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TECHNICAL REPORT: VOLUME 77-2

Geothermal Exploration Architecture

Energy Research and Development Administration

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ABSTRACT

A basic modular exploration sequence which includes a carefully balanced selection of geological, geochemical, and geophysical modules is developed for geothermal prospecting in the eastern Basin and Range. The cost per square mile for application of this exploration architecture is $461.00. If one were to expand this basic system to include virtually all techniques being routinely employed in geothermal prospecting today, then the cost per square mile would increase to $790.00. This latter expenditure rate is difficult to justify, but some increase above the $461.00 basic cost appears to be warranted to make exploration costs about equal to land acquisition costs and model-test drilling costs. Total costs per discovery appear to range from $6M to $27M depending upon assumptions, when the costs of exploring for "dry" prospects are included in the costs of the discoveries. Development and operating costs are not included in the analysis.

The basic exploration architecture described here is compared with others previously advanced in the literature. While differences in approach are abundant, there is a central core of exploration activities and an order to these activities to which most of us "architects" probably would subscribe. If a common basic is used for computing costs of individual exploration modules, then there is no great cost disparity between any of the architectures reviewed.

1.0 Introduction

The design of exploration campaigns (herein termed exploration architecture) intended to discover economically viable resources, be they geothermal, base metal, oil and gas, uranium, or whatever, is not a totally objective science. Further, exploration architecture is a dynamic thing which changes as more is learned about a) a specific geological area, b) a specific resource type, or c) the methods used in exploration. Thus, it is seldom that two industrial concerns will agree on a particular exploration architecture for a given commodity in a given area at a given time. Nevertheless, there are certain guidelines which most follow, consciously or subconsciously, in arriving at the design of an exploration campaign. In the following, I present my current notions on exploration architecture suited to discovery of convective hydrothermal systems in the eastern Basin and Range physiographic province of the western USA.

The approach to exploration architecture that I use is not new. Similar forms of it have appeared in the literature for years; three basic and useful references from the mining literature are Hawkes and Webb (1962), Pfleider (1968), and Ward (1972). As noted by Grose (1971), "The modern exploration approach to geothermal energy is basically similar to that of metaliferous mineral deposits and oil and gas. However, the science and technology of development of geothermal resources is young and untested by long experience of success and failure." Articles on exploration architecture which reflect different and broader experience bases than I am able to provide are Banwell (1970), Combs and Muffler (1973), Greider (1975), Dolan (1975), Furumoto (1975), McNitt (1975), and

Meidav and Tonani (1975). My analysis largely ignores these works at the outset since my intent is development of exploration architecture suited to detection of hidden geothermal resources in a relatively large region, whereas the earlier authors mostly start with the assumption that a small prospect area has been identified. Later I shall compare my findings with theirs.

2.0 Basic Principles of Exploration Architecture

An exploration sequence should consist of a number of optional modules, each of which depicts one or more specific geological, geochemical, geophysical, or "physical" activities. Figure 1 is a generalized modular exploration system. Decisions to proceed along the various paths indicated depend upon results of prior modules, upon economic analyses made at critical junctures, upon one's experience with the area and the commodity, and upon the exploration tools at one's disposal. The intensity of total expenditures on geology, geochemistry, and geophysics, the distribution of expenditures between these three basic sub-disciplines, and the specific activities under each sub-discipline, vary widely from company to company, from one commodity to another, from one area to another, and from time to time. The particular manner in which I present my concepts of exploration architecture (Ward, 1972) i.e. via a collection of optional hard modules, is itself often contested; many prefer shadowy boundaries between options. Nevertheless, I shall stay with this concept here because I believe that hard modules force one to make hard decisions which ultimately lead to cost-effective exploration. My notion is that the least expensive modules come first in the exploration sequence *provided* that they produce sufficient data points of reliable quality to permit a logical sequence of decisions. At every point where an economic appraisal is indicated, the exploration program or prospect could be terminated or continued. The tendency to continue regardless of the economic forecast must be restrained. Of course, value judgments on such matters depend upon the risk one is prepared to take at any decision-making juncture. Risk is usually assessed by deriving an expected value of a venture at any branch point in an exploration architecture (e.g. Newendorp, 1976). The risk for one optional path of Figure 1 is expected to be different to that for another. Indeed, risk might be lower in Figure 1, if say, the *detailed exploration* modules were eliminated entirely. Development of a risk decision strategy depends upon years of experience with numerous prospects in numerous parts of the world. Since that is not the data base from which I draw, I merely note in Figure 1, that economic appraisals must be conducted at all branch points. This then allows the reader to inject his own risk decision strategy upon a basic piece of exploration architecture. Given this overview of exploration architecture, let us now proceed to suggest architecture suited to exploration for convective hydrothermal systems in the eastern part of the Great Basin of the USA.

3.0 The "Full Option" Approach

Some may contend that land acquisition and drilling for geothermal resources in the eastern part of the Great Basin is so expensive that one ought to conduct nearly all possible modules of an exploration sequence prior to land acquisition and certainly prior to drilling. Let us evaluate this extremum. Figure 2 portrays a hugh array of geological, geochemical, geophysical and hydrological modules which might be employed prior to drilling a geothermal prospect while Figure 3 and Table 1 give estimates of the costs associated with such a program and the basis for the estimates, respectively.

On Figure 4, the geologic map of Utah, we have marked a 90 mile by 150 mile area. This area is largely underlain by Tertiary extrusives but includes later intrusives and volcanics. It contains most of the KGRA's in Utah and is believed to be a region of major crustal perturbation (Eaton, 1975). Roosevelt Hot Springs KGRA, the most prominent geothermal prospect in Utah, lies near the center of its northern border. Let us initially assume that we are interested in any 30 mile by 30 mile (900 square miles) block within this 13,500 square mile area. Figure 3 and Table 1 then provide reasonable, but not uncontested, cost estimates for each module of the exploration sequence for this 900 square mile area. The total cost of exploration for a 900 square mile area would then be $0.710M. For the entire 90 mile by 150 mile region, the total cost of the "full option" exploration would be $10.7M, not including land acquisition, drilling, or production testing.

Also shown at the end of each modular step of Figure 3, is the fraction of the initial area remaining to be considered after each phase; the fractional reduction in area after each phase is my best estimate and it is subject to debate. However, if one believes this area reduction pattern, then only 8% of the total area will remain for drilling. Eight percent of the initial test area of 900 square miles is 72 square miles or about the maximum dimension of one geothermal prospect, if Roosevelt Hot Springs is of typical size. Thus, for the whole 150 mile by 90 mile zone underlain by Tertiary volcanics, we assume a maximum of 15 geothermal prospects.

Grieder (1975) assumes 0.38 of all prospects warrant temperature gradient holes whereas I assume 0.21 of the area studied. I would drill 0.08 of the area whereas he would drill 0.25 of the prospects. My figures are lower than Greider's because I am covering blind areas and prospects whereas Greider is covering prospects only. My estimates of area reduction by phase, given in Figure 3, were based upon a simple formula of 25% area reduction after phases I, II, IV, and VI, and 50% area reduction after phases III, V; this formula was derived from my personal experience in reqional exploration in the mining industry and from comparison of mining and geothermal objectives, problems, and techniques. Greider's estimates of prospect reduction appear to be based upon his personal industrial experience and upon that of the geothermal industry in general. The two estimate schemes appear to be in broad agreement, however subjective.

4.0 The "Restricted Option" Approach

Not too many practitioners of geothermal exploration will agree that the full option approach ought to be employed. Accordingly, in this section I have deleted those methods which have not been proven to me to produce consistently meaningful data. Others may be able to prove me wrong now or at some time in the future. I shall welcome challenge at any time. Table 2 and Figures 5 and 6 show one logical restricted option architecture. Costs have been cut, relative to the full option approach, to \$0.415M per 900 square mile area and would total \$6.2M per 13,500 square miles.

While I cannot agree, some would argue that modules 3, 4, and 5 ought to be deleted also, leaving the net cost for 900 square miles at \$0.360M and for 13,500 square miles at \$5.4M.

Others would argue that some form of passive seismic technique (either microearthquake, earth noise, teleseismic studies, or some combination thereof) ought to be included. If so, and if passive siesmic methods are placed in phase VI, then minimum budgets of $0.455M per 900 square miles or $6.8M per 13,500 square miles must be allocated. Still others would argue for active seismic in phase VI and it is difficult to conceive of less than $100K additional per 900 square miles for budgets of $0.515M per 900 square miles or $7.7M per 13,500 square miles.

In both of these latter estimates, we have retained the cost of modules 3, 4, and 5 because we need more early regional data if we are to apply seismic methods with intelligence at the target definition stage.

5.0 The "MT Option" Approach

The most significant observation brought out at the "Workshop on Electrical Exploration Methods in the Geothermal Environment", held at Snowbird, Utah in November, 1976, was that the magnetotelluric method (MT) characteristically obtains a resistivity less than one ohm-m, at depths in the range 2 to 15 km, beneath a geothermal prospect. This observation suggests that we ought to use MT always as a reconnaissance electrical method. Experience at Roosevelt Hot Springs demonstrates that a minimum station density for detection of this low resistivity zone is one station per square mile. For an area 30 miles by 30 miles, or 900 square miles, 900 observations would be required if this were the initial tool in the exploration sequence. However, if MT is left until the area is reduced to 0.28 of its original size (Figures 7 and 8 and Table 3), then only 207 observations would be required. A nominal cost of $1600 per station is suggested leading to MT costs of $330K per 900 square miles. This cost might be shaved considerably by employing the combined MT/Telluric method, but we have no strong scientific basis for so doing at the present time. If we are to afford the MT method in such scope, then modules 4 and 5 perhaps ought not to be afforded because the regional structural information provided by gravity and aeromagnetics may not be necessary when regional electrical structural information is provided by MT. This approach then leads to costs of $0.700M per 900 square miles or $10.5M per 13,500 square miles.

6.0 Comparative Costs of Various Approaches

In Table 4 I have summarized the exploration costs per 900 square miles, per 13,500 square miles, and per square mile for the several optional approaches discussed here. We observe that costs can range from $400 to $778 per square mile; these costs are not excessive in reference to exploration for any type of resource.

To these costs must be added the costs of a) land acquisition, which we assume to be $0.450M based on acquiring 45,000 acres* at $10 per acre, and b) model test drilling which we assume to be $0.500M for one hole to 5,000 feet. If a prospect warrants a production test we add $1.500M for three holes to 5,000 feet and $0.500M for production testing and for additional geoscientific efforts such as mapping faults by active seismic methods and defining the hydrologic regime by whatever methods are available.

*Note that an individual company is limited to 25,000 leased federal acres per state at the present time so it is doubtful that a company would commit its 25,000 acre allotment to one prospect plus seek an additional 20,000 from state and private acreage. In this respect, Greider (1975) uses 7,500 acres per prospect; such a limited acreage would cover only the heart of the prospect at RHS KGRA.

If we assume that one prospect only can result from exploration of a 900 square mile area, as discussed earlier, then a maximum of 15 prospects will be discovered in southwestern Utah by the types of exploration architecture described here. Each of these 15 prospects will require one model test drill hole to 5,000 feet. Greider (1975) notes that the industry average is less than one producer for every 16 model test holes drilled. In Table 4 we have assumed both 1 in 15 and 5 in 15 producers per model test hole drilled. The worst case states that our brands of exploration architecture are no better than those industry has used in the past, while the best case states that we shall do substantially better than has been done (or that with the discovery of the resource at Roosevelt Hot Springs, southwest Utah is elephant country where odds of discovery are higher).

It is of interest to compute that variations in costs of exploration, restricted to the various assumptions made so far, do not perturb total costs per discovery by more than ±10% about the mean; and that this perturbation percentage is independent of the number of discoveries per prospect drilled. Even when land acquisition costs are reduced to 1/3 of the entries given above, the perturbation of total costs caused by variations in exploration architecture are only ± 13% about the mean. It would seem to us that two conclusions can be drawn from these last two sentences: a) the inertia of drilling and testing costs overwhelms exploration costs, and b) all effort should be exerted in exploration to reduce the number of "dry" prospect wells and to reduce the cost of production testing.

7.0 Conclusions

We conclude that geoscience studies are comparatively inexpensive in geothermal exploration in the eastern Basin and Range. Our route to this conclusion is tenuous. Nevertheless, it appears to be justified to spend at least $1.5M to $2.0M on geoexploration per discovery so identified through a modular exploration sequence. The "full option" sequence described above appears to be excessive while the basic "restricted option" appears to be conservative. Some compromise between the two is appropriate. The impact of various exploration costs on total costs per discovery is minimal.

There would appear to be physical room, according to our area reduction schedule of Figure 3 for a maximum of 15 prospects in southwestern Utah. If we assume that a minimum of 300 megawatts may be developed per prospect, then southwestern Utah ought to yield as much as 4500 megawatts. Based on comparing early and late experience at the Geysers in California, 1500 megawatts per prospect or 22,500 megawatts total, ought to be the maximum expected of southwestern Utah. The total area considered is 13,500 square miles. The maximum area of the Roosevelt Hot Springs prospect is of order 72 square miles. Thus, the whole of the Tertiary volcanic belt of southwestern Utah, if totally productive, would have 188 prospects, whereas we have assumed that at most it is 8% productive, or that it contains 15 potential geothermal *prospects*. We are inclined to reduce these *prospects* to a minimum of one and a maximum of five *discoveries* so that the total geothermal power development in Utah might range from a minimum of 300 megawatts to a maximum of 7500 megawatts. Each discovery will cost $5.95M to $6.99M if 5 are discovered or $21.65M to $26.95M if only one new discovery is made.

This cost per discovery is justifiable when development costs will be much larger (Greider, 1975) and when 300 to 1500 megawatts per discovery can be developed. Ultimately, then we must conclude that a fairly thorough exploration architecture ought to be employed. We are conditioned, of course, by the fact that we know we are hunting for elephants in elephant country.

8.0 Epilogue

The above analysis was written without detailed reference to other articles on geothermal exploration architecture. This procedure minimizes historical bias and focuses on architecture suited to the eastern Great Basin. It is of interest, therefore, at this juncture to compare our analysis with analyses performed by others in prior years. Four previous articles are used for this purpose, those of Banwell (1970), (essentially repeated in Banwell (1974)). Combs and Muffler (1973), Greider (1975), and Dolan (1975). To be fair to Greider, it should be mentioned that only a small part of his article was devoted to exploration architecture. Figures 9 through 16 present the technological and cash flows for each of these four architectures. It should be appreciated that I have taken considerable liberty in converting the texts and figures of these authors to the structured frame of reference I am using. Further, the cost estimates for their architectures are mine and not theirs; while designed to ensure uniformity and thereby facilitate comparisons, there is no assurance that any one author would concur with my costing basis or my intended depth of study. (In fact, Greider estimates $95K per prospect for all of this exploration,whereas using his words, some indirect knowledge of his company's habits, and my costing basis, I estimate $420K for a 900 square mile area).

Words added to Figures 9 through 16, beyond those already given, would be superfluous. Each figure requires study unto itself and comparison with all other figures in this report. One overwhelming observation is that if one accepts my costing basis, then the costs for the four new architectures range from $420K to $595K per 900 square miles, a range totally encompassed by my range of $360K to $710K given in Table 4.

As one final study, I have attempted to find common denominators between my "restricted option" and the options that Banwell, Combs and Muffler, Greider, and Dolan would take. I cannot call the resulting option a consensus because I have no assurance that these authors would agree with me. However, if I understand their writings, then the compromise option of Figures 17 and 18 would satisfy each of us in basic content whether we are doing grass roots exploration of a large territory or are evaluating a prospect. It seems to me to represent the lowest common denominator, costing $360K per prospect or per 900 square miles, to which each of us would like to add some tens of thousands of dollars to satisfy our curiosities; the end result ought to be a budget in the $400K to $600K range, or possibly higher.

Acknowledgements

I wish to thank Messrs. R. Christiansen, L. Ball, N. E. Goldstein, B. Greider, and A. H. Truesdell for helpful discourse while preparing this manuscript. While each of them has influenced my thinking, no one of them is in any way responsible for the assumptions, analyses, or conclusions I have drawn.

References

Banwell, C. J., 1970, Geophysical techniques in geothermal exploration, Geothermics, Special Issue 2, p. 32-57.

Banwell, D. J., 1974, Geophysical methods in geothermal exploration, in Geothermal Energy, Paris, The Unesco Press, p. 41-48.

Combs, J., and L. J. P. Muffler, 1973, Exploration for geothermal resources, in Geothermal Energy, edited by P. Kruger, and C. Otte, Stanford, Stanford University Press, p. 95-128.

Dolan, Wm., 1975, in Report on "Geophysical Methods Applied to Detection, Delineation, and Evaluation of Geothermal Resources", University of Utah, October.

Eaton, G. P., 1975, Characteristics of a transverse crustal boundary in the Basin and Range province of southern Nevada, GSA Abstract, 1975 Annual Meeting.

Furumoto, A. S., 1975, A coordinated exploration program for geothermal sources on the island of Hawaii, Proceedings, Second U.N. Symposium on the Development and Use of Geothermal Resources, v. 2, p. 993-1001.

Greider, B., 1975, Unpublished manuscript.

Grose, L. T., 1971, Geothermal energy: geology, exploration, and developments, Part I, Mineral Industry Bull., 16, 6, 14 p.

Hawkes, H. E., and J. S. Webb, 1962, Geochemistry in mineral exploration, New York, Harper and Row.

McNitt, J. R., 1975, Summary of the United Nations geothermal exploration experience, 1965 to 1975, Second U.N. Symposium on the Development and Use of Geothermal Resources, v. 2, p. 1127-1134.

Meidav, T., and F. Tonani, 1975, A critique of geothermal exploration techniques, Proceedings, Second U.N. Symposium on the Development and Use of Geothermal Resources, v. 2, p. 1143-1154.

Newendorp, P. D., 1976, Use of decision trees can help simplify complex problems, Oil and Gas Journal, October 18 and 25.

Pfleider, Eugene P., 1968, Surface mining, New York, AIME, Mudd Series.

Ward, S. H., 1972, Mining geophysics-new techniques and concepts, Mining Congress Journal, v. 58, p. 58-68.

List of Tables

Table 1

Full Option

Module	Scientist Man-Years	Technician Man-Years	Labor Man-Years	Support Costs	Total Costs	Quantity
1	0.25	0.50		5K	30K	
2	0.15	0.15		3K	15K	
3	0.10	0.10		2K	10K	50 Dates
4	0.10	0.10		17K	25K	3000 Line Miles
5	0.25		0.25	2.5K	20K	1500 Stations
6	0.05	0.05		1K	5K	
7	0.05	0.05		1K	5K	
8	0.25	1.00	0.50	10K	50K	200 Analyses
9	0.20	0.50	0.20	6K	30K	100 Holes
10	0.20	0.20	0.20	2K	20K	
11	0.10	0.10	0.10	1K	10K	
12	0.50	0.50	1.50	25K	80K	900 Obs.
13	0.25	0.50		75K	100K	25 Holes
14	0.10	0.50	0.25	1.5K	20K	25 Holes
15	0.10	0.25	0.10	3K	15K	25 Holes
16	0.20	0.20	0.10	3K	20K	
17	0.25	0.75	0.10	9K	40K	
18	0.50	0.50	.50	55K	100K	180 Line Miles
19	0.50	0.50	1.50	20K	75K	
20	0.50	0.25		5K	40K	
Totals	4.55	6.70	5.30	246K	710K	

Basis:
1) Scientist man-year 60K (salary + overhead)
2) Technician man-year 20K (salary + overhead)
3) Local Labor man-year 10K (salary + overhead)
4) Support costs are minimal.
5) Hardware amortization covered in overhead.
6) Reconnaissance electrical (Module 12) costs based on 4 bipole-dipole readings per section but self-potential, tellurics, MT, or tellurics/MT might be considered and might reduce costs.
7) Detailed electrical (Module 19) costs based on dipole-dipole resistivity.

Table 2

Restricted Option

Module	Scientist Man-Years	Technician Man-Years	Labor Man-Years	Support Costs	Total Costs	Quantity
1	0.25	0.50		5K	30K	
2	0.15	0.15		3K	15K	
3	0.10	0.10		2K	10K	50 Dates
4	0.10	0.10		17K	25K	3000 Line Miles
5	0.25		0.25	2.5K	20K	1500 Stations
8	0.20	0.50	0.20	6K	30K	100 Analyses
9	0.20	0.50	0.20	6K	30K	100 Holes
10	0.20	0.20	0.20	2K	20K	
13	0.25	0.50		75K	100K	25 Holes
15	0.10	0.25	0.10	3K	15K	25 Holes
16	0.05	0.05	0.05	0.5K	5K	
19	0.50	0.50	1.50	20K	75K	180 Line Miles
20	0.50	0.25		5K	40K	
Totals	2.85	3.60	2.50	147K	415K	

Basis:
1) Scientist man-year 60K (salary + overhead)
2) Technician man-year 20K (salary + overhead)
3) Local labor man-year 10K (salary + overhead)
4) Support costs are minimal.
5) Hardware amortization covered in overhead.
6) Detailed electrical (Module 19) costs based on dipole-dipole resistivity.

Table 3

MT Option

Module	Scientist Man-Years	Technician Man-Years	Labor Man-Years	Support Costs	Total Costs	Quantity
1	0.25	0.50		5K	30K	
2	0.15	0.15		3K	15K	
3	0.10	0.10		2K	10K	50 Dates
8	0.20	0.50	0.20	6K	30K	100 Analyses
9	0.20	0.50	0.20	6K	30K	100 Holes
10	0.20	0.20	0.20	2K	20K	
12	(per sounding basis			330K	330K	207 Soundings
13	0.25	0.50		75K	100K	25 Holes
15	0.10	0.25	0.10	3K	15K	25 Holes
16	0.05	0.05	0.05	0.5K	5K	
19	0.50	0.50	1.50	20K	75K	180 Line-miles
20	0.50	0.25		5K	40K	
Totals	2.50	3.50	2.25	458K	700K	

Basis:
1) Scientist man-year 60K (salary + overhead)
2) Technician man-year 20K (salary + overhead)
3) Local Labor man-year 10K (salary + overhead)
4) Support costs are minimal.
5) Hardware amortization covered in overhead.
6) MT costs at $1600 per sounding.
7) Detailed electrical (module 19) costs based on dipole-dipole resistivity.

Table 4

Option	Exploration Cost/900 sq.mi.	Exploration Cost/13,500 sq. mi.	Exploration Cost/sq.mi.	Exploration Cost/Discovery	Land Cost/ Discovery	Model Test Cost/Discovery	Production Test Cost/Discovery	Total Cost/ Discovery
Full	$710K	$10.7M	$790	$2.14M*($10.7M)+	$1.35M*($6.75M)+	$1.50M*($7.50M)+	$2.00M*($2.00M)+	$6.09M*($26.95M)+
Table 2 (basic)	$415K	$ 6.2M	$461	$1.24M ($6.2M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.09M ($22.45M)
Table 2 (basic, less age dating, gravity and aeromagnetics)	$360K	$ 5.4M	$400	$1.10M ($5.4M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$5.95M ($21.65M)
Table 2 (basic, plus passive seismic)	$455K	$ 6.8M	$506	$1.36M ($6.8M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.21M ($23.05M)
Table 2 (basic, plus active seismic)	$515K	$ 7.7M	$572	$1.54M ($7.7M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.39M ($23.95M)
MT Option (no gravity, or areomagnetics)	$700K	$10.5M	$778	$2.10M ($10.5M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.95M ($26.75M)

* Assumes 5 discoveries of 15 prospects drilled.

\+ Assumes 1 discovery of 15 prospects drilled.

List of Illustrations

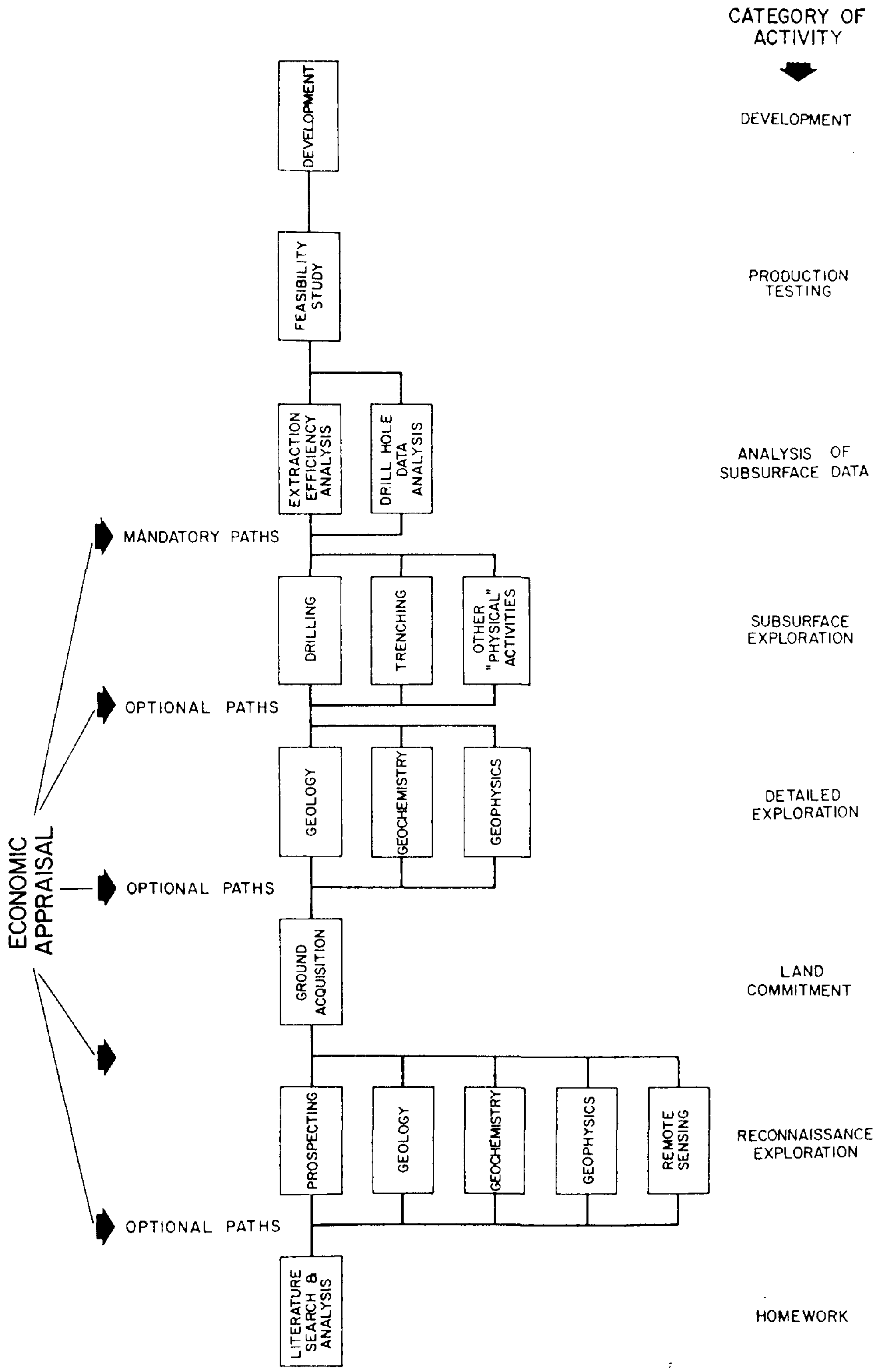
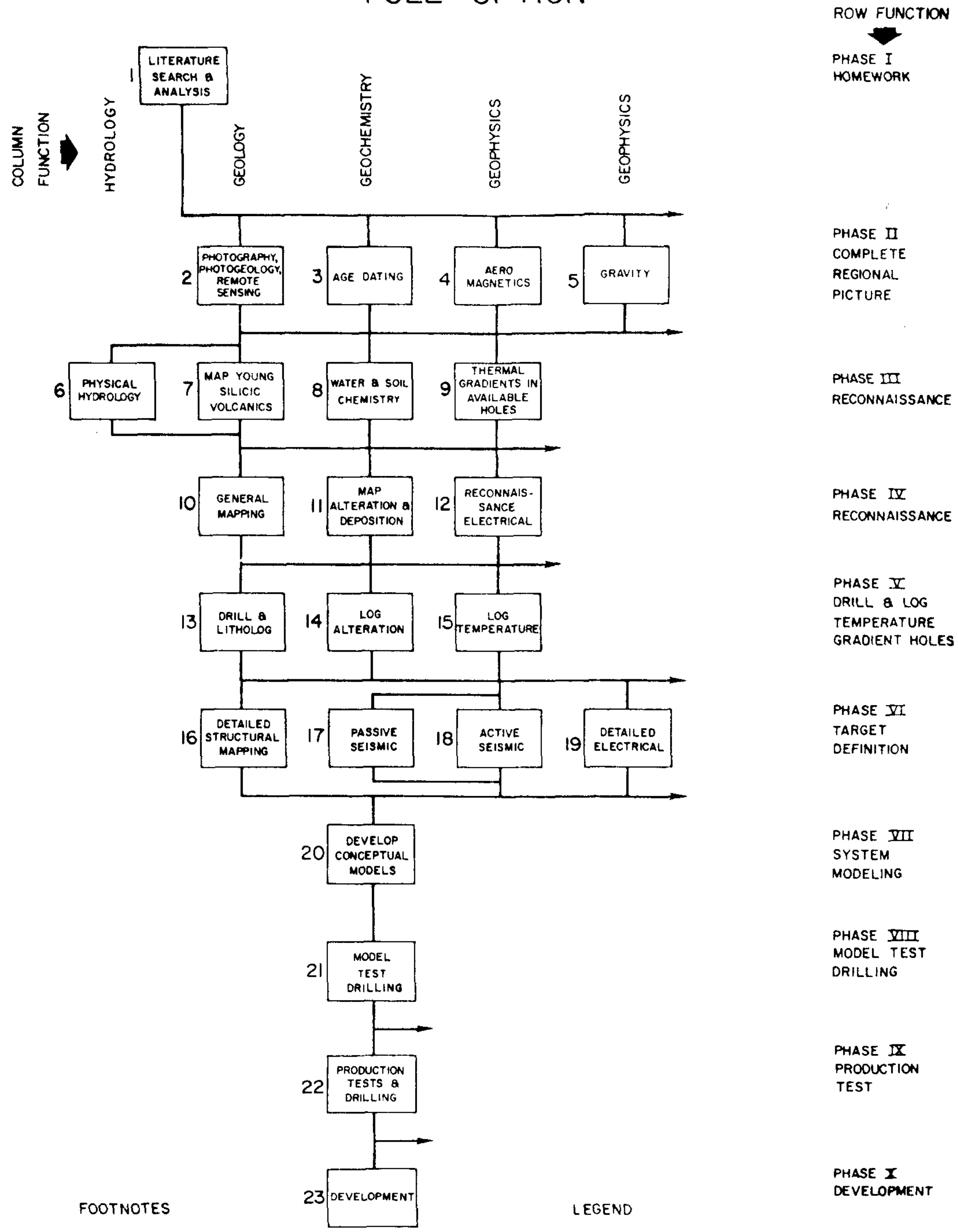

CATEGORY OF ACTIVITY
DEVELOPMENT
PRODUCTION TESTING
ANALYSIS OF SUBSURFACE DATA
SUBSURFACE EXPLORATION
DETAILED EXPLORATION
LAND COMMITMENT
RECONNAISSANCE EXPLORATION
HOMEWORK
DEVELOPMENT
FEASIBILITY STUDY
EXTRACTION EFFICIENCY ANALYSIS
DRILL HOLE DATA ANALYSIS
DRILLING
TRENCHING
OTHER "PHYSICAL" ACTIVITIES
GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
GROUND ACQUISITION
PROSPECTING
GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
REMOTE SENSING
LITERATURE SEARCH & ANALYSIS
ECONOMIC APPRAISAL
MANDATORY PATHS
OPTIONAL PATHS
OPTIONAL PATHS
OPTIONAL PATHS

Figure 1

FULL OPTION



FOOTNOTES

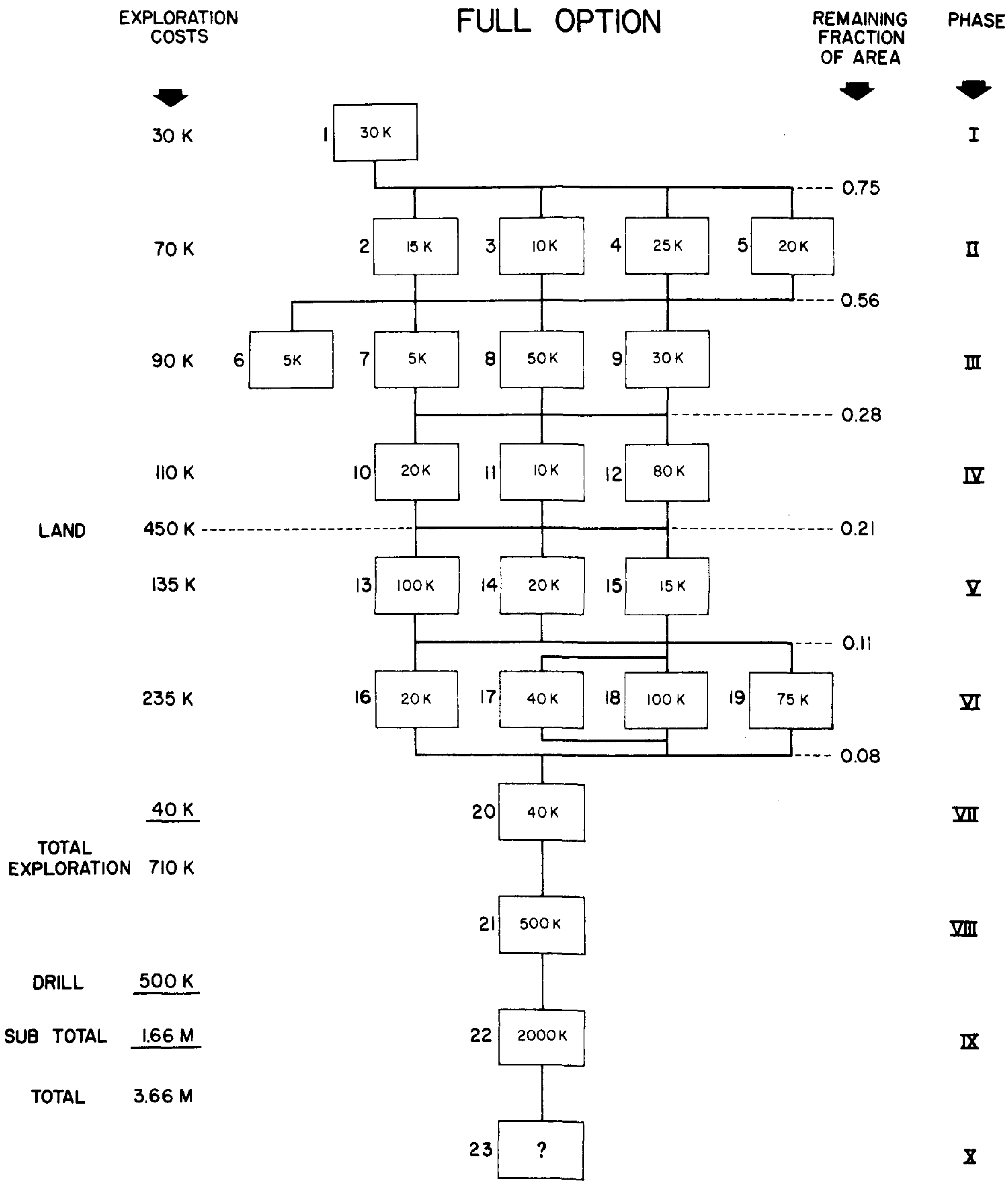
1. PHYSICAL HYDROLOGY - SPRING TEMPERATURE, FLOWRATES
2. WATER CHEMISTRY - GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES
3. SOIL CHEMISTRY - TRACE ELEMENT ANALYSIS

LEGEND

→ REJECT PART OF AREA

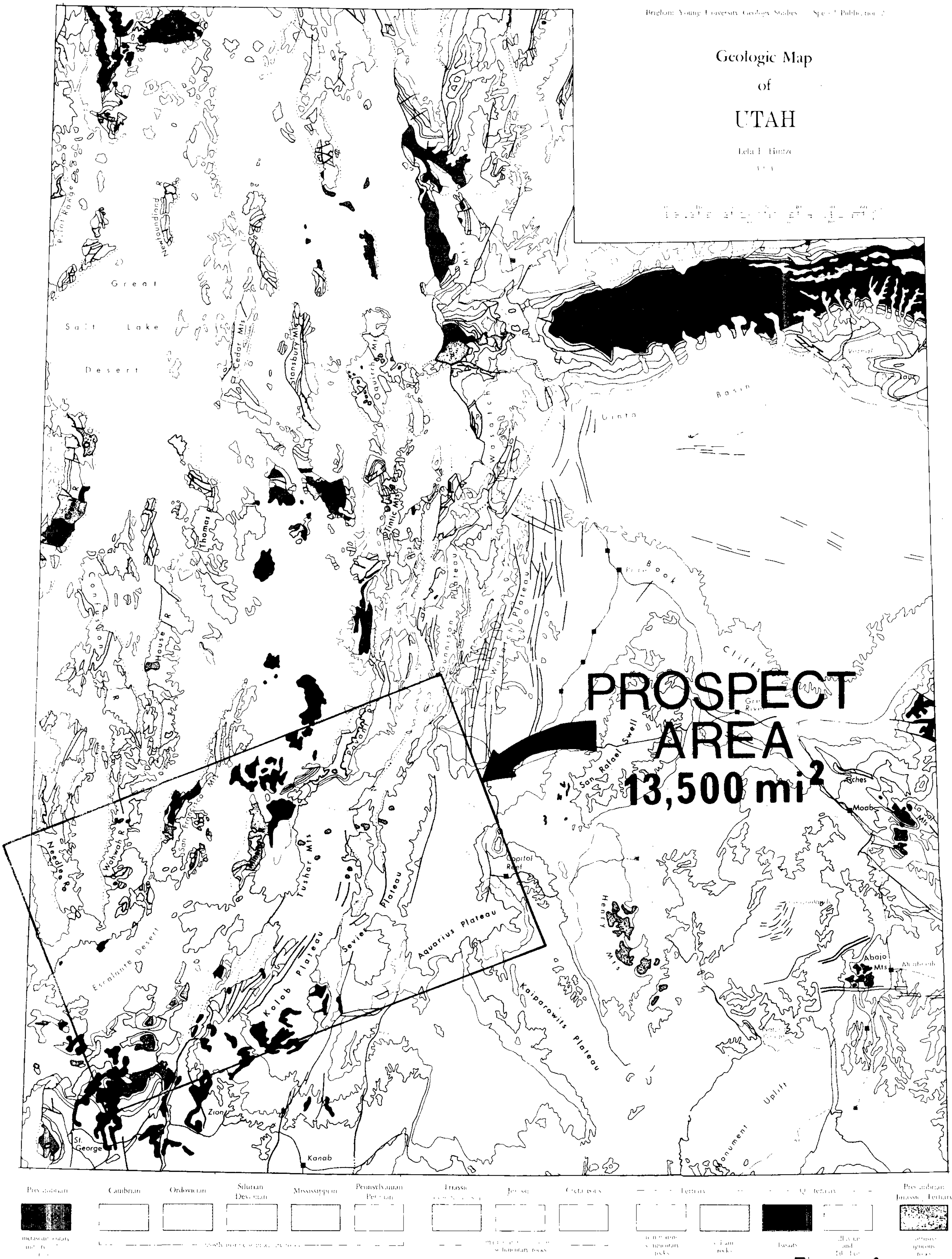
12 SPLIT MODULE

Figure 2

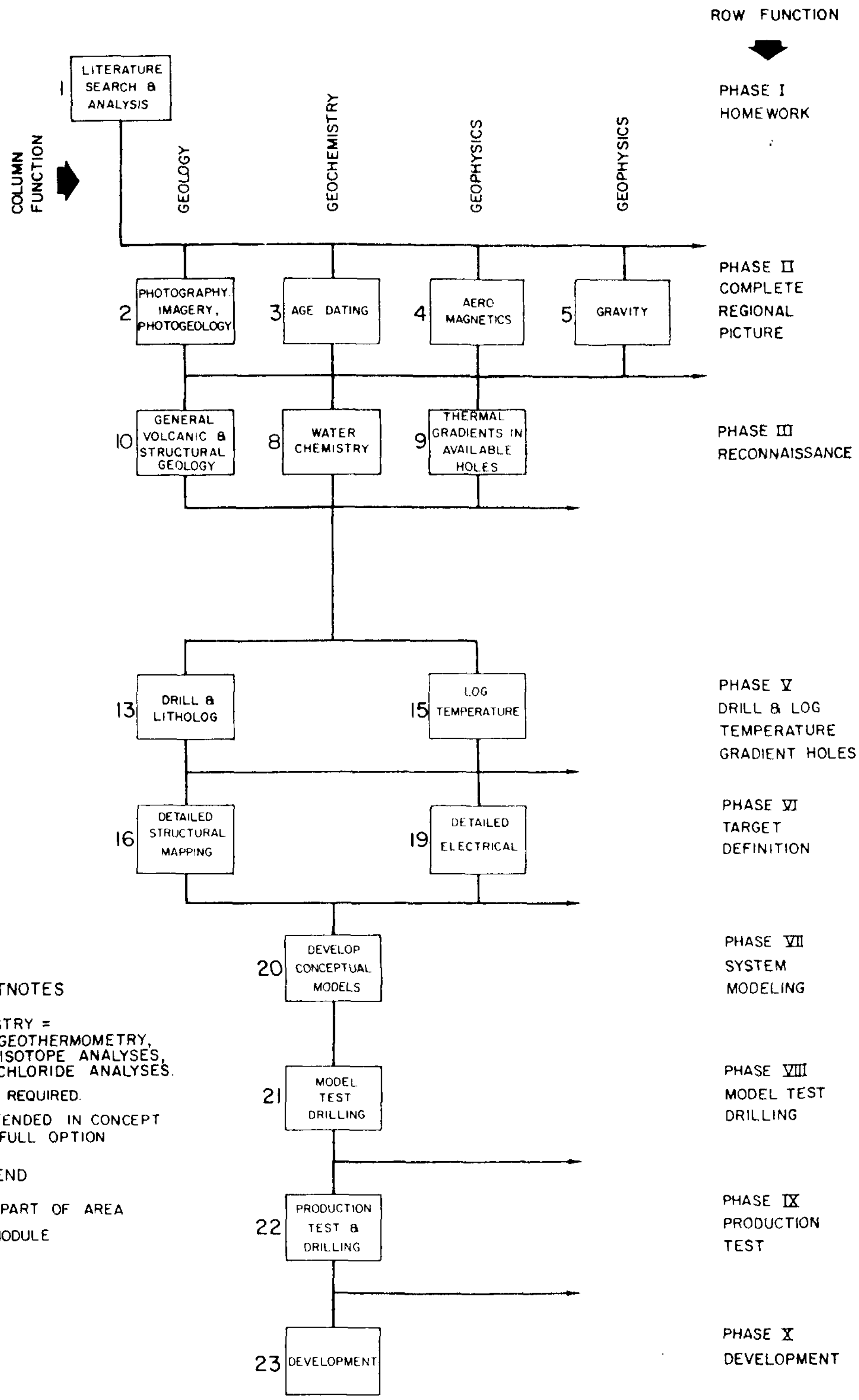


EXPLORATION COSTS
FULL OPTION
REMAINING FRACTION OF AREA
PHASE
30 K
1 30 K
I
0.75
70 K
2 15 K
3 10 K
4 25 K
5 20 K
II
0.56
90 K
6 5K
7 5K
8 50K
9 30K
III
0.28
110 K
10 20K
11 10K
12 80K
IV
LAND 450 K
0.21
135 K
13 100K
14 20K
15 15K
V
0.11
235 K
16 20K
17 40K
18 100K
19 75K
VI
0.08
40 K
20 40K
VII
TOTAL EXPLORATION 710 K
21 500K
VIII
DRILL 500 K
SUB TOTAL 1.66 M
22 2000K
IX
TOTAL 3.66 M
23 ?
X

Figure 3


Geologic Map
of
UTAH
Great
Salt Lake
Desert
Newfoundland R
Cedar Mts
Stansbury Mts
Oquirrh Mts
Tintic Mts
Thomas
House R
Wasatch Plateau
Wasatch Mts
Uinta Basin
Book Cliffs
Green River
San Rafael Swell
PROSPECT
AREA
13,500 mi²
Arches
Moab
La Sal Mts
Capitol Reef
Henry Mts
Abajo Mts
Wah Wah R
San Francisco Mts
Tushar Mts
Sevier Plateau
Aquarius Plateau
Escalante Desert
Kolob Plateau
Kaiparowits Plateau
Monument Uplift
Zion
St. George
Kanab
Precambrian
Cambrian
Ordovician
Silurian Devonian
Mississippian
Pennsylvanian Permian
Triassic
Jurassic
Cretaceous
Tertiary
Quaternary
basalts
Figure 4

RESTRICTED OPTION



FOOTNOTES

1. WATER CHEMISTRY = GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES.
2. NO PHASE IV REQUIRED.
3. MODULE 2 EXTENDED IN CONCEPT RELATIVE TO FULL OPTION

LEGEND

→ REJECT PART OF AREA

12 SPLIT MODULE

Figure 5

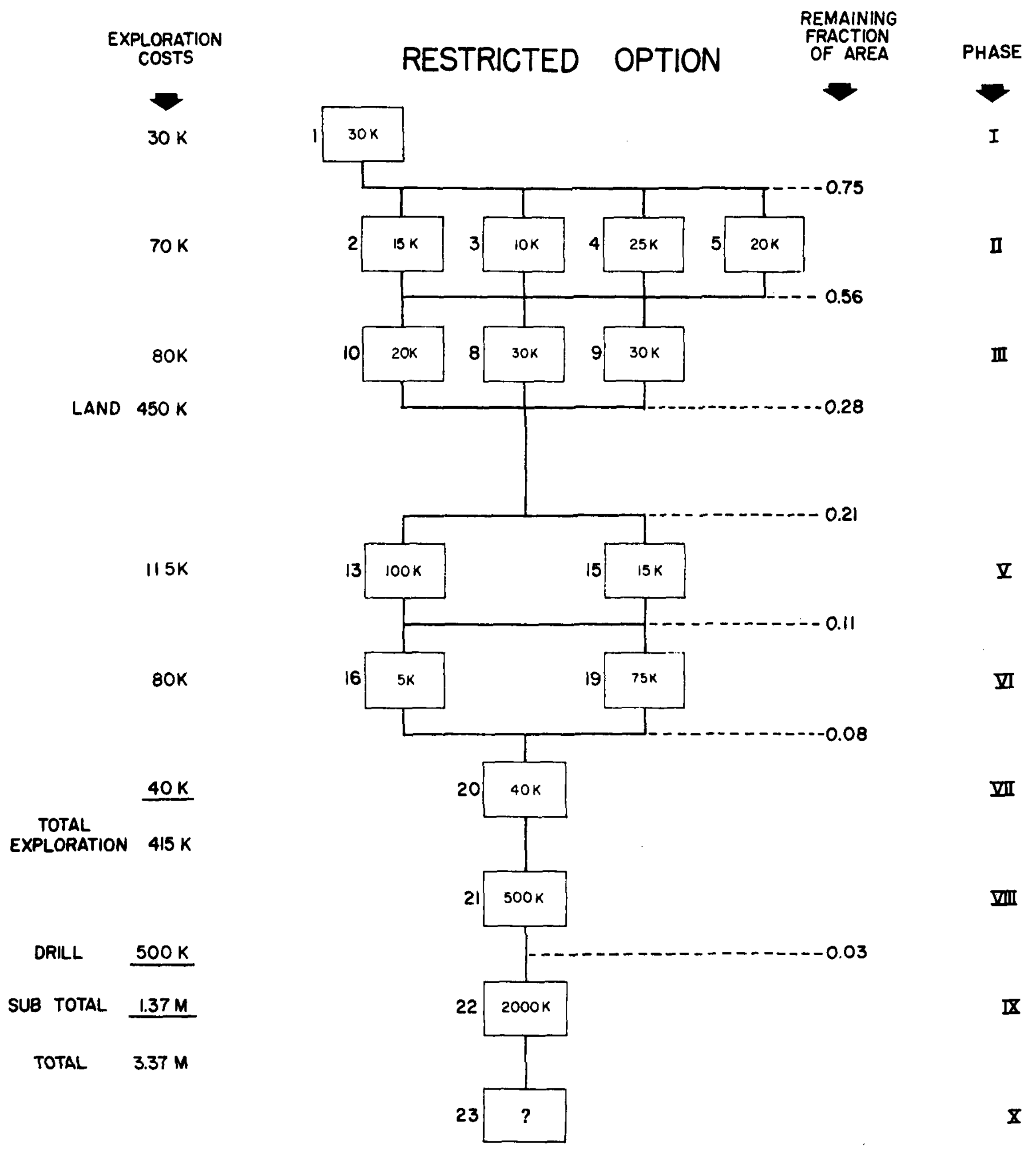

EXPLORATION COSTS
RESTRICTED OPTION
REMAINING FRACTION OF AREA
PHASE
30 K
1 30 K
I
0.75
70 K
2 15 K
3 10 K
4 25 K
5 20 K
II
0.56
80K
10 20K
8 30K
9 30 K
III
LAND 450 K
0.28
0.21
115K
13 100 K
15 15 K
V
0.11
80K
16 5K
19 75K
VI
0.08
40 K
20 40 K
VII
TOTAL EXPLORATION 415 K
21 500 K
VIII
DRILL 500 K
0.03
SUB TOTAL 1.37 M
22 2000 K
IX
TOTAL 3.37 M
23 ?
X

Figure 6

MT OPTION

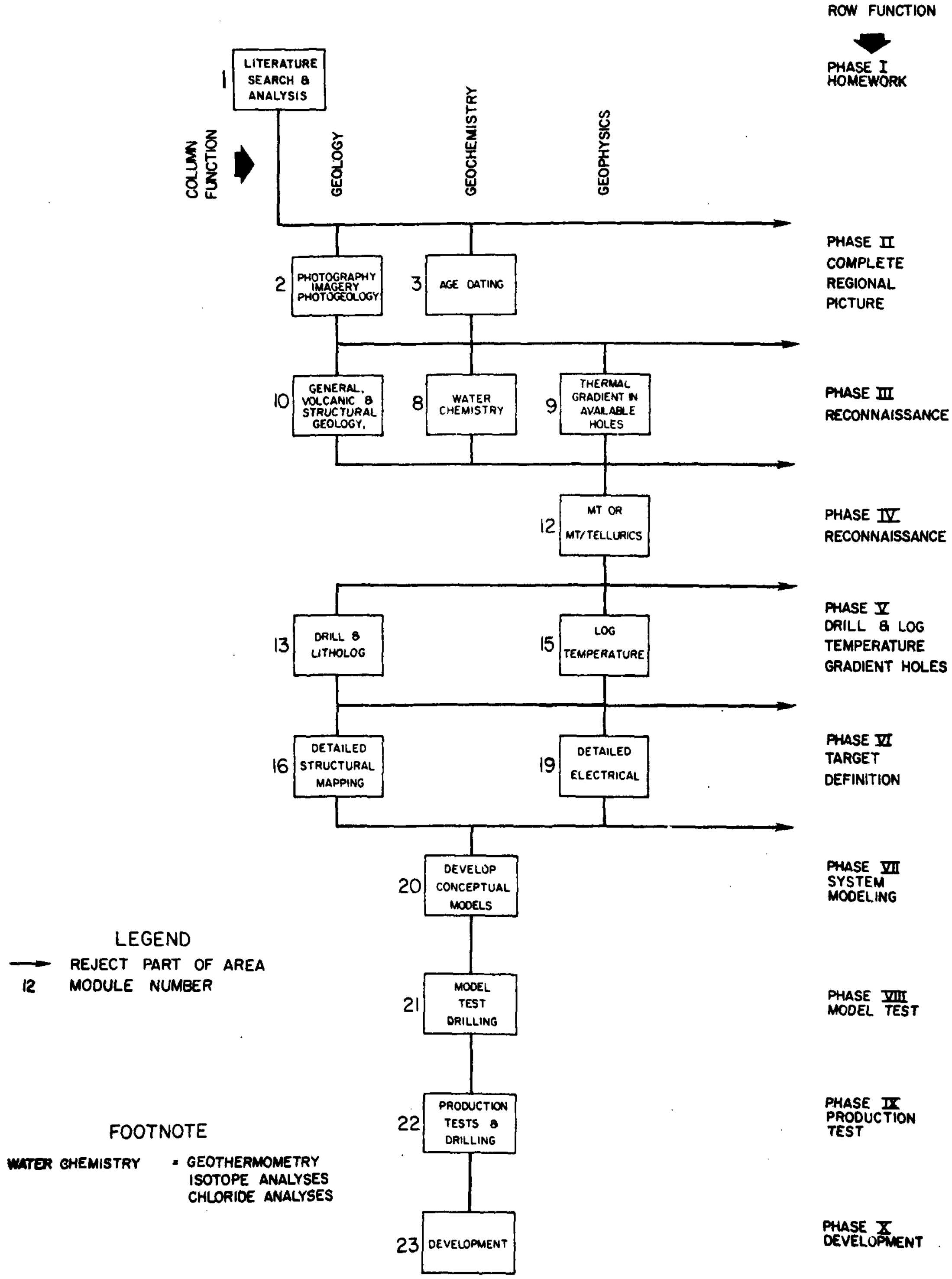


Figure 7

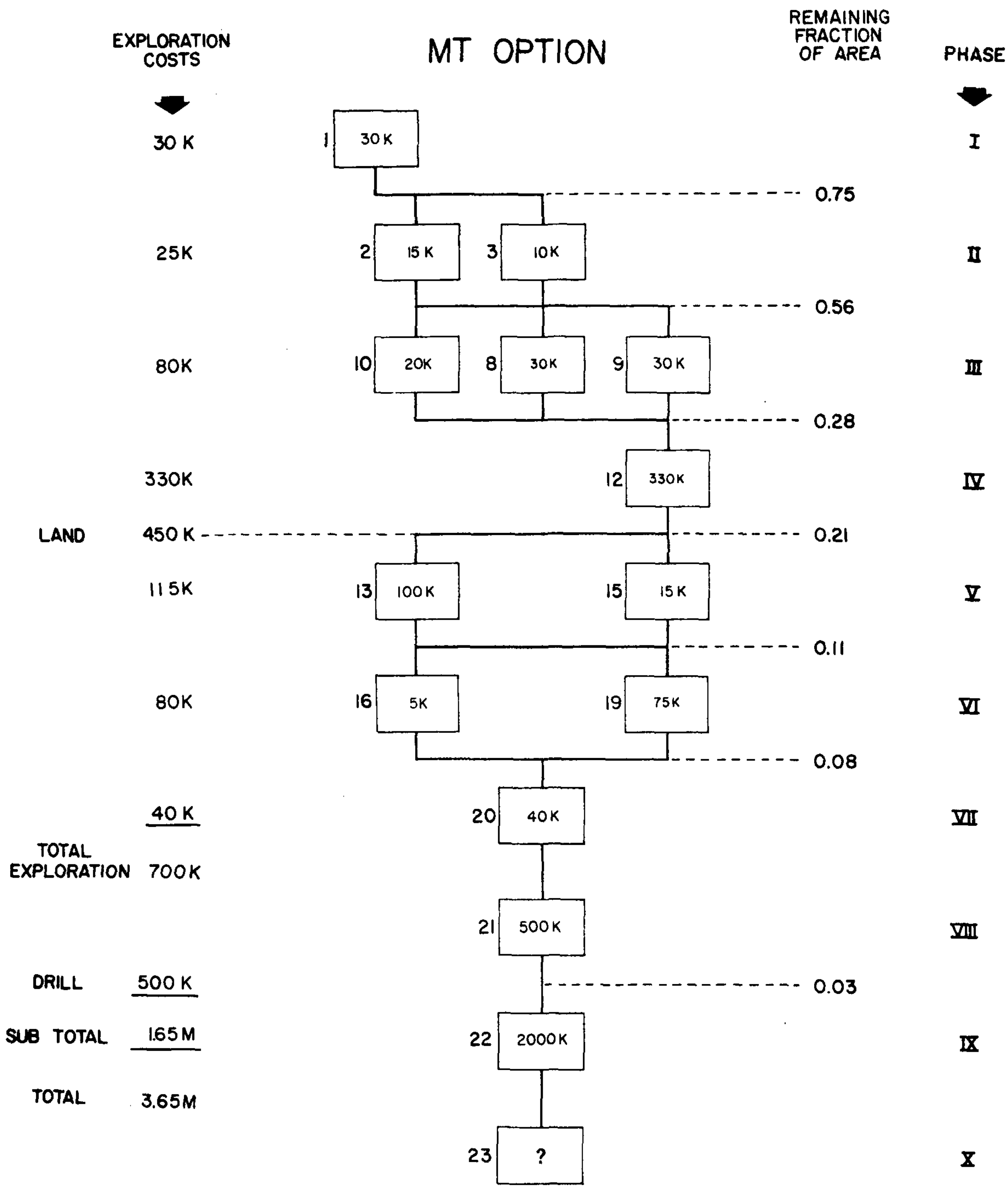

EXPLORATION COSTS
MT OPTION
REMAINING FRACTION OF AREA
PHASE
30 K
1 30 K
I
0.75
25K
2 15 K
3 10K
II
0.56
80K
10 20K
8 30K
9 30 K
III
0.28
330K
12 330K
IV
LAND
450 K
0.21
115K
13 100K
15 15 K
V
0.11
80K
16 5K
19 75K
VI
0.08
40 K
20 40K
VII
TOTAL EXPLORATION 700K
21 500 K
VIII
DRILL 500 K
0.03
SUB TOTAL 1.65 M
22 2000 K
IX
TOTAL 3.65M
23 ?
X

Figure 8

BANWELL OPTION

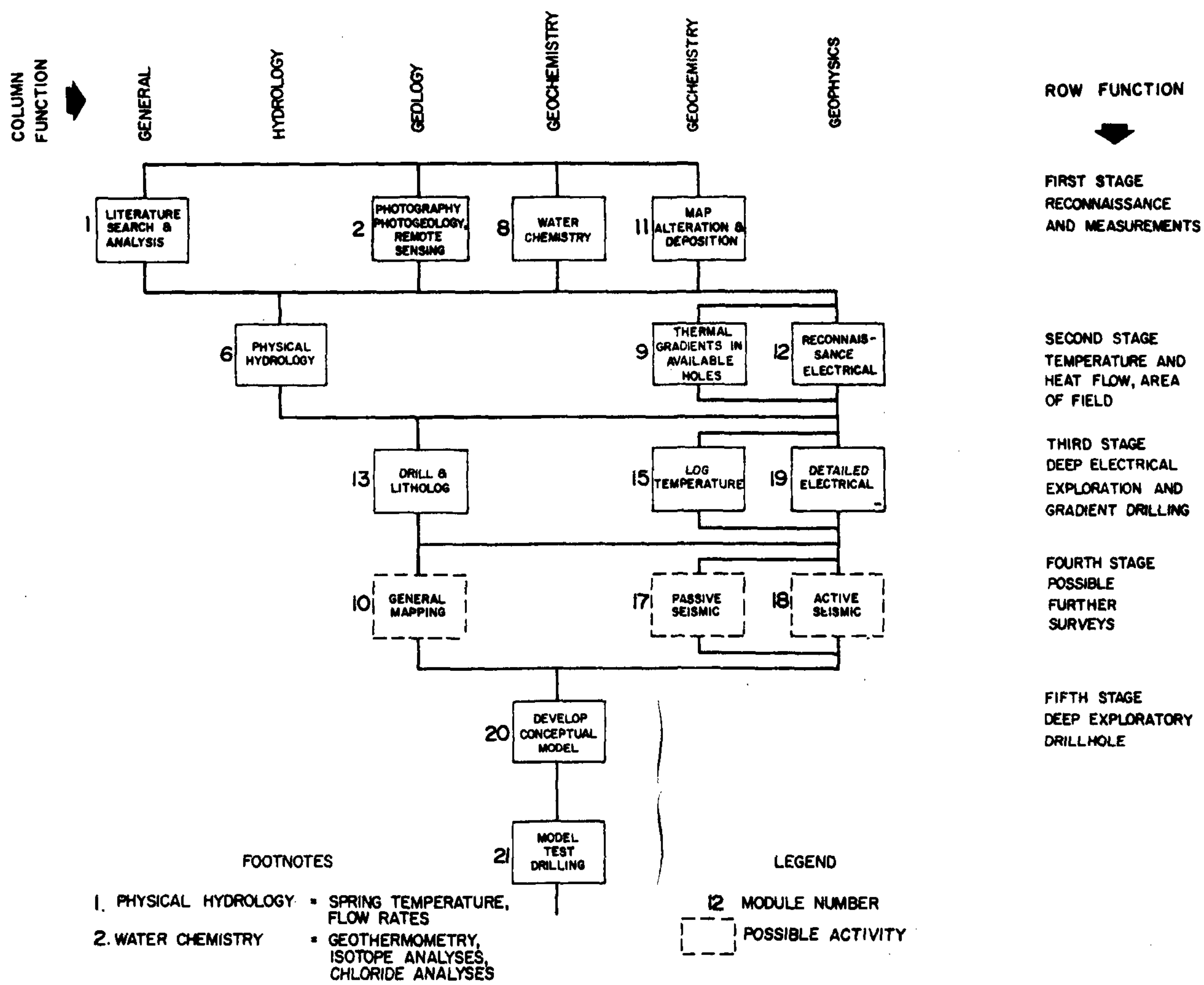


Figure 9

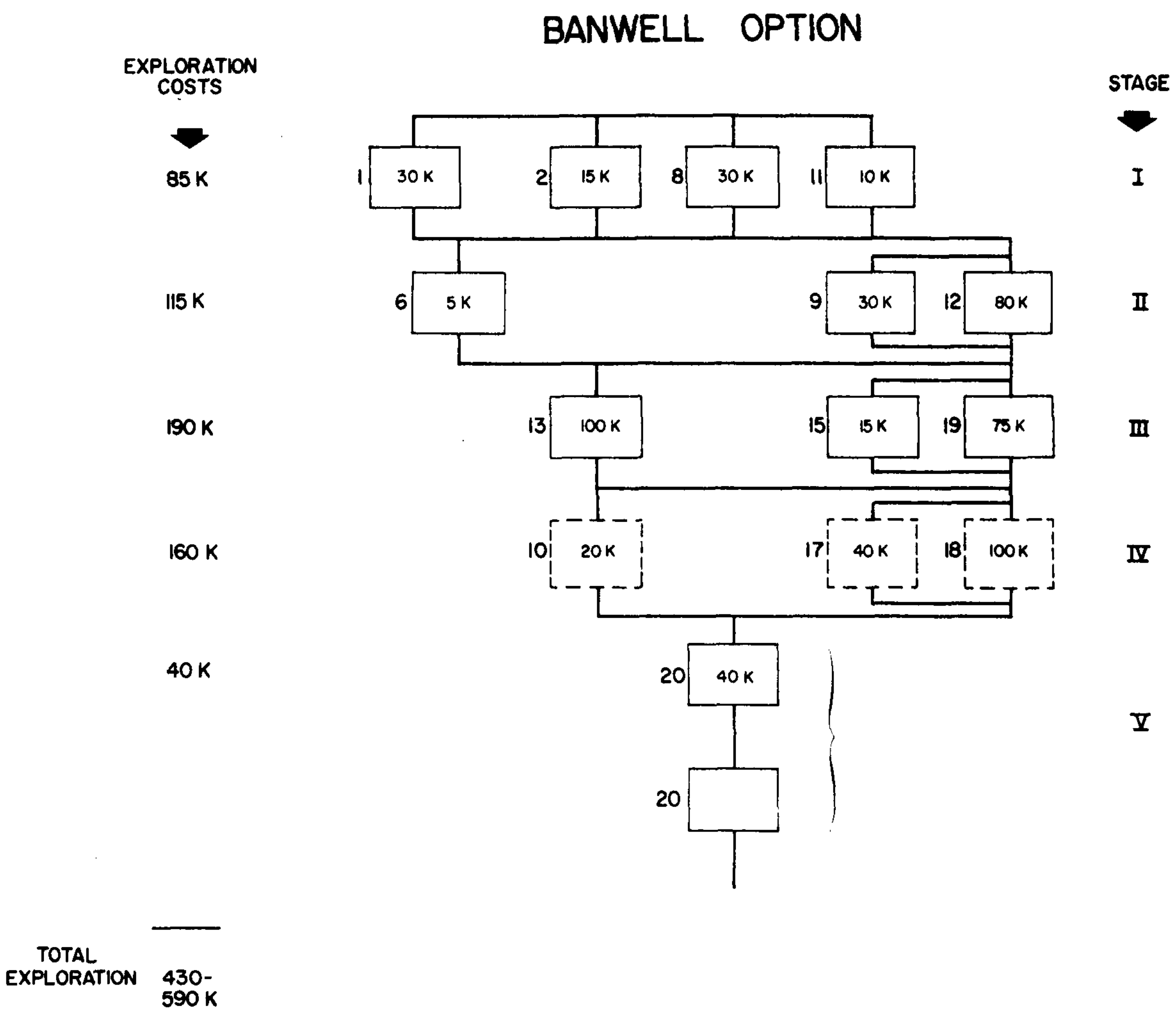

BANWELL OPTION
EXPLORATION COSTS
STAGE
85 K
115 K
190 K
160 K
40 K
TOTAL EXPLORATION
430-590 K
1
30 K
2
15 K
8
30 K
11
10 K
I
6
5 K
9
30 K
12
80 K
II
13
100 K
15
15 K
19
75 K
III
10
20 K
17
40 K
18
100 K
IV
20
40 K
20
V

Figure 10

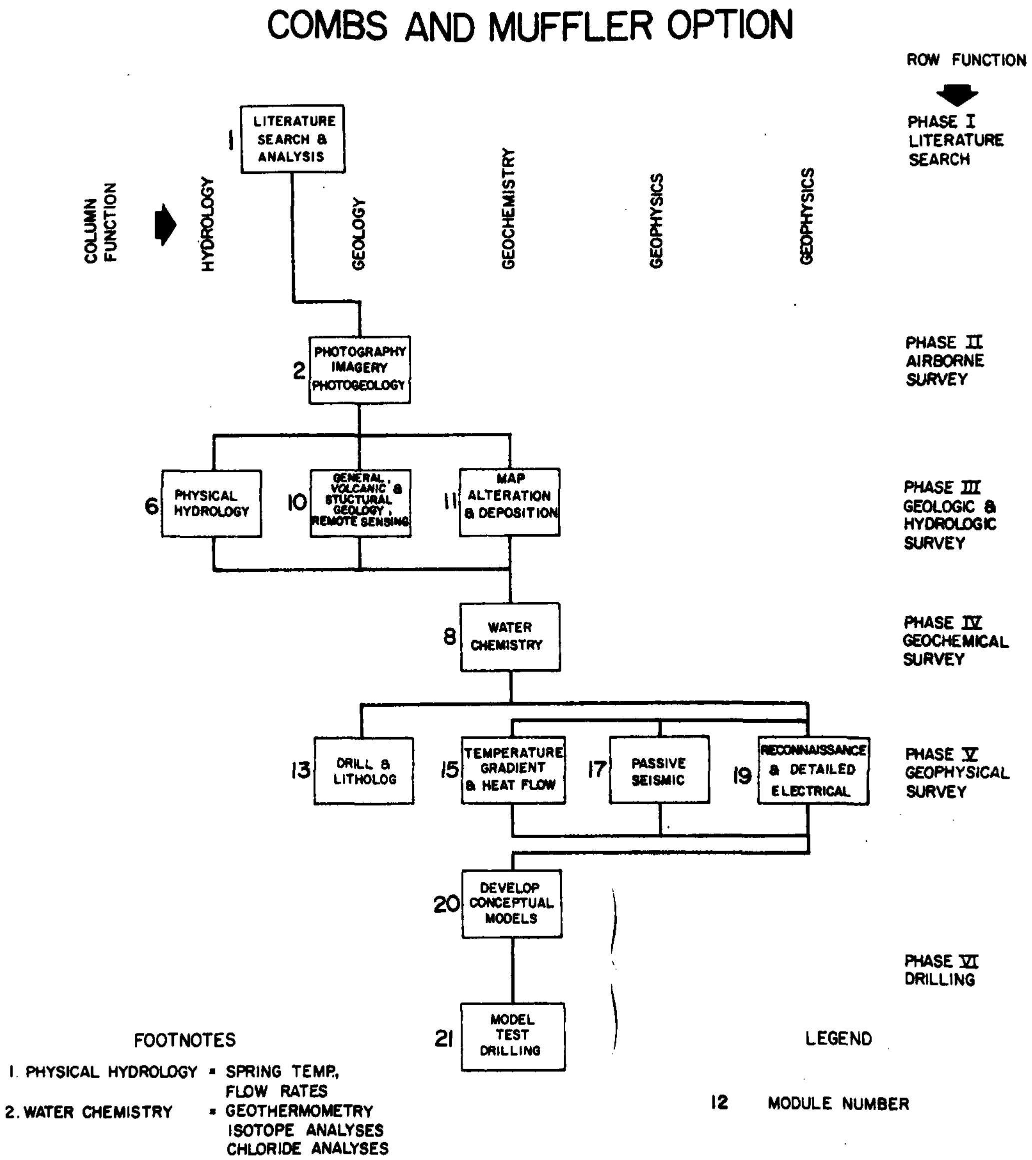

COMBS AND MUFFLER OPTION
ROW FUNCTION
COLUMN FUNCTION
HYDROLOGY
GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
GEOPHYSICS
1 LITERATURE SEARCH & ANALYSIS
PHASE I LITERATURE SEARCH
2 PHOTOGRAPHY IMAGERY PHOTOGEOLOGY
PHASE II AIRBORNE SURVEY
6 PHYSICAL HYDROLOGY
10 GENERAL, VOLCANIC & STUCTURAL GEOLOGY, REMOTE SENSING
11 MAP ALTERATION & DEPOSITION
PHASE III GEOLOGIC & HYDROLOGIC SURVEY
8 WATER CHEMISTRY
PHASE IV GEOCHEMICAL SURVEY
13 DRILL & LITHOLOG
15 TEMPERATURE GRADIENT & HEAT FLOW
17 PASSIVE SEISMIC
19 RECONNAISSANCE & DETAILED ELECTRICAL
PHASE V GEOPHYSICAL SURVEY
20 DEVELOP CONCEPTUAL MODELS
PHASE VI DRILLING
21 MODEL TEST DRILLING
FOOTNOTES
1. PHYSICAL HYDROLOGY - SPRING TEMP, FLOW RATES
2. WATER CHEMISTRY - GEOTHERMOMETRY ISOTOPE ANALYSES CHLORIDE ANALYSES
LEGEND
12 MODULE NUMBER

Figure 11

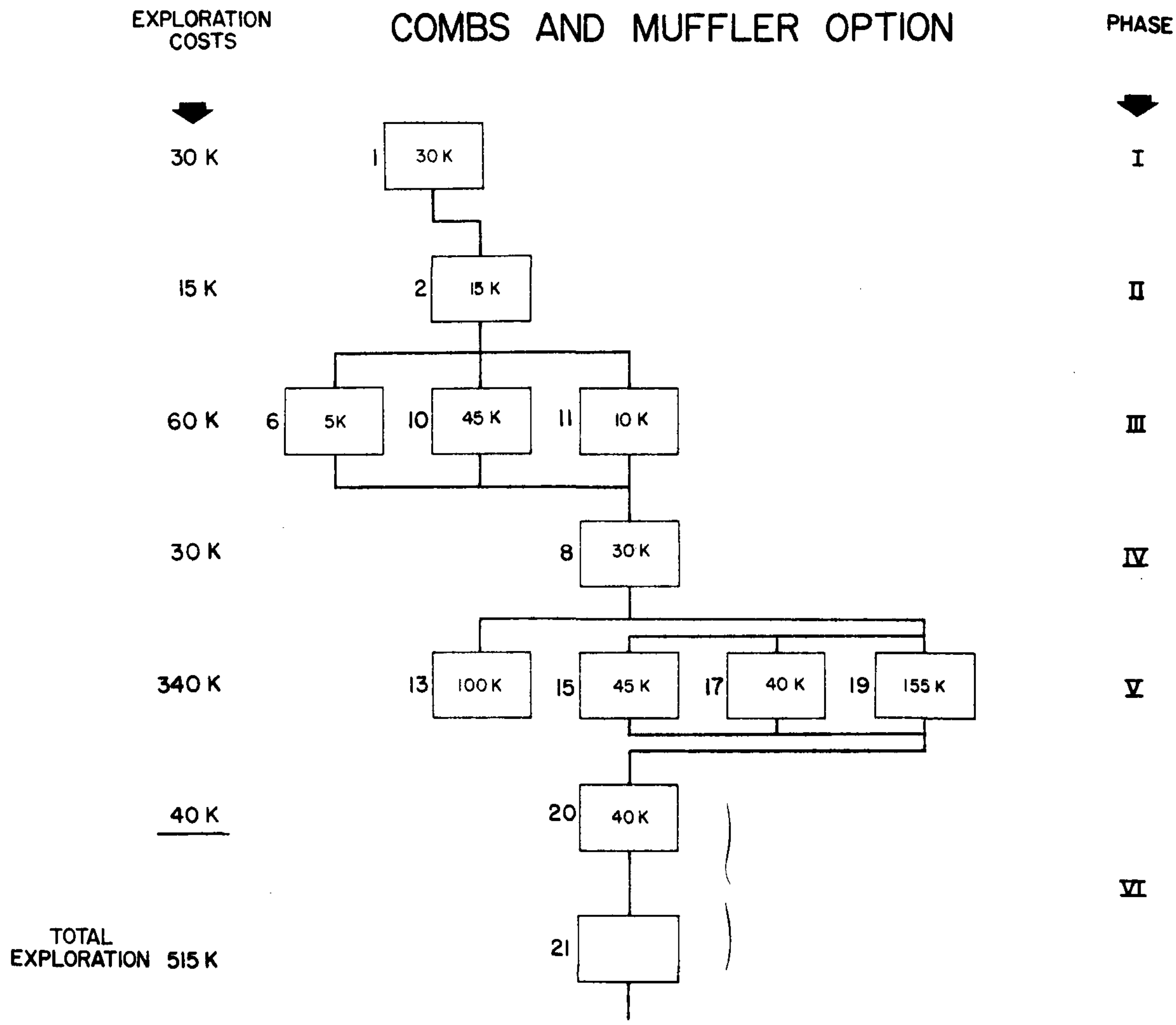
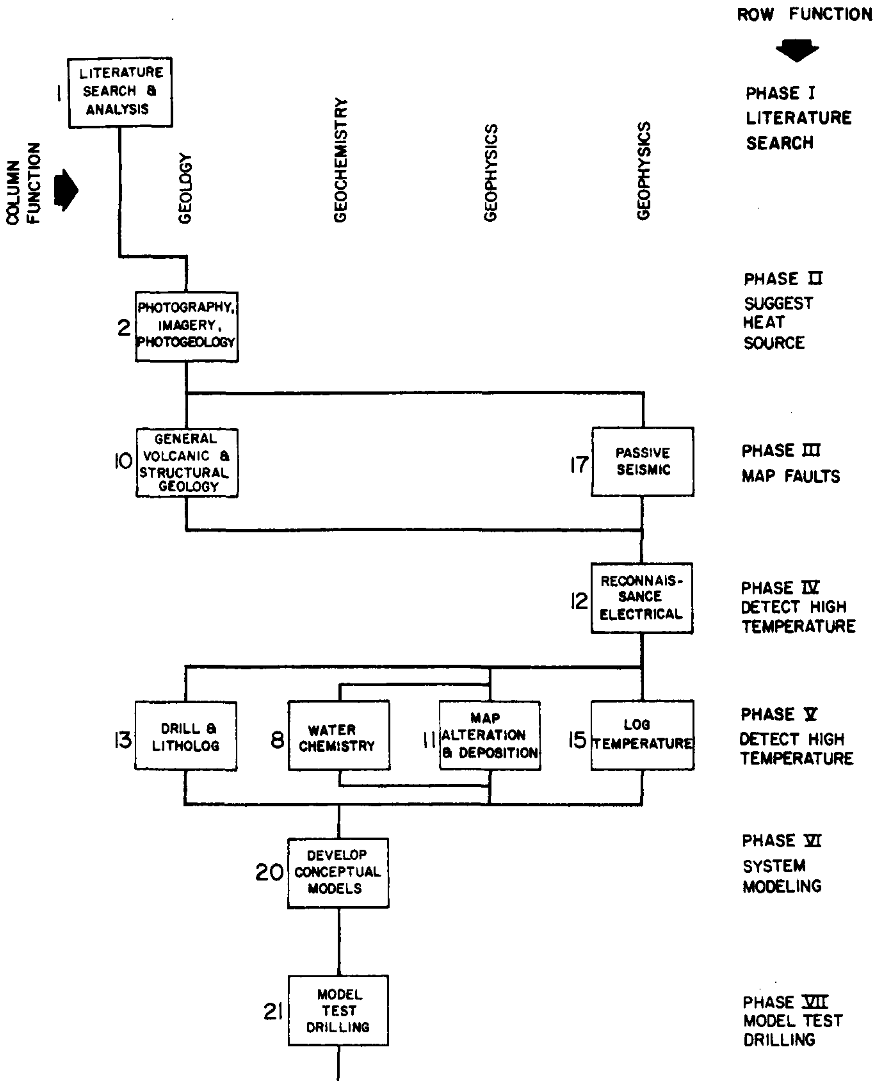

EXPLORATION COSTS
COMBS AND MUFFLER OPTION
PHASE
30 K
15 K
60 K
30 K
340 K
40 K
TOTAL EXPLORATION 515 K
1
30 K
2
15 K
6
5K
10
45 K
11
10 K
8
30 K
13
100 K
15
45 K
17
40 K
19
155 K
20
40 K
21
I
II
III
IV
V
VI

Figure 12

GREIDER OPTION



FOOTNOTE

1. WATER CHEMISTRY = GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES.

LEGEND

12 MODULE NUMBER

Figure 13

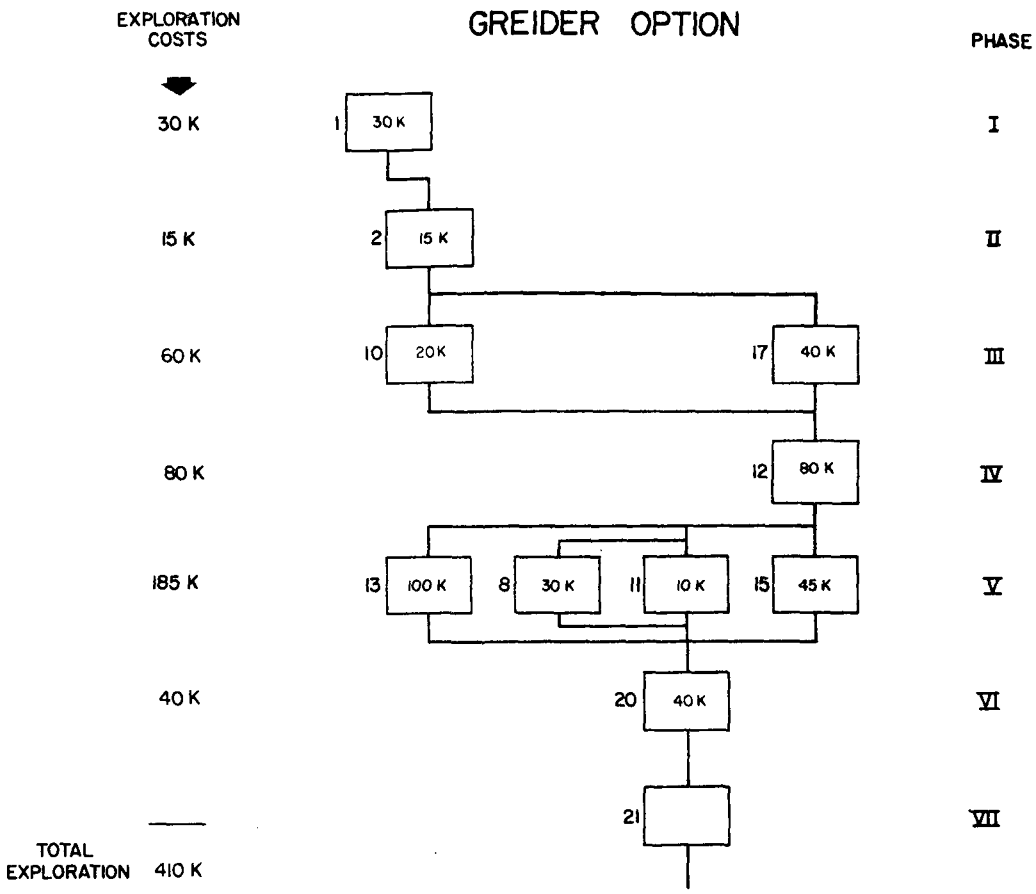
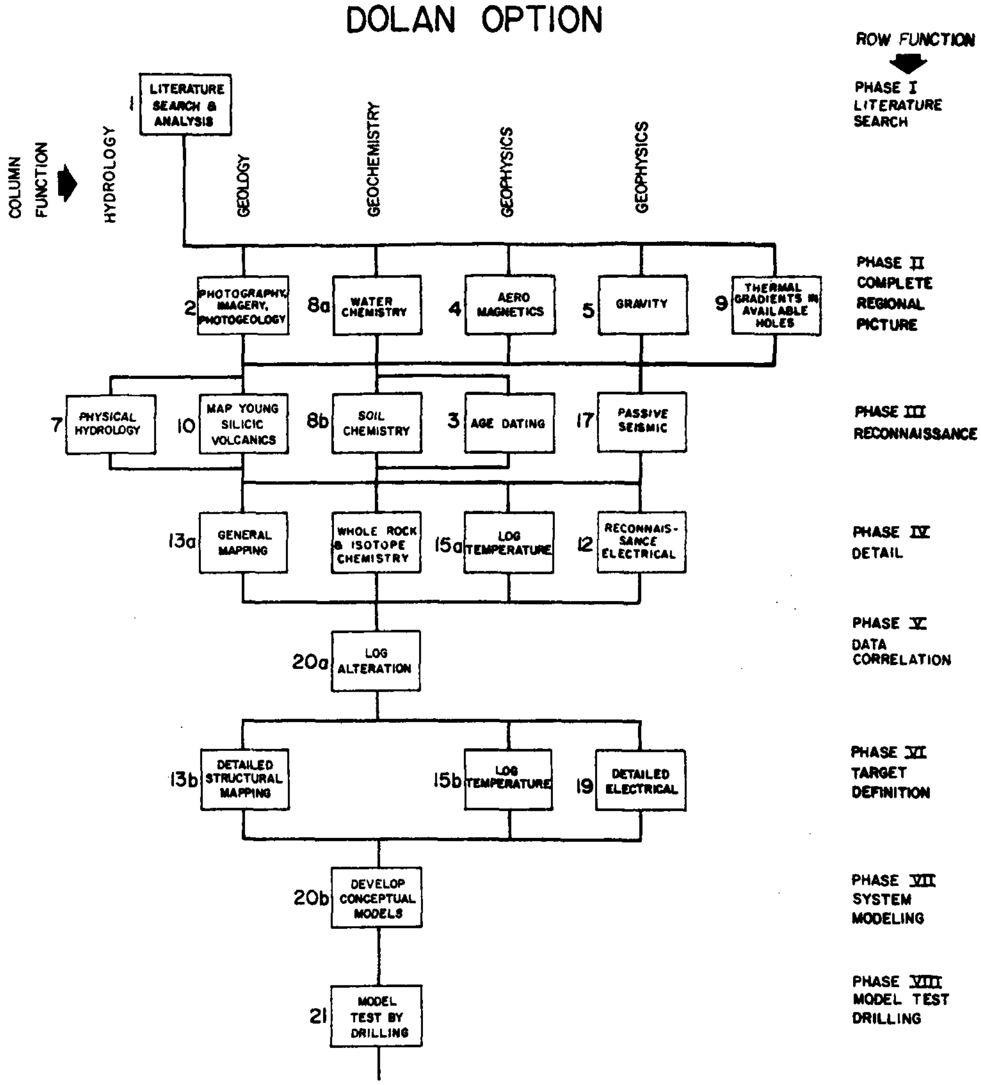

EXPLORATION COSTS
GREIDER OPTION
PHASE
30 K
1
30 K
I
15 K
2
15 K
II
60 K
10
20 K
17
40 K
III
80 K
12
80 K
IV
185 K
13
100 K
8
30 K
11
10 K
15
45 K
V
40 K
20
40 K
VI
21
VII
TOTAL EXPLORATION
410 K

Figure 14

DOLAN OPTION



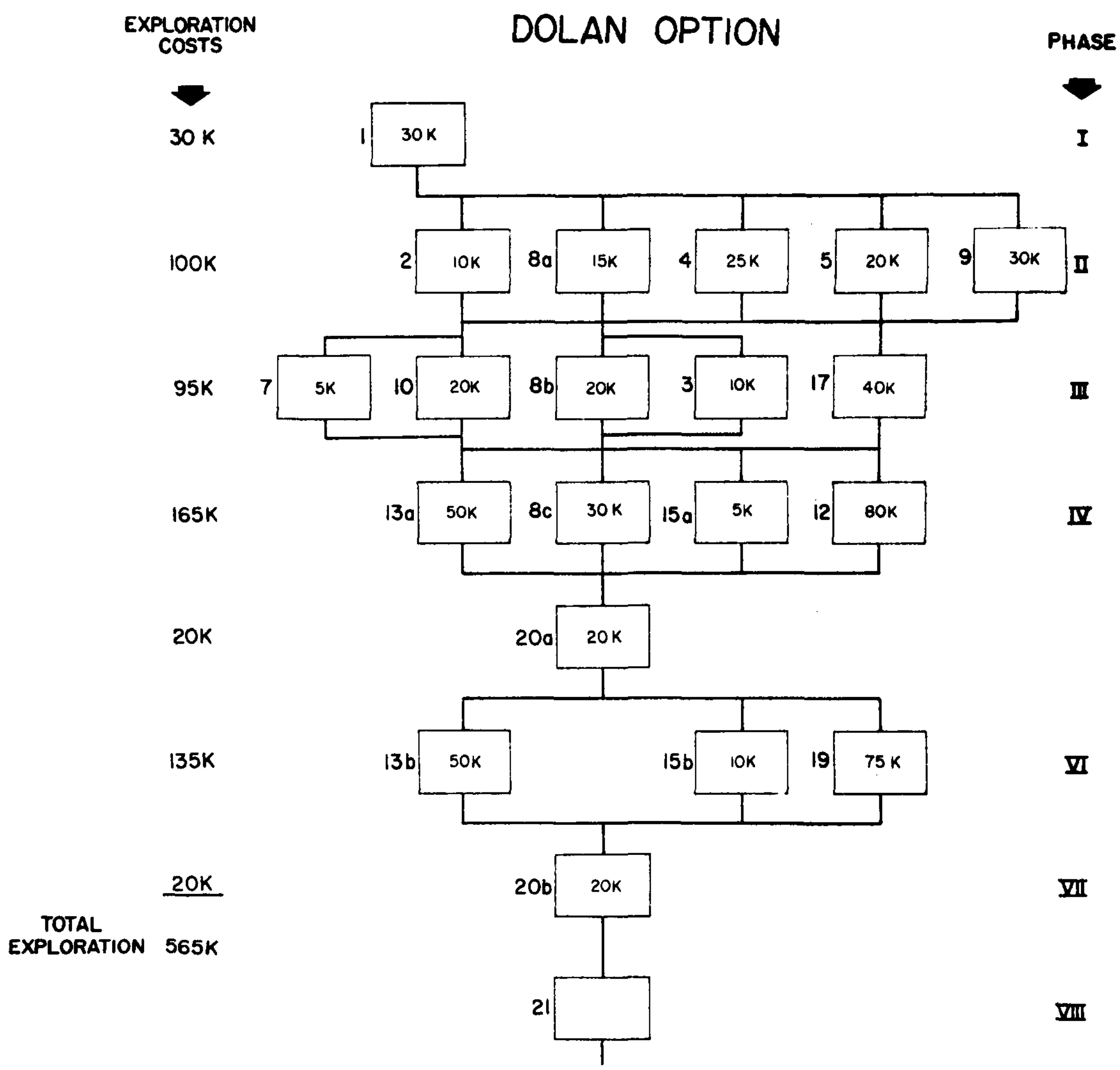
FOOTNOTES

1. WATER CHEMISTRY * GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES

LEGEND

12 MODULE NUMBER
12b SPLIT MODULE

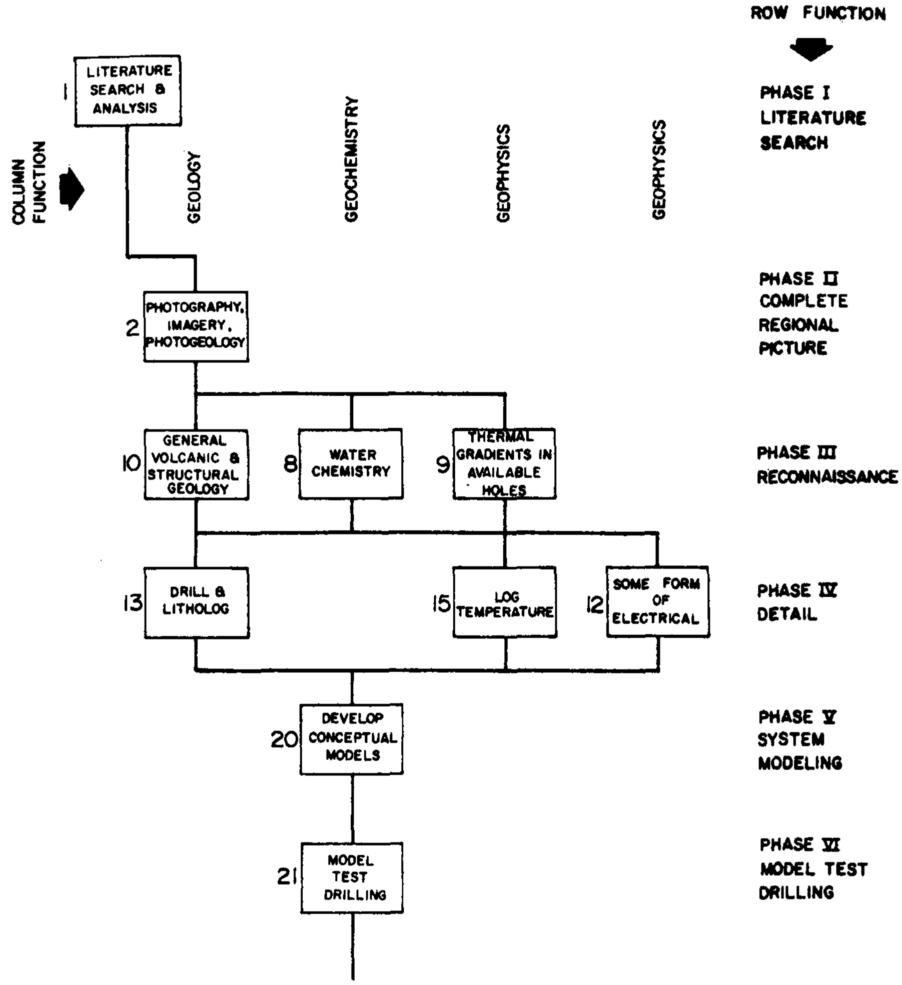
Figure 15



EXPLORATION COSTS
DOLAN OPTION
PHASE
30 K
1 30 K
I
100K
2 10K
8a 15K
4 25K
5 20K
9 30K
II
95K
7 5K
10 20K
8b 20K
3 10K
17 40K
III
165K
13a 50K
8c 30 K
15a 5K
12 80K
IV
20K
20a 20K
135K
13b 50K
15b 10K
19 75 K
VI
20K
20b 20K
VII
TOTAL EXPLORATION 565K
21
VIII

Figure 16

"COMPROMISE" OPTION



FOOTNOTE

1. WATER CHEMISTRY = GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES.

2. ELECTRICAL IS RECONNAISSANCE, DETAILED OR BOTH, SPECIFIC METHOD NOT DEFINED.

LEGEND

12 MODULE NUMBER

Figure 17

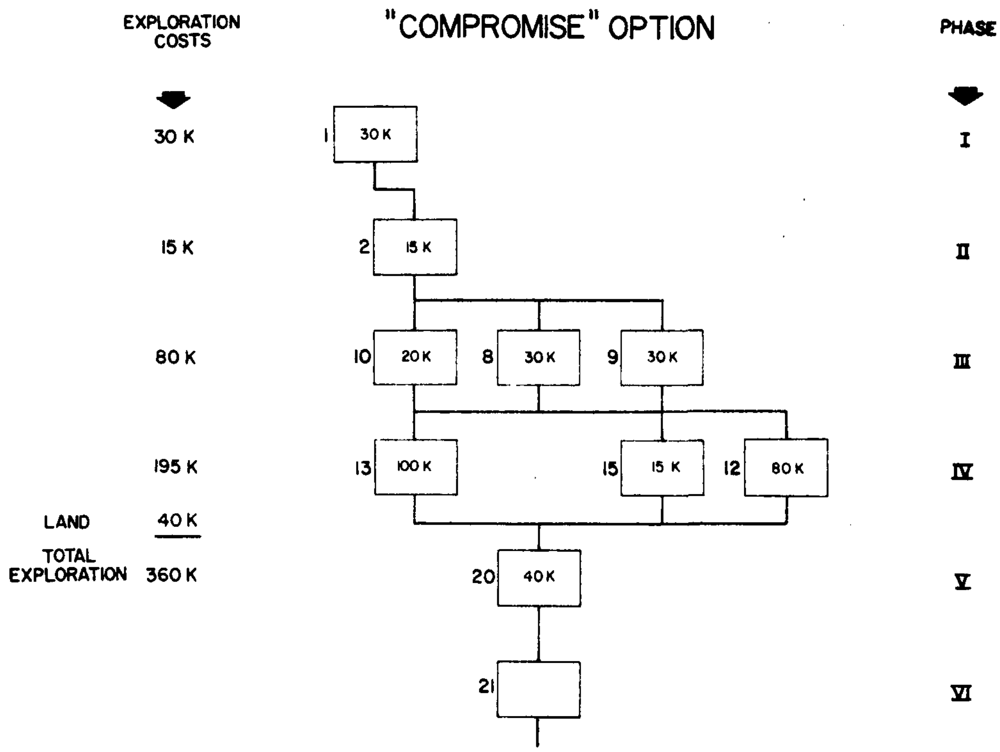

EXPLORATION COSTS
"COMPROMISE" OPTION
PHASE
30 K
15 K
80 K
195 K
LAND 40 K
TOTAL EXPLORATION 360 K
1 30 K
2 15 K
10 20 K
8 30 K
9 30 K
13 100 K
15 15 K
12 80 K
20 40 K
21
I
II
III
IV
V
VI

Figure 18

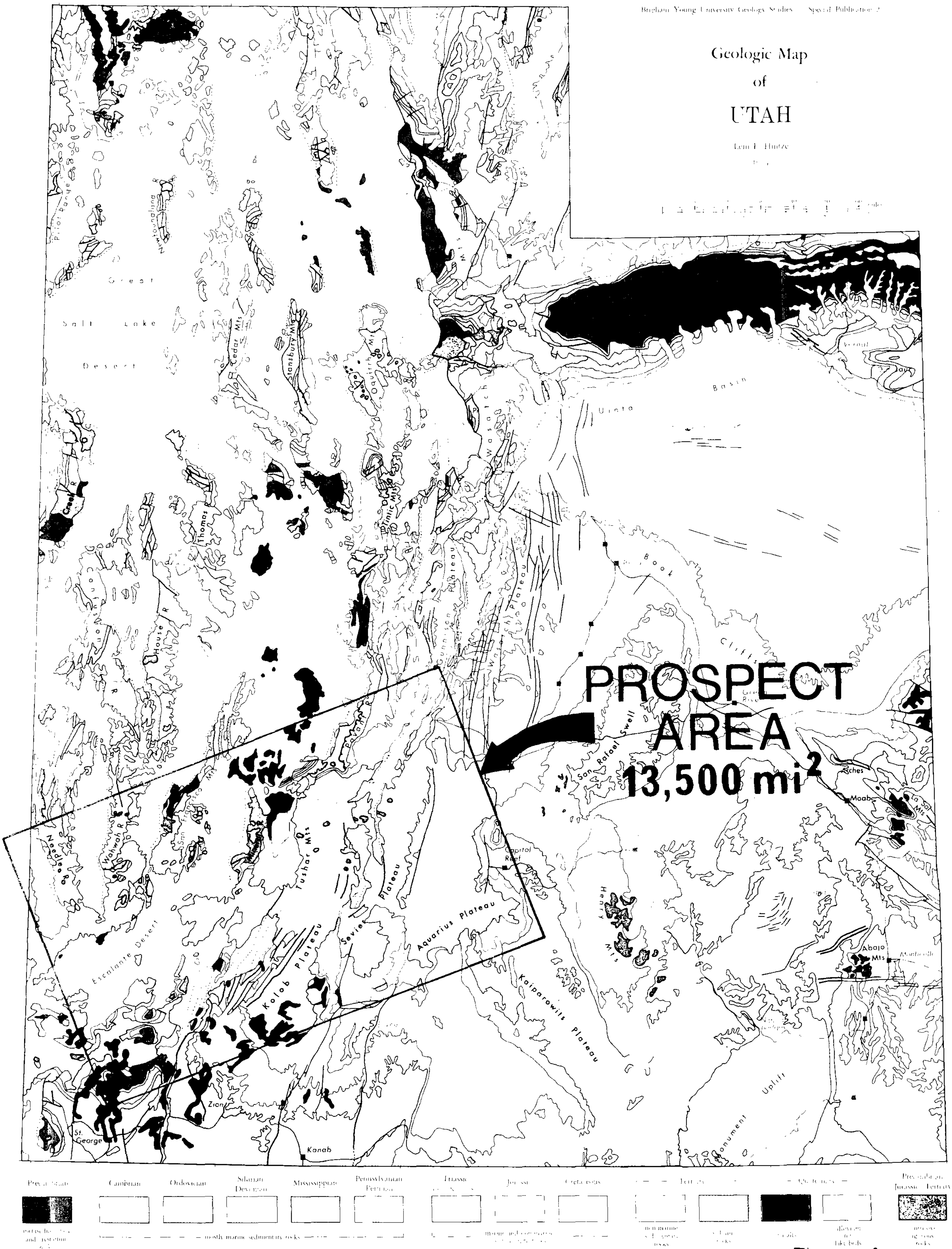

Geologic Map
of
UTAH
PROSPECT
AREA
13,500 mi²
Great
Salt Lake
Desert
Cedar Mts
Stansbury Mts
Oquirrh Mts
Wasatch
Uinta
Basin
Vernal
Book
Cliffs
San Rafael Swell
Green River
Arches
Moab
La Sal Mts
Thomas R
House R
Needle R
Wah Wah R
Tushar Mts
Sevier Plateau
Aquarius Plateau
Kolob Plateau
Escalante Desert
Capitol Reef
Henry Mts
Kaiparowits Plateau
Abajo Mts
Monument
Uplift
Zion
St. George
Kanab
Cambrian
Ordovician
Mississippian
Triassic
Cretaceous

Figure 4

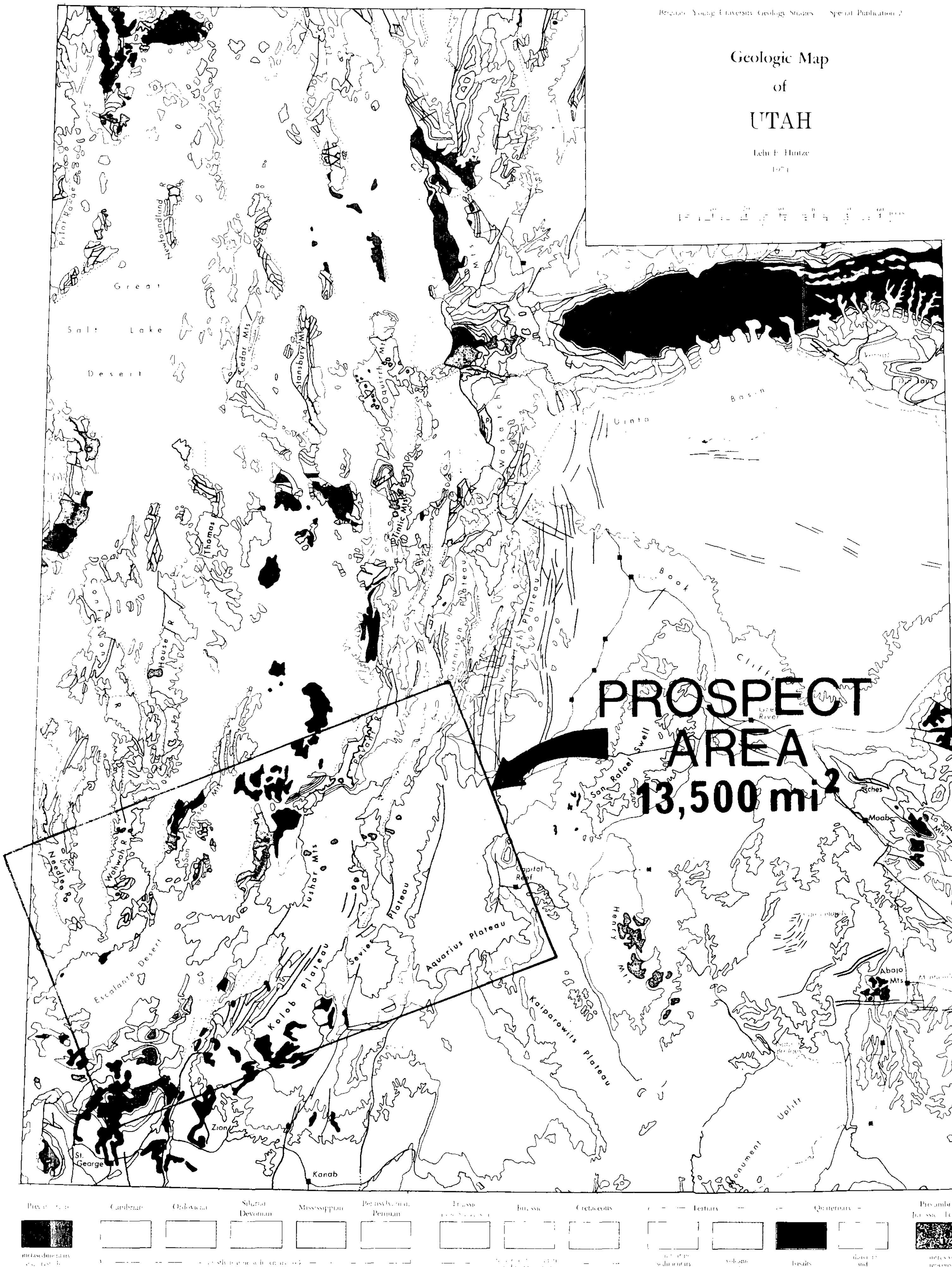

Geologic Map
of
UTAH
PROSPECT
AREA
13,500 mi²
Great Salt Lake Desert
Uinta Basin
Book Cliffs
San Rafael Swell
Capitol Reef
Henry Mts
Kaiparowits Plateau
Aquarius Plateau
Sevier Plateau
Kolob Plateau
Tushar Mts
Escalante Desert
Needle Ra
Wah Wah R
San Francisco Mts
House R
Thomas R
Cedar Mts
Stansbury Mts
Oquirrh Mts
Tintic Mts
Newfoundland R
Pilot Range
Wasatch Plateau
Gunnison Plateau
Moab
La Sal Mts
Abajo Mts
Monument Uplift
Zion
St. George
Kanab
Cambrian
Ordovician
Silurian
Devonian
Mississippian
Pennsylvanian
Permian
Triassic
Jurassic
Cretaceous
Tertiary
Quaternary
Precambrian

Figure 4

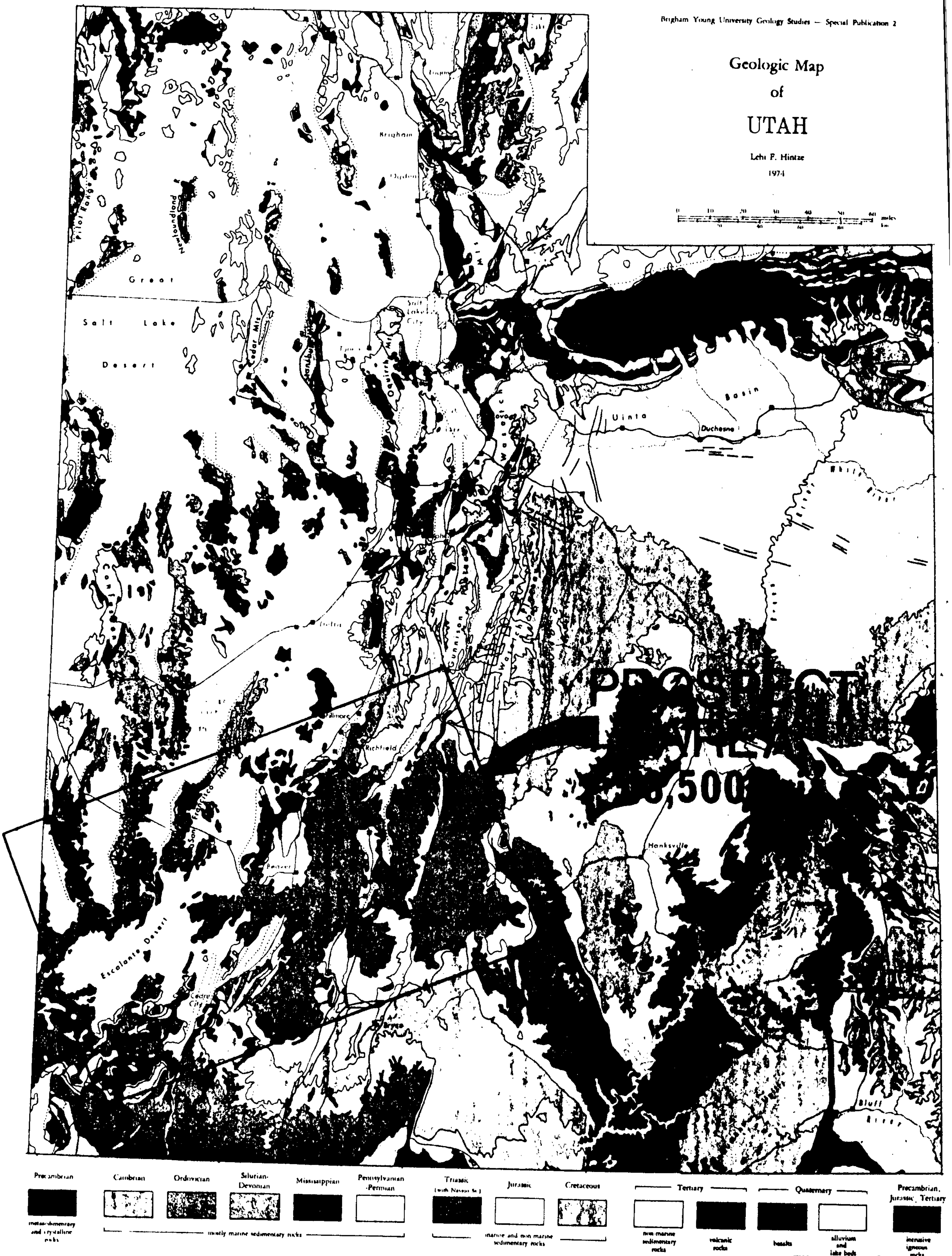

Brigham Young University Geology Studies — Special Publication 2
Geologic Map
of
UTAH
Lehi F. Hintze
1974
miles
km
Great
Salt Lake
Desert
Newfoundland
Brigham
Ogden
Salt Lake City
Oquirrh
Uinta
Basin
Duchesne
Delta
Fillmore
Richfield
Beaver
Hanksville
Escalante Desert
Cedar City
Bluff
PROSPECT
Precambrian
Cambrian
Ordovician
Silurian-Devonian
Mississippian
Pennsylvanian-Permian
Triassic
Jurassic
Cretaceous
Tertiary
Quaternary
Precambrian, Jurassic, Tertiary
metasedimentary and crystalline rocks
mostly marine sedimentary rocks
marine and non marine sedimentary rocks
non-marine sedimentary rocks
volcanic rocks
basalts
alluvium and lake beds
intrusive igneous rocks

Figure 4

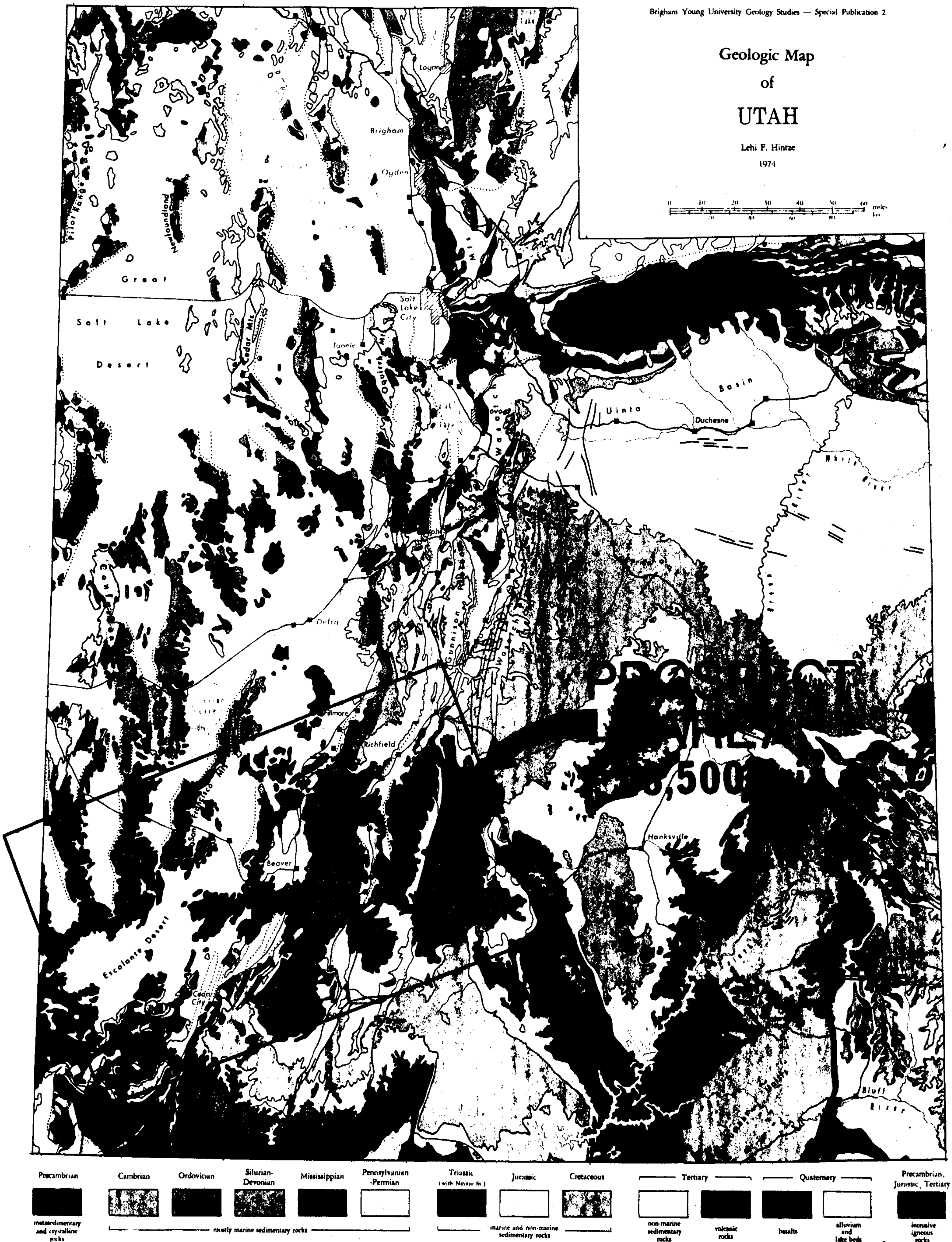
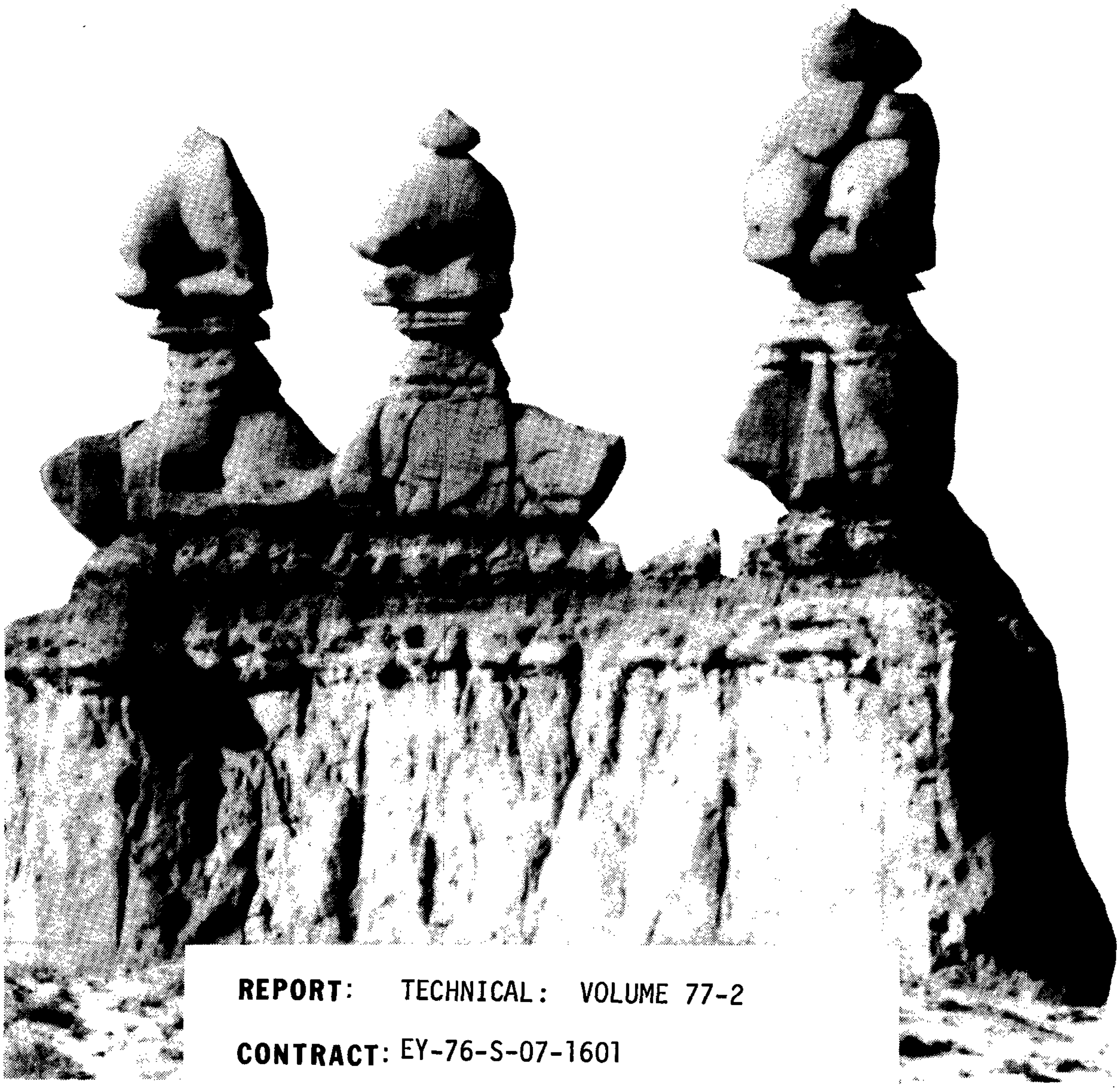

Brigham Young University Geology Studies — Special Publication 2
Geologic Map
of
UTAH
Lehi F. Hintze
1974
miles
km
Logan
Brigham
Ogden
Pilot Range
Newfoundland R.
Great
Salt Lake
Desert
Salt Lake City
Tooele
Cedar Mts
Oquirrh Mts
Wasatch
Provo
Uinta
Basin
Duchesne
White River
Delta
Gunnison
Fillmore
Richfield
Beaver
Hanksville
Escalante Desert
Cedar City
Bluff
River
Precambrian
Cambrian
Ordovician
Silurian-Devonian
Mississippian
Pennsylvanian-Permian
Triassic (with Navajo Ss.)
Jurassic
Cretaceous
Tertiary
Quaternary
Precambrian, Jurassic, Tertiary
metasedimentary and crystalline rocks
mostly marine sedimentary rocks
marine and non-marine sedimentary rocks
non-marine sedimentary rocks
volcanic rocks
basalts
alluvium and lake beds
intrusive igneous rocks

Figure 4

DEPARTMENT OF
GEOLOGY AND GEOPHYSICS



REPORT: TECHNICAL: VOLUME 77-2

CONTRACT: EY-76-S-07-1601

AGENCY: ERDA

TITLE: GEOTHERMAL EXPLORATION ARCHITECTURE

AUTHORS: S. H. Ward

DATE: April, 1977

UNIVERSITY OF UTAH SALT LAKE CITY, UTAH 84112

TECHNICAL REPORT: VOLUME 77-2

Geothermal Exploration Architecture

Energy Research and Development Administration

Contract EY-76-S-07-1601

S. H. Ward

Table of Contents

ABSTRACT

A basic modular exploration sequence which includes a carefully balanced selection of geological, geochemical, and geophysical modules is developed for geothermal prospecting in the eastern Basin and Range. The cost per square mile for application of this exploration architecture is $461.00. If one were to expand this basic system to include virtually all techniques being routinely employed in geothermal prospecting today, then the cost per square mile would increase to $790.00. This latter expenditure rate is difficult to justify, but some increase above the $461.00 basic cost appears to be warranted to make exploration costs about equal to land acquisition costs and model-test drilling costs. Total costs per discovery appear to range from $6M to $27M depending upon assumptions, when the costs of exploring for "dry" prospects are included in the costs of the discoveries. Development and operating costs are not included in the analysis.

The basic exploration architecture described here is compared with others previously advanced in the literature. While differences in approach are abundant, there is a central core of exploration activities and an order to these activities to which most of us "architects" probably would subscribe. If a common basic is used for computing costs of individual exploration modules, then there is no great cost disparity between any of the architectures reviewed.

1.0 Introduction

The design of exploration campaigns (herein termed exploration architecture) intended to discover economically viable resources, be they geothermal, base metal, oil and gas, uranium, or whatever, is not a totally objective science. Further, exploration architecture is a dynamic thing which changes as more is learned about a) a specific geological area, b) a specific resource type, or c) the methods used in exploration. Thus, it is seldom that two industrial concerns will agree on a particular exploration architecture for a given commodity in a given area at a given time. Nevertheless, there are certain guidelines which most follow, consciously or subconsciously, in arriving at the design of an exploration campaign. In the following, I present my current notions on exploration architecture suited to discovery of convective hydrothermal systems in the eastern Basin and Range physiographic province of the western USA.

The approach to exploration architecture that I use is not new. Similar forms of it have appeared in the literature for years; three basic and useful references from the mining literature are Hawkes and Webb (1962), Pfleider (1968), and Ward (1972). As noted by Grose (1971), "The modern exploration approach to geothermal energy is basically similar to that of metaliferous mineral deposits and oil and gas. However, the science and technology of development of geothermal resources is young and untested by long experience of success and failure." Articles on exploration architecture which reflect different and broader experience bases than I am able to provide are Banwell (1970), Combs and Muffler (1973), Greider (1975), Dolan (1975), Furumoto (1975), McNitt (1975), and

Meidav and Tonani (1975). My analysis largely ignores these works at the outset since my intent is development of exploration architecture suited to detection of hidden geothermal resources in a relatively large region, whereas the earlier authors mostly start with the assumption that a small prospect area has been identified. Later I shall compare my findings with theirs.

2.0 Basic Principles of Exploration Architecture

An exploration sequence should consist of a number of optional modules, each of which depicts one or more specific geological, geochemical, geophysical, or "physical" activities. Figure 1 is a generalized modular exploration system. Decisions to proceed along the various paths indicated depend upon results of prior modules, upon economic analyses made at critical junctures, upon one's experience with the area and the commodity, and upon the exploration tools at one's disposal. The intensity of total expenditures on geology, geochemistry, and geophysics, the distribution of expenditures between these three basic sub-disciplines, and the specific activities under each sub-discipline, vary widely from company to company, from one commodity to another, from one area to another, and from time to time. The particular manner in which I present my concepts of exploration architecture (Ward, 1972) i.e. via a collection of optional hard modules, is itself often contested; many prefer shadowy boundaries between options. Nevertheless, I shall stay with this concept here because I believe that hard modules force one to make hard decisions which ultimately lead to cost-effective exploration. My notion is that the least expensive modules come first in the exploration sequence *provided* that they produce sufficient data points of reliable quality to permit a logical sequence of decisions. At every point where an economic appraisal is indicated, the exploration program or prospect could be terminated or continued. The tendency to continue regardless of the economic forecast must be restrained. Of course, value judgments on such matters depend upon the risk one is prepared to take at any decision-making juncture. Risk is usually assessed by deriving an expected value of a venture at any branch point in an exploration architecture (e.g. Newendorp, 1976). The risk for one optional path of Figure 1 is expected to be different to that for another. Indeed, risk might be lower in Figure 1, if say, the *detailed exploration* modules were eliminated entirely. Development of a risk decision strategy depends upon years of experience with numerous prospects in numerous parts of the world. Since that is not the data base from which I draw, I merely note in Figure 1, that economic appraisals must be conducted at all branch points. This then allows the reader to inject his own risk decision strategy upon a basic piece of exploration architecture. Given this overview of exploration architecture, let us now proceed to suggest architecture suited to exploration for convective hydrothermal systems in the eastern part of the Great Basin of the USA.

3.0 The "Full Option" Approach

Some may contend that land acquisition and drilling for geothermal resources in the eastern part of the Great Basin is so expensive that one ought to conduct nearly all possible modules of an exploration sequence prior to land acquisition and certainly prior to drilling. Let us evaluate this extremum. Figure 2 portrays a hugh array of geological, geochemical, geophysical and hydrological modules which might be employed prior to drilling a geothermal prospect while Figure 3 and Table 1 give estimates of the costs associated with such a program and the basis for the estimates, respectively.

On Figure 4, the geologic map of Utah, we have marked a 90 mile by 150 mile area. This area is largely underlain by Tertiary extrusives but includes later intrusives and volcanics. It contains most of the KGRA's in Utah and is believed to be a region of major crustal perturbation (Eaton, 1975). Roosevelt Hot Springs KGRA, the most prominent geothermal prospect in Utah, lies near the center of its northern border. Let us initially assume that we are interested in any 30 mile by 30 mile (900 square miles) block within this 13,500 square mile area. Figure 3 and Table 1 then provide reasonable, but not uncontested, cost estimates for each module of the exploration sequence for this 900 square mile area. The total cost of exploration for a 900 square mile area would then be $0.710M. For the entire 90 mile by 150 mile region, the total cost of the "full option" exploration would be $10.7M, not including land acquisition, drilling, or production testing.

Also shown at the end of each modular step of Figure 3, is the fraction of the initial area remaining to be considered after each phase; the fractional reduction in area after each phase is my best estimate and it is subject to debate. However, if one believes this area reduction pattern, then only 8% of the total area will remain for drilling. Eight percent of the initial test area of 900 square miles is 72 square miles or about the maximum dimension of one geothermal prospect, if Roosevelt Hot Springs is of typical size. Thus, for the whole 150 mile by 90 mile zone underlain by Tertiary volcanics, we assume a maximum of 15 geothermal prospects.

Grieder (1975) assumes 0.38 of all prospects warrant temperature gradient holes whereas I assume 0.21 of the area studied. I would drill 0.08 of the area whereas he would drill 0.25 of the prospects. My figures are lower than Greider's because I am covering blind areas and prospects whereas Greider is covering prospects only. My estimates of area reduction by phase, given in Figure 3, were based upon a simple formula of 25% area reduction after phases I, II, IV, and VI, and 50% area reduction after phases III, V; this formula was derived from my personal experience in reqional exploration in the mining industry and from comparison of mining and geothermal objectives, problems, and techniques. Greider's estimates of prospect reduction appear to be based upon his personal industrial experience and upon that of the geothermal industry in general. The two estimate schemes appear to be in broad agreement, however subjective.

4.0 The "Restricted Option" Approach

Not too many practitioners of geothermal exploration will agree that the full option approach ought to be employed. Accordingly, in this section I have deleted those methods which have not been proven to me to produce consistently meaningful data. Others may be able to prove me wrong now or at some time in the future. I shall welcome challenge at any time. Table 2 and Figures 5 and 6 show one logical restricted option architecture. Costs have been cut, relative to the full option approach, to $0.415M per 900 square mile area and would total $6.2M per 13,500 square miles.

While I cannot agree, some would argue that modules 3, 4, and 5 ought to be deleted also, leaving the net cost for 900 square miles at $0.360M and for 13,500 square miles at $5.4M.

Others would argue that some form of passive seismic technique (either microearthquake, earth noise, teleseismic studies, or some combination thereof) ought to be included. If so, and if passive siesmic methods are placed in phase VI, then minimum budgets of $0.455M per 900 square miles or $6.8M per 13,500 square miles must be allocated. Still others would argue for active seismic in phase VI and it is difficult to conceive of less than $100K additional per 900 square miles for budgets of $0.515M per 900 square miles or $7.7M per 13,500 square miles.

In both of these latter estimates, we have retained the cost of modules 3, 4, and 5 because we need more early regional data if we are to apply seismic methods with intelligence at the target definition stage.

5.0 The "MT Option" Approach

The most significant observation brought out at the "Workshop on Electrical Exploration Methods in the Geothermal Environment", held at Snowbird, Utah in November, 1976, was that the magnetotelluric method (MT) characteristically obtains a resistivity less than one ohm-m, at depths in the range 2 to 15 km, beneath a geothermal prospect. This observation suggests that we ought to use MT always as a reconnaissance electrical method. Experience at Roosevelt Hot Springs demonstrates that a minimum station density for detection of this low resistivity zone is one station per square mile. For an area 30 miles by 30 miles, or 900 square miles, 900 observations would be required if this were the initial tool in the exploration sequence. However, if MT is left until the area is reduced to 0.28 of its original size (Figures 7 and 8 and Table 3), then only 207 observations would be required. A nominal cost of $1600 per station is suggested leading to MT costs of $330K per 900 square miles. This cost might be shaved considerably by employing the combined MT/Telluric method, but we have no strong scientific basis for so doing at the present time. If we are to afford the MT method in such scope, then modules 4 and 5 perhaps ought not to be afforded because the regional structural information provided by gravity and aeromagnetics may not be necessary when regional electrical structural information is provided by MT. This approach then leads to costs of $0.700M per 900 square miles or $10.5M per 13,500 square miles.

6.0 Comparative Costs of Various Approaches

In Table 4 I have summarized the exploration costs per 900 square miles, per 13,500 square miles, and per square mile for the several optional approaches discussed here. We observe that costs can range from $400 to $778 per square mile; these costs are not excessive in reference to exploration for any type of resource.

To these costs must be added the costs of a) land acquisition, which we assume to be $0.450M based on acquiring 45,000 acres* at $10 per acre, and b) model test drilling which we assume to be $0.500M for one hole to 5,000 feet. If a prospect warrants a production test we add $1.500M for three holes to 5,000 feet and $0.500M for production testing and for additional geoscientific efforts such as mapping faults by active seismic methods and defining the hydrologic regime by whatever methods are available.

*Note that an individual company is limited to 25,000 leased federal acres per state at the present time so it is doubtful that a company would commit its 25,000 acre allotment to one prospect plus seek an additional 20,000 from state and private acreage. In this respect, Greider (1975) uses 7,500 acres per prospect; such a limited acreage would cover only the heart of the prospect at RHS KGRA.

If we assume that one prospect only can result from exploration of a 900 square mile area, as discussed earlier, then a maximum of 15 prospects will be discovered in southwestern Utah by the types of exploration architecture described here. Each of these 15 prospects will require one model test drill hole to 5,000 feet. Greider (1975) notes that the industry average is less than one producer for every 16 model test holes drilled. In Table 4 we have assumed both 1 in 15 and 5 in 15 producers per model test hole drilled. The worst case states that our brands of exploration architecture are no better than those industry has used in the past, while the best case states that we shall do substantially better than has been done (or that with the discovery of the resource at Roosevelt Hot Springs, southwest Utah is elephant country where odds of discovery are higher).

It is of interest to compute that variations in costs of exploration, restricted to the various assumptions made so far, do not perturb total costs per discovery by more than ±10% about the mean; and that this perturbation percentage is independent of the number of discoveries per prospect drilled. Even when land acquisition costs are reduced to 1/3 of the entries given above, the perturbation of total costs caused by variations in exploration architecture are only ± 13% about the mean. It would seem to us that two conclusions can be drawn from these last two sentences: a) the inertia of drilling and testing costs overwhelms exploration costs, and b) all effort should be exerted in exploration to reduce the number of "dry" prospect wells and to reduce the cost of production testing.

7.0 Conclusions

We conclude that geoscience studies are comparatively inexpensive in geothermal exploration in the eastern Basin and Range. Our route to this conclusion is tenuous. Nevertheless, it appears to be justified to spend at least $1.5M to $2.0M on geoexploration per discovery so identified through a modular exploration sequence. The "full option" sequence described above appears to be excessive while the basic "restricted option" appears to be conservative. Some compromise between the two is appropriate. The impact of various exploration costs on total costs per discovery is minimal.

There would appear to be physical room, according to our area reduction schedule of Figure 3 for a maximum of 15 prospects in southwestern Utah. If we assume that a minimum of 300 megawatts may be developed per prospect, then southwestern Utah ought to yield as much as 4500 megawatts. Based on comparing early and late experience at the Geysers in California, 1500 megawatts per prospect or 22,500 megawatts total, ought to be the maximum expected of southwestern Utah. The total area considered is 13,500 square miles. The maximum area of the Roosevelt Hot Springs prospect is of order 72 square miles. Thus, the whole of the Tertiary volcanic belt of southwestern Utah, if totally productive, would have 188 prospects, whereas we have assumed that at most it is 8% productive, or that it contains 15 potential geothermal *prospects*. We are inclined to reduce these *prospects* to a minimum of one and a maximum of five *discoveries* so that the total geothermal power development in Utah might range from a minimum of 300 megawatts to a maximum of 7500 megawatts. Each discovery will cost $5.95M to $6.99M if 5 are discovered or $21.65M to $26.95M if only one new discovery is made.

This cost per discovery is justifiable when development costs will be much larger (Greider, 1975) and when 300 to 1500 megawatts per discovery can be developed. Ultimately, then we must conclude that a fairly thorough exploration architecture ought to be employed. We are conditioned, of course, by the fact that we know we are hunting for elephants in elephant country.

8.0 Epilogue

The above analysis was written without detailed reference to other articles on geothermal exploration architecture. This procedure minimizes historical bias and focuses on architecture suited to the eastern Great Basin. It is of interest, therefore, at this juncture to compare our analysis with analyses performed by others in prior years. Four previous articles are used for this purpose, those of Banwell (1970), (essentially repeated in Banwell (1974)). Combs and Muffler (1973), Greider (1975), and Dolan (1975). To be fair to Greider, it should be mentioned that only a small part of his article was devoted to exploration architecture. Figures 9 through 16 present the technological and cash flows for each of these four architectures. It should be appreciated that I have taken considerable liberty in converting the texts and figures of these authors to the structured frame of reference I am using. Further, the cost estimates for their architectures are mine and not theirs; while designed to ensure uniformity and thereby facilitate comparisons, there is no assurance that any one author would concur with my costing basis or my intended depth of study. (In fact, Greider estimates $95K per prospect for all of this exploration,whereas using his words, some indirect knowledge of his company's habits, and my costing basis, I estimate $420K for a 900 square mile area).

Words added to Figures 9 through 16, beyond those already given, would be superfluous. Each figure requires study unto itself and comparison with all other figures in this report. One overwhelming observation is that if one accepts my costing basis, then the costs for the four new architectures range from $420K to $595K per 900 square miles, a range totally encompassed by my range of $360K to $710K given in Table 4.

As one final study, I have attempted to find common denominators between my "restricted option" and the options that Banwell, Combs and Muffler, Greider, and Dolan would take. I cannot call the resulting option a consensus because I have no assurance that these authors would agree with me. However, if I understand their writings, then the compromise option of Figures 17 and 18 would satisfy each of us in basic content whether we are doing grass roots exploration of a large territory or are evaluating a prospect. It seems to me to represent the lowest common denominator, costing $360K per prospect or per 900 square miles, to which each of us would like to add some tens of thousands of dollars to satisfy our curiosities; the end result ought to be a budget in the $400K to $600K range, or possibly higher.

Acknowledgements

I wish to thank Messrs. R. Christiansen, L. Ball, N. E. Goldstein, B. Greider, and A. H. Truesdell for helpful discourse while preparing this manuscript. While each of them has influenced my thinking, no one of them is in any way responsible for the assumptions, analyses, or conclusions I have drawn.

References

Banwell, C. J., 1970, Geophysical techniques in geothermal exploration, Geothermics, Special Issue 2, p. 32-57.

Banwell, D. J., 1974, Geophysical methods in geothermal exploration, in Geothermal Energy, Paris, The Unesco Press, p. 41-48.

Combs, J., and L. J. P. Muffler, 1973, Exploration for geothermal resources, in Geothermal Energy, edited by P. Kruger, and C. Otte, Stanford, Stanford University Press, p. 95-128.

Dolan, Wm., 1975, in Report on "Geophysical Methods Applied to Detection, Delineation, and Evaluation of Geothermal Resources", University of Utah, October.

Eaton, G. P., 1975, Characteristics of a transverse crustal boundary in the Basin and Range province of southern Nevada, GSA Abstract, 1975 Annual Meeting.

Furumoto, A. S., 1975, A coordinated exploration program for geothermal sources on the island of Hawaii, Proceedings, Second U.N. Symposium on the Development and Use of Geothermal Resources, v. 2, p. 993-1001.

Greider, B., 1975, Unpublished manuscript.

Grose, L. T., 1971, Geothermal energy: geology, exploration, and developments, Part I, Mineral Industry Bull., 16, 6, 14 p.

Hawkes, H. E., and J. S. Webb, 1962, Geochemistry in mineral exploration, New York, Harper and Row.

McNitt, J. R., 1975, Summary of the United Nations geothermal exploration experience, 1965 to 1975, Second U.N. Symposium on the Development and Use of Geothermal Resources, v. 2, p. 1127-1134.

Meidav, T., and F. Tonani, 1975, A critique of geothermal exploration techniques, Proceedings, Second U.N. Symposium on the Development and Use of Geothermal Resources, v. 2, p. 1143-1154.

Newendorp, P. D., 1976, Use of decision trees can help simplify complex problems, Oil and Gas Journal, October 18 and 25.

Pfleider, Eugene P., 1968, Surface mining, New York, AIME, Mudd Series.

Ward, S. H., 1972, Mining geophysics-new techniques and concepts, Mining Congress Journal, v. 58, p. 58-68.

List of Tables

Table 1

Full Option

Module	Scientist Man-Years	Technician Man-Years	Labor Man-Years	Support Costs	Total Costs	Quantity
1	0.25	0.50		5K	30K	
2	0.15	0.15		3K	15K	
3	0.10	0.10		2K	10K	50 Dates
4	0.10	0.10		17K	25K	3000 Line Miles
5	0.25		0.25	2.5K	20K	1500 Stations
6	0.05	0.05		1K	5K	
7	0.05	0.05		1K	5K	
8	0.25	1.00	0.50	10K	50K	200 Analyses
9	0.20	0.50	0.20	6K	30K	100 Holes
10	0.20	0.20	0.20	2K	20K	
11	0.10	0.10	0.10	1K	10K	
12	0.50	0.50	1.50	25K	80K	900 Obs.
13	0.25	0.50		75K	100K	25 Holes
14	0.10	0.50	0.25	1.5K	20K	25 Holes
15	0.10	0.25	0.10	3K	15K	25 Holes
16	0.20	0.20	0.10	3K	20K	
17	0.25	0.75	0.10	9K	40K	
18	0.50	0.50	.50	55K	100K	180 Line Miles
19	0.50	0.50	1.50	20K	75K	
20	0.50	0.25		5K	40K	
Totals	4.55	6.70	5.30	246K	710K	

Basis:
1) Scientist man-year 60K (salary + overhead)
2) Technician man-year 20K (salary + overhead)
3) Local Labor man-year 10K (salary + overhead)
4) Support costs are minimal.
5) Hardware amortization covered in overhead.
6) Reconnaissance electrical (Module 12) costs based on 4 bipole-dipole readings per section but self-potential, tellurics, MT, or tellurics/MT might be considered and might reduce costs.
7) Detailed electrical (Module 19) costs based on dipole-dipole resistivity.

Table 2

Restricted Option

Module	Scientist Man-Years	Technician Man-Years	Labor Man-Years	Support Costs	Total Costs	Quantity
1	0.25	0.50		5K	30K	
2	0.15	0.15		3K	15K	
3	0.10	0.10		2K	10K	50 Dates
4	0.10	0.10		17K	25K	3000 Line Miles
5	0.25		0.25	2.5K	20K	1500 Stations
8	0.20	0.50	0.20	6K	30K	100 Analyses
9	0.20	0.50	0.20	6K	30K	100 Holes
10	0.20	0.20	0.20	2K	20K	
13	0.25	0.50		75K	100K	25 Holes
15	0.10	0.25	0.10	3K	15K	25 Holes
16	0.05	0.05	0.05	0.5K	5K	
19	0.50	0.50	1.50	20K	75K	180 Line Miles
20	0.50	0.25		5K	40K	
Totals	2.85	3.60	2.50	147K	415K	

Basis:
1) Scientist man-year 60K (salary + overhead)
2) Technician man-year 20K (salary + overhead)
3) Local labor man-year 10K (salary + overhead)
4) Support costs are minimal.
5) Hardware amortization covered in overhead.
6) Detailed electrical (Module 19) costs based on dipole-dipole resistivity.

Table 3

MT Option

Module	Scientist Man-Years	Technician Man-Years	Labor Man-Years	Support Costs	Total Costs	Quantity
1	0.25	0.50		5K	30K	
2	0.15	0.15		3K	15K	
3	0.10	0.10		2K	10K	50 Dates
8	0.20	0.50	0.20	6K	30K	100 Analyses
9	0.20	0.50	0.20	6K	30K	100 Holes
10	0.20	0.20	0.20	2K	20K	
12	(per sounding basis			330K	330K	207 Soundings
13	0.25	0.50		75K	100K	25 Holes
15	0.10	0.25	0.10	3K	15K	25 Holes
16	0.05	0.05	0.05	0.5K	5K	
19	0.50	0.50	1.50	20K	75K	180 Line-miles
20	0.50	0.25		5K	40K	
Totals	2.50	3.50	2.25	458K	700K	

Basis:
1) Scientist man-year 60K (salary + overhead)
2) Technician man-year 20K (salary + overhead)
3) Local Labor man-year 10K (salary + overhead)
4) Support costs are minimal.
5) Hardware amortization covered in overhead.
6) MT costs at $1600 per sounding.
7) Detailed electrical (module 19) costs based on dipole-dipole resistivity.

Table 4

Option	Exploration Cost/900 sq.mi.	Exploration Cost/13,500 sq. mi.	Exploration Cost/sq.mi.	Exploration Cost/Discovery	Land Cost/ Discovery	Model Test Cost/Discovery	Production Test Cost/Discovery	Total Cost/ Discovery
Full	$710K	$10.7M	$790	$2.14M*($10.7M)+	$1.35M*($6.75M)+	$1.50M*($7.50M)+	$2.00M*($2.00M)+	$6.09M*($26.95M)+
Table 2 (basic)	$415K	$ 6.2M	$461	$1.24M ($6.2M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.09M ($22.45M)
Table 2 (basic, less age dating, gravity and aeromagnetics)	$360K	$ 5.4M	$400	$1.10M ($5.4M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$5.95M ($21.65M)
Table 2 (basic, plus passive seismic)	$455K	$ 6.8M	$506	$1.36M ($6.8M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.21M ($23.05M)
Table 2 (basic, plus active seismic)	$515K	$ 7.7M	$572	$1.54M ($7.7M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.39M ($23.95M)
MT Option (no gravity, or areomagnetics)	$700K	$10.5M	$778	$2.10M ($10.5M)	$1.35M ($6.75M)	$1.50M ($7.50M)	$2.00M ($2.00M)	$6.95M ($26.75M)

* Assumes 5 discoveries of 15 prospects drilled.

\+ Assumes 1 discovery of 15 prospects drilled.

List of Illustrations

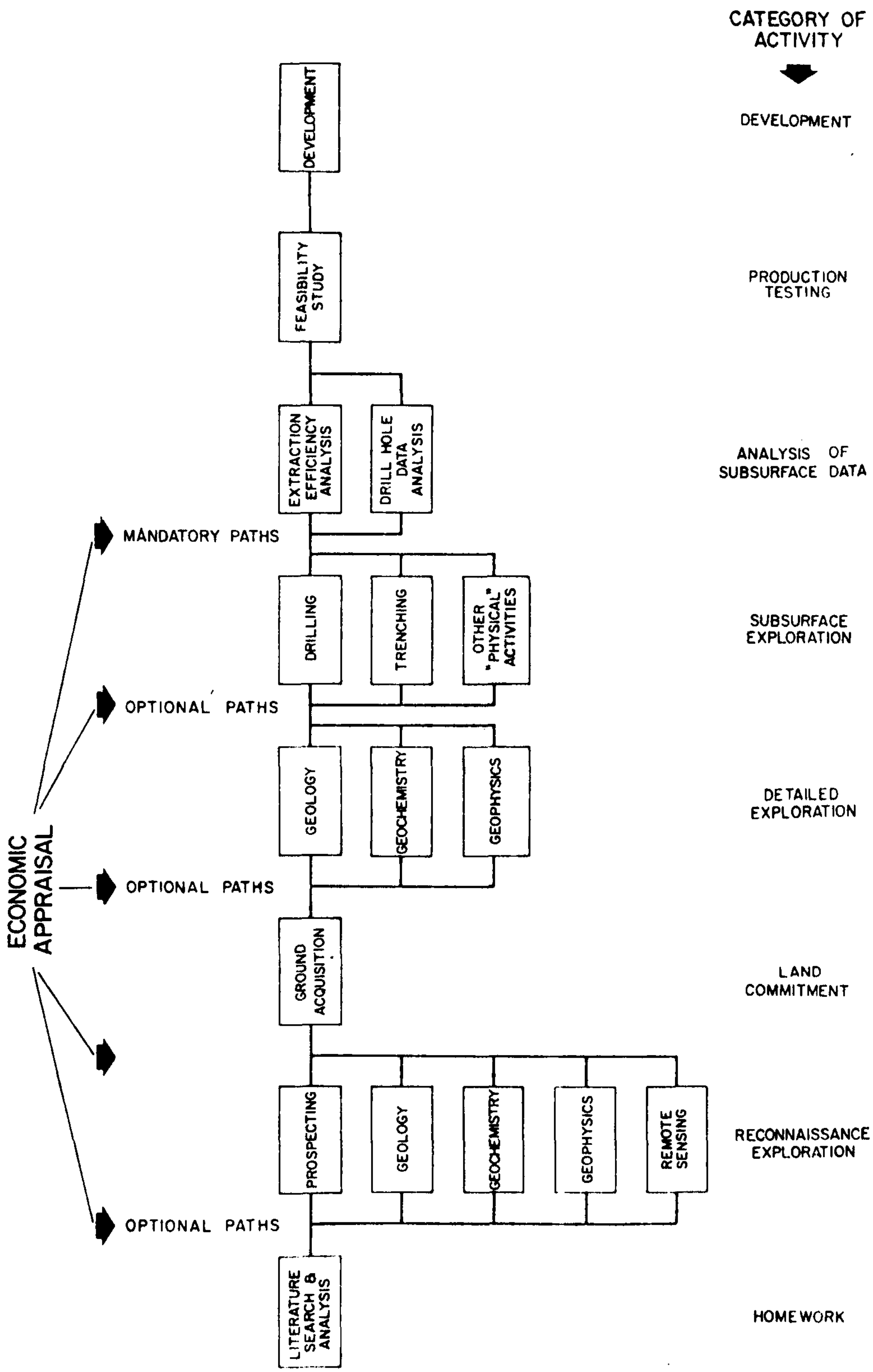
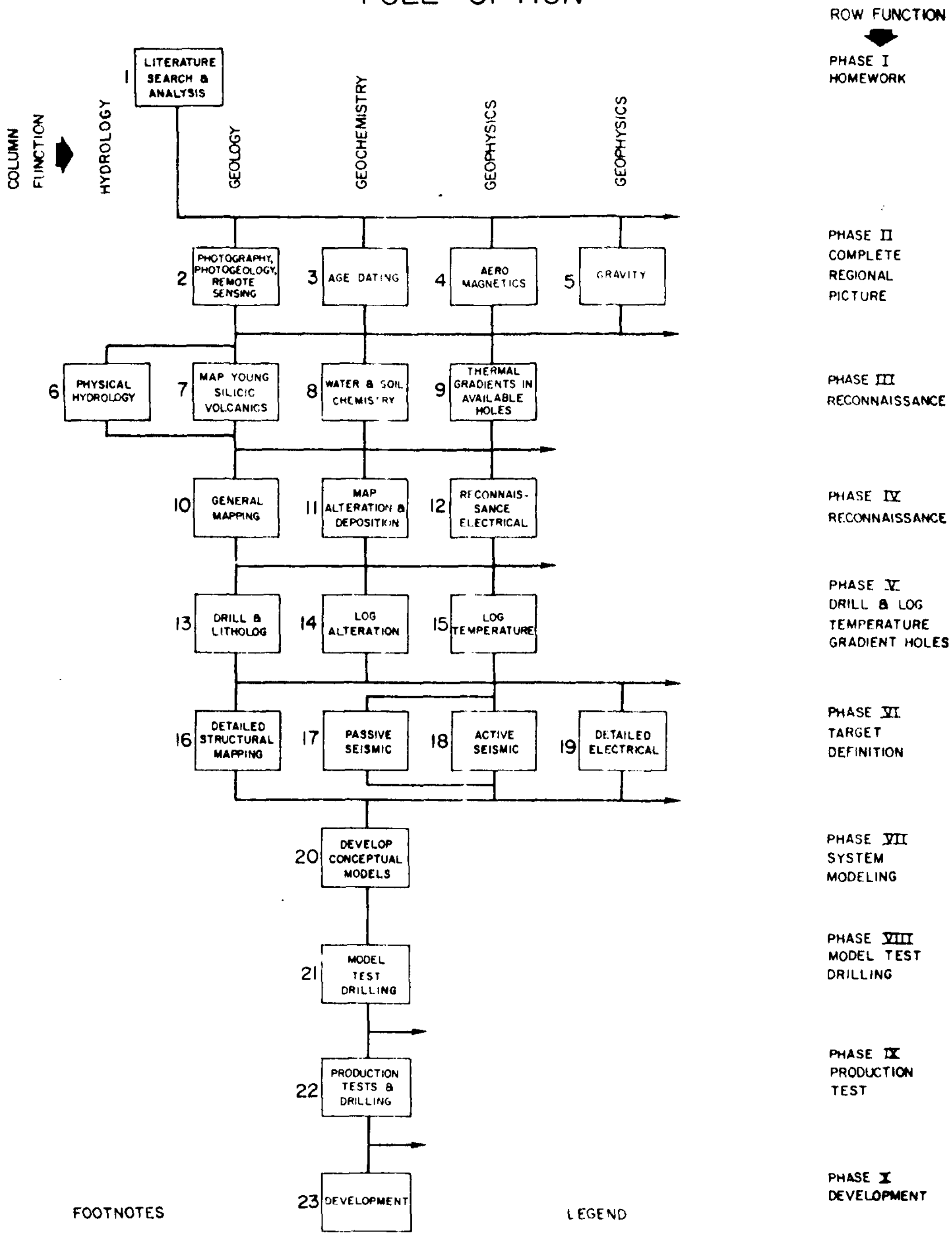

CATEGORY OF ACTIVITY
DEVELOPMENT
PRODUCTION TESTING
ANALYSIS OF SUBSURFACE DATA
SUBSURFACE EXPLORATION
DETAILED EXPLORATION
LAND COMMITMENT
RECONNAISSANCE EXPLORATION
HOMEWORK
DEVELOPMENT
FEASIBILITY STUDY
EXTRACTION EFFICIENCY ANALYSIS
DRILL HOLE DATA ANALYSIS
DRILLING
TRENCHING
OTHER "PHYSICAL" ACTIVITIES
GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
GROUND ACQUISITION
PROSPECTING
GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
REMOTE SENSING
LITERATURE SEARCH & ANALYSIS
MANDATORY PATHS
OPTIONAL PATHS
OPTIONAL PATHS
OPTIONAL PATHS
ECONOMIC APPRAISAL

Figure 1

FULL OPTION



FOOTNOTES

1. PHYSICAL HYDROLOGY - SPRING TEMPERATURE, FLOWRATES
2. WATER CHEMISTRY - GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES
3. SOIL CHEMISTRY - TRACE ELEMENT ANALYSIS

LEGEND

→ REJECT PART OF AREA

12 SPLIT MODULE

Figure 2

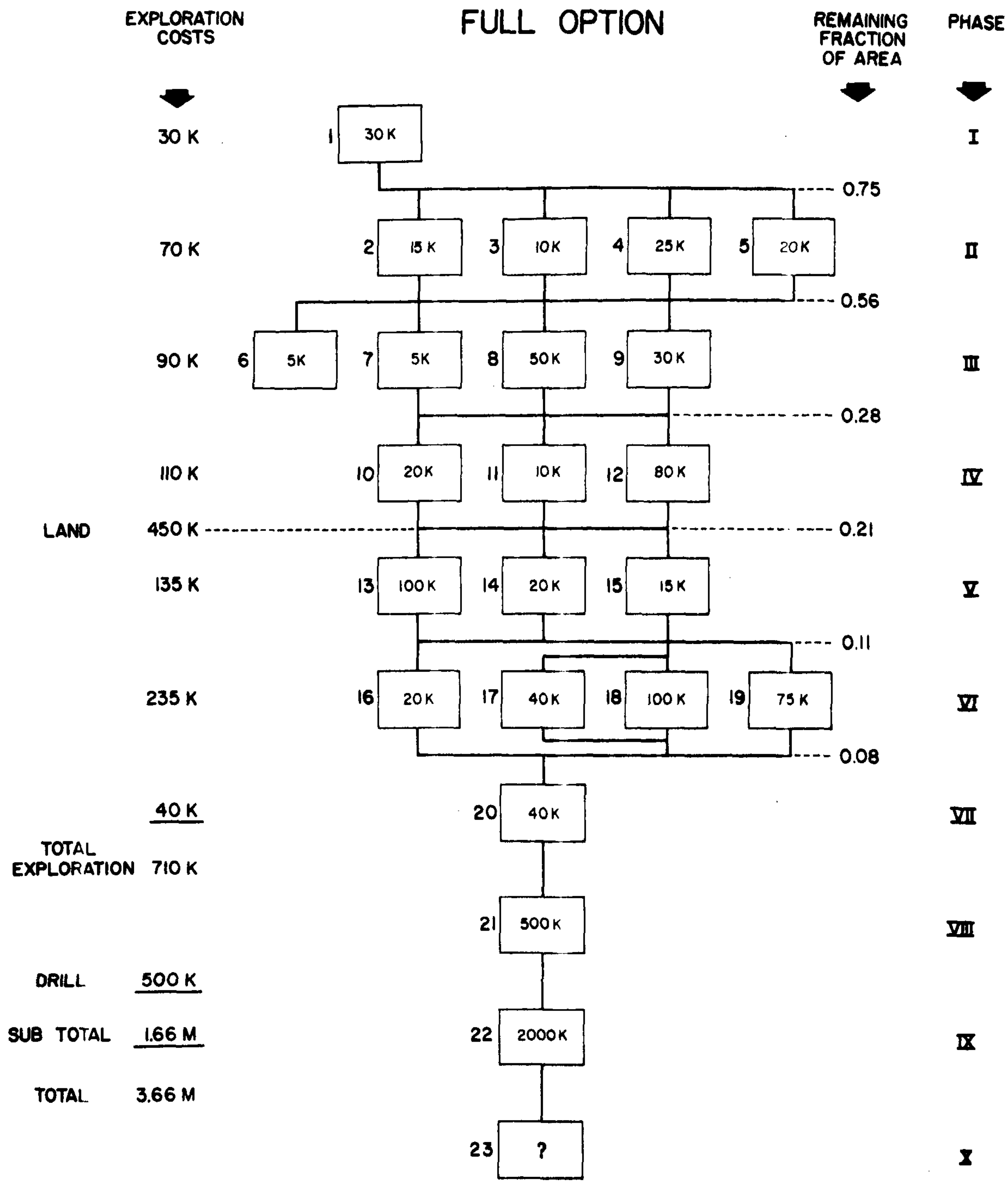

EXPLORATION COSTS
FULL OPTION
REMAINING FRACTION OF AREA
PHASE
30 K
1 30 K
I
0.75
70 K
2 15 K
3 10 K
4 25 K
5 20 K
II
0.56
90 K
6 5K
7 5K
8 50 K
9 30 K
III
0.28
110 K
10 20 K
11 10 K
12 80 K
IV
LAND 450 K
0.21
135 K
13 100 K
14 20 K
15 15 K
V
0.11
235 K
16 20 K
17 40 K
18 100 K
19 75 K
VI
0.08
40 K
20 40 K
VII
TOTAL EXPLORATION 710 K
21 500 K
VIII
DRILL 500 K
SUB TOTAL 1.66 M
22 2000 K
IX
TOTAL 3.66 M
23 ?
X

Figure 3

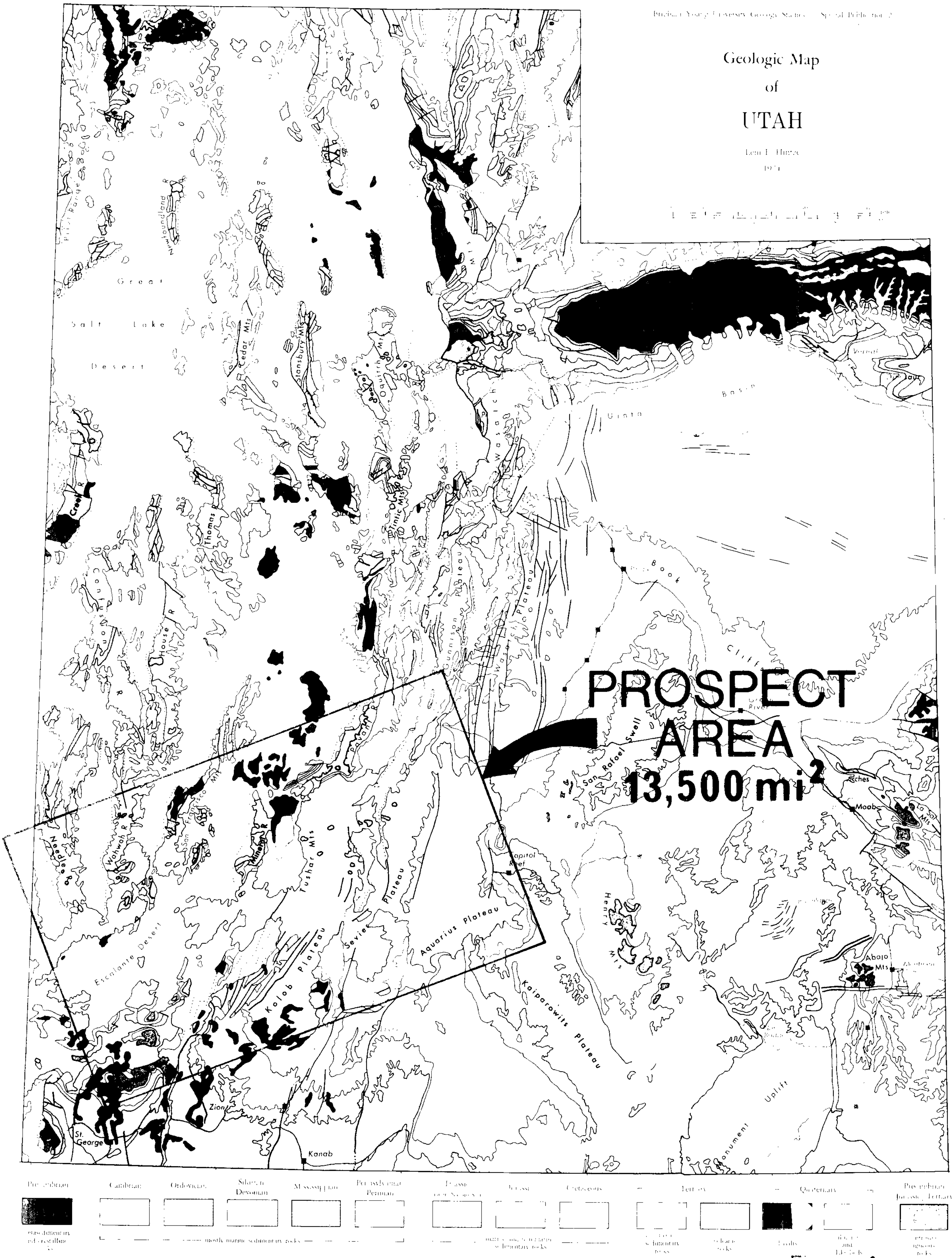
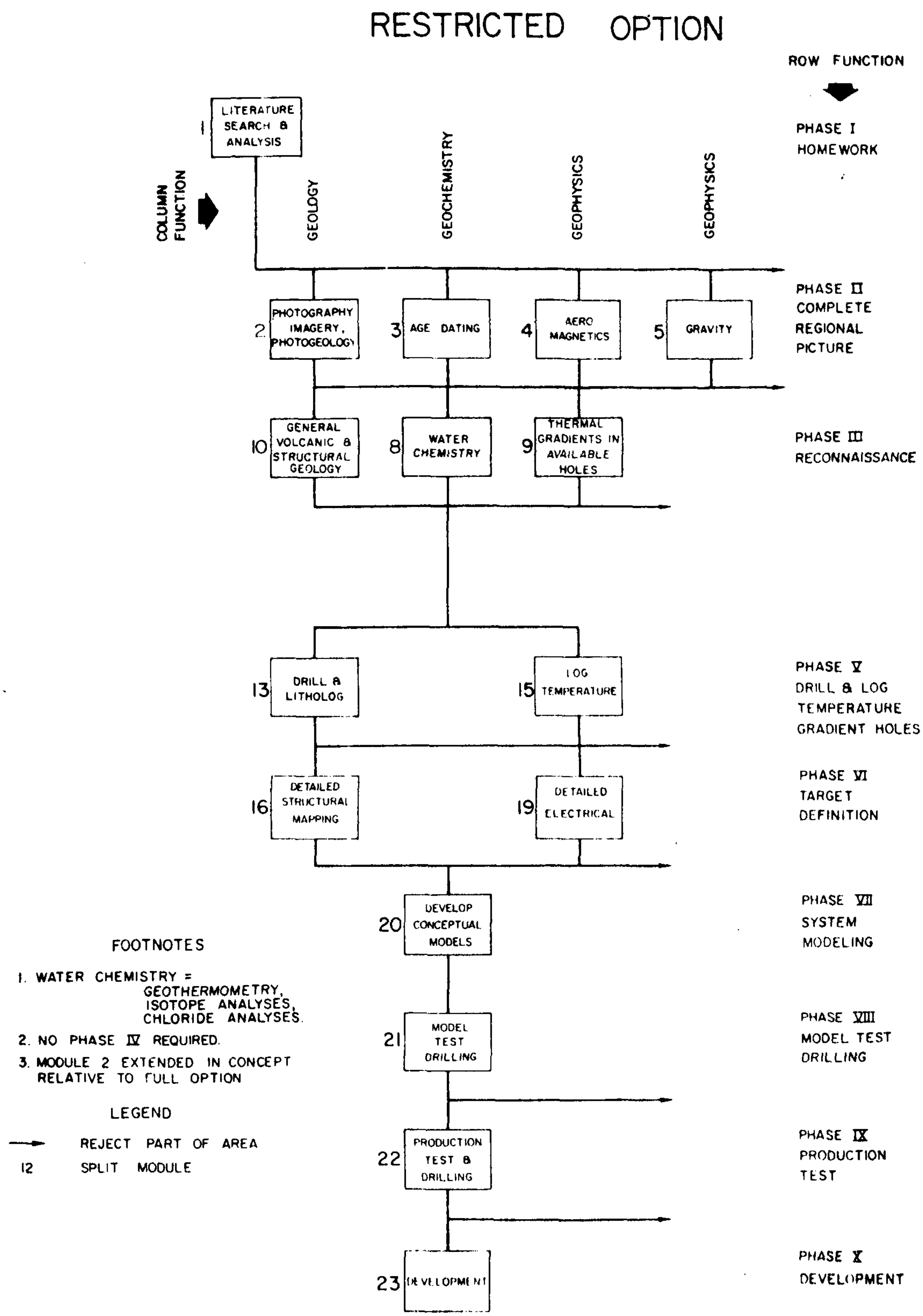

Geologic Map
of
UTAH
Great Salt Lake Desert
Newfoundland R
Cedar Mts
Stansbury Mts
Oquirrh Mts
Wasatch
Uinta
Basin
Vernal
Thomas R
Tintic Mts
Gunnison Plateau
Wasatch Plateau
Book Cliffs
House R
Escalante Desert
Wahwah R
San Francisco Mts
Mineral R
Pavant
Tushar Mts
Sevier Plateau
Aquarius Plateau
Kolob Plateau
Capitol Reef
Henry Mts
Kaiparowits Plateau
Monument Uplift
San Rafael Swell
Moab
La Sal Mts
Abajo Mts
Zion
St. George
Kanab
PROSPECT AREA
13,500 mi²
Cambrian
Ordovician
Silurian
Devonian
Mississippian
Pennsylvanian
Permian
Jurassic
Cretaceous
Tertiary
Quaternary

Figure 4


RESTRICTED OPTION
ROW FUNCTION
COLUMN FUNCTION
GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
GEOPHYSICS
1 LITERATURE SEARCH & ANALYSIS
PHASE I HOMEWORK
2 PHOTOGRAPHY IMAGERY, PHOTOGEOLOGY
3 AGE DATING
4 AERO MAGNETICS
5 GRAVITY
PHASE II COMPLETE REGIONAL PICTURE
10 GENERAL VOLCANIC & STRUCTURAL GEOLOGY
8 WATER CHEMISTRY
9 THERMAL GRADIENTS IN AVAILABLE HOLES
PHASE III RECONNAISSANCE
13 DRILL & LITHOLOG
15 LOG TEMPERATURE
PHASE V DRILL & LOG TEMPERATURE GRADIENT HOLES
16 DETAILED STRUCTURAL MAPPING
19 DETAILED ELECTRICAL
PHASE VI TARGET DEFINITION
20 DEVELOP CONCEPTUAL MODELS
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22 PRODUCTION TEST & DRILLING
PHASE IX PRODUCTION TEST
23 DEVELOPMENT
PHASE X DEVELOPMENT
FOOTNOTES
1. WATER CHEMISTRY = GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES.
2. NO PHASE IV REQUIRED.
3. MODULE 2 EXTENDED IN CONCEPT RELATIVE TO FULL OPTION
LEGEND
REJECT PART OF AREA
12 SPLIT MODULE

Figure 5

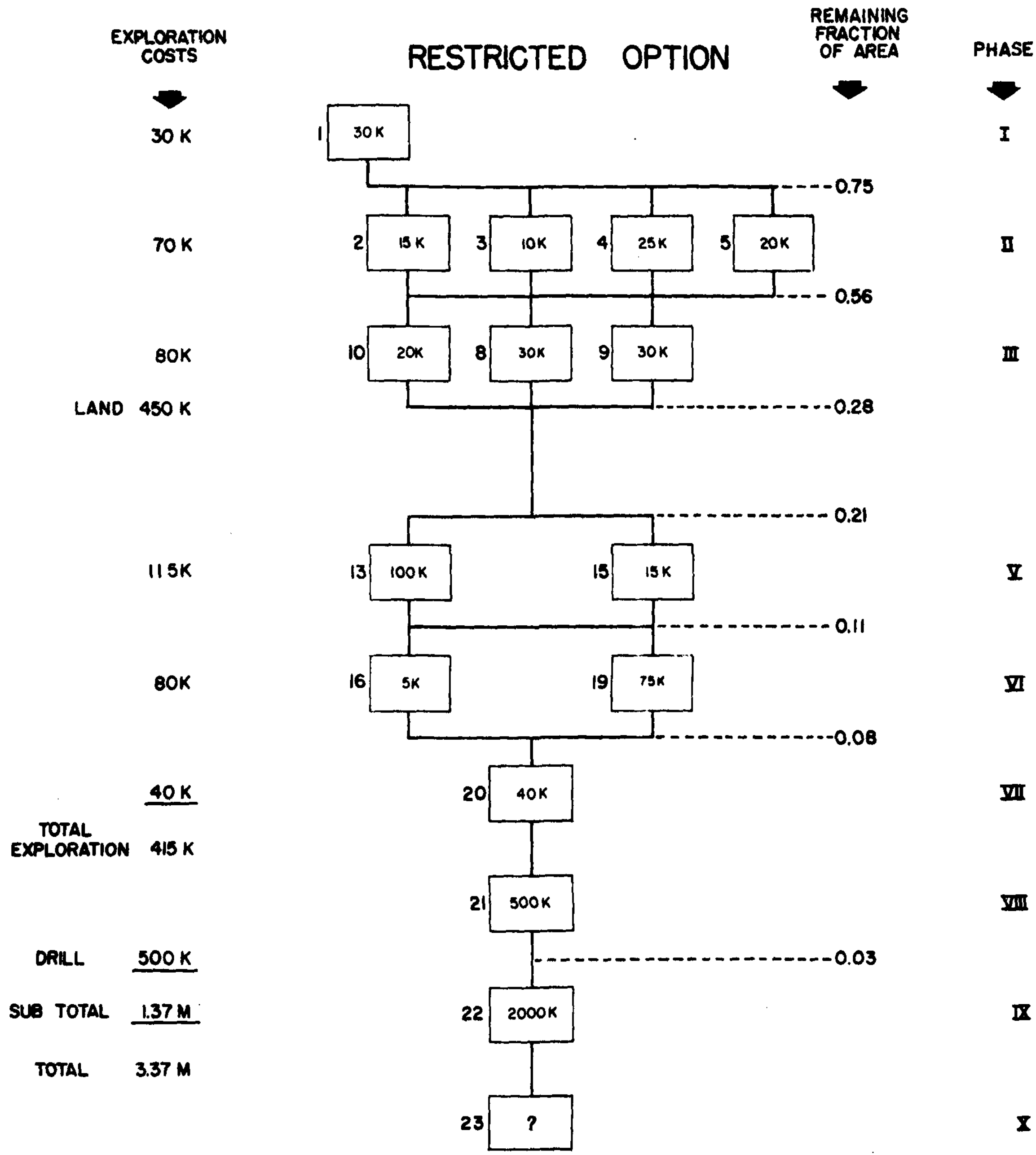
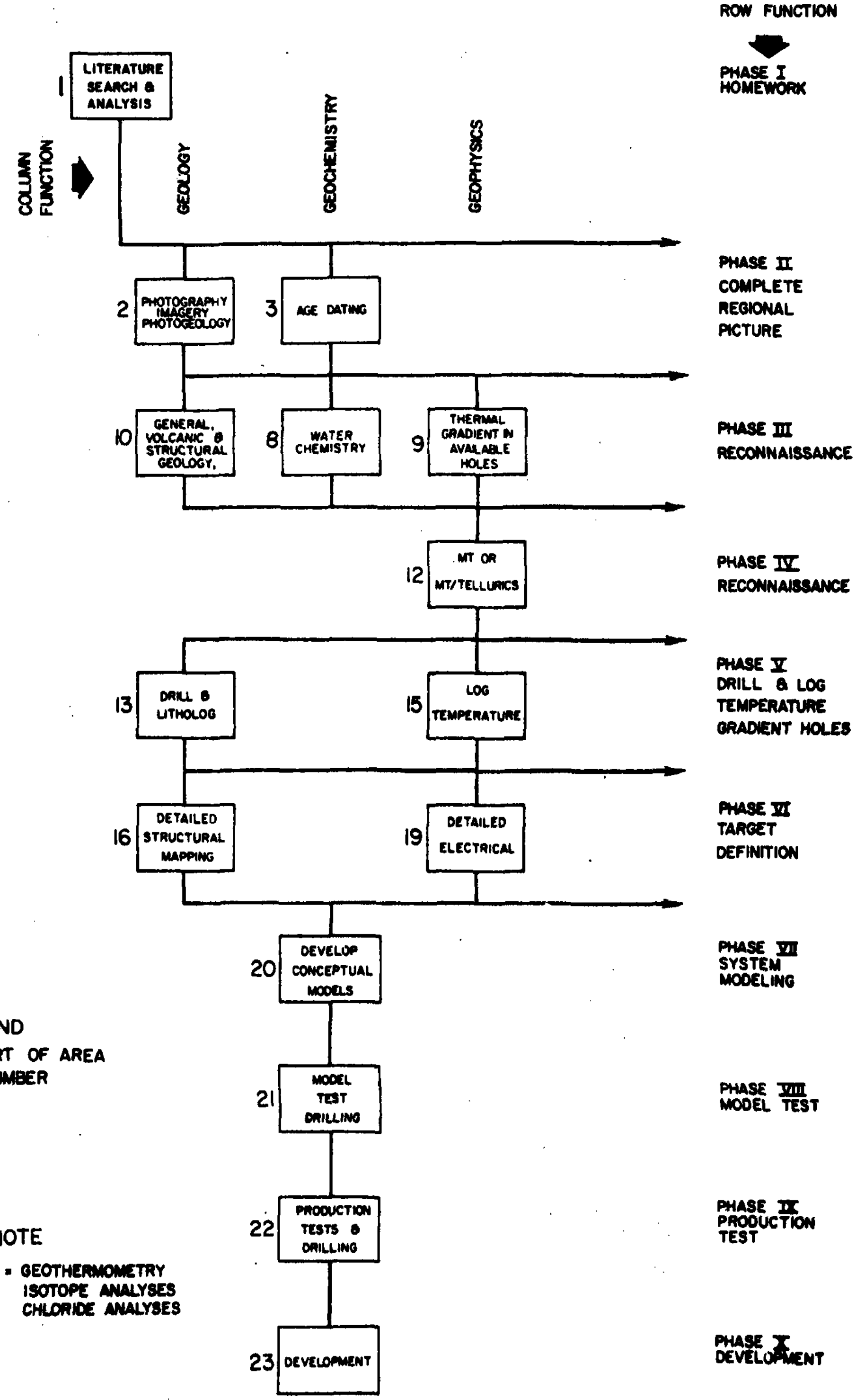

RESTRICTED OPTION
EXPLORATION COSTS
REMAINING FRACTION OF AREA
PHASE
30 K
1 30 K
I
0.75
70 K
2 15 K
3 10 K
4 25 K
5 20 K
II
0.56
80K
10 20K
8 30K
9 30K
III
LAND 450 K
0.28
0.21
115K
13 100K
15 15K
V
0.11
80K
16 5K
19 75K
VI
0.08
40 K
20 40K
VII
TOTAL EXPLORATION 415 K
21 500K
VIII
DRILL 500 K
0.03
SUB TOTAL 1.37 M
22 2000K
IX
TOTAL 3.37 M
23 ?
X

Figure 6

MT OPTION



LEGEND

→ REJECT PART OF AREA

12 MODULE NUMBER

FOOTNOTE

WATER CHEMISTRY = GEOTHERMOMETRY
ISOTOPE ANALYSES
CHLORIDE ANALYSES

Figure 7

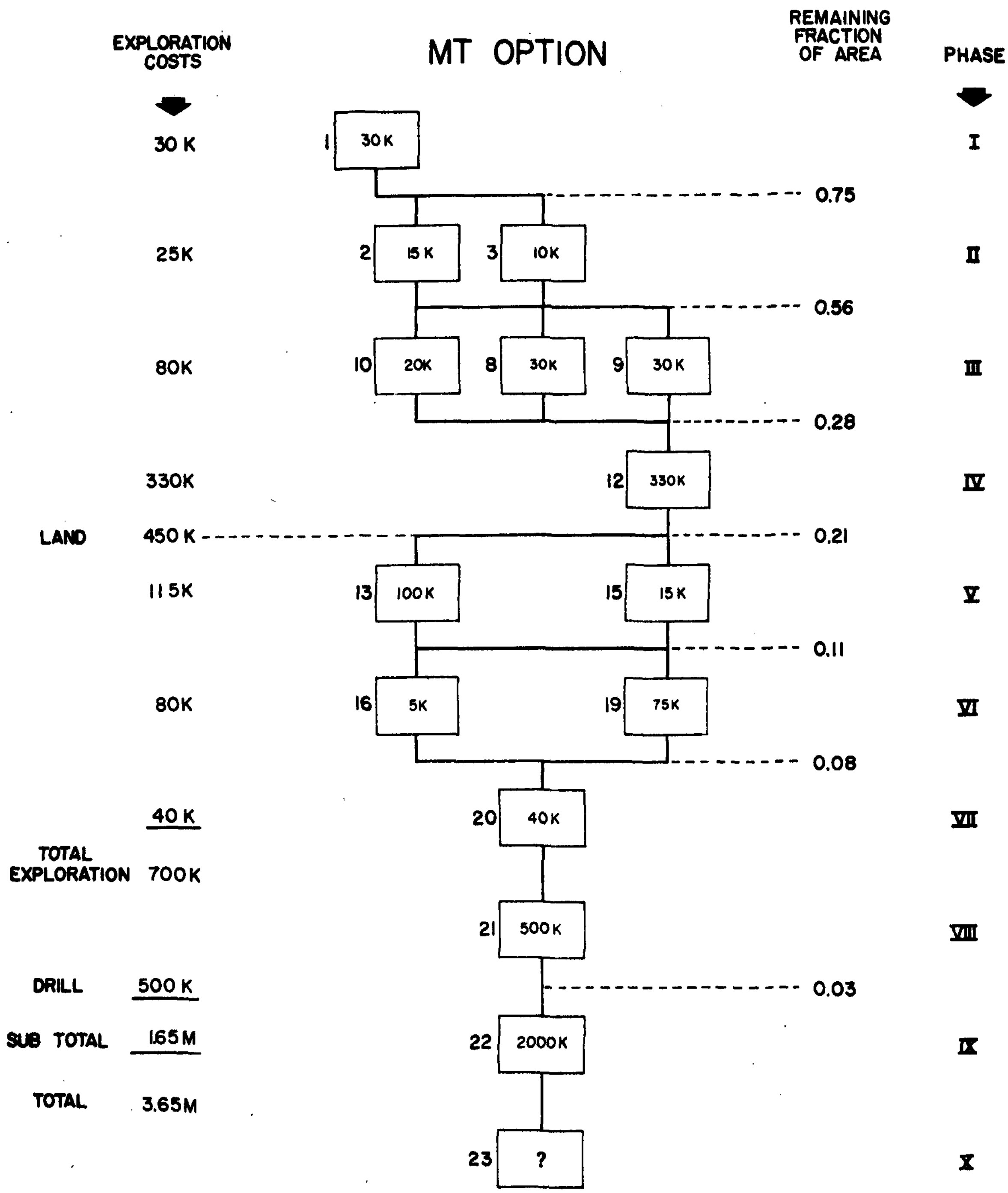

EXPLORATION COSTS
MT OPTION
REMAINING FRACTION OF AREA
PHASE
30 K
1 30 K
I
0.75
25K
2 15 K
3 10K
II
0.56
80K
10 20K
8 30K
9 30 K
III
0.28
330K
12 330K
IV
LAND 450 K
0.21
115K
13 100K
15 15K
V
0.11
80K
16 5K
19 75K
VI
0.08
40 K
20 40K
VII
TOTAL EXPLORATION 700K
21 500K
VIII
DRILL 500 K
0.03
SUB TOTAL 1.65M
22 2000K
IX
TOTAL 3.65M
23 ?
X

Figure 8

BANWELL OPTION

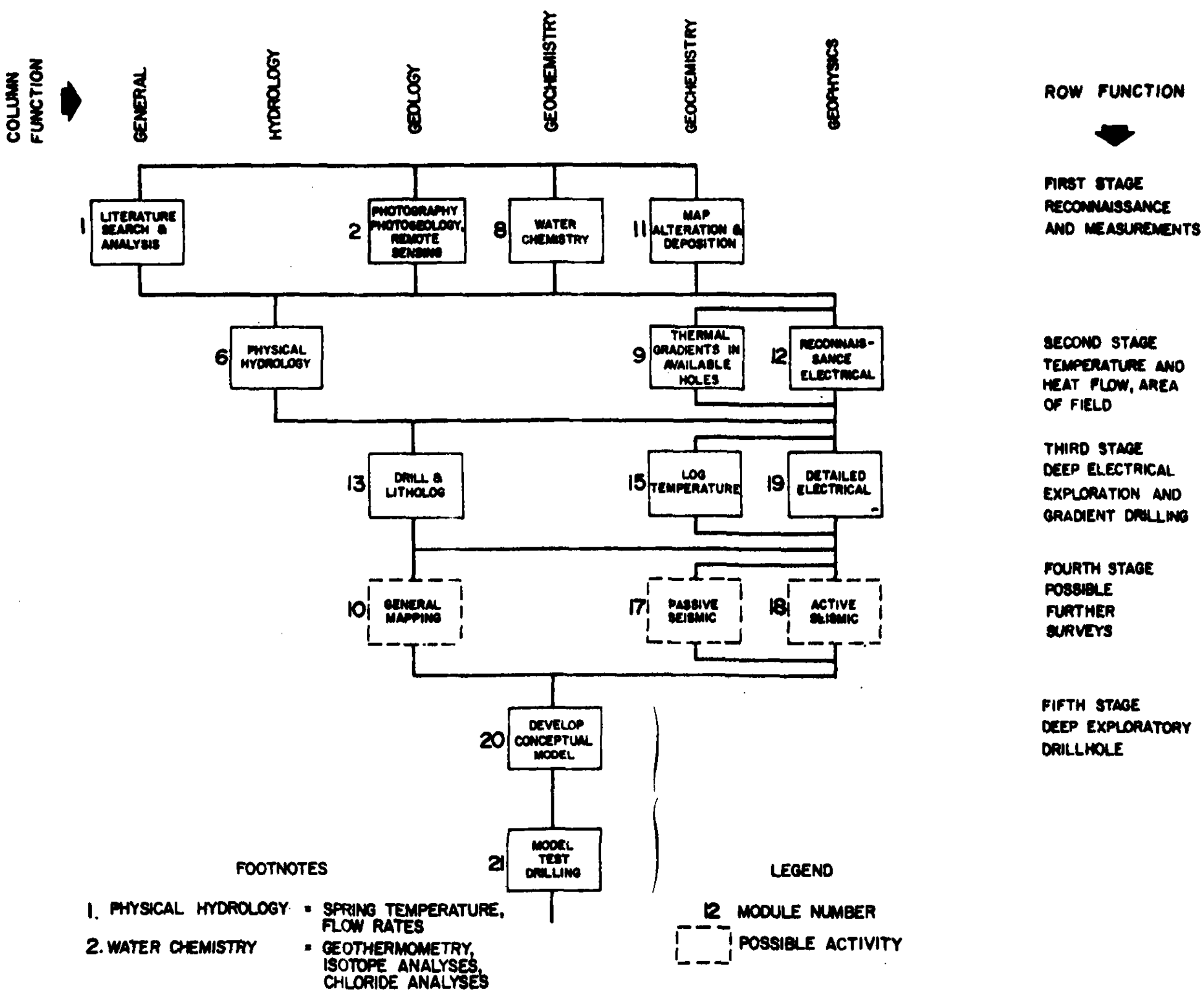


Figure 9

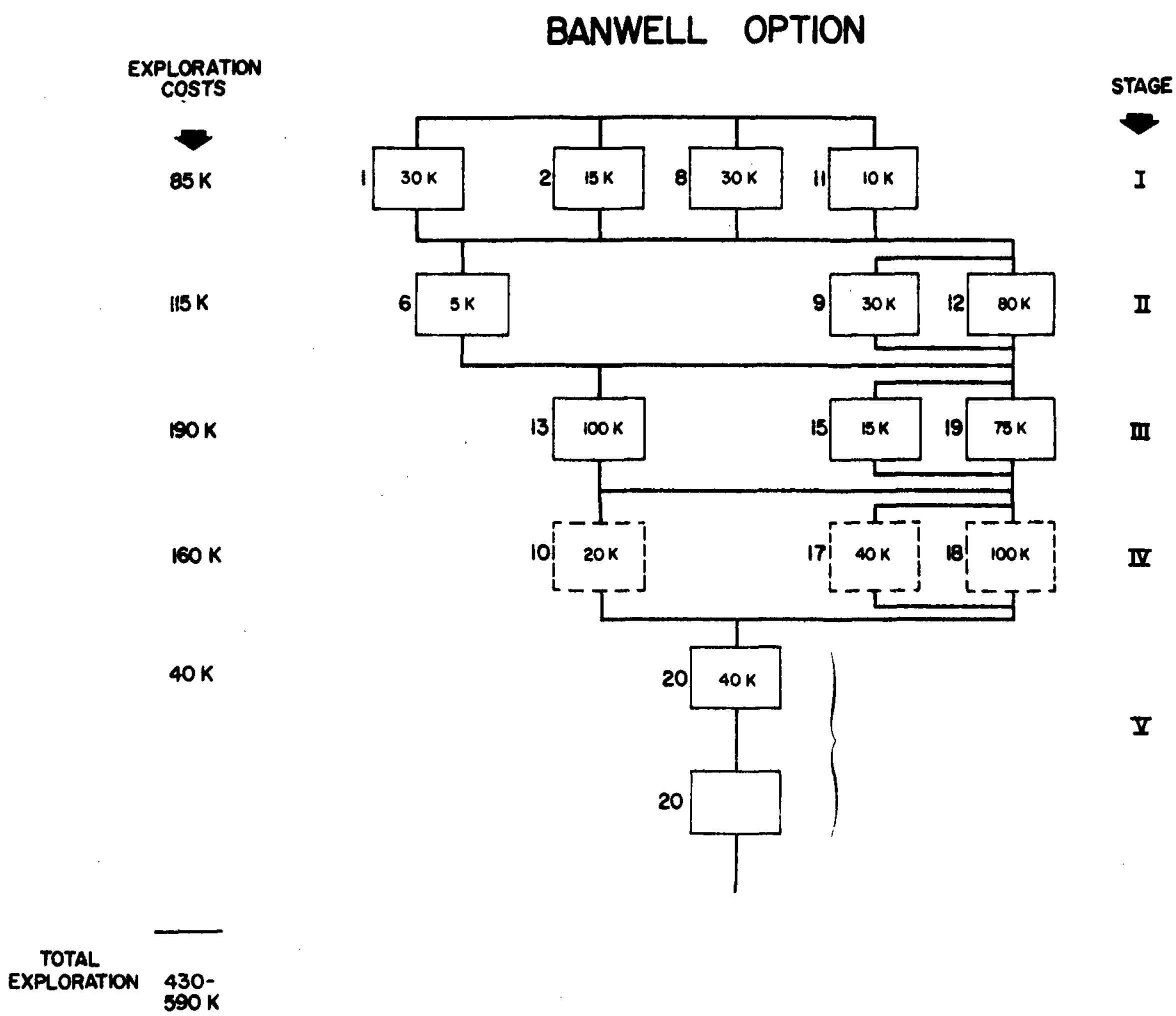

BANWELL OPTION
EXPLORATION COSTS
STAGE
85 K
1 30 K
2 15 K
8 30 K
11 10 K
I
115 K
6 5 K
9 30 K
12 80 K
II
190 K
13 100 K
15 15 K
19 75 K
III
160 K
10 20 K
17 40 K
18 100 K
IV
40 K
20 40 K
20
V
TOTAL EXPLORATION 430-590 K

Figure 10

COMBS AND MUFFLER OPTION

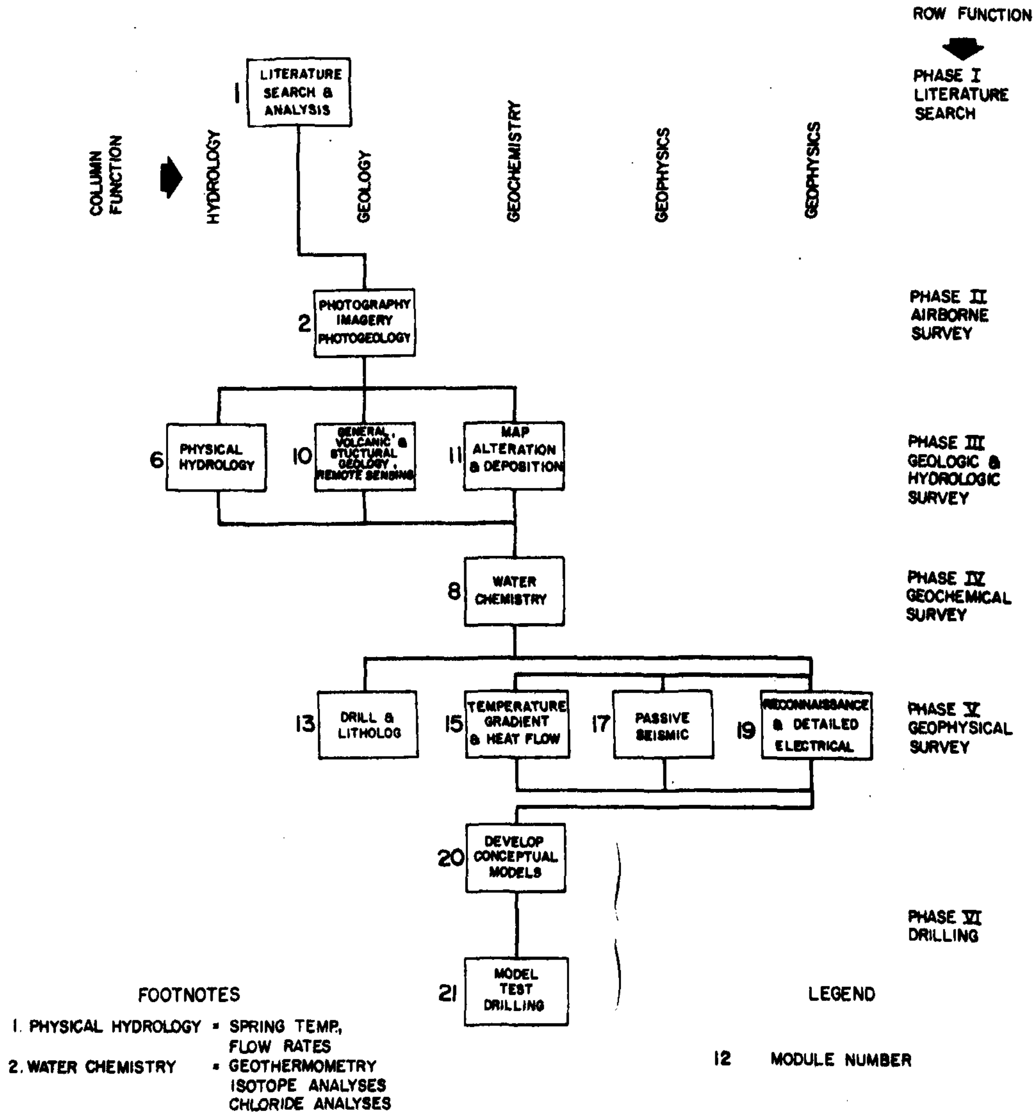


Figure 11

COMBS AND MUFFLER OPTION

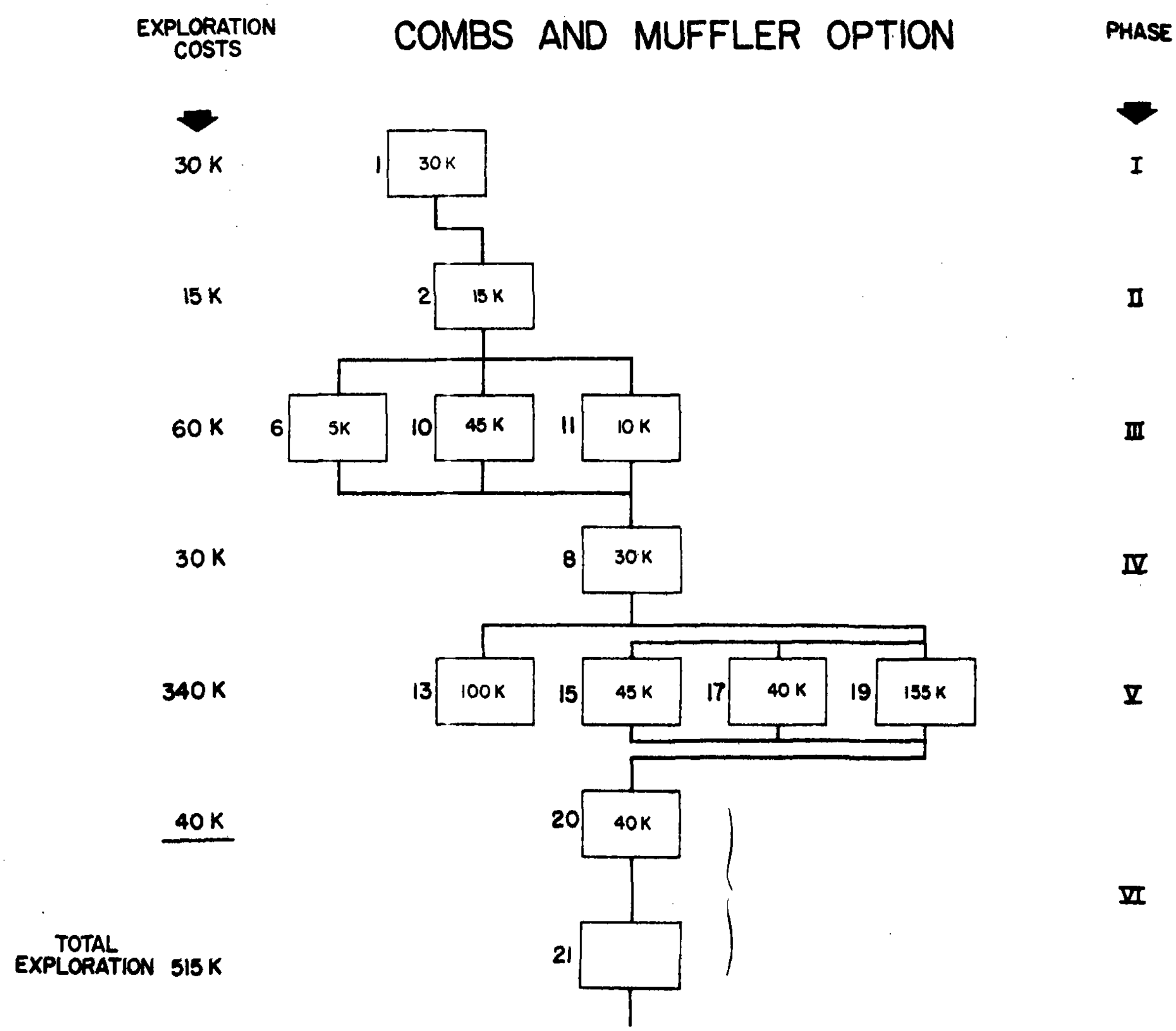
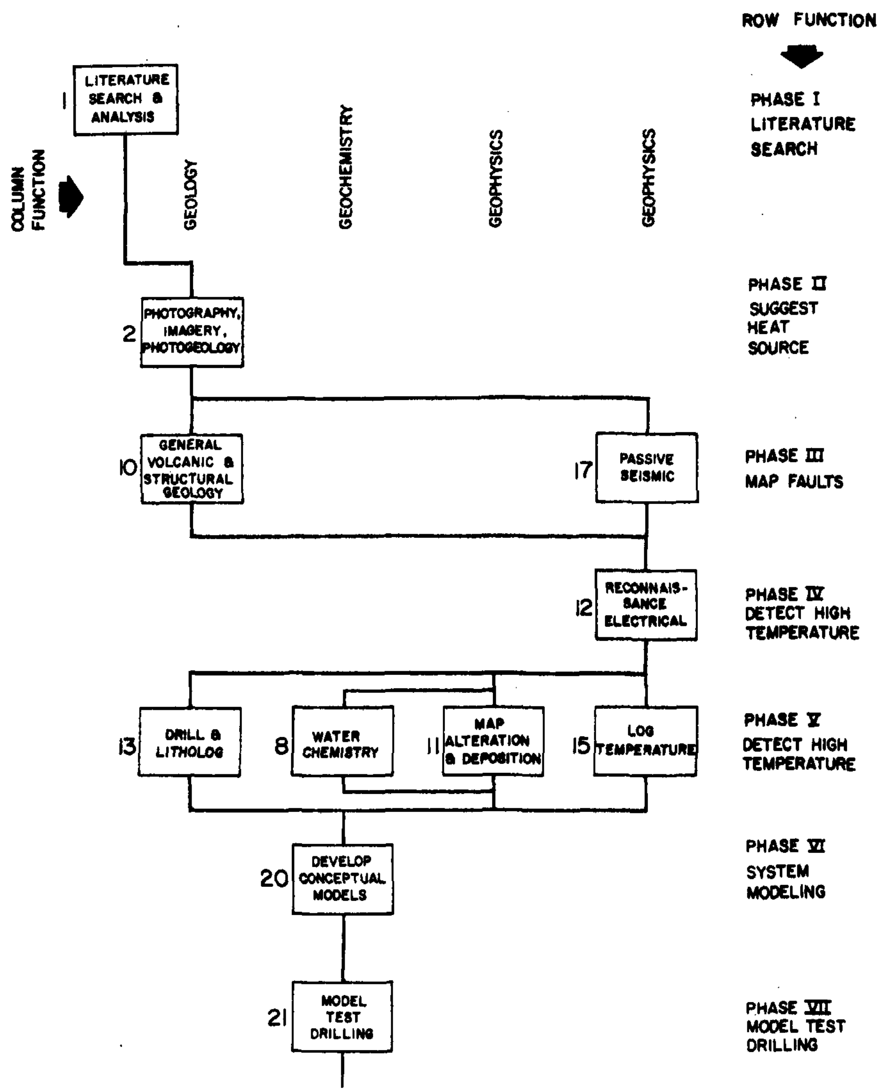


Figure 12

GREIDER OPTION



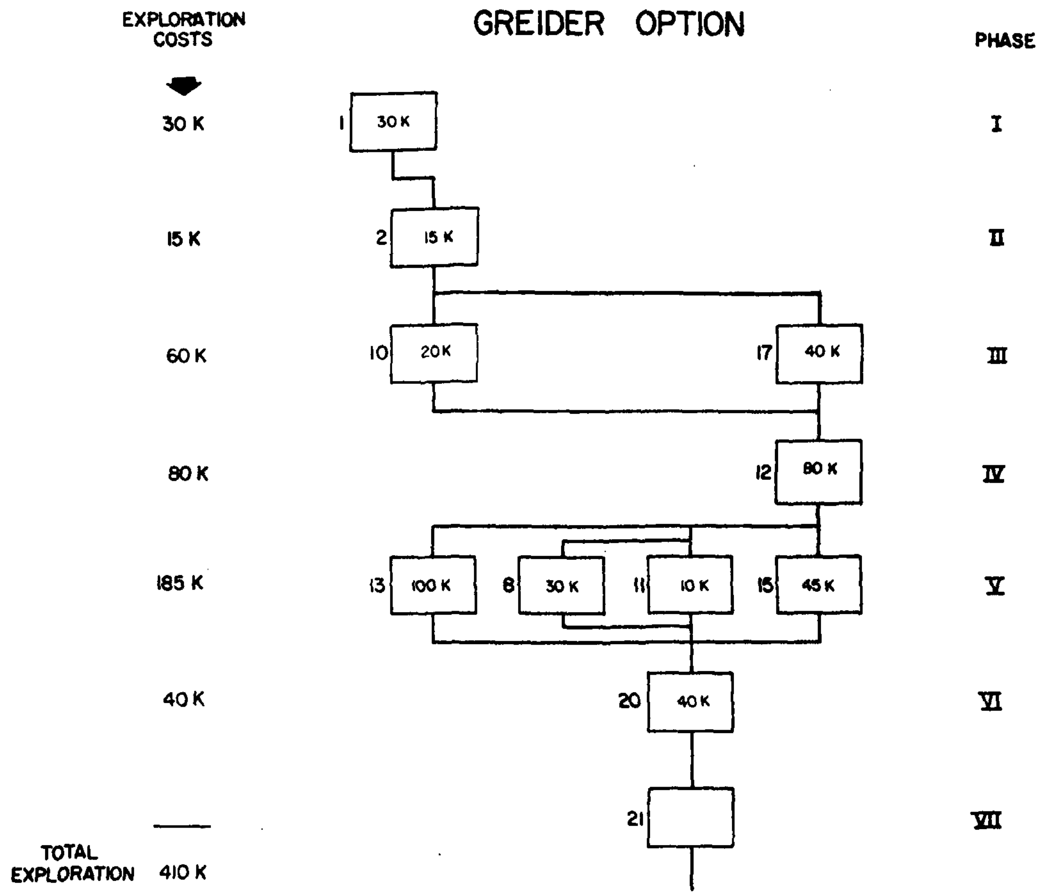
FOOTNOTE

1. WATER CHEMISTRY = GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES.

LEGEND

12 MODULE NUMBER

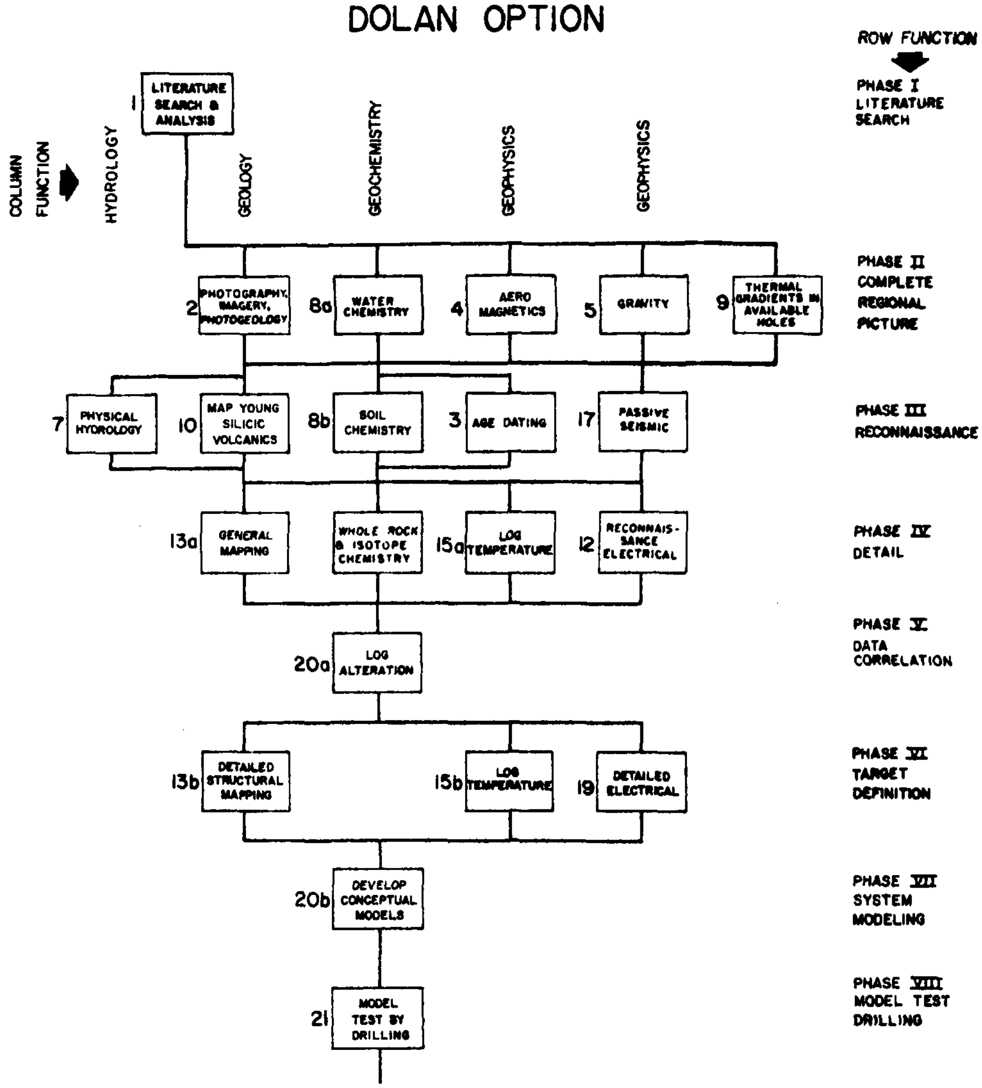
Figure 13



EXPLORATION COSTS
GREIDER OPTION
PHASE
30 K
1 30 K
I
15 K
2 15 K
II
60 K
10 20K
17 40 K
III
80 K
12 80 K
IV
185 K
13 100 K
8 30 K
11 10 K
15 45 K
V
40 K
20 40 K
VI
21
VII
TOTAL EXPLORATION 410 K

Figure 14

DOLAN OPTION



FOOTNOTES

1. WATER CHEMISTRY • GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES

LEGEND

12 MODULE NUMBER
12b SPLIT MODULE

Figure 15

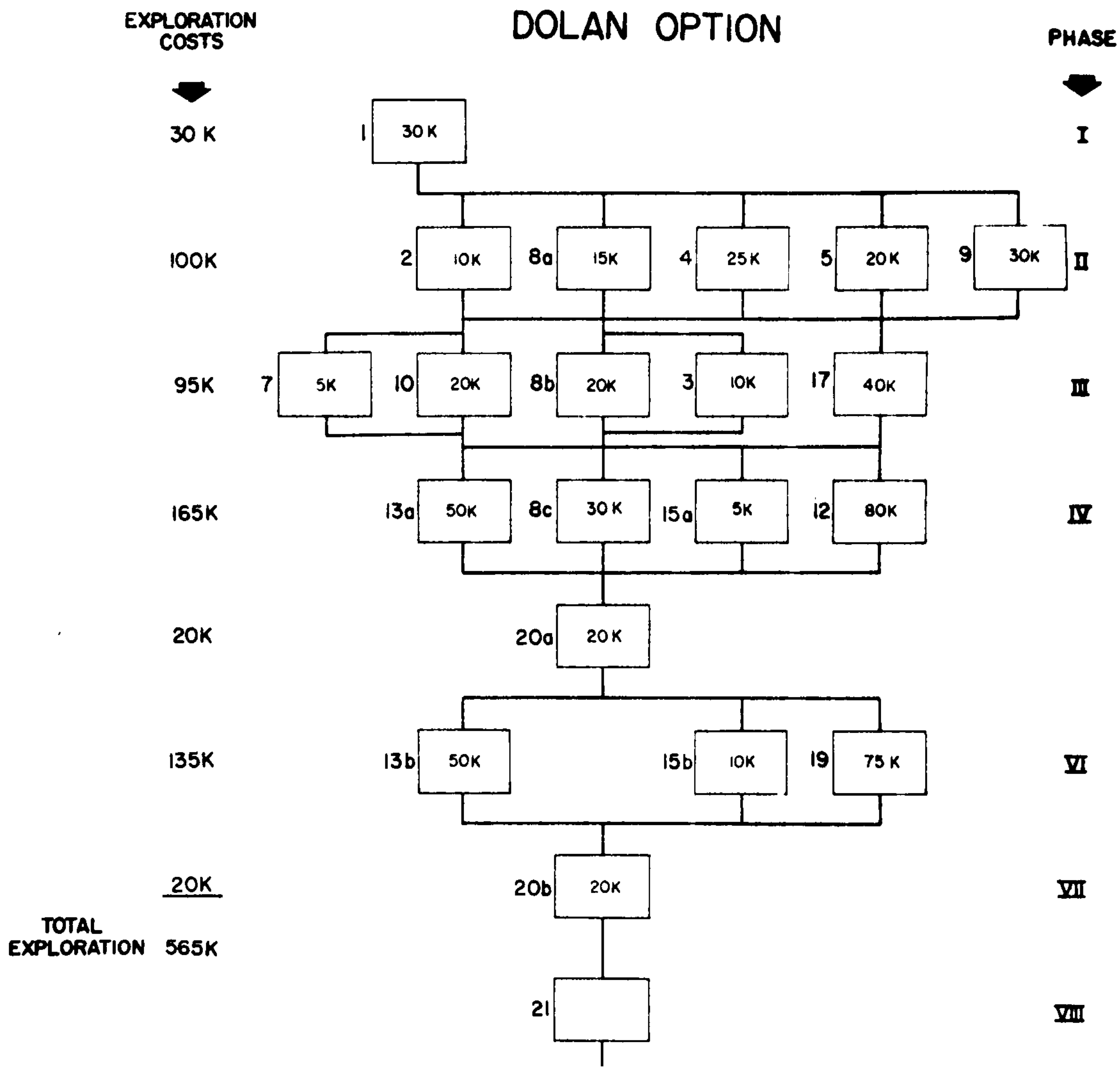
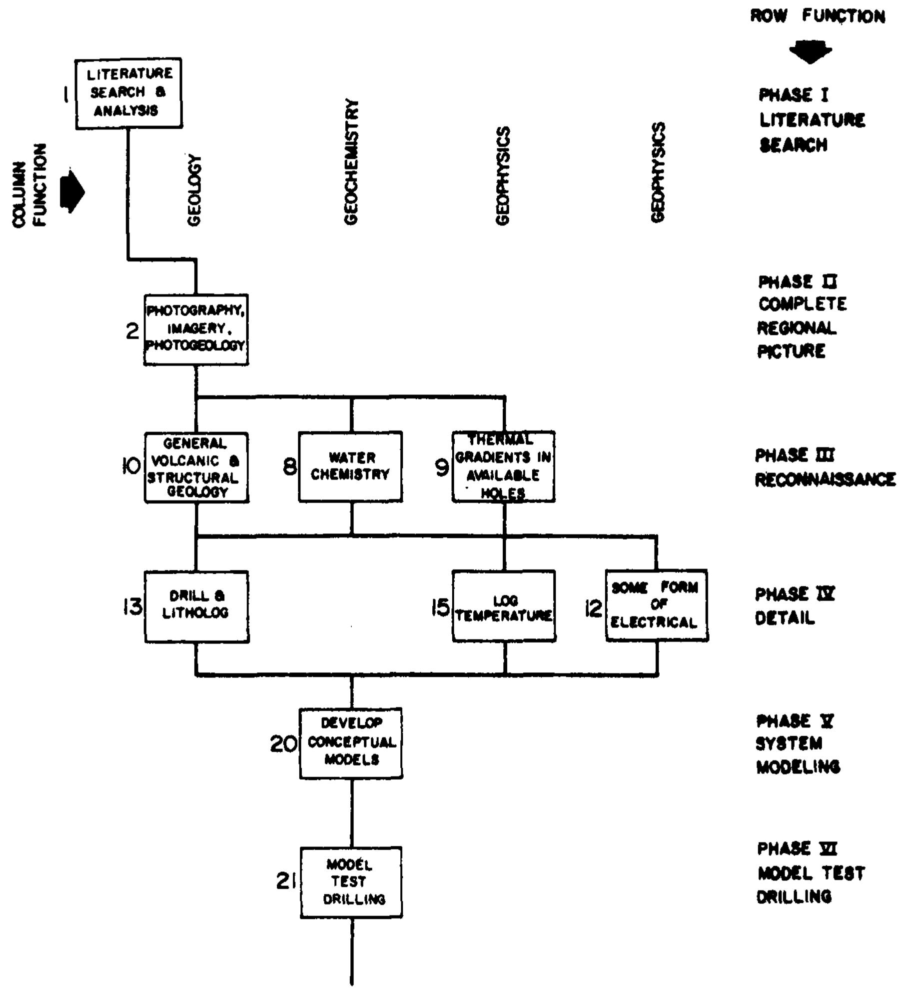

EXPLORATION COSTS
DOLAN OPTION
PHASE
30 K
1 30 K
I
100K
2 10K
8a 15K
4 25K
5 20K
9 30K
II
95K
7 5K
10 20K
8b 20K
3 10K
17 40K
III
165K
13a 50K
8c 30 K
15a 5K
12 80K
IV
20K
20a 20K
135K
13b 50K
15b 10K
19 75 K
VI
20K
20b 20K
VII
TOTAL EXPLORATION 565K
21
VIII

Figure 16

"COMPROMISE" OPTION



FOOTNOTE

1. WATER CHEMISTRY = GEOTHERMOMETRY, ISOTOPE ANALYSES, CHLORIDE ANALYSES.
2. ELECTRICAL IS RECONNAISSANCE, DETAILED OR BOTH, SPECIFIC METHOD NOT DEFINED.

LEGEND

12 MODULE NUMBER

Figure 17

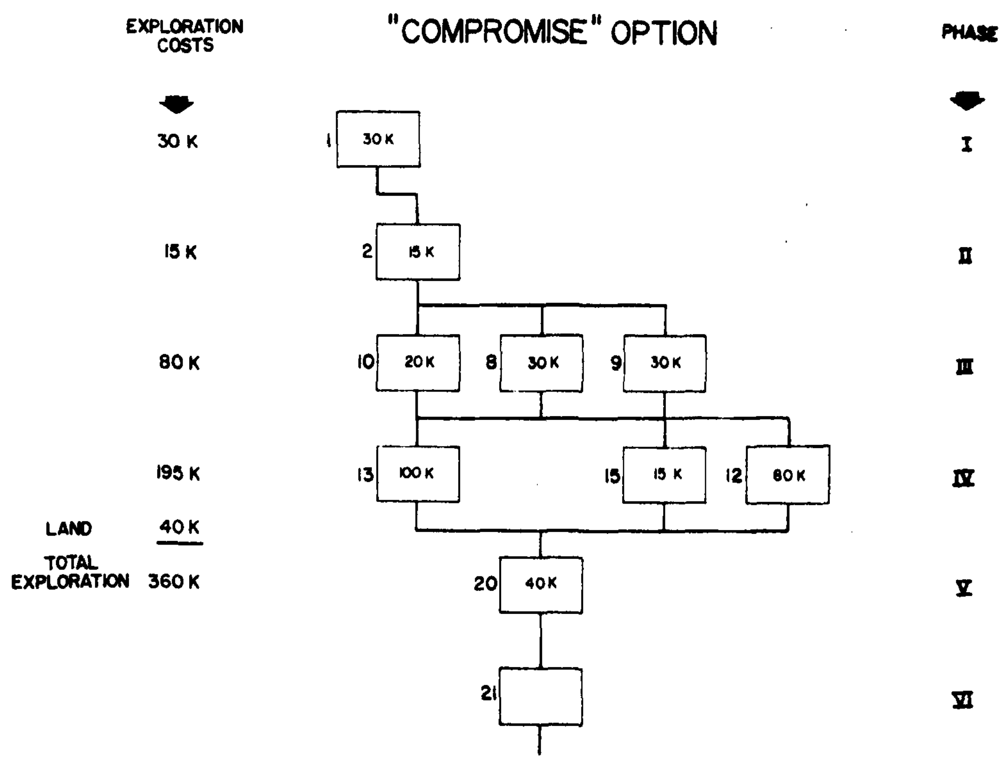

"COMPROMISE" OPTION
EXPLORATION COSTS
PHASE
30 K
1
30 K
I
15 K
2
15 K
II
80 K
10
20 K
8
30 K
9
30 K
III
195 K
13
100 K
15
15 K
12
80 K
IV
LAND
40 K
TOTAL EXPLORATION
360 K
20
40 K
V
21
VI

Figure 18