000 feet A.T. by means of the Super-wide Zeiss mounted in a Lear jet. Flight lines are 25 miles apart and the area is flown twice for both morning and afternoon low sun-angle illuminations. At a cost of $20 per line mile, the total cost of data acquisition is approximately $8000. Mobilization from Salt Lake City is assumed.

Geological Studies: The primary objective of these studies is to produce a geologic map at a scale of 1:62,500 to 1:125,000 using existing geological information, supplemented by structural and lithologic information (field checked) interpreted from the air photography, IR thermal scannings, and satellite imagery. The geological studies would also include a literature study, hydrothermal alteration investigations and sample collection for geochemical and rock age-dating investigations. A cost of $60,000 is estimated, which cover six months of a senior geologist's time, plus a field assistant and associated office, field, and travel expenses.

Geochemical Studies: Major element, trace element and radioelement analyses would be made on samples from hot springs, cold springs, and rocks in the region. These studies would include chemical geothermometry based on major element abundances. Samples from approximately 50 locations would be collected and analyzed. The estimated cost, mainly laboratory expenses, is $20,000.

<u>Regional Gravity</u>: Between 300 and 400 gravity stations, approximately one station per six-seven square miles, will be occupied using bench mark elevations wherever possible and topographic map elevations elsewhere. Terrain-corrected Bouguer anomaly maps will have an accuracy of ± 1 milligal. A cost of $15,000 to $20,000 to produce the anomaly map is estimated.

<u>Rock Age-Dating</u>: K-Ar, whole rock, analyses will be made on some 20 samples of igneous intrusive and extrusive rocks in the area. A cost of $5,000 is estimated to check the ages of thermal events recorded in the rocks.

<u>Passive Seismic-Regional Seismotectonic Studies</u>: Four or five semipermanent seismometer locations will be monitored in the area for a period of up to one year. Local earthquake events $M > 1$, together with a study of existing earthquake data, will be used to develop a picture of the local seismicity and present tectonics. Estimated cost of study is $70,000.

<u>Passive Seismic-Microearthquake and Ground Noise Studies</u>: Seismometer arrays will be laid out and monitored at various valley sites for periods of three to four weeks per site. Microearthquakes, $M < 1$, and noise data will be processed to find areas of swarm activity. Estimated cost is about $100,000.

<u>Hydrologic Studies</u>: Hydrologic studies of the area will be carried out for base line information on the hydrologic balance. A map of the ground water flow net, showing areas of recharge and discharge will be prepared and used in conjunction with geochemical results. The estimated cost is $40,000.

Regional Magnetic Variometry (or Regional Magnetotellurics): Up to 25 stations in the area will be occupied to record long period magnetic variations (up to 24 hours) of long period electric-magnetic (MT) variations to determine whether indications of a thin, hot crust occur. Estimated cost is $50,000.

Heat Flow: Twelve holes to depths of about 500 feet will be drilled to supplement existing heat flow data for the region. These holes will not be drilled in a low-density aerial pattern, but rather will be drilled for local detail in a few specific areas in order to assist in the selection of areas for detail phase exploration. As such, the heat flow work may be considered as the transition phase between reconnaissance and detail phases. Cost of drilling analyses is estimated at $60,000.

APPENDIX C

BASIS OF SURVEY COSTS

DETAIL PHASE

Aeromagnetics: The aeromagnetic survey would consist of approximately 400 line-miles, at a survey altitude 500 feet A.T. and a line separation one-third mile. The survey would be flown with a fixed-wing aircraft carrying a high-sensitivity alkali-vapor magnetometer. A ground magnetometer is maintained for diurnal corrections. Based on mobilization and demobilization from and to Salt Lake City, the line-mile cost is estimated to be $22 or approximately $8,800 for the survey and the production of a contour map. Survey coverage would be mainly over valley areas, extending slightly over the lower flanks of adjacent ranges. The cost does not include a geological interpretation.

Ground Magnetics: Approximately 120 square miles of magnetic coverage would be obtained with stations along roads and geophysical survey lines. A station density of approximately two or three stations per square mile is required with fill-in stations where needed to detail areas of steeper magnetic relief. A portable proton magnetometer and operator are required for a period of no more than two weeks. Base stations will be reoccupied three times daily and diurnal correction will be applied to the observed readings. The estimated cost for the survey and the production of a contour map is $3,400.

Geologic Studies: The objectives of the geologic studies are to obtain a geologic map of the study area at a scale of 1:24,000, and, using geophysical data and available subsurface information, to develop geologic cross-sections through the area and to select sites for heat flow holes. Three man-months of a senior geologist's time is estimated, which with travel, field, and office expense amounts to a cost of $15,000.

Gravity: Approximately 120 square miles of gravity coverage will be obtained, average station density of three per square mile with fill-in stations where needed in areas of steeper relief and around known or suspected hot springs areas. Gravity data will be reduced, corrected and presented as a terrain-corrected Bouguer anomaly map. Expected error is less than one milligal. The estimated cost to acquire the data and prepare the Bougher map is $15,000.

Passive Seismic, Microearthquake Studies (MEQ): A large array of geophones will be laid out and local earthquakes will be continuously recorded for a period of three to four weeks. Data will be analyzed for hypocenter locations, Poisson's ratios, and fault-plane solutions. The estimated field and laboratory cost is $30,000.

Passive Seismic, MEQ and Teleseismic Studies: This survey is similar to the MEQ survey but with a longer recording period, and the data are analyzed both for the MEQ survey and in terms of the relative P-wave arrival times from teleseismic events. The delay pattern of P-arrivals will be plotted and interpreted in terms of depth to bedrock and for possible geothermal-related anomalies. Six to eight weeks of field time are estimated and the data acquisition and processing cost is $50,000.

Passive Seismic-Ground Noise Studies: The spatial variation in ambient background microseisms as a function of frequency is determined at 50 to 80 locations. This amounts to slightly less than one station per square mile, but a denser station network would be installed around geothermal manifestations. The velocity spectral densities, normalized relative to a reference station, are calculated for quiet intervals, interpreted and plotted for several frequency bands; e.g., 2-4 Hz, 4-8 Hz, 8-10 Hz, and 12-14 Hz. In addition, the propagation characteristics of the microseisms will be investigated by means of a high-resolution wave-number analysis from multielement array data to determine the apparent velocity and direction of coherent seismic waves at 12 to 20 sites within the area. Estimated cost of the data acquisition and laboratory processing is $50,000.

Active Seismic: Approximately 25 line miles of seismic reflection and refraction survey will be conducted along selected lines for structural control. A generalized structural model will be constructed on the basis of the reflection and refraction interpretation, and the model tested by means of finite element computations. A cost of $50,000 is estimated.

Electrical Resistivity Studies: The electrical resistivity studies consist of reconnaissance E-field ratio tellurics, with three scalar MT stations per line for control, followed by dipole-dipole surveying. Fifty line-miles (80 line-km) of tellurics with 500 meter dipoles will be surveyed at 0.05 and 8 Hz. Selected lines, totaling 40 line-kms, will be resurveyed by means of the dipole-dipole array with a combination of one kilometer, 500 meter, and 250 meter dipoles, N up to 10. The cost of the telluric study, based on an average cost of $200 per station, is $32,000. The cost of the dipole-dipole survey based on an average cost of $1000 per line-mile ($625 per line-km) is estimated at $25,000. A small amount of computer modeling for data interpretation would add an additional $2000 to the survey cost and bring the total cost of electrical resistivity studies to $59,000.

Self Potential: Self potential readings will be made along geophysical survey lines crossing the area of interest. No more than two weeks of effort by a two-man crew would be needed to conduct an orientation survey to determine whether SP effects occur over or near geothermal manifestations. The estimated cost should be approximately the same as ground magnetics, $3400.

Heat Flow: Thirty heat flow holes to 50 meters will be drilled, temperatures and thermal conductiveness measured. Once the thermal gradient in the area is verified, an additional 20 to 30 holes could be drilled to 20 meters in depth for additional information. The total cost of this work is estimated at $60,000.

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FIGURE CAPTIONS

Fig. 1. Northern Nevada high heat flow area (after Sass, 1971).

Fig. 2. Effectiveness scatter diagram, reconnaissance phase.

Fig. 3. Effectiveness scatter diagram, detail phase.

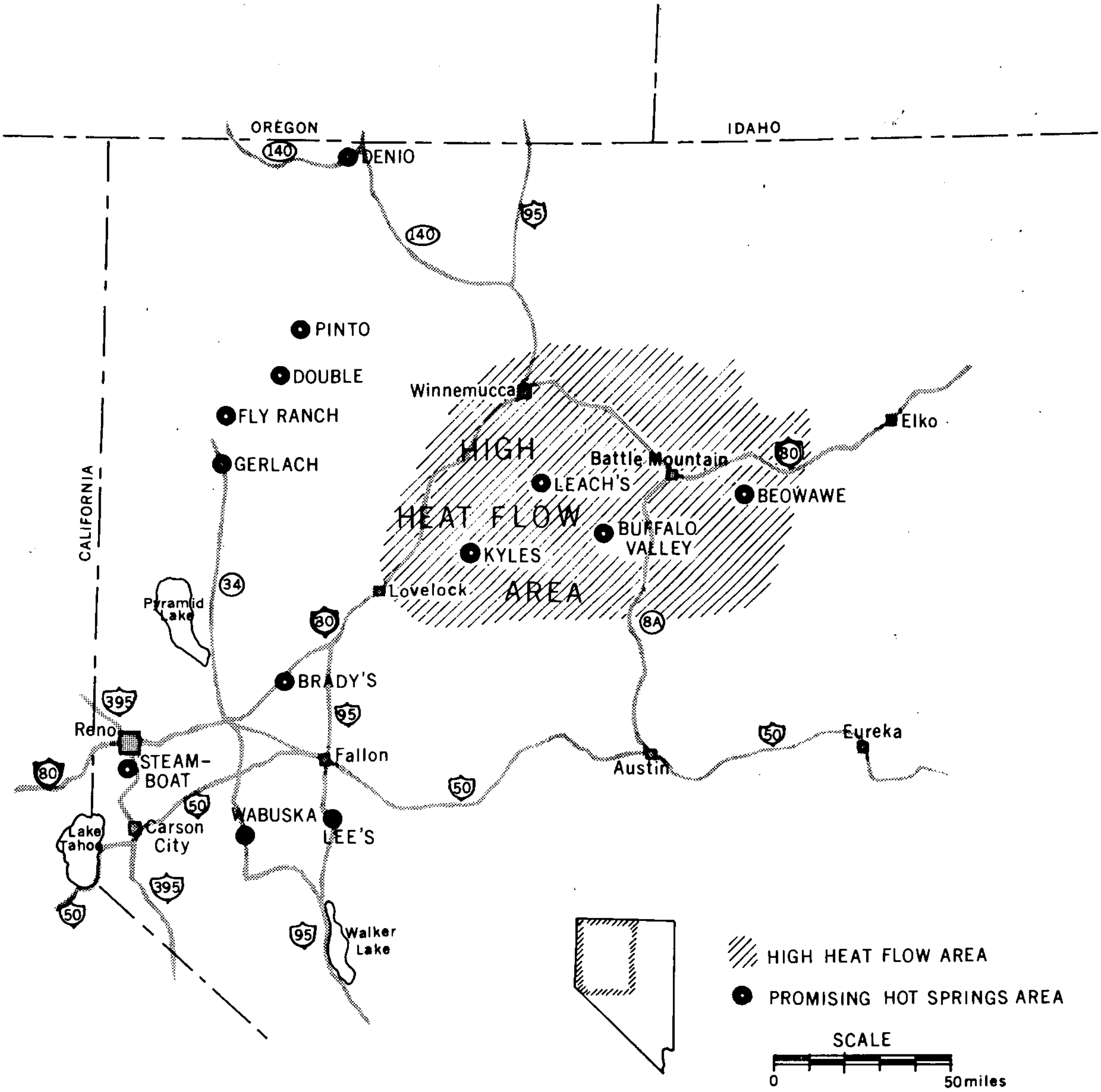
Fig. 4. Program chart, reconnaissance phase.

Fig. 5. Program chart, detail phase.

Fig. 6. Partial exploration decision tree based on the northern Nevada strategy analysis and cost estimates.

Fig. 7. Detailed decision tree for follow-up geophysics and confirmatory drilling: Case I, acreage acquired before second phase.

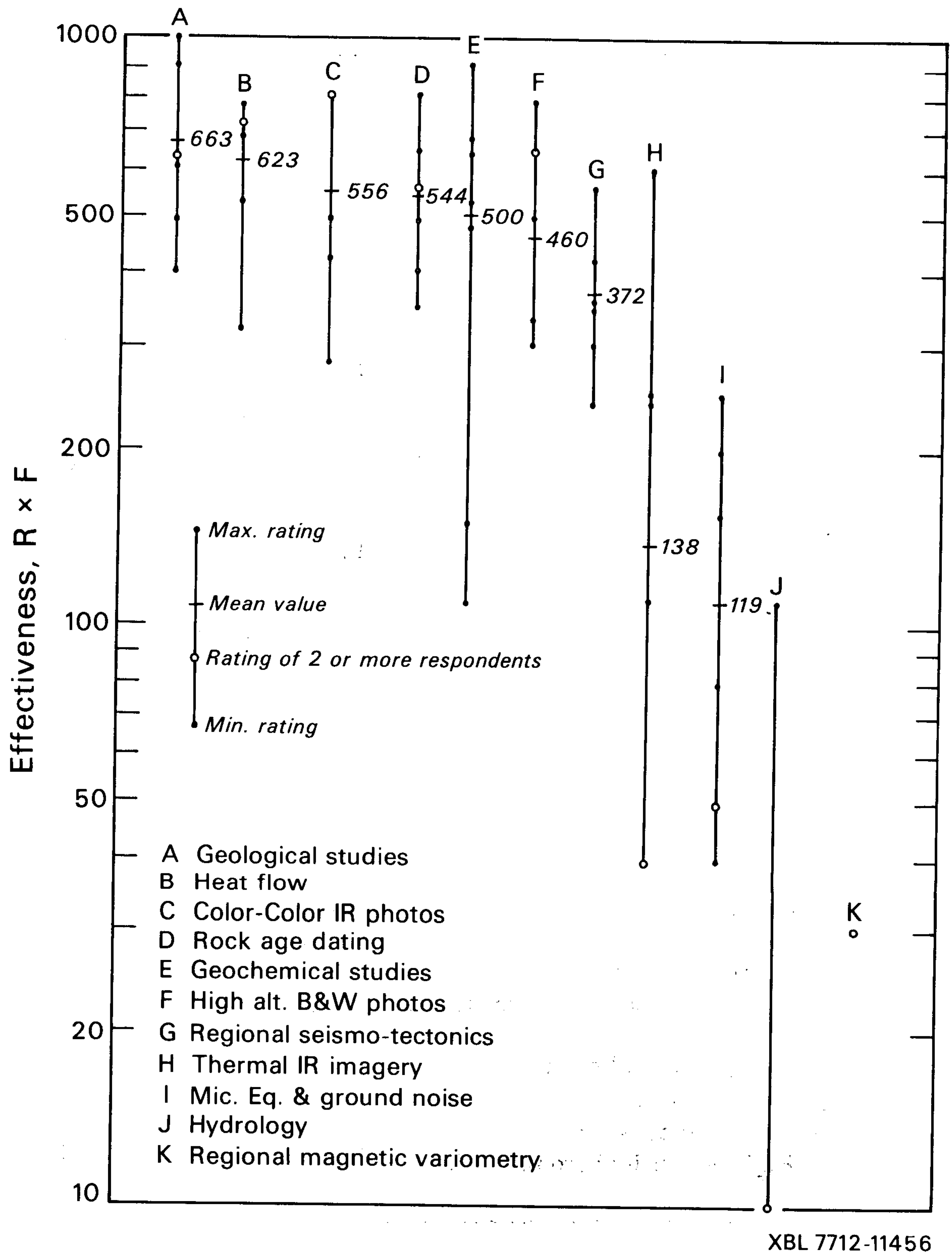
Fig. 8. Detailed decision tree for follow-up geophysics and confirmatory drilling: Case II, acreage deferred to third phase.



Hot Springs in Northwestern Nevada

XBL 735 676

Fig. 1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Rating of 2 or more respondents
Min. rating
A Geological studies
B Heat flow
C Color-Color IR photos
D Rock age dating
E Geochemical studies
F High alt. B&W photos
G Regional seismo-tectonics
H Thermal IR imagery
I Mic. Eq. & ground noise
J Hydrology
K Regional magnetic variometry
XBL 7712-11456

Fig. 2

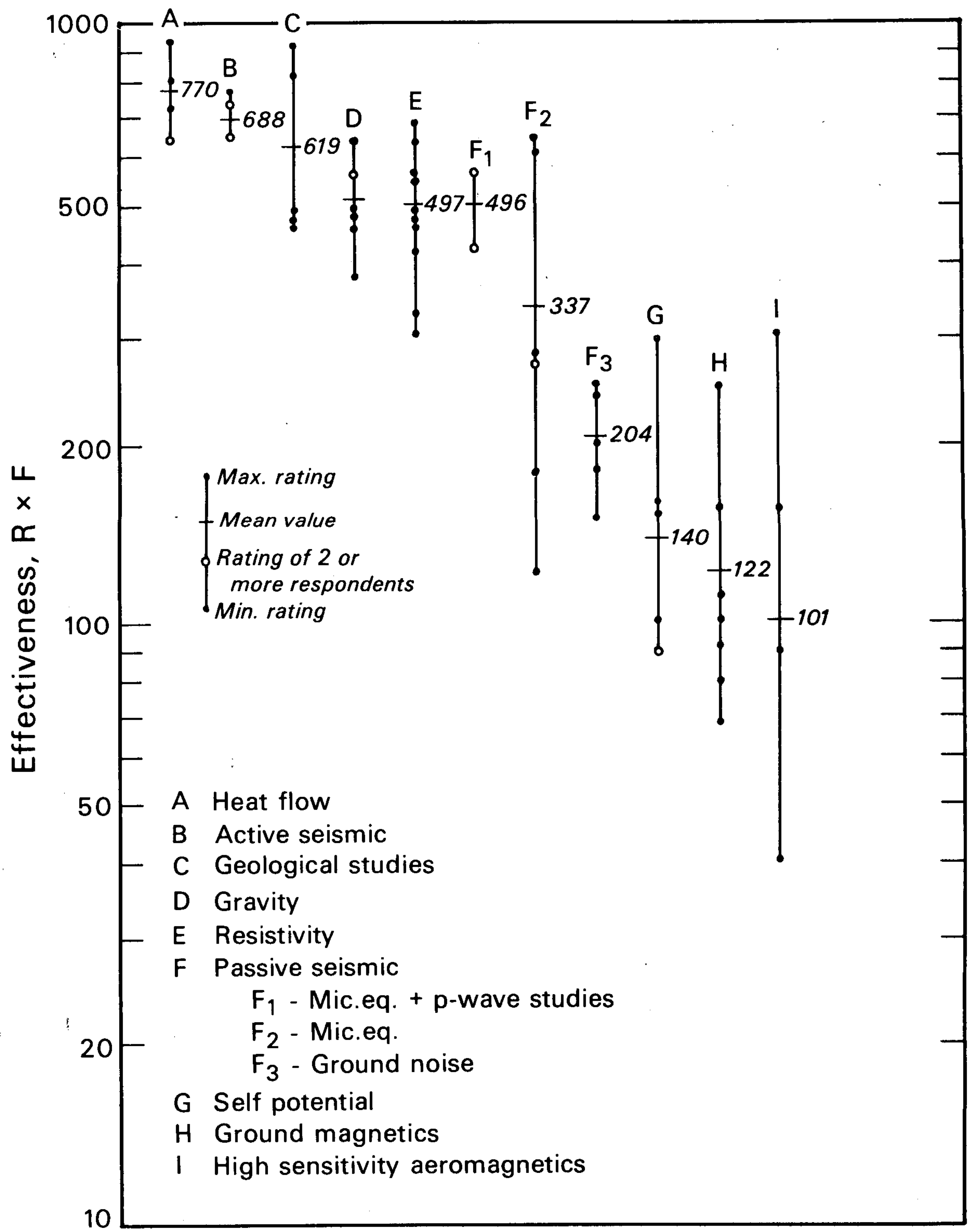

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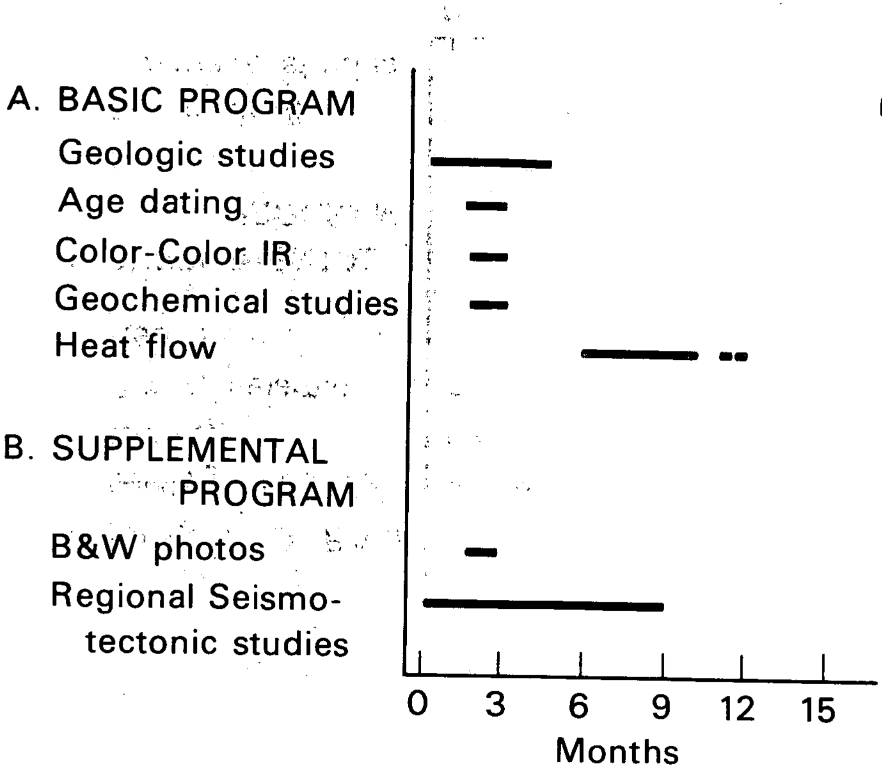
Fig. 3



	Cost ($thous)	Effectiveness rating	Cost-effectiveness factor
A. BASIC PROGRAM			
Geologic studies	60	663	11
Age dating	5	544	109
Color-Color IR	16	556	35
Geochemical studies	20	500	25
Heat flow	60	623	10
B. SUPPLEMENTAL PROGRAM			
B&W photos	8	460	58
Regional Seismo-tectonic studies	70	372	5

XBL 7712-11458

Fig. 4

	Cost ($thous)	Effectiveness rating	Cost-effectiveness factor
A. BASIC PROGRAM			
Geologic studies	15	619	41
Gravity	15	506	34
Active seismic	50	688	14
Heat flow	60	770	13
B. SUPPLEMENTAL PROGRAM			
Resistivity	59	497	8
Micro-eq. & p-wave studies	50	496	10

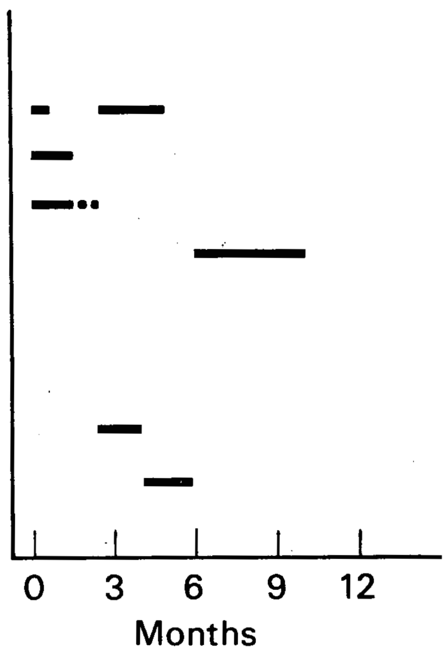


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Fig. 5

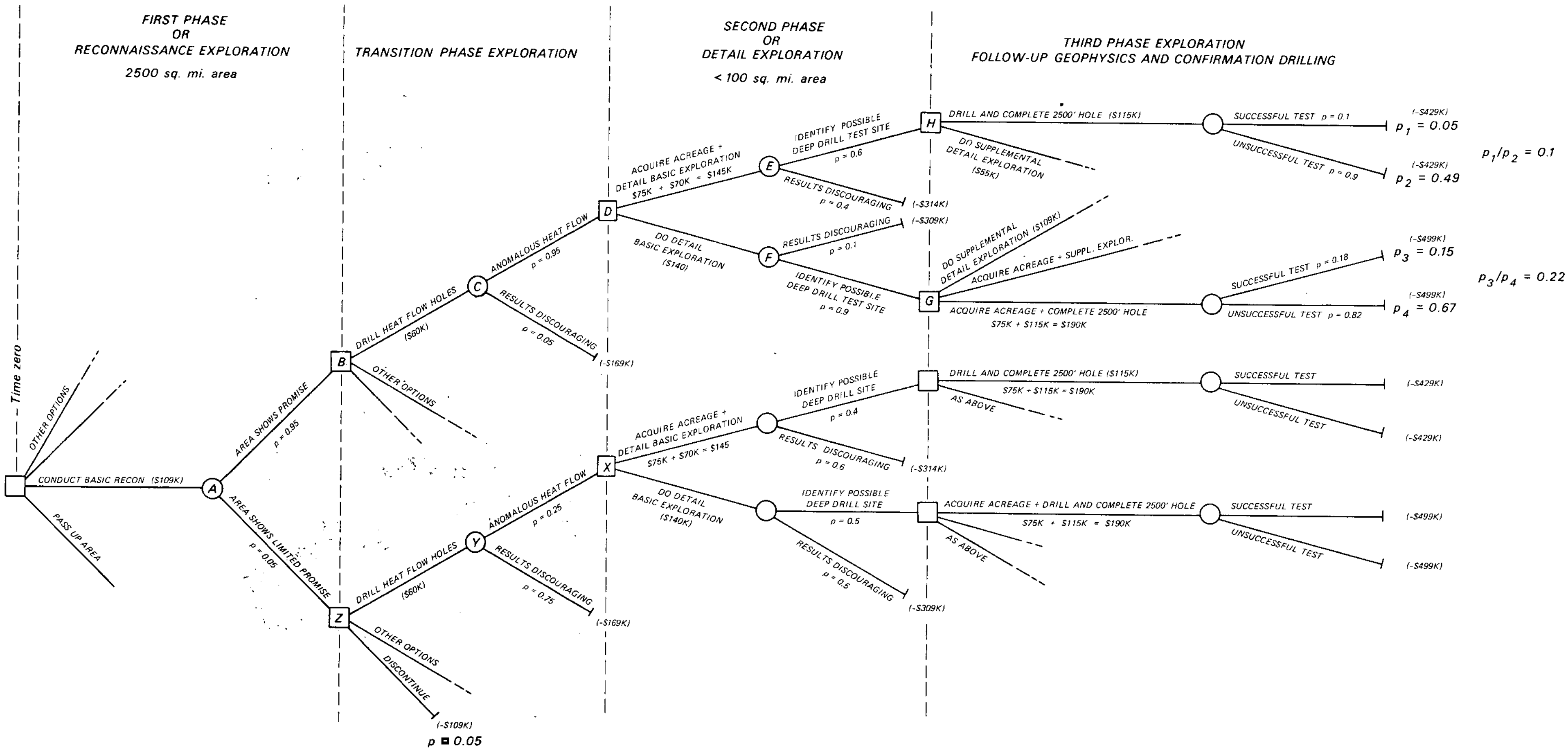

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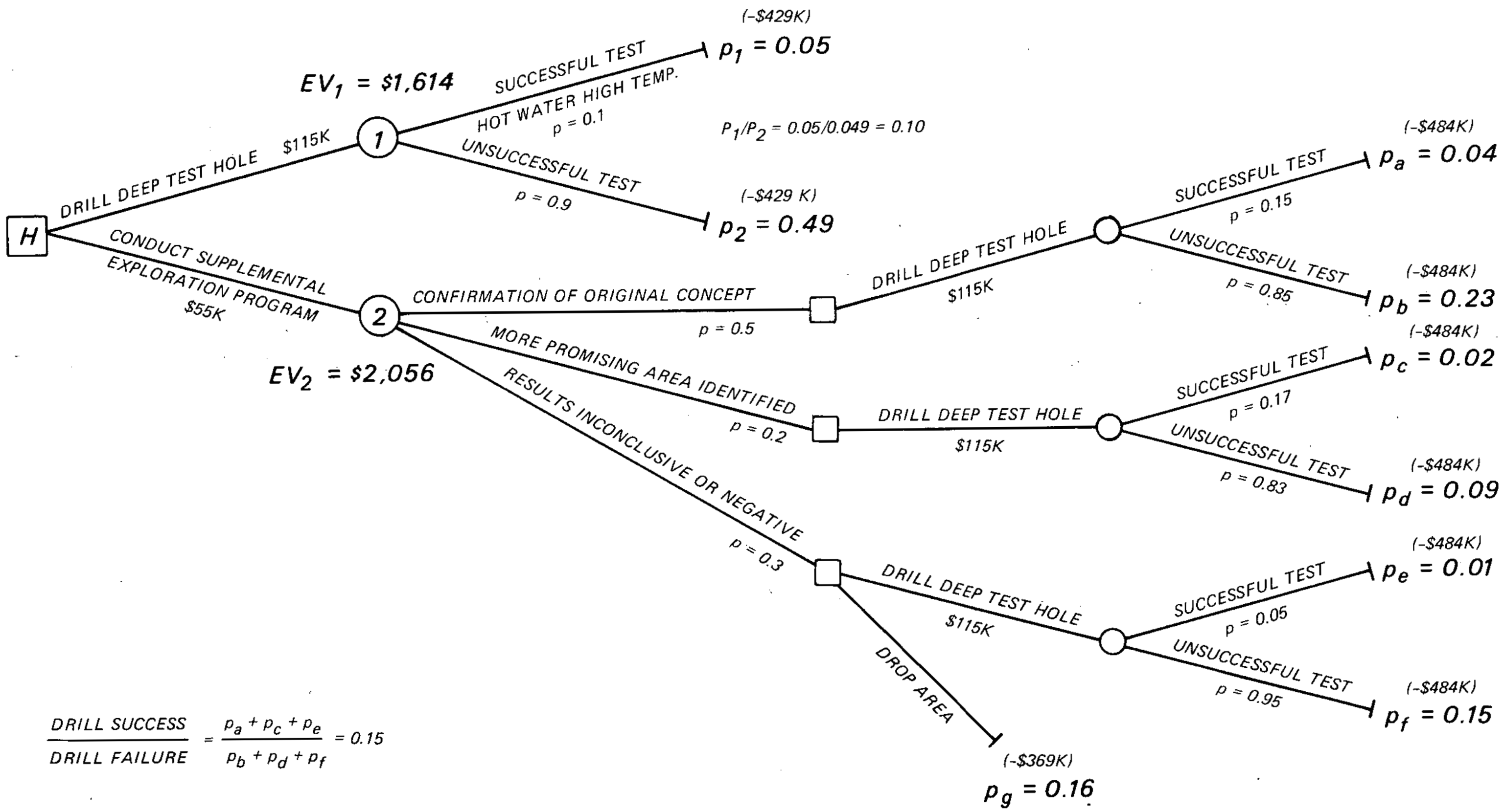
Fig. 6



$$\frac{\text{DRILL SUCCESS}}{\text{DRILL FAILURE}} = \frac{p_a + p_c + p_e}{p_b + p_d + p_f} = 0.15$$

$$\frac{\text{OVERALL SUCCESS}}{\text{OVERALL FAILURE}} = \frac{p_a + p_c + p_e}{p_b + p_d + p_f + p_g} = 0.11$$

XBL 7712-11454

Fig. 7

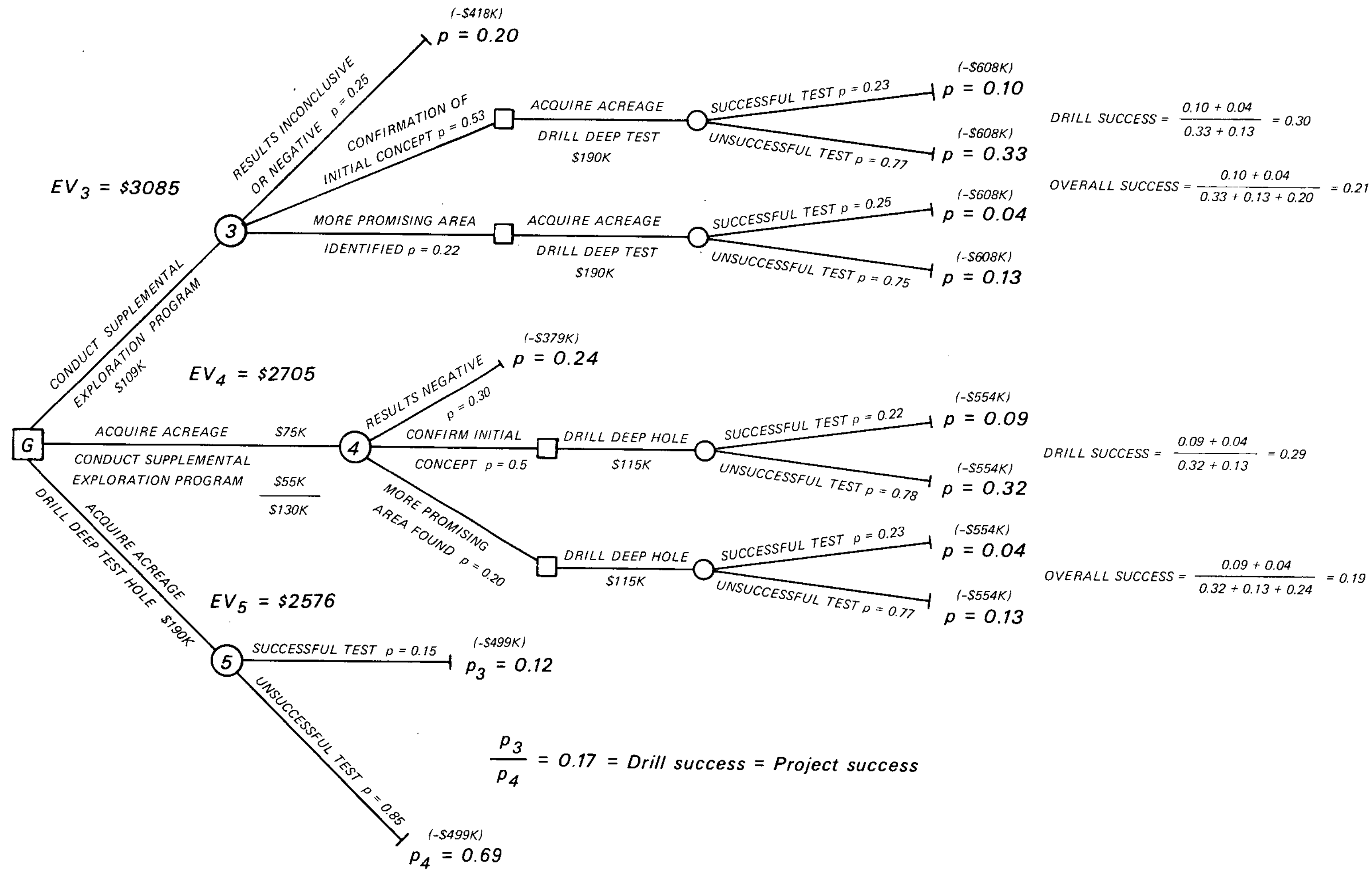


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Fig. 8