Proposal Submitted to

U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, California 94612

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108

TITLE: Research and Technology Development for DOE's Geothermal Reservoir Definition Program

TYPE OF REQUEST: Continuation of Present Contract

PERIOD OF THIS PROPOSAL: December 1, 1984 Through November 30, 1985

CO-INVESTIGATORS: J. N. Moore
D. L. Nielson
S. H. Ward

S. H. Ward
Stanley H. Ward, Director
Earth Science Laboratory
University of Utah Research Institute

Phillip M Wright
Phillip M. Wright
Technical Vice President
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November 12, 1984

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INTRODUCTION

The work proposed herein is, for the most part, a continuation of fruitful research directions that have been developed over the past year. The majority of the work is directed at delineating productive fractures and fracture systems in geothermal systems. We believe we have made significant progress over the past term of the present contract, but a great deal remains to be done.

SUMMARY OF ACCOMPLISHMENTS AND OVERVIEW OF PROPOSED RESEARCH

During the past contract year, UURI has accomplished a significant amount of research work. A brief summary of results is given in this section along with an indication of work proposed for next year.

Geologic Models of Fractured Geothermal Reservoirs

Our work at Baca has resulted in a structural model of this geothermal system that explains the distribution of observed fracturing. The resurgent doming has caused the upper part of the system to extend, a process that has opened fractures. However, the lower part of the system is in compression, and fractures are scarce. Fluids appear to be carried up from depth in only a few, through-going fractures. Studies of lithology and hydrothermal alteration have also proven fruitful. An alteration zoning pattern has been developed, and one primary conclusion from the alteration mineralogy is that the upper parts of the system are cooler now than they once were.

Additional work at Baca is warranted, and is proposed herein. We would like to study lithology and hydrothermal alteration in units below the Bandelier Tuff, and study possible zoning around some of the fluid entries there. Such studies would help refine our present system model. We would also like to begin application of similar work to other geothermal systems, such as Los Azufres.

We are joining Los Alamos in a joint proposal to OBES to extend the Baca work throughout the Valles caldera. The OBES proposal will include further drilling, and may eventually lead to a series of deeper holes sponsored by the Continental Scientific Drilling Program.

Geochemistry

Our work on drill chip samples donated to us by Union Geothermal from the

Salton Sea geothermal field has developed interesting results. We have shown that there are light hydrocarbons and other organic gases contained in fluid inclusions. Fluid inclusions are microscopic bubbles within mineral grains that are partly occupied by liquids and partly by gases at room temperature. They represent the hydrothermal fluid that formed the particular mineral. In addition to methane, ethane and propane, the Salton Sea fluid inclusions were found to contain both COS and CS_2, which have not been reported before in geothermal systems.

We have preliminary evidence of zoning of gases in the two wells studied. Our proposed research for the coming year would allow us to pursue zoning and other studies that may eventually lead to a better understanding of the chemical evolution of active geothermal systems.

Fracture Detection Using Borehole Electrical Geophysical Techniques

Our work has resulted in development of computer algorithms for modeling the expected electrical anomalies due to fractures in the wall rock beyond a borehole. Appropriate algorithms to do this have not been available before, so our developments have pushed the state of the art ahead measurably. We have modeled the following problems:

(1) Single borehole and cross-borehole resistivity,

(2) Borehole-to-surface resistivity,

(3) Borehole-to-surface and borehole-to-borehole mise-à-la-masse (the fracture itself is energized), and

(4) Surface-to-borehole time domain electromagnetics.

These modeling programs are currently being used to help select an optimum system for detecting fractures that could be implemented in the field. Their use has led to a potentially patentable field system that would deploy electrodes partly down a borehole and partly on the surface to measure a set of electrical data that would give redundant indications of fractures in the wall of a wellbore, and thereby increase confidence in interpretation.

During the coming year, we would like to pursue development of such a surveying system. We would also like to have a more detailed look at several additional electrical techniques that funds were inadequate to study last year.

PROJECT 1

DEVELOPMENT OF GEOLOGIC MODELS OF FRACTURED GEOTHERMAL RESERVOIRS

Cost: $68,035

Background

To date, our work on formulation of geologic models of fractured geothermal reservoirs has concentrated on the extensive subsurface data available from the Baca geothermal system in the Valles caldera, New Mexico. The Baca area is located in the center of the Redondo Dome, the resurgent dome of the Valles caldera. Modeling of the development of this feature has allowed us to predict the depth to the magma body which produced the doming. It has also allowed us to predict the stress environment and resultant fracturing which controls the convection and advection of geothermal fluids. Simply speaking, the formation of the dome produced an area of fracturing related to extension in the upper portion of the structure. This fracturing extends approximately halfway from the surface to the underlying intrusive body. Beneath this zone of extension, compressive stress has resulted in rock of relatively lower permeability and no known fluid entries. An important control on fracture permeability is contributed by the Jemez fault zone, which is an older, reactivated structure. We believe that this fault in fact controls the deep circulation of geothermal fluids and is thus the most important exploration target in the field. To this time, it has not been properly tested by drilling.

Examination and analysis of cuttings and core have revealed a well-defined pattern of hydrothermal alteration in caldera-related felsic volcanics and sediments as well as underlying pre-caldera rocks. The mineralogy and distribution of alteration relative to the active geothermal system can be used to help locate fluid-flow channels and to provide insight into the system's thermal history.

Alteration in the Baca field, from the surface through the base of the Pliocene Paliza Canyon Formation (an interval averaging about 2200 meters in thickness and encompassing all documented thermal fluid entries) can be discussed conveniently in terms of three distinct types: argillic, propylitic and phyllic. Argillic alteration forms a high-level blanket developed principally in formerly permeable, mostly non-welded felsic Quaternary tuffs of post-Bandelier Tuff age. This alteration is characterized by the assemblage smectite, mixed-layer illite-smectite (ordered), quartz and pyrite.

Beneath the argillic zone, the Bandelier Tuff, up to 1800 meters in thickness, the subjacent Lower Tuffs and the underlying Paliza Canyon Formation are pervasively propylitized. In the thick, densely welded Bandelier, propylitization is very weak. In the underlying, poorly welded Lower Tuffs, intensity of propylitization is weak overall but locally moderate, reflecting greater initial permeability. Strong propylitization is confined to the relatively reactive intermediate-composition volcanics of the Paliza Canyon Formation in which the alteration may partially pre-date the active geothermal system.

Within the propylitic zone, active thermal fluid channels, whether faults or restricted stratigraphic aquifers, are commonly but not invariably associated with intense phyllic alteration. Sericite (or micaceous illite), quartz and pyrite are the principal constituents of these phyllic zones; chlorite, calcite and potassium feldspar are locally present. Results of alteration studies in Baca-18 show a phyllic assemblage characteristic of thermal fluid production in nearby wells. However, the alteration has been complete enough that the zone has been completely sealed. At present, we cannot distinguish between zones which sustain production and those which have been effectively sealed by the alteration process.

The distribution of several alteration phases in the Baca wells indicates that relatively cool rocks at high levels in the geothermal system have been hotter in the past. For example, ordered, mixed-layer illite-smectites, believed to form at temperatures exceeding about 100°C, are presently found in near-surface Baca rocks at temperatures as low as 30°C. This relationship indicates either that isotherms have collapsed due to cooling of the system, that they have retreated without overall heat loss due to structural uplift, or that the system has shifted laterally.

Our work to this time has identified three types of permeable conduits in the Baca geothermal system. These can be categorized as follows:

1. Former fluid channels sealed by alteration. These include both stratigraphically and structurally controlled fluid entries;
2. Open conduits which do not produce geothermal fluids. Again, these are both stratigraphic and structural intervals and are characterized as lost circulation zones. These permeable zones do not communicate with the reactivated fault zones which are thought to be the principal fluid conduits in the system;
3. Geothermal production zones. All commercial production zones apparently are structurally controlled while subcommercial zones are controlled by both structures and stratigraphic intervals.

The processes investigated here are similar to those in other geothermal systems. We propose to continue studying the processes at Baca and take advantage of samples available from other fracture-controlled systems. These other systems include Los Azufres, Mexico; Coso, California; Wendel-Amedee, California; Yellowstone National Park, Wyoming, and Ascension Island, South

Atlantic Ocean. In addition, appropriate samples may become available through DOE's Cascades drilling program.

Publications

The following publications have been produced as a part of this project to date.

Hulen, J. B., and Nielson, D. L., 1982, Stratigraphic permeability in the Baca geothermal system, Redondo Creek area, Valles caldera, New Mexico: Geothermal Resources Council Transactions, v. 6, p. 27-30.

Hulen, J. B., and Nielson, D. L., 1983, Stratigraphy of the Bandelier Tuff and characterization of high-level clay alteration in borehole B-20, Redondo Creek area, Valles caldera, New Mexico: Geothermal Resources Council Transactions, v. 7, p. 163-168.

Hulen, J. B., and Nielson, D. L., in preparation, Hydrothermal alteration in the upper portion of the Valles caldera, New Mexico: Journal of Geophysical Research, Special Volume on the Valles caldera.

Nielson, D. L., and Hulen, J. B., 1983, Geologic model of the Baca geothermal reservoir, Valles caldera, New Mexico: Proceedings Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, p. 145-150.

Nielson, D. L., and Hulen, J. B., 1984, Internal geology and evolution of the Redondo Dome, Valles caldera, New Mexico: Jour. Geophys. Research Special volume on calderas and associated igneous rocks, v. 89, p. 8695-8711.

Nielson, D. L., and Hulen, J. B., 1984, Results of deep drilling in the Valles caldera, New Mexico (abstract): Invited paper, International Symposium on Continental Drilling, Tarrytown, N.Y.

Nielson, D. L., and Hulen, J. B., in press, Observations in an active hydrothermal system through deep drilling: Valles caldera, New Mexico: Columbia University Press, International Symposium on Observation of the Continental Crust Through Drilling.

Scope of Work

1.1 Lithology and Alteration at Baca. We will determine the details of the lithologies and alteration mineralogy of the units beneath the Bandelier Tuff in the Baca project area. The Paliza Canyon Formation contains several important fluid entries which have not been characterized at this time.

1.2 Refine Models. These data will be used to refine our models of the development and preservation of fracture permeability.

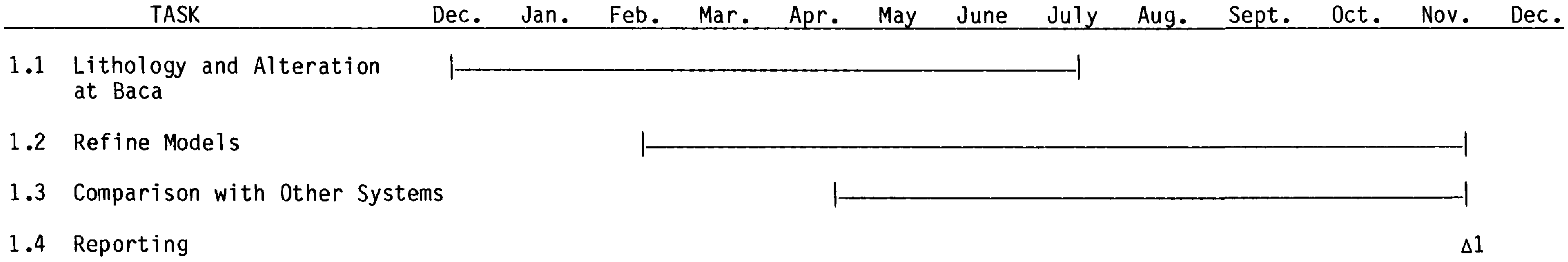
1.3 Comparison with Other Systems. As appropriate, these data will be compared with other fracture controlled geothermal systems.

1.4 Reporting. The results of our findings will be presented at a professional meeting and a report will be prepared which will be submitted for publication in a professional journal.

1. DEVELOPMENT OF GEOLOGIC MODELS OF FRACTURED GEOTHERMAL RESERVOIRS

SCHEDULE AND DELIVERABLES

FY 1985



Deliverables

1. Technical report or journal publication

DEVELOPMENT OF GEOLOGIC MODELS OF FRACTURED GEOTHERMAL RESERVOIRS

BUDGET

	Days		Amount
A. Salaries and Wages:			
1. Senior Personnel		$20,753	
J. B. Hulen	90		
D. L. Nielson	46		
2. Other Personnel		1,824	
Staff Analyst	5		
Draftsperson	10		
Secretary	10		
Total Salaries and Wages			$22,577
B. Employee Benefits:			
1. .39 of A.1 & A.2			8,805
C. Permanent Equipment:			-0-
D. Expendable Supplies and Equipment:			
1. Drafting Supplies		$ 250	
2. Office Supplies		125	
Total Expendable Supplies and Equipment			375
E. Travel:			
1. Trips to Los Alamos (2)			1,620
F. Reports and Publications:			
1. Printing, Binding and Distribution Costs			475
G. Data Processing:			
1. PRIME 400			500
H. Other Costs:			
1. X-ray Analyses		$4,200	
2. Geochemical Analyses		1,500	
Total Other Costs			5,700

I.	Total Direct Costs:	$40,052
J.	Indirect Costs:	
	1. .45 of "I"	18,023
K.	General and Administrative Costs:	
	1. .145 of "I"	5,808
L.	Total Direct, Indirect and G & A Costs:	$63,883
M.	Fee:	
	1. .065 of "L"	4,152
N.	Total Project Costs:	$68,035

PROJECT 2

GEOCHEMICAL STUDIES OF DRILL CHIP SAMPLES FROM GEOTHERMAL AREAS

Costs: Project Work: \$67,210 Equipment: \$14,900

Background

Gases are important components of geothermal fluids and may exert considerable influence on both the fluid's behavior and the formation of secondary minerals. Analyses of fluid samples discharged from deep geothermal wells have revealed widely variable gas contents and compositions. CO_2 and H_2S are the predominant gases in most hot water- and vapor-dominated geothermal systems (Ellis, 1979). However, hydrocarbons (mainly CH_4), H_2S, NH_3, N_2, and H_2 may be significant, particularly in sedimentary terrains (Ellis, 1979).

Minor concentrations of other hydrocarbons and sulfur compounds have also recently been identified in geothermal waters. Long chain hydrocarbons, including a variety of normal and branched alkanes, alkenes, and cyclic compounds have been found in geothermal systems associated with sedimentary and volcanic rocks (Stoiber et al., 1971; Gunter, 1978; Ellis, 1979; Nehring and Truesdell, 1979; Nehring et al., 1982). In addition, our data suggest that gases in the sub-system C-O-S, including SO_2, COS and CS_2, may be present and locally abundant in some geothermal fluids (Adams and Moore, in prep.). However, detailed investigations on the occurrence, origin and behavior of these minor gases in geothermal systems are lacking.

Current Research

Our interest in the gas contents of geothermal fluids developed as a result of our studies on fluid-mineral equilibria and trace element distributions in active geothermal systems (Capuano and Cole, 1982; Christensen et al., 1983; Moore et al., 1983). These investigations, as well as those by Gutierrez and Aumonto (1982) at Los Azufres and McKibben (1979) at the Salton Sea, among others, provide abundant evidence that the compositions of the geothermal fluids in many active systems must have varied widely during their evolution. The composition of the paleogeothermal fluids can be estimated indirectly from the hydrothermal minerals through the application of activity diagrams (Helgason, 1967; Bird et al., 1984) or directly from analyses of the solutions trapped within fluid inclusions during alteration (Roedder, 1972). Although thermometric measurements have been made on fluid inclusions from active geothermal systems, chemical analyses of the solutions contained within them are lacking. The need to obtain detailed information on the fluid compositions during alteration, and a better understanding of gas distributions in geothermal fluids in general prompted us to sample two wells in the Salton Sea geothermal field drilled by the Union Oil Company. These wells penetrate a thick sequence of increasingly indurated deltaic sediments. Our petrographic observations indicate that the reservoir rocks have had a relatively simple thermal history and that temperatures near the base of the wells must have exceeded 225-250°C during alteration.

Fluid inclusions in samples of the drill chips were thermally decrepitated at temperature of 375°C and analyzed by a combined gas chromatograph/mass spectrometer. CO_2 was the most abundant gas found, comprising from 36 to 97 mole percent of the total gas. The remaining gases include COS, CS_2, H_2S, SO_2 and the aliphatic hydrocarbons, methane, ethane, and propane. The presence of COS and CS_2 is particularly interesting because these gases have not been reported from other geothermal systems. Both COS and CS_2 have, however, been identified in soil gases collected over fossil hydrothermal deposits and appear to result from weathering of sulfides (Gardner et al., 1984). Their presence in the Salton Sea samples suggests that these gases may also form where hot waters contact organic-rich sedimentary rock. Unsaturated hydrocarbons and NH_3 were not detected. The compositions of the gases in terms of their molecular proportions are presented in Table 1.

Despite the overall similarities in the alteration patterns in the two wells, the gas compositions indicate that the fluid chemistries varied both within and between the wells. In well A carbon and sulfur vary inversely (Table 1) while the total carbon content increases with increasing total gas, suggesting that at least two populations of inclusions are present. The two populations can be distinguished on the basis of $\Sigma C/\Sigma S$ ratios. In contrast, carbon and sulfur vary proportionally in well B and the gases contain H_2S, indicating that different fluids or a third fluid was involved in the alteration here.

Figures 1a and 1b summarize the distribution of hydrocarbons in the two wells. A significant feature of these data is the relatively low ratio of methane to the total hydrocarbon concentration in well A. These data are at variance with the "usual" hydrocarbon ratios of both geothermal steam (Ellis, 1979) and naturally occurring hydrothermal solutions. Fluid inclusions have been analyzed for hydrocarbons in volcanic (Petersil'ye and Pavlova, 1976; Sommer, 1974), igneous (Konnerup-Madsen et al., 1979; Andreeva and Molchanov, 1978), and metamorphic rocks (Voytov et al., 1971), and in hydrothermal quartz (Murray, 1957; Naumov et al., 1976; Kvenvolden and Roedder, 1971). These studies have shown that methane is the dominant hydrocarbon and that the hydrocarbons were produced by reduction of CO_2 and pyrolysis of methane rather than by degradation of organic matter. While the reasons for the low methane ratios in the Salton Sea samples are not yet clear, the consistency of our data suggests that they are not simply a result of analytic errors or gas

TABLE 1

WELL A - MOLECULAR FRACTIONS OF TOTAL GAS

($x\ 10^{-3}$)

Depth	CS_2	SO_2	COS	H_2S	C_1	C_2	C_3	CO_2
790-820	12	108	15	0	59	48	96	364
820-850	371	0.2	0	0	89	50	83	408
1120-1150	17	43	0	0	94	150	246	449
1180-1210	26	66	0	0	50	116	105	638
2000-2020	28	28	0	0	42	270	178	454
2020-2040	16	6	4	0	111	167	75	620
2220-2240	35	51	0	0	64	208	122	527
3160-3180	40	164	29	0	24	43	40	660
3200-3220	43	22	0	0	86	194	184	472
3440-3460	26	164	0	0	26	126	120	538
3900-3920	36	133	22	0	2	21	16	770
3920-3940	30	85	23	0	60	91	120	581
4060-4080	13	55	24	0	20	118	103	667
4160-4180	31	53	15	0	58	166	135	542
4520-4540	7	123	31	0	148	211	144	337
4660-4680	17	54	15	0	16	152	150	537
4960-4980	18	35	16	0	82	136	118	594
5100-5120	58	54	0	0	8	80	55	746

WELL B - MOLECULAR FRACTIONS OF TOTAL GAS

($x\ 10^{-3}$)

Depth	CS_2	SO_2	COS	H_2S	C_1	C_2	C_3	CO_2
100-130	1	1	0	23	39	7	17	912
560-610	2	0	0	0	37	7	69	885
790-820	0	0	0	0	0	0	13	987
910-940	0	442	0	0	0	0	205	353
1060-1090	67	1	12	0	28	15	12	65
1060-1090	70	1	13	0	2	0.2	1	910
1360-1390	22	0	3	2	30	2	18	923
1660-1690	0	0	0	0	296	70	240	390
1960-1990	49	15	11	0	0	19	9	897
2380-2410	0	148	0	0	59	110	22	660
2590-2620	15	0	3	2	11	1	3	966
2740-2770	44	51	19	0	3	10	66	859
2890-2920	12	7	12	12	8	40	46	864
3010-3040	86	23	164	134	17	88	107	381
3190-3220	0	0	0	0	159	42	58	742
3400-3420	21	28	19	0	2	12	14	903
3600-3660	105	14	3	0	79	2	32	164
3820-3840	42	14	17	0	0	21	10	896
3940-3960	15	50	30	43	1	12	11	841
4220-4240	16	73	12	0	0	6	0	945

WELL A

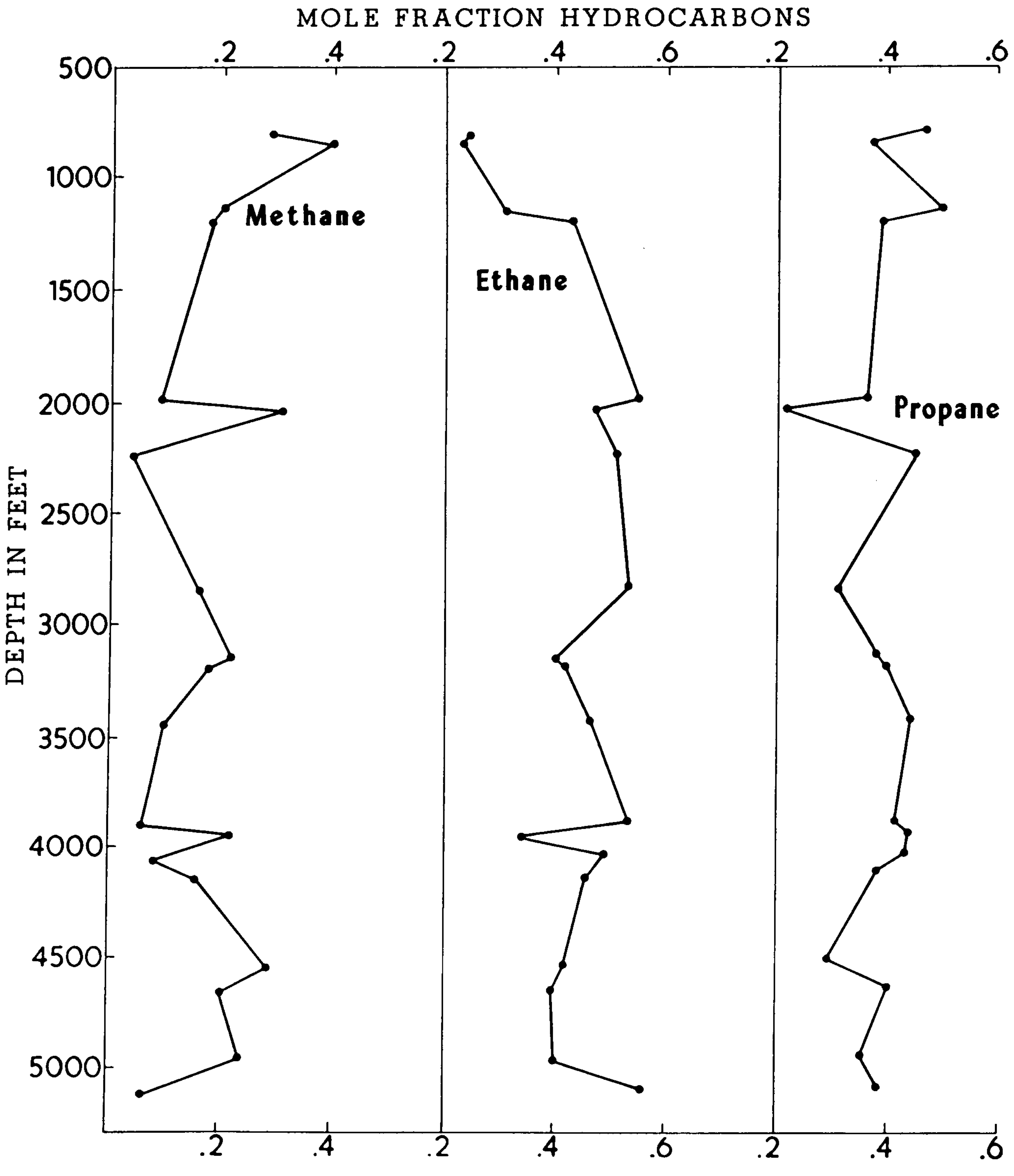


Figure 1a

WELL B

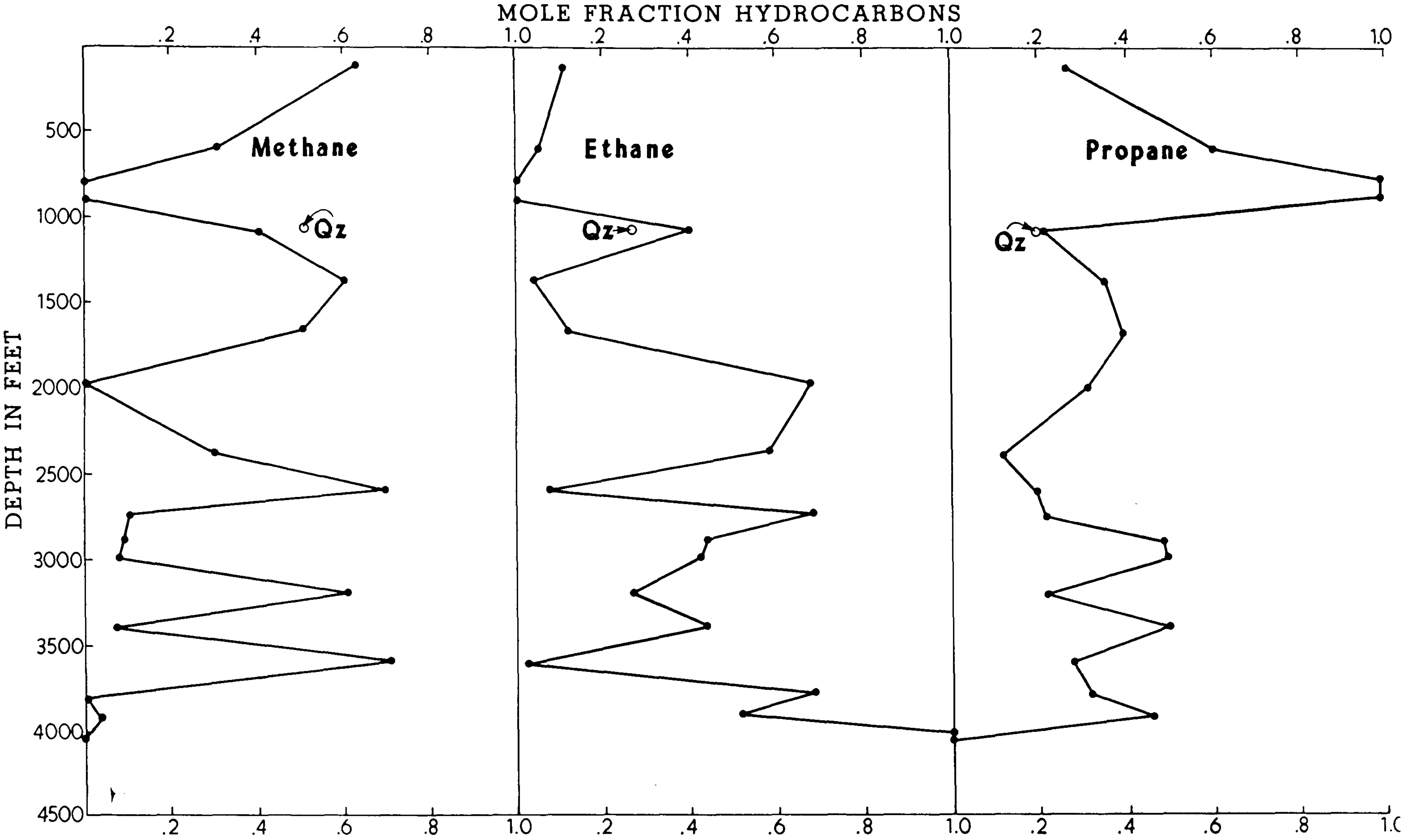


Figure 1b

loss. We are currently investigating other possibilities.

Proposed Research

The data we have collected to date indicate that fluid inclusion studies do indeed offer a promising approach to unraveling the chemical evolution of active geothermal systems. These data, however, also emphasize the need for detailed microscopic studies of the inclusions in the altered rocks as well as a better understanding of the relationship between gas chemistry, temperature, mineralogy, abundance and maturation of organic material and fluid chemistry.

The investigations proposed here are directed toward this goal and will include both petrographic and chemical investigations. It is our intention to take additional samples from the Salton Sea wells for this work. However, other thermal systems, such as Los Azufres or Meager Creek, where core is available would be equally suitable.

To help further this research, we are requesting funds to purchase a petrographic microscope and heating stage specifically suited to fluid inclusion work. The equipment would cost $14,900, and this amount is included in the budget presented here.

References

Andreeva, T. A., and Molchanov, V. I., 1978, Hydrogen and hydrocarbon gases in the composition of the gaseous inclusions in rocks: Sov. Geol. Geophys., v. 19, p. 24-29.

Aleksandrova, E. S., Bannikova, L. A., and Sushchevskaya, T. M., 1980, Errors in gas analysis in thermal explosion of inclusions: Geochem. Int., v. 17, p. 66-71.

Bird, D. K., Schiffman, P., Elders, W. A., Williams, A. E., and McDowell, S. D., 1984, Calc-silicate mineralization in active geothermal systems: Econ. Geol., v. 79, p. 671-695.

Capuano, R. M., and Cole, D. R., 1982, Fluid-mineral equilibria in a high temperature geothermal system, Roosevelt Hot Springs, Utah: Geochim. Cosmochim. Acta, v. 46, p. 1353-1364.

Christensen, O. D., Capuano, R. M., and Moore, J. N., 1983, Trace element distribution in an active geothermal system, Roosevelt Hot Springs Thermal Area, Utah: J. Volcanol. Geotherm. Research, v. 16, p. 99-129.

Ellis, A. J., 1979, Explored geothermal systems, in Geochemistry of Hydrothermal Ore Deposits, H. L. Barnes ed., Wiley, New York, p. 632-683.

Gardner, M. D., Kelser, S. E., Creech, M., and Cloke, P. L., 1984, Factors affecting sulfur gas anomalies in overburden: Exploration for ore deposits of the North American Cordillera: Symposium of the Assoc. of Exploration Geochemists, Abstracts with Program, p. 40.

Gunter, B. D., 1978, C1-C4 hydrocarbons in hydrothermal gases: Geochim. Cosmochim. Acta, v. 42, p. 137-139.

Gutierrez, A., and Aumento, F., 1982, The Los Azufres, Michoacan, Mexico, geothermal field, in J. Lavigne and J. B. W. Day (guest editors), Hydrogeothermal studies, 26th International Geological Congress, Jour. Hydrology, v. 56, p. 137-162.

Helgason, H. C., 1967, Solution chemistry and metamorphism, in Researches in Geochemistry, Vol. 2, P. H. Abelson, ed., New York, Wiley, p. 362-402.

Konnerup-Madsen, J., Larsen, E., and Rose-Hansen, J., 1979, Hydrocarbon-rich fluid inclusions in minerals from the alkaline Ilimaussag intrusion, South Greenland: Bull. Mineral., v. 102, p. 642-653.

Kvenvolden, K. A., and Roedder, E., 1971, Fluid inclusions in quartz crystals from Southwest Africa: Geochim. Cosmochim. Acta, v. 35, p. 1209-1229.

McKibben, M. A., 1979, Ore minerals in the Salton Sea geothermal system, Imperial Valley, California, U.S.A.: Inst. of Geophys. and Planet. Phys. Univ. of California, Riverside, UCR/IGPP-79/17, 90 p.

Moore, J. N., Adams, M. C., and Stauder, T., 1983, Geochemistry of the Meager Creek geothermal field, British Columbia, Canada: Geotherm. Res. Council, Trans., v. 7, p. 315-319.

Murray, R. C., 1957, Hydrocarbon fluid inclusions in quartz: Bull. Am. Ass. Pet. Geol., v. 41, p. 950-956.

Naumov, G. B., Mironova, O. F., and Naumov, V. B., 1976, Carbon compounds in inclusions in hydrothermal quartz: Geochem. Int., v. 13, p. 164-171.

Nehring, N. L., and Truesdell, A. H., 1979, Hydrocarbon gases in some volcanic and geothermal systems: Geotherm. Res. Council, Trans., v. 2, p. 483-486.

Nehring, N. L., Des Marais, D. J., and Truesdell, A. H., 1982, Thermal decomposition of hydrocarbons in the Cerro Prieto, Mexico, geothermal reservoir: Geotherm. Res. Council, Trans., v. 6, p. 305-307.

Pezersil'ye, N. A., and Pavlova, M. A., 1976, Organic compounds in volcanic and metamorphic rocks: Int. Geol. Rev., v. 20, p. 339-344..

Roedder, E., 1972, Composition of fluid inclusions: U.S. Geol. Surv. Prof. Paper 440 JJ, 164 p.

Sommer, M. A. II, 1974, Analysis and interpretation of the gases released from various sites in rocks and minerals: Diss. Abstr. Int., v. 35, p. 897b.

Stoiber, R. E., Leggett, D. C., Jenkins, T. F., Murrman, R. P., and Rose, W. I., Jr., 1971, Organic compounds in volcanic gas from Santiaquito Volcano, Guatemala: Geol. Soc. Amer. Bull., v. 87, p. 2299-2302.

Voytov, G. I. Shirokova, I. Y, Pinisenko, V. Y., Katsonis, A. N., and Spektor, I. L., 1971, Gas composition in quartz veins of the Krivay Rog amphibolite series: Acid. Sci. UUSR, Dakl., Earth Sci. Sect., v. 207, p. 233-236.

Scope of Work

Task 2.1 Sample Preparation and Analyses. The minerals selected for study will be carefully cleaned of organic material and crushed prior to analysis. The samples will be analyzed for alkane and alkene hydrocarbons, H_2O, CO_2, CS_2, COS, SO_2 and H_2S using a helium carrier gas. In addition, the concentrations of long chain hydrocarbons (C_5-C_{20}), aromatics, carboxylic acids, NH_3 and N_2, will be determined in selected samples. These analyses will help to evaluate any hydrocarbon decomposition reactions. The gas analyses will be conducted by Mr. David Osborne of MIDECO using a combined gas chromatograph/mass spectrometer. These facilities are housed in Salt Lake City.

Task 2.2 Interpretation. The data obtained from this work will be evaluated for its exploration significance and integrated with petrologic and thermal data to develop an evolutionary model of the thermal system.

Task 2.3 Reporting. A technical report will be written on the work and at least one presentation will be made before a professional society. The material would be submitted to a journal for publication.

2. GEOCHEMICAL STUDIES OF DRILL CHIP SAMPLES FROM GEOTHERMAL AREAS

SCHEDULE AND DELIVERABLES

FY 1985

TASK	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2.1 Sample Preparation and Analyses	|—	—	—	—	—	—	—	—|					
2.2 Interpretation Models				|—	—	—	—	—	—	—	—	—|	
2.3 Reporting												Δ1	

Deliverables

1. Technical report or journal publication

GEOCHEMICAL STUDIES OF DRILL CHIP SAMPLES
FROM GEOTHERMAL AREAS

BUDGET

	Days		Amount
A. Salaries and Wages:			
1. Senior Personnel		$15,223	
M. C. Adams	62		
J. N. Moore	54		
2. Other Personnel		2,394	
Staff Analyst	3		
Draftsperson	5		
Secretary	5		
Technician	5		
3. Wages - Professional		7,798	
Research Assistant	163		
Total Salaries and Wages			$25,415
B. Employee Benefits:			
1. 39.0% of A.1 and A.2		$6,871	
2. 9.5% of A.3		741	
Total Employee Benefits			7,612
C. Permanent Equipment: (See Attachment 1 - Equipment Request)			-0-
D. Expendable Supplies and Equipment:			
1. Drafting Supplies		$185	
2. Office Supplies		50	
Total Expendable Supplies and Equipment			235
E. Travel:			
1. Two trips to DOE/SAN			1,230
F. Reports and Publications:			
1. Printing, Binding and Distribution Costs			475
G. Data Processing:			
1. PRIME 400 Computer			600

H.	Other Costs:	
	1. Gas Analyses	4,000
I.	Total Direct Costs:	$39,567
J.	Indirect Costs:	
	1. 45.0% of "I"	17,805
K.	General and Administrative:	
	1. 14.5% of "I"	5,737
L.	Total Direct, Indirect and G & A Costs:	$63,109
M.	Fee:	
	1. 6.5% of "L"	4,101
N.	Total Project Costs:	$67,210

ATTACHMENT 1

Equipment Request

The following equipment is requested to support the task: "Geochemical Studies of Drill Chip Samples from Geothermal Areas".

Fluid Inclusion Microscope	$14,900*

* Includes 6.5% Fee

PROJECT 3

FRACTURE DETECTION USING BOREHOLE ELECTRICAL GEOPHYSICAL TECHNIQUES

Cost: $67,305 Equipment: $50,320

Background

In FY 84, we stated the background for our studies under this project as follows:

"The most formidable problem in exploration for geothermal resources is precise location of fractures and fracture zones. Dry holes which have missed fractures or fracture zones are expensively plentiful throughout the geothermal industry. To attempt to alleviate this problem, we propose an exploratory study of means to detect fractures and fracture zones via electrical systems deployed in a single well, deployed partly in one well and partly in another, and deployed partly on surface and partly in one well. This class of systems is referred to as borehole geophysics and is distinct from well logging in that a large separation between transmitter and receiver permits exploration to hundreds of meters from a well."

We addressed the problem of detection of fracture zones by conducting numerical model studies of the anomalies to be expected with the following techniques:

1) single-borehole and cross-borehole resistivity,
2) borehole-to-surface resistivity,
3) borehole-to-surface and borehole-to-borehole mise-à-la-masse, and
4) surface-to-borehole time-domain electromagnetics.

We have, via a thorough literature survey, ruled out the radar and induced-polarization techniques. Manpower and financial resources did not permit study of the magnetometric resistivity (MMR) technique beyond the literature survey. We did identify, via our literature survey, another technique that warrants study, and that is the VLF frequency-domain electromagnetic technique.

Accomplishments in FY 1984

Literature Survey. Our first concern was early completion of a literature survey of all borehole electrical geophysical techniques regardless of application. The report by Ross and Ward (1984) documents our findings. Minor updates to that document appear in the more detailed reports referenced below.

Single-Borehole and Cross-Borehole Resistivity Modeling. Prior to award of the subject contract, (using in-house funds) Yang and Ward (1985a) released a study of single-borehole and cross-borehole numerical resistivity modeling. Their abstract follows.

"Hole-to-hole resistivity measurement is a useful method of detecting deeply buried fractures and ore deposits in the subsurface. With drilling costs continually rising, there is a growing need for developing methods of borehole geophysics such as this. In this study, we present theoretical results relating to detection of thin oblate spheroids and ellipsoids with arbitrary attitude.

If we assume that individual fractures within a fracture zone are connected to each other and are of finite lateral and vertical extent, then we can model the fracture zone as a thin conductive oblate ellipsoid or spheroid with arbitrary orientation of the major axis. Detection of such deeply buried fracture zones is the object of this study. In this study, the effects of the surface of the earth are neglected and the body is assumed to be enclosed within an infinite homogeneous mass. The surface of the body is divided into a series of subsurfaces, and a numerical solution of the Fredholm integral equation is applied. Once a solution for the surface charge distribution is determined, the potential can be specified anywhere by means of Coulomb's law. The theoretical model results indicate that cross-borehole resistivity measurements are a more effective technique than single-borehole measurements for delineating resistivity anomalies in the vicinity of a borehole. In some cases, the depth to the center of the body and the dip and strike of the major axes of the body can be estimated."

Borehole-to-Surface Resistivity Modeling. Subsequent to the award of the subject contract, Yang and Ward (1985b) released a study of borehole-to-surface numerical modeling. They found that this method could provide useful information on the attitude and the depth to the center of a conductive oblate spheroid. Only crude information could be provided on the lateral location of the center of the spheroid.

Borehole-to-Surface and Borehole-to-Borehole Mise-à-la-masse. Beasley and Ward (1984) recorded a study of the mise-à-la-masse method applied to the detection of conductive fracture zones when potential measurements are made either on the surface or in adjacent boreholes. We quote from their abstract.

"A numerical scheme applying the method of integral equations has been developed for borehole-to-borehole and borehole-to-surface modeling of the apparent resistivity (ρ_a) response of a thin conductive body in a half-space; the inhomogeneity simulates a geothermal fracture zone. The algorithm is applicable for the direct current case when the buried electrode is either inside (mise-à-la-masse) or outside (near-miss) of the body. In implementing the scheme, the integral equation is transformed into a matrix equation as a result of discretizing the inhomogeneity into rectangular subcells. All properties are assumed to be constant within each subcell. The rectangular subcells are used throughout execution of the algorithm.

The computed surface and subsurface apparent resistivity responses are examined for similar bodies with different orientations: (1) vertical, (2) horizontal, (3) dipping at 60°, and (4) dipping at 30°. The different bodies produce apparent resistivity cross-section plots which differ little from each other with the exception of orientation. In plan view, estimates of orientation, areal extent, and dip can often be made. The maximum depth at which a body can be located and still produce a detectable surface anomaly is dependent upon the buried electrode position and contrast in conductivity. Locating the buried electrode just outside of the body does not significantly alter the results from those of when the electrode is embedded in the inhomogeneity."

Surface-to-Borehole Time-Domain Electromagnetics. West and Ward (1984) analyzed the application of the time-domain electromagnetic (TEM) method to detection of fracture zones. The transmitting coil, of necessity, was restricted to the surface of the earth but the receiver was placed in boreholes adjacent to the fracture zone. Their abstract follows.

"Borehole geophysical methods can be very useful in the detection of subsurface fracture zones and mineral deposits which are nearby, but not intersected by boreholes. One electrical borehole technique which can be applied to this problem is the surface-to-borehole transient electromagnetic (TEM) method. This study provides modeling results of the borehole TEM responses of a fracture zone that is contained in a conductive host and energized by a large-loop transmitter. A preliminary assessment of the detectability of the fracture zone is presented and directions for future research efforts are defined.

A conductive, horizontal, tabular body in a homogenous half-space was chosen to simulate a 3-D fracture zone composed of individual, interconnected fractures. Theoretical borehole TEM responses for several models of practical interest were computed using a direct integral-equation formulation. The anomalous TEM response (secondary response) is the result of a complex interaction between vortex and galvanic currents within the body. Distortion of the secondary response by the conductive host effects does not affect the interpretation of the body depth but it does lead to erroneous estimates of the conductivity and the size of the body. Increasing the host resistivity decreases the host effects and increases the response of the body, while decreasing body-borehole separation and body depth increase the secondary response. The decrease in the vortex response due to decreasing transmitter-body coupling is offset by an increase in the galvanic response at late times; however this phenomenon is model-dependent.

This study indicates much promise for the borehole TEM method but the application of the technique for fracture detection in a geothermal environment is limited by the lack of existing hardware and limited modeling capabilities. Future research should concentrate on resolving these problems by developing: (1) high-temperature, large-moment borehole magnetic sensors which can withstand the harsh geothermal environment, (2) high-power, rapid turn-off transmitters to increase the ratio of signal to natural noise, thereby increasing the radius of detection of the tool, and (3) efficient computational schemes capable of modeling arbitrarily-oriented, 3-D bodies in a multi-layered earth in order to improve the interpretational capability of the TEM technique."

Problems Identified, FY 84

In the above studies, we found that the anomalies with borehole-to-surface and cross-borehole methods were not always large. Anomalies with the mise-à-la-masse and TEM borehole geophysical methods were sometimes larger.

We have not, however, analyzed the ratio of signal to noise for any of the methods and this needs to be done before the feasibility of application of any one of the techniques can be evaluated. Noise here must include effects of topography and random or ordered variations in the resistivity of the host medium in which the fracture zones occur. It must also include the effects of drill casing plus natural and artifical field electromagnetic noise.

Sensors capable of withstanding the hostile environment of a high-temperature geothermal well have not been identified for any of the methods, although we believe this to be much less of a problem for resistivity techniques than for electromagnetic techniques which include TEM, VLF, and MMR.

Significant Technology Invented

We believe that our research has led to a potentially patentable multi-array borehole resistivity method which is described in the following pages.

Multi-Array Borehole Resistivity System

The potential invention relates to a means of converting a conventional long lateral array used in well logging (current electrodes A_B and B_∞) to a multi-array system capable of providing hole-to-surface ($A_B B_\infty M_S N_S$), and surface-to-borehole ($A_S B_\infty M_B N_B$) measurements. Rapid sequencing of electrode combinations is necessary so that all measurements are made before the logging sonde has moved significantly down the borehole.

The following sequence of measurements is envisioned:

1.	$B_\infty A_B M_B N_B$	long lateral
2.	$B_\infty A_B M_S(-4) N_S(-3)$	borehole-to-surface
3.	$B_\infty A_B M_S(-3)(N_S)(-2)$	borehole-to-surface
4.	$B_\infty A_B M_S(-2) N_S(-1)$	borehole-to-surface

5.	$B_{\infty}A_{B}M_{S}(-1)N_{S}(0)$	borehole-to-surface
6.	$B_{\infty}A_{B}M_{S}(0)N_{S}(1)$	borehole-to-surface
7.	$B_{\infty}A_{B}M_{S}(1)N_{S}(2)$	borehole-to-surface
8.	$B_{\infty}A_{B}M_{S}(2)N_{S}(3)$	borehole-to-surface
9.	$B_{\infty}A_{B}M_{S}(3)N_{S}(4)$	borehole-to-surface
10.	$B_{\infty}A_{S}(-4)M_{B}N_{B}$	surface-to-borehole
11.	$B_{\infty}A_{S}(-3)M_{B}N_{B}$	surface-to-borehole
12.	$B_{\infty}A_{S}(-2)M_{B}N_{B}$	surface-to-borehole
13.	$B_{\infty}A_{S}(-1)M_{B}N_{B}$	surface-to-borehole
14.	$B_{\infty}A_{S}(0)M_{B}N_{B}$	surface-to-borehole
15.	$B_{\infty}A_{S}(1)M_{B}N_{B}$	surface-to-borehole
16.	$B_{\infty}A_{S}(2)M_{B}N_{B}$	surface-to-borehole
17.	$B_{\infty}A_{S}(3)M_{B}N_{B}$	surface-to-borehole
18.	$B_{\infty}A_{S}(4)M_{B}N_{B}$	surface-to-borehole

Because logging speeds are typically 10 m/minute, it is necessary to switch through all of these 18 electrode connections in less than 6 seconds so that the logging sonde has not moved through more than 0.1 m during a sequence.

Referring to Figure 2, the electrodes A_S, M_S, and N_S can be in a single section through the borehole for section surveys (electrode locations -4 through +4) or deployed offset from the borehole for azimuth surveys (electrode locations a through h). The section survey in the surface-to-hole measuring mode is especially useful for determining depth to the center of the body while the azimuth survey is useful for determining the direction to the body from the borehole and the attitude of the body. The hole-to-surface measurement is best for locating the lateral position of the body.

The mise-à-la-masse method is also accomodated by the multi-array. When the electrode A_B lies in the body, the body is directly energized. Then measurements of potential via $M_S N_S$ yield the conventional mise-à-la-masse result.

If more than one borehole is available, then cross-borehole measurements are also facilitated and mise-à-la-masse potential measurements can then be made subsurface as well as surface. Figure 3 illustrates a two borehole multi-array. Rapid switching between all electrode pairs is then generalized from that presented earlier.

With all of the electrode positions used, electrical geotomography can be used in interpretation. We visualize three-dimensional data inversion to effect geotomographic interpretation.

The invention is the concept of a multi-array borehole geophysical survey, the layout of electrodes at surface each connected to a switch at the logging truck, and the concept of rapid switching of current and potential electrodes. These items are considered to be new and patentable.

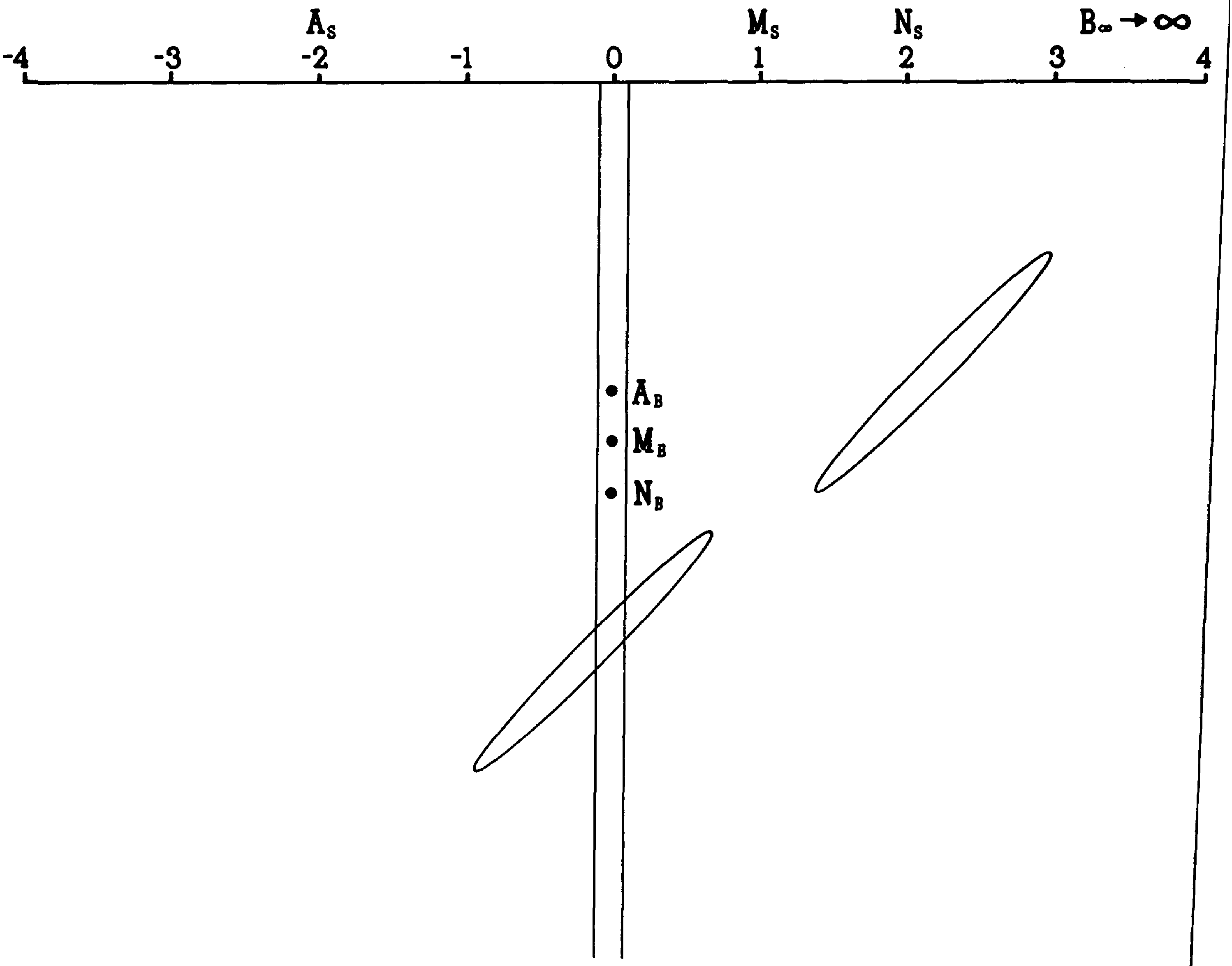
Methods Which Require Further Study

The following is our prioritized list of methods which warrant further study.

1. Multi-Array Borehole Resistivity Method

Compute borehole-to-surface, surface-to-borehole, cross-borehole, and mise-à-la-masse forward anomalies for a concise set of subsurface models. Use available computations whenever possible, but extend to application of the finite-element method so that the effects of topography, overburden, buried topography, random geological noise, and ordered geological noise (contacts and layering) may be evaluated. Attempt to develop an inverse scheme for the multi-array borehole resistivity system, using all available data sets, which could lead to development of a surface-subsurface geotomographic method of

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



- ● LONG LATERAL ARRAY — $A_B B_\infty M_B N_B$
- ● SURFACE-TO-BOREHOLE — $A_S B_\infty M_B N_B$
- ● BOREHOLE-TO-SURFACE — $A_B B_\infty M_S N_S$
- ● MISE-A-LA-MASSE — A_B in fracture zone $M_B N_B$ or $M_S N_S$

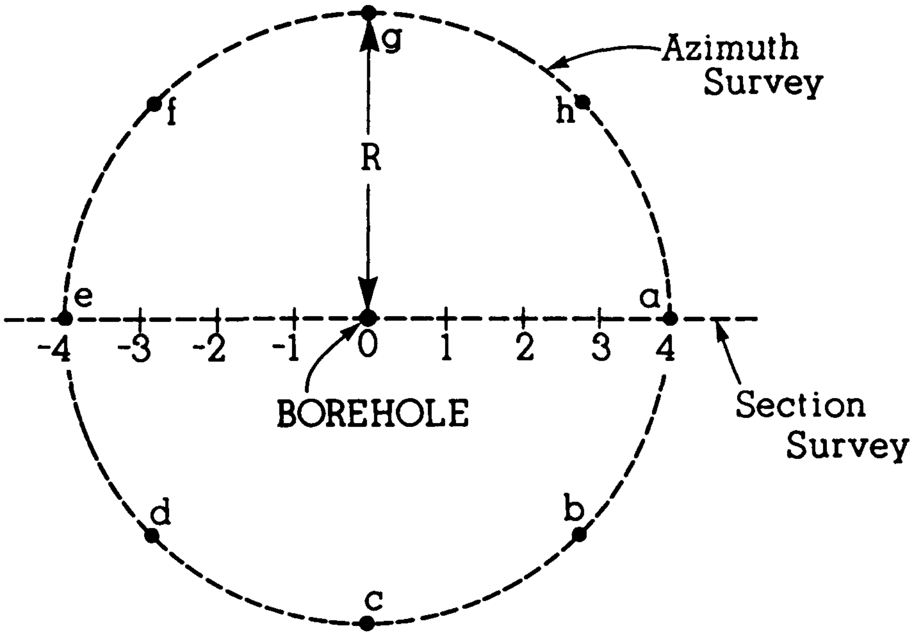
*CONVENTIONAL LOGGING TRUCK

*POTENTIAL AND CURRENT ELECTRODES ON SURFACE AND DOWNHOLE

*RAPID SEQUENCING THROUGH ELECTRODES

FIGURE 1

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



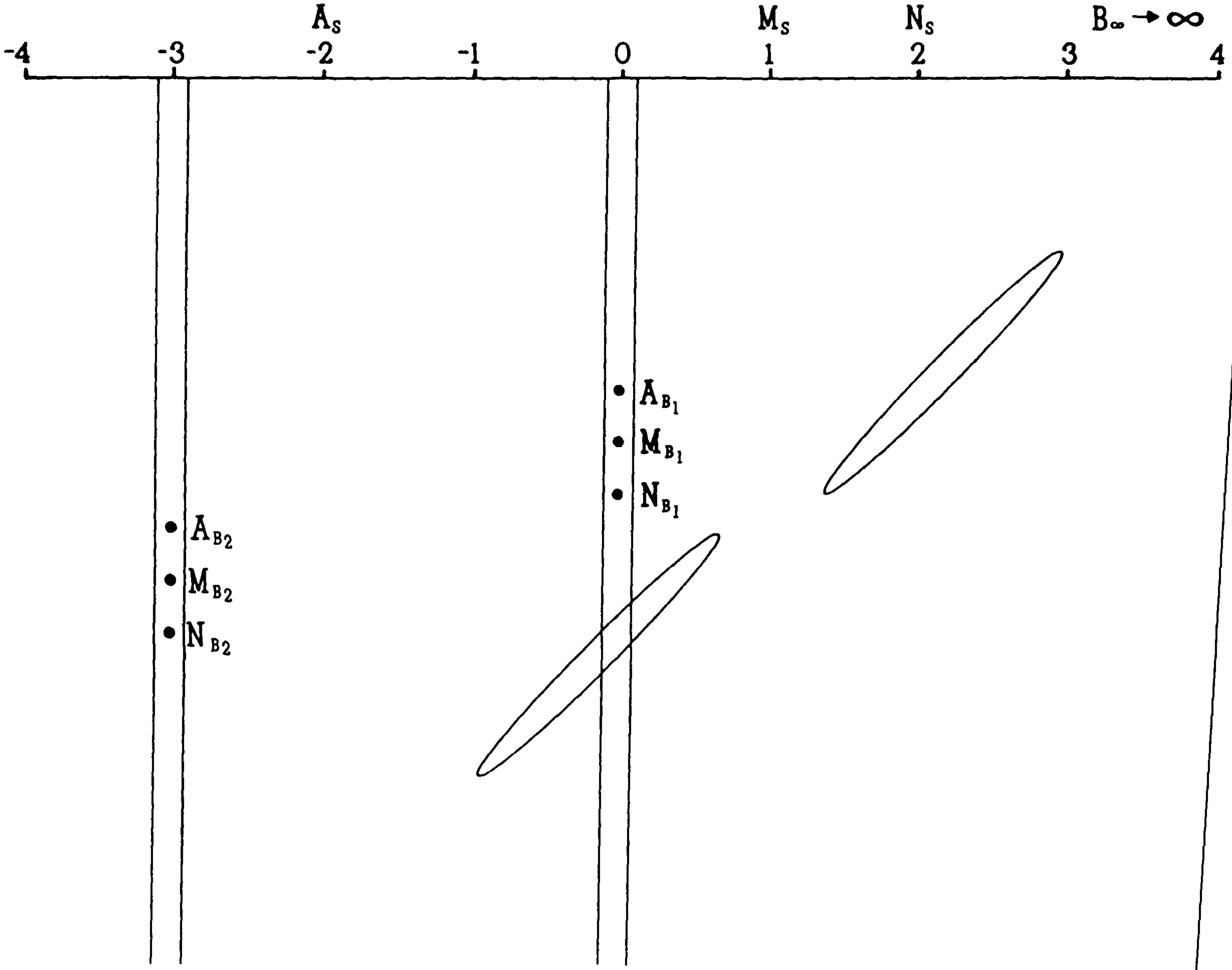
PLAN VIEW

LOCATIONS OF A_s : -4,-3,-2,-1,0,1,2,3,4 SECTION SURVEY

a,b,c,d,e,f,g,h AZIMUTH SURVEY

FIGURE 2

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



- ● LONG LATERAL ARRAY — $A_B B_\infty M_B N_B$
- ● SURFACE-TO-BOREHOLE — $A_S B_\infty M_B N_B$
- ● BOREHOLE-TO-SURFACE — $A_B B_\infty M_S N_S$
- ● MISE-A-LA-MASSE — A_B in fracture zone $M_B N_B$ or $M_S N_S$

*CONVENTIONAL LOGGING TRUCK

*POTENTIAL AND CURRENT ELECTRODES ON SURFACE AND DOWNHOLE

*RAPID SEQUENCING THROUGH ELECTRODES

FIGURE 3

interpretation of electrical geophysical data. Evaluate the ratio-of-signal to noise for each method, including the effects of casing, natural and artificial field noise, as well as geological noise. Identify downhole probes suitable for the above task and state their current and projected temperature ranges. (State-of-the-art probes are available for temperatures to 250°C).

2. Evaluate via studies similar to those listed in 1) above of the ratios of signal to noise, the probable relative feasibilities of application of the TEM, VLF, and MMR methods to detection of fracture zones in geothermal exploration. No electromagnetic detection probes are known to have been used at temperatures above 100°C.

3. It is probable that a prototype multi-array borehole resistivity system can be defined and recommended for test surveys in FY 85. In order to begin test work, we will require a relatively simple wellbore logging capability. We are therefore requesting equipment funds, as shown on the attached budget, of $50,320 for purchase of wellbore resistivity logging equipment. We would modify this equipment so that we could perform multiple-electrode surveys with electrodes in both the wellbore and on the surface.

References

Beasley, C. W., and Ward, S. H., in preparation, Theoretical borehole-to-borehole and borehole-to-surface resistivity anomalies of geothermal fracture zones.

Ross, H. P., and Ward, S. H., 1984, Borehole electrical geophysical methods: A review of the state-of-the-art and preliminary evaluation of the application to fracture mapping in geothermal systems: Univ. of Utah Research Inst., Earth Science Lab. Rept. DOE/SAN/12196-2.

West, R. C., and Ward, S. H., in preparation, The borehole transient EM response of a 3-D fracture zone in a conductive half-space.

Yang, F. W., and Ward, S. H., 1985, Single- and cross-borehole resistivity anomalies of thin ellipsoids and spheroids: Geophysics, **50**, April.

Yang, F. W., and Ward, S. H., 1985, On sensitivity of surface-to-borehole resistivity measurements to the attitude and the depth to the center of a 3-D oblate spheroid: Geophysics, **50**, in press.

Scope of Work

3.1 Develop Interpretation. Perform forward modeling of the borehole-to-surface, surface-to-borehole, cross-borehole, and mise-à-la-masse methods to evaluate the feasibility of a multi-array borehole resistivity system. Include the effects of topography, overburden, buried topography, random geological noise, ordered geological noise, cultural noise, and natural field noise.

Commence development of an inverse scheme with the goal of developing electrical geotomography.

3.2 Electromagnetic Borehole System. Perform forward modeling of the TEM, VLF, and MMR methods so as to evaluate the ratio of signal to noise. Noise sources to be considered for study include topography, overburden, buried topography, random geological noise, ordered geological noise, cultural noise, and natural field noise.

3.3 Initial Testing. Begin field test work by modeling a commercial wellbore resistivity logger for use with a multiple array of electrodes in the wellbore and on surface.

3.4 Testing at Other Sites. If additional funds become available, beyond the amount requested herein, initiate development of a prototype and plan for testing it at such sites as Valles caldera and Los Azufres.

3.5 Reporting. At least one technical report would result from this work.

3. FRACTURED DETECTION USING BOREHOLE ELECTRICAL GEOPHYSICAL TECHNIQUES

SCHEDULE AND DELIVERABLES

FY 1985

TASK	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
3.1 Develop Interpretation	|—	—	—	—	—	—	—	—	—	—	—	—|	
3.2 Electromagnetic Borehole System	|—	—	—	—	—	—	—	—	—	—	—	—|	
3.3 Initial Testing							|—	—	—	—	—	—|	
3.4 Testing at Other Sites							|—	—	—	—	—	—|	
3.5 Reporting												Δ1	

Deliverables

1. Technical report

FRACTURE DETECTION USING BOREHOLE ELECTRICAL GEOPHYSICAL TECHNIQUES

BUDGET

A. Salaries and Wages:			
	Days		Amount
1. Senior Personnel			
P. E. Wannamaker	5	$ 678	
2. Other Personnel		3,318	
Staff Analyst	5		
Draftsperson	22		
Secretarial	22		
Technician	115		
3. Wages - Professional		24,125	
S. H. Ward	25		
Research Assistants (2)	326		
Total Salaries and Wages			$28,121
B. Employee Benefits:			
1. 39.0% of A.1 and A.2		$ 1,558	
2. 9.5 % of A.3		2,292	
Total Employee Benefits			3,850
C. Permanent Equipment: (See Attachment 2 - Equipment Request)			-0-
D. Expendable Supplies and Equipment:			
1. Drafting Supplies		$ 200	
2. Office Supplies		75	
Total Expendable Supplies and Equipment			275
E. Travel:			-0-
F. Reports and Publications:			
1. Printing, Binding and Distribution Costs			575
G. Data Processing:			
1. PRIME 400 Computer			6,800
H. Other Costs:			-0-
I. Total Direct Costs:			$39,621

J. Indirect Costs:	
1. 45.0% of "I"	$17,829
K. General and Administrative:	
1. 14.5% of "I"	$ 5,745
L. Total Direct, Indirect and G & A Costs:	$63,195
M. Fee:	
1. 6.5% of "L"	$ 4,110
N. Total Project Costs:	$67,305

ATTACHMENT 2

Equipment Request

The following equipment is requested to support the task: "Fracture Detection Using Borehole Electrical Geophysical Techniques".

Wellbore Resistivity Logger	$50,320*

* Includes 6.5% Fee

RESUMES OF KEY PERSONNEL

RESUME

Joseph N. Moore

DATE OF BIRTH: January 21, 1948

POSITION: Geologist/Project Manager and Section Manager of Geochemical Group, Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah

EDUCATION:
B.S., Geology, 1969, City College of New York
M.S., Geology, 1972, Pennsylvania State University
Ph.D., Geology, 1975, Pennsylvania State University

SOCIETY AFFILIATIONS:
Geological Society of America
Geothermal Resources Council

HONORS AND AWARDS:
1971, Sigma Xi Grant
1971, Paul D. Krynine Fund Award
1972, Sir William Logan Medallion
1973, Phi Kappa Phi Honor Society
1978, American Men and Women in Science

PROFESSIONAL EXPERIENCE:

1979-present	Section Manager, the Geochemistry group, Earth Science Laboratory. Responsibilities include management of ESL geochemical programs and analytical facilities as well as the development of new geochemical techniques for use in geothermal exploration.
1977-1979	Geologist, Earth Science Laboratory. Conduct and supervise geologic programs in known geothermal resource areas of the Basin and Range.
1975-1977	Staff geologist, Uranium Division/The Anaconda Co. Primary responsibilities included developing an exploration program in volcanic terrains for hydrothermal uranium deposits and detailed and reconnaissance mapping in the Basin and Range.
1972-1975	Graduate Teaching Assistant, Pennsylvania State University. Duties included preparation of laboratories and laboratory lectures for basic physical geology and mineralogy courses.
1970-1972	Graduate Research Assistant, Pennsylvania State University. Research involved a comparison of igneous and impact breccias.
1971 summer	Geologist, Johns-Manville Ltd. Detailed mapping in the Stillwater Complex, Montana.
1968-1969 summers	Geologic Field Assistant, U.S.G.S., Dr. Nicholas Ratcliffe, party chief. Assist in detailed bedrock mapping of Taconic geology in southwestern Massachusetts.

1968	Part-Time Laboratory Assistant, Lamont Geological Observatory, Paleomagnetism Section, Dr. Neil Opdyke, supervisor. Duties included cutting, preparation, and magnetic analysis of deep sea drill cores.

PUBLICATIONS:

"Northeast Breccia Pipes and Dikes," Moore, J. N. and Gold, D. P., International Geologic Congress (24th Session) Guidebook, Monteregian Hills: Diatremes, Kimberlites, Lamprophyres, and Intrusive Breccias West of Montreal (1972).

"Mixed-Volatile Equilibria in Calcareous Rocks from the Alta Aureole, Utah," Moore, J. N. and Kerrick, D. M., Am. Jour. Sci., 276, 502-524 (1976).

"Geology of Roosevelt Hot Springs KGRA Beaver Co., Utah," Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore J. N. and Samberg, S. M., University of Utah Research Institute, Earth Science Laboratory Report (IDO/78-1701.b.1.1.3), 120 p. (1978).

"Geology of the Cove Fort-Sulphurdale KGRA," Moore, J. N. and Samberg S. M., Bibliographic Annotations and Petrographic Descriptions by B. Sibbett, University of Utah Research Institute, Earth Science Laboratory (IDO/78-1701.b.1.1.5), 44 p. (1979).

"Geology Map of the San Emidio Geothermal Area," University of Utah Research Institute, Earth Science Laboratory (EG-78-C-07-1701) 8 p. (1979).

"Geology, Geochemistry, and Geophysics of the Roosevelt Hot Springs KGRA, Utah," Basic Geology for the Exploration of Geothermal Systems, GRC Technical Training Course #5, 24 p. (1980).

Geochemistry of solids in geothermal systems, Moore, J. N., National Conference on renewable energy resources technologies, Honolulu, 1980.

"Trace Element Geochemical Zoning in the Roosevelt Hot Springs Thermal Area, Utah," Christensen, O. C., Moore, J. N. and Capuano, R. M., Geothermal Resources Council Trans., 4, 149-152 (1980).

"A Summary of the Geology and Geophysics of the San Emidio KGRA, Washoe County, Nevada," Mackelprang, C. E., Moore, J. N. and Ross, H. P., Geothermal Resources Council Transaction, 4, 221-224 (1980).

Road log to geothermal systems in central Utah, Nielson, D. L., Moore, J. N., and Forrest, R. J., 1980, in Nielson, D. L. (ed.), Geothermal Systems in Central Utah, Geothermal Resources Guidebook to Field Trip No. 7, p.44

"Hg and As soil geochemistry as a technique for mapping permeable structure over a hot-water geothermal system", Capuano, R. M., and Moore, J. N., [abs.] Geol. Society America, Rocky Mt. Section 12, no. 5, 269 (1980).

"K/Ar Ages of the Pyramid Sequence in the Vicinity of the San Emidio Geothermal Area, Washoe County, Nevada," Evans, S. H., Moore, J., Adams, M., Isochron/West, No. 31, 19-21 (1981).

"The Roosevelt Hot Springs, Utah Geothermal Resource - An Integrated Case Study," Ross, H. P., Nielson, D. L., Glenn, W. E, Moore, J. N., Smith, Christian and Christensen, O. D., 66th Annual AAPG Meeting, San Francisco, June (1981).

"Geochemical Indicators of a High-Temperature Geothermal System" [abs.], Moore, J. N., Capuano, R. M., and Christensen, O. D., 9th International Geochemical Exploration Symposium, Saskatoon, Canada, May 12-14 (1982).

"An Exploration Case Study of the Roosevelt Hot Springs Geothermal System, Utah, Ross, H. P., Nielson, D. L., and Moore, J. N., Amer. Assoc. of Petrol. Geologists Bulletin, v. 66, p. 879-902 (1982).

"The Cove Fort-Sulphurdale KGRA - A Geological and Geophysical Case Study" Ross, H. P., Moore, J. N. and Christensen, O. D., ESL Report 90, 29 p. (1982).

"Mercury as a Pathfinder Element in the Exploration of Vapor Dominated Geothermal Systems" Moore, J. N., Christensen, O. D., and Bamford, R., Geothermal Resources Council Transactions, v. 6, p. 99-102, (1982).

"Geologic map of the McCoy geothermal prospect, Adams, M. C., Moore, J. N., and Struhsacker, E., ESL Report 111 (DOE/ID/12019-92), (1982).

"Trace Element Distribution in an Active Hydrothermal System, Roosevelt Hot Springs Thermal Area, Utah," Christensen, O. D., Capuano, R., Moore, J. N., J. Volcanology and Geothermal Research, v. 16, p. 99-129 (1983).

"Nevada Geothermal Areas; Steamboat Springs, Brady Hot Springs, Humbolt House Colado, Beowawe," Moore, J. N. and Cerling, B. W., eds., Guidebook for Field Trip #2, GRC, 1980 Annual Meeting, 95 p. (1983).

"Preliminary geothermal assessment of the Tuttapani thermal area, Madhya Prodesh, India: Geothermal Resources Council Transactions, in press.

"Geochemistry of the Meager Creek geothermal field, Moore, J. N., Adams, M. C., and Stauder, J. J., British Columbia Geothermal Resources Council, in press.

RESUME

Dennis L. Nielson

POSITION: Section Manager - Geology, Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah

EDUCATION:
B.A., Geology, 1970, Beloit College, Beloit, Wisconsin
M.A., Geology, 1972, Dartmouth College, Hanover, New Hampshire
Ph.D., Geology, 1974, Dartmouth College, Hanover, New Hampshire

SHORT COURSES:
Volcanic Rocks and Their Vent Areas, University of Nevada, Reno, 1977
Engineering Management by Objectives for Improving Productivity, University of Utah, 1978
Geothermal and Hydrothermal Systems, Yellowstone Institute, 1978
Economics of Minerals and Energy Projects, AIME, 1981

SOCIETY AFFILIATIONS:
American Geophysical Union
Geological Society of America
Geothermal Resources Council
Society of Economic Geologists
Utah Geological Association

HONORS AND AWARDS:
Haven Science Prize, Beloit College (1970)
NDEA Title IV Fellowship - Dartmouth College (1971-1974)
American Men and Women of Science
President, Basin and Range Section, Geothermal Resources Council (1979)

PROFESSIONAL EXPERIENCE:

7/80-present: Section Manager - Geology. Earth Science Laboratory, University of Utah Research Institute. Responsible for overall technical quality of geologic work and management of the geologic staff.

7/79-present: Geologist/Project Manager, Earth Science Laboratory, University of Utah Research Institute. Project manager for the following programs under Department of Energy contracts: Geothermal Exploration and Assessment Technology Program, Industry Coupled Program, M-X/Renewable Energy Systems Program. Responsible for coordinating technical work at Roosevelt Hot Springs KGRA, Utah; and Beowawe; Tuscarora; Colado; McCoy; Soda Lake-Stillwater KGRAs, NV. Formulation and technical review of procurements, contract monitoring , and program design. Principal investigator for the geothermal exploration of Ascension Island, South Atlantic Ocean, under contract to U.S. Department of Energy and U.S. Air Force. Participated in a program to assess the state-of-the-art and recommend needed research in an industry sponsored program in solution mining and

	hydrometallurgy. Have participated in numerous DOE advisory committees including those concerned with the Baca Geothermal Demonstration Power Plant, Deep Continental Scientific Drilling Program, and the Hot Dry Rock Project.
1979-present	Instructor, Yellowstone Institute, for a course on Calderas and Hydrothermal Systems which concentrates on the formation of calderas, ash-flow tuff stratigraphy, and the geology of hydrothermal systems in the caldera environment.
4/78-7/79	Geologist, Earth Science Laboratory, University of Utah Research Institute. Develop case studies for geothermal resource areas in western U.S. Responsibilities include supervision of geologic programs, geologic mapping, synthesis and publication of exploration data, and formation of exploration criteria.
6/74-4/78	Staff Geologist, The Anaconda, Co., Salt Lake City, Utah. Uranium exploration in frontier project areas in the United States. Responsible for generating and supervising projects through the initial drilling stages. Experience in Precambrian plutonic and metasedimentary environments and Tertiary volcanic and sedimentary environments. Activities included detailed mapping, quadrangle mapping, regional reconnaissance, interpreting geophysical and geochemical data, supervising rotary and diamond drilling, and land acquisition through leasing and claim staking.
1971 summer	Field Geologist, Great Lakes Exploration Co. (subsidiary of Bear Creek Mining Co.). Reconnaissance mapping in the Precambrian Shield of the Upper Peninsula of Michigan and northern Wisconsin. The mapping was designed to locate areas having potential for massive sulfide deposits.
1970 summer	Field Geologist, Great Lakes Exploration Co. (subsidiary of Bear Creek Mining Co.). Quadrangle mapping and geochemical surveys of water wells and soils in conjunction with a massive sulfide exploration program in northern Wisconsin.
1968 fall	Field Assistant, Bear Creek Mining Co. Base metal exploration in the Upper Peninsula of Michigan and northern Wisconsin. Duties included drafting, supervising diamond drilling, and assisting with field mapping.

PUBLICATIONS:

PAPERS AND TECHNICAL REPORTS

Nielson, D. L., 1973, Silica diffusion at Ascutney Mountain, Vermont: Contributions to Mineralogy and Petrology, v. 40, p. 141-148.

Nielson, D. L., Clark, R. G., Lyons, J. B., Englund, E. J., and Borns, D. J., 1976, Gravity models and mode of emplacement of the New Hampshire Plutonic Series, in Lyons, P. C., and Brownlow, A. H. (eds.) Studies in New England Geology: Geological Society of America Memoir 146, 301-318.

Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S. M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 12, 121 p.

Nielson, D. L., 1978, Radon in geothermal exploration, theory and an example from Roosevelt Hot Springs KGRA, Utah: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 14, 31 p.

Nielson, D. L., and Moore, J. N., 1979, The exploration significance of low-angle faults in the Roosevelt Hot Springs and Cove Fort-Sulphurdale Geothermal Systems, Utah: Geothermal Resources Council Transactions, v. 3, p.503-506.

Nielson, D. L. (ed.) 1979, Program Review: Geothermal Exploration and Assessment Technology Program including a report of the Reservoir Engineering Technical Advisory Group: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 29, 128 p.

Foley, D., Nielson, D. L., and Nichols, C. R., 1980, Geothermal systems of the Yellowstone Caldera: Geothermal Resources Council Field Trip No. 1, 69 p.

Glenn, W. E., Hulen, J. B., and Nielson, D. L., 1980, A comprehensive study of LASL Well C/T-2 Roosevelt Hot Springs KGRA, Utah and application to geothermal well logging: Los Alamos Scientific Laboratory, Rept. LA-8686-MS, 175 p.

Nielson, D. L. (ed.) 1980, Geothermal Systems in Central Utah: Geothermal Resources Council Guidebook to Field Trip No. 7, 54 p.

Nielson, D. L., 1980, Summary of the geology of the Roosevelt Hot Springs Geothermal System, Utah: in Nielson, D. L. (ed.), Geothermal Systems in Central Utah, Geothermal Resources Council Guidebook to Field Trip No. 7, p.25-29.

Nielson, D. L., Moore, J. N., and Forrest, R. J., 1980, Road log to geothermal systems in central Utah: in Nielson, D. L. (ed.), Geothermal Systems in Central Utah, Geothermal Resources Guidebook to Field Trip No. 7, p.44-54.

Sibbett, B. S., and Nielson, D. L., 1980, Geology of the central Mineral Mountains, Beaver County, Utah: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 33, 42 p.

Ward, S. H., Ross, H. P., and Nielson, D. L., 1981, Exploration strategy for high-temperature hydrothermal systems in the Basin and Range Province: Am. Assoc. Petroleum Geologists Bull., 65/1 p.86-102. Reprinted in Energy Minerals, AAPG reprint Series No. 25, p. 232-248.

Nielson, D. L., 1981, The bedrock geology of the Hillsboro quadrangle, New Hampshire: N. H. Dept. of Resources and Economic Development Bull. No. 8, 76 p.

Ross, H. P., Nielson, D. L., and Moore, J. N., 1982, Roosevelt Hot Springs geothermal system, Utah-Case Study: Am. Assoc. Petroleum Geologists Bull., v. 66, no. 7, p. 879-902.

Nielson, D. L., (ed.), 1982, Overthrust belt of Utah: Utah Geological Association Publication 10, 335 p.

Hulen, J. B. and Nielson, D. L., 1982, Stratigraphic permeability in the Baca geothermal system, Redondo Creek area, Valles Caldera, New Mexico: Geothermal Resources Council Transactions, v. 6, p. 27-30.

Evans, S. H. and Nielson, D. L., 1982, Thermal and tectonic history of the Mineral Mountains intrusive complex: Geothermal Resources Council Transactions, v. 6, p. 15-18.

Foley, D., Nielson, D. L., and Nichols, C. R., 1982, Road Logs: West Yellowstone to Canyon Junction, Canyon Junction to Mud Volcano - Sulphur Cauldron Area, Canyon Junction to Tower Junction, Tower Junction to Mammoth Hot Springs, Mammoth Hot Springs to Norris Junction, Madison Junction to Old Faithful, in Reid, S. G. and Foote, D. J. (eds.) Geology of Yellowstone Park Area: Wyoming Geological Association Guidebook.

Hulen, J. B. and Nielson, D. L., 1983, Stratigraphy of the Bandelier Tuff and characterization of high-level clay alteration in borehole B-20, Redondo Creek area, Valles Caldera, New Mexico: Geothermal Resources Council Transaction, v. 7, p. 163-168.

Nielson, D. L., and Hulen, J. B., 1983, Geologic model of the Baca geothermal reservoir, Valles caldera, New Mexico: Proceedings Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, p. 145-150.

Nielson, D. L., and Hulen, J. B., 1984, Internal geology and evolution of the Redondo Dome, Valles caldera, New Mexico: Jour. Geophys. Research Special volume on calderas and associated igneous rocks, in press.

ABSTRACTS

Nielson, D. L., 1973, Contact metamorphism and molecular diffusion at Ascutney Mountain, Vermont: Geological Society of America, Abstracts with Programs, Northeastern Section, p.203.

Nielson, D. L., Lyons, J. B., and Clark, R. G., 1973, Gravity and structural interpretations of the mode of emplacement of the New Hampshire Plutonic Series: Geological Society of America, Abstracts with Programs 1973 Annual Meetings, p.750.

Nielson, D. L., Sibbett, B. S., and McKinney, D. B., 1979, Geology and structural control of the geothermal system at Roosevelt Hot Springs KGRA, Beaver County, Utah (abs.): American Association of Petroleum Geologists Bull., v. 63/5, p.836.

Ward, S. H., Chapman, D. S., Evans, S. H., Nielson, D. L., Wannamaker, P. E., and Wilson, W. R., 1979, Roosevelt Hot Springs Geothermal System: Geologic and geophysical models: IAVCEI Abstracts and timetables, IUGG XVII General Assembly, Canberra, Australia.

Nielson, D. L, 1980, Geology of low- and intermediate-temperature hydrothermal systems: National Conference on Renewable Energy Technologies, Proceedings, Honolulu, p.8-3 to 8-4.

Sibbett, B. S., and Nielson, D. L.,1980, The Mineral Mountains intrusive complex, Utah: Geological Society of America, Abstracts with Programs, Rocky Mountain Section, v. 12, No. 6, p.305.

Ward, S. H., Ross, H. P., and Nielson, D. L., 1980, Strategy of exploration for high temperature hydrothermal systems in the Basin and Range Province (abs.): Am. Assoc. Petroleum Geologists Bull., v. 64/5, p.799.

Ross, H. P., Nielson, D. L., and Glenn, W. E., et al., 1981, Roosevelt Hot Springs, Utah geothermal resource-integrated case study (abs.): Am. Assoc. Petroleum Geolgists Bull., v. 65/5, p. 982.

Nielson, D. L., and Hulen, J. B., 1984, Results of deep drilling in the Valles caldera, New Mexico (abstract): Invited paper, International Symposium on Continental Drilling, Tarrytown, N.Y.

RESUME

Stanley H. Ward

BIRTHPLACE AND DATE: Vancouver, B.C., Canada, January 16, 1923

POSITION: Professor, Department of Geology and Geophysics, College of Mines and Mineral Industries, University of Utah, Salt Lake City, Utah
Director, University of Utah Research Institute, Earth Science Laboratory, Salt Lake City, Utah

EDUCATION: 1940, John Oliver High School, Vancouver, Canada
B.A.Sc., Engineering Physics, 1949, University of Toronto, Toronto, Ontario, Canada
M.A., Geophysics, 1950, University of Toronto
Ph.D., Geophysics, 1952, University of Toronto

SOCIETY AFFILIATIONS: Fellow, Royal Astronomical Society
Fellow, Institute of Electrical and Electronic Engineers
Fellow, Geological Society of America
Member, Society of Exploration Geophysicists
Member, Geothermal Resources Council

Member, European Association of Exploration Geophysicists
Member, Canadian Institute of Mining and Metallurgy
Member, American Geophysical Union
Member, International Union of Geodesy and Geophysics
Member, Society of Sigma Xi
Member, Professional Engineers of the Province of Ontario
Member, Australian Society of Exploration Geophysicists

PROFESSIONAL EXPERIENCE:

4/78-present	Director, Earth Science Laboratory, University of Utah Research Institute. Responsible for the management of research activities of a professional staff of 29 and a support staff of 30. Responsible for administration of funds totalling $10,000,000.
7/73-6/80	Director, University of Utah Seismograph Stations. Responsible for the management of research activities of a professional staff of 6 and a support staff of 8. Responsible for administration of funds totalling $132,000.
7/70-6/80	Professor, Department of Geology and Geophysics, University of Utah. Research and teaching concerned with electromagnetic exploration with the objectives including the search for minerals, oil and gas, and geothermal energy, deep probing of the earth's crust, and study of the lunar interior.
1959-1970	University of California, Berkeley, Professor of Geophysical

Engineering. Research and teaching concerned with electromagnetic exploration with the objectives including the search for minerals and oil, deep probing of the earth's crust, study of the earth's magnetosphere, and study of the lunar interior.

1958-present Consulting Geophysical Engineer. Consults to mining, petroleum, geothermal, aerospace and instrument companies and to governmental agencies; designs, supervises, and interprets data from exploration campaigns; originates, invents, advises regarding hardware and software utilized in mining exploration, petroleum exploration, and geothermal exploration; primarily concerned with electromagnetic exploration; consults on special government problems; clients have included:

Phelps Dodge Corporation
Kennecott Copper Corp.
Noranda Mines Ltd. - Canada
Placer Development Ltd. - Canada
Brenda Mines Ltd. - Canada
Craigmont Mines Ltd. - Canada
Endako Mines Ltd. - Canada
Scurry Rainbow Oil Co. - Canada
Pure Oil Company
Amax Exploration, Inc.
Commonwealth Scientific and Industrial Research Organization, Australia
Colonial Sugar Refining Co., Australia
Sinclair Oil and Gas Co.
United States Steel Corp.
Varian Associates
The Bunker Hill Co.
Peerless Gas and Oil Co.
The U.S. Dept. of Justice
Cyprus Mines Corp.
Morrison-Knudson Co., Inc.
The National Aeronautics and Space Administration
Westinghouse Electric Corp.
Universidade Federal Do Bahia Instituto de Geosciencias E Instituto de Fisico-Brazil
Engenheiros Consultores Associados, S.A. - Brazil
Exxon Corporate Research Laboratory, Newark
Atlantic Richfield Co., Dallas
Greatland Exploration Ltd., Anchorage
McPhar Instrument Corporation, Toronto
Exxon Production Research Laboratory, Houston
Quintana Minerals Corp. Houston
General Electric Corporate Laboratory, Schnectady
CRA Exploration Pty. Ltd., Melbourne
Royal Dutch Shell, Amsterdam
Houston Oil and Gas Corporation, Denver
SERU Nucleaire (Canada) Limitee, Montreal, Canada
Getty Oil Co., Salt Lake City
Anglo American of South Africa, Johannesburg
BP Minerals, Vancouver

1953-1958	Managing Director and Chief Geophysicist, Nucom Ltd. (subsidiary of American Metal Climax Inc.). Supervised geophysical aspects of exploration program involving as many as 275 men; supervised operation of three helicopter-borne electromagnetic prospecting units; supervised gravity, magnetic, electromagnetic surveys; prepared budgets of $500,000 yearly for research and operations; interpreted data from mining geophysical surveys; collaborated in design of airborne, ground and drill hole prospecting systems; prepared reports on surveys and papers for publication in scientific and professional journals.
1949-1953	Managing Director and Chief Geophysicist, McPhar Geophysics Ltd. Directed operations and research of geophysical contracting firm; interpreted data from mining geophysical surveys; supervised staff of forty engineers, technicians, clerical staff; prepared cost estimates for surveys; collaborated in design of airborne, ground and drill hole electromagnetic prospecting systems; prepared reports on surveys and papers for publication in scientific and professional journals.

PUBLICATIONS AND REPORTS:

113 Publications
31 Abstracts
14 Contract Reports

Mainly in geophysical exploration and exploration strategies for minerals and geothermal energy.

Proposal Submitted to

U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, California 94612

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108

TITLE: Research and Technology Development for DOE's Geothermal Reservoir Definition Program

TYPE OF REQUEST: Continuation of Present Contract

PERIOD OF PROPOSAL: December 1, 1984 Through November 30, 1985

CO-INVESTIGATORS: J. N. Moore
D. L. Nielson
S. H. Ward

November 12, 1984

Earth Science Laboratory

University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108
(801) 524-3422

Proposal Submitted to

U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, California 94612

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108

TITLE: Research and Technology Development for DOE's Geothermal Reservoir Definition Program

TYPE OF REQUEST: Continuation of Present Contract

PERIOD OF THIS PROPOSAL: December 1, 1984 Through November 30, 1985

CO-INVESTIGATORS: J. N. Moore
D. L. Nielson
S. H. Ward

S. H. Ward
Stanley H. Ward, Director
Earth Science Laboratory
University of Utah Research Institute

Phillip M Wright
Phillip M. Wright
Technical Vice President
University of Utah Research Institute

November 12, 1984

Proposal Submitted to

U.S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, California 94612

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108

TITLE: Research and Technology Development for DOE's Geothermal Reservoir Definition Program

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CO-INVESTIGATORS: J. N. Moore
D. L. Nielson
S. H. Ward

November 12, 1984

TABLE OF CONTENTS

INTRODUCTION

The work proposed herein is, for the most part, a continuation of fruitful research directions that have been developed over the past year. The majority of the work is directed at delineating productive fractures and fracture systems in geothermal systems. We believe we have made significant progress over the past term of the present contract, but a great deal remains to be done.

SUMMARY OF ACCOMPLISHMENTS AND OVERVIEW OF PROPOSED RESEARCH

During the past contract year, UURI has accomplished a significant amount of research work. A brief summary of results is given in this section along with an indication of work proposed for next year.

Geologic Models of Fractured Geothermal Reservoirs

Our work at Baca has resulted in a structural model of this geothermal system that explains the distribution of observed fracturing. The resurgent doming has caused the upper part of the system to extend, a process that has opened fractures. However, the lower part of the system is in compression, and fractures are scarce. Fluids appear to be carried up from depth in only a few, through-going fractures. Studies of lithology and hydrothermal alteration have also proven fruitful. An alteration zoning pattern has been developed, and one primary conclusion from the alteration mineralogy is that the upper parts of the system are cooler now than they once were.

Additional work at Baca is warranted, and is proposed herein. We would like to study lithology and hydrothermal alteration in units below the Bandelier Tuff, and study possible zoning around some of the fluid entries there. Such studies would help refine our present system model. We would also like to begin application of similar work to other geothermal systems, such as Los Azufres.

We are joining Los Alamos in a joint proposal to OBES to extend the Baca work throughout the Valles caldera. The OBES proposal will include further drilling, and may eventually lead to a series of deeper holes sponsored by the Continental Scientific Drilling Program.

Geochemistry

Our work on drill chip samples donated to us by Union Geothermal from the

Salton Sea geothermal field has developed interesting results. We have shown that there are light hydrocarbons and other organic gases contained in fluid inclusions. Fluid inclusions are microscopic bubbles within mineral grains that are partly occupied by liquids and partly by gases at room temperature. They represent the hydrothermal fluid that formed the particular mineral. In addition to methane, ethane and propane, the Salton Sea fluid inclusions were found to contain both COS and CS_2, which have not been reported before in geothermal systems.

We have preliminary evidence of zoning of gases in the two wells studied. Our proposed research for the coming year would allow us to pursue zoning and other studies that may eventually lead to a better understanding of the chemical evolution of active geothermal systems.

Fracture Detection Using Borehole Electrical Geophysical Techniques

Our work has resulted in development of computer algorithms for modeling the expected electrical anomalies due to fractures in the wall rock beyond a borehole. Appropriate algorithms to do this have not been available before, so our developments have pushed the state of the art ahead measurably. We have modeled the following problems:

(1) Single borehole and cross-borehole resistivity,

(2) Borehole-to-surface resistivity,

(3) Borehole-to-surface and borehole-to-borehole mise-à-la-masse (the fracture itself is energized), and

(4) Surface-to-borehole time domain electromagnetics.

These modeling programs are currently being used to help select an optimum system for detecting fractures that could be implemented in the field. Their use has led to a potentially patentable field system that would deploy electrodes partly down a borehole and partly on the surface to measure a set of electrical data that would give redundant indications of fractures in the wall of a wellbore, and thereby increase confidence in interpretation.

During the coming year, we would like to pursue development of such a surveying system. We would also like to have a more detailed look at several additional electrical techniques that funds were inadequate to study last year.

PROJECT 1

DEVELOPMENT OF GEOLOGIC MODELS OF FRACTURED GEOTHERMAL RESERVOIRS

Cost: $68,035

Background

To date, our work on formulation of geologic models of fractured geothermal reservoirs has concentrated on the extensive subsurface data available from the Baca geothermal system in the Valles caldera, New Mexico. The Baca area is located in the center of the Redondo Dome, the resurgent dome of the Valles caldera. Modeling of the development of this feature has allowed us to predict the depth to the magma body which produced the doming. It has also allowed us to predict the stress environment and resultant fracturing which controls the convection and advection of geothermal fluids. Simply speaking, the formation of the dome produced an area of fracturing related to extension in the upper portion of the structure. This fracturing extends approximately halfway from the surface to the underlying intrusive body. Beneath this zone of extension, compressive stress has resulted in rock of relatively lower permeability and no known fluid entries. An important control on fracture permeability is contributed by the Jemez fault zone, which is an older, reactivated structure. We believe that this fault in fact controls the deep circulation of geothermal fluids and is thus the most important exploration target in the field. To this time, it has not been properly tested by drilling.

Examination and analysis of cuttings and core have revealed a well-defined pattern of hydrothermal alteration in caldera-related felsic volcanics and sediments as well as underlying pre-caldera rocks. The mineralogy and distribution of alteration relative to the active geothermal system can be used to help locate fluid-flow channels and to provide insight into the system's thermal history.

Alteration in the Baca field, from the surface through the base of the Pliocene Paliza Canyon Formation (an interval averaging about 2200 meters in thickness and encompassing all documented thermal fluid entries) can be discussed conveniently in terms of three distinct types: argillic, propylitic and phyllic. Argillic alteration forms a high-level blanket developed principally in formerly permeable, mostly non-welded felsic Quaternary tuffs of post-Bandelier Tuff age. This alteration is characterized by the assemblage smectite, mixed-layer illite-smectite (ordered), quartz and pyrite.

Beneath the argillic zone, the Bandelier Tuff, up to 1800 meters in thickness, the subjacent Lower Tuffs and the underlying Paliza Canyon Formation are pervasively propylitized. In the thick, densely welded Bandelier, propylitization is very weak. In the underlying, poorly welded Lower Tuffs, intensity of propylitization is weak overall but locally moderate, reflecting greater initial permeability. Strong propylitization is confined to the relatively reactive intermediate-composition volcanics of the Paliza Canyon Formation in which the alteration may partially pre-date the active geothermal system.

Within the propylitic zone, active thermal fluid channels, whether faults or restricted stratigraphic aquifers, are commonly but not invariably associated with intense phyllic alteration. Sericite (or micaceous illite), quartz and pyrite are the principal constituents of these phyllic zones; chlorite, calcite and potassium feldspar are locally present. Results of alteration studies in Baca-18 show a phyllic assemblage characteristic of thermal fluid production in nearby wells. However, the alteration has been complete enough that the zone has been completely sealed. At present, we cannot distinguish between zones which sustain production and those which have been effectively sealed by the alteration process.

The distribution of several alteration phases in the Baca wells indicates that relatively cool rocks at high levels in the geothermal system have been hotter in the past. For example, ordered, mixed-layer illite-smectites, believed to form at temperatures exceeding about 100°C, are presently found in near-surface Baca rocks at temperatures as low as 30°C. This relationship indicates either that isotherms have collapsed due to cooling of the system, that they have retreated without overall heat loss due to structural uplift, or that the system has shifted laterally.

Our work to this time has identified three types of permeable conduits in the Baca geothermal system. These can be categorized as follows:

1. Former fluid channels sealed by alteration. These include both stratigraphically and structurally controlled fluid entries;
2. Open conduits which do not produce geothermal fluids. Again, these are both stratigraphic and structural intervals and are characterized as lost circulation zones. These permeable zones do not communicate with the reactivated fault zones which are thought to be the principal fluid conduits in the system;
3. Geothermal production zones. All commercial production zones apparently are structurally controlled while subcommercial zones are controlled by both structures and stratigraphic intervals.

The processes investigated here are similar to those in other geothermal systems. We propose to continue studying the processes at Baca and take advantage of samples available from other fracture-controlled systems. These other systems include Los Azufres, Mexico; Coso, California; Wendel-Amedee, California; Yellowstone National Park, Wyoming, and Ascension Island, South

Atlantic Ocean. In addition, appropriate samples may become available through DOE's Cascades drilling program.

Publications

The following publications have been produced as a part of this project to date.

Hulen, J. B., and Nielson, D. L., 1982, Stratigraphic permeability in the Baca geothermal system, Redondo Creek area, Valles caldera, New Mexico: Geothermal Resources Council Transactions, v. 6, p. 27-30.

Hulen, J. B., and Nielson, D. L., 1983, Stratigraphy of the Bandelier Tuff and characterization of high-level clay alteration in borehole B-20, Redondo Creek area, Valles caldera, New Mexico: Geothermal Resources Council Transactions, v. 7, p. 163-168.

Hulen, J. B., and Nielson, D. L., in preparation, Hydrothermal alteration in the upper portion of the Valles caldera, New Mexico: Journal of Geophysical Research, Special Volume on the Valles caldera.

Nielson, D. L., and Hulen, J. B., 1983, Geologic model of the Baca geothermal reservoir, Valles caldera, New Mexico: Proceedings Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, p. 145-150.

Nielson, D. L., and Hulen, J. B., 1984, Internal geology and evolution of the Redondo Dome, Valles caldera, New Mexico: Jour. Geophys. Research Special volume on calderas and associated igneous rocks, v. 89, p. 8695-8711.

Nielson, D. L., and Hulen, J. B., 1984, Results of deep drilling in the Valles caldera, New Mexico (abstract): Invited paper, International Symposium on Continental Drilling, Tarrytown, N.Y.

Nielson, D. L., and Hulen, J. B., in press, Observations in an active hydrothermal system through deep drilling: Valles caldera, New Mexico: Columbia University Press, International Symposium on Observation of the Continental Crust Through Drilling.

Scope of Work

1.1 Lithology and Alteration at Baca. We will determine the details of the lithologies and alteration mineralogy of the units beneath the Bandelier Tuff in the Baca project area. The Paliza Canyon Formation contains several important fluid entries which have not been characterized at this time.

1.2 Refine Models. These data will be used to refine our models of the development and preservation of fracture permeability.

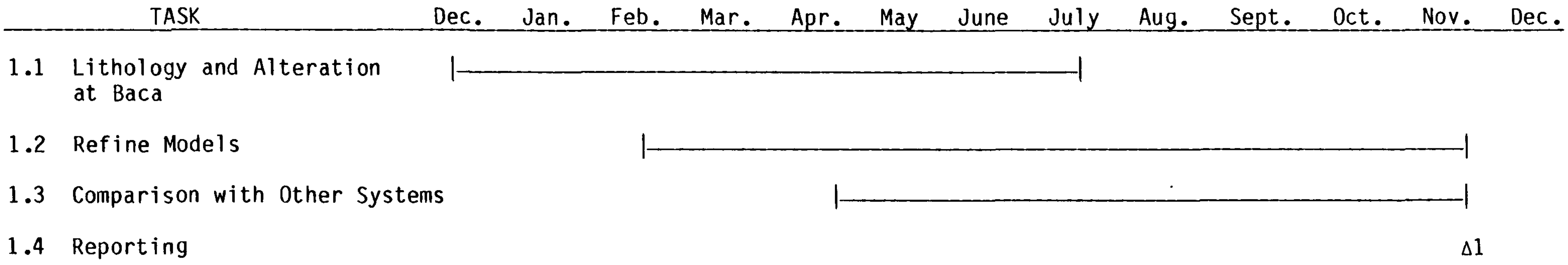
1.3 Comparison with Other Systems. As appropriate, these data will be compared with other fracture controlled geothermal systems.

1.4 Reporting. The results of our findings will be presented at a professional meeting and a report will be prepared which will be submitted for publication in a professional journal.

1. DEVELOPMENT OF GEOLOGIC MODELS OF FRACTURED GEOTHERMAL RESERVOIRS

SCHEDULE AND DELIVERABLES

FY 1985



Deliverables

1. Technical report or journal publication

DEVELOPMENT OF GEOLOGIC MODELS OF FRACTURED GEOTHERMAL RESERVOIRS

BUDGET

		Days		Amount
A.	Salaries and Wages:			
	1. Senior Personnel		$20,753	
	J. B. Hulen	90		
	D. L. Nielson	46		
	2. Other Personnel		1,824	
	Staff Analyst	5		
	Draftsperson	10		
	Secretary	10		
	Total Salaries and Wages			$22,577
B.	Employee Benefits:			
	1. .39 of A.1 & A.2			8,805
C.	Permanent Equipment:			-0-
D.	Expendable Supplies and Equipment:			
	1. Drafting Supplies		$ 250	
	2. Office Supplies		125	
	Total Expendable Supplies and Equipment			375
E.	Travel:			
	1. Trips to Los Alamos (2)			1,620
F.	Reports and Publications:			
	1. Printing, Binding and Distribution Costs			475
G.	Data Processing:			
	1. PRIME 400			500
H.	Other Costs:			
	1. X-ray Analyses		$4,200	
	2. Geochemical Analyses		1,500	
	Total Other Costs			5,700

I.	Total Direct Costs:	$40,052
J.	Indirect Costs:	
	1. .45 of "I"	18,023
K.	General and Administrative Costs:	
	1. .145 of "I"	5,808
L.	Total Direct, Indirect and G & A Costs:	$63,883
M.	Fee:	
	1. .065 of "L"	4,152
N.	Total Project Costs:	$68,035

PROJECT 2

GEOCHEMICAL STUDIES OF DRILL CHIP SAMPLES FROM GEOTHERMAL AREAS

Costs: Project Work: \$67,210 Equipment: \$14,900

Background

Gases are important components of geothermal fluids and may exert considerable influence on both the fluid's behavior and the formation of secondary minerals. Analyses of fluid samples discharged from deep geothermal wells have revealed widely variable gas contents and compositions. CO_2 and H_2S are the predominant gases in most hot water- and vapor-dominated geothermal systems (Ellis, 1979). However, hydrocarbons (mainly CH_4), H_2S, NH_3, N_2, and H_2 may be significant, particularly in sedimentary terrains (Ellis, 1979).

Minor concentrations of other hydrocarbons and sulfur compounds have also recently been identified in geothermal waters. Long chain hydrocarbons, including a variety of normal and branched alkanes, alkenes, and cyclic compounds have been found in geothermal systems associated with sedimentary and volcanic rocks (Stoiber et al., 1971; Gunter, 1978; Ellis, 1979; Nehring and Truesdell, 1979; Nehring et al., 1982). In addition, our data suggest that gases in the sub-system C-O-S, including SO_2, COS and CS_2, may be present and locally abundant in some geothermal fluids (Adams and Moore, in prep.). However, detailed investigations on the occurrence, origin and behavior of these minor gases in geothermal systems are lacking.

Current Research

Our interest in the gas contents of geothermal fluids developed as a result of our studies on fluid-mineral equilibria and trace element distributions in active geothermal systems (Capuano and Cole, 1982; Christensen et al., 1983; Moore et al., 1983). These investigations, as well as those by Gutierrez and Aumonto (1982) at Los Azufres and McKibben (1979) at the Salton Sea, among others, provide abundant evidence that the compositions of the geothermal fluids in many active systems must have varied widely during their evolution. The composition of the paleogeothermal fluids can be estimated indirectly from the hydrothermal minerals through the application of activity diagrams (Helgason, 1967; Bird et al., 1984) or directly from analyses of the solutions trapped within fluid inclusions during alteration (Roedder, 1972). Although thermometric measurements have been made on fluid inclusions from active geothermal systems, chemical analyses of the solutions contained within them are lacking. The need to obtain detailed information on the fluid compositions during alteration, and a better understanding of gas distributions in geothermal fluids in general prompted us to sample two wells in the Salton Sea geothermal field drilled by the Union Oil Company. These wells penetrate a thick sequence of increasingly indurated deltaic sediments. Our petrographic observations indicate that the reservoir rocks have had a relatively simple thermal history and that temperatures near the base of the wells must have exceeded 225-250°C during alteration.

Fluid inclusions in samples of the drill chips were thermally decrepitated at temperature of 375°C and analyzed by a combined gas chromatograph/mass spectrometer. CO_2 was the most abundant gas found, comprising from 36 to 97 mole percent of the total gas. The remaining gases include COS, CS_2, H_2S, SO_2 and the aliphatic hydrocarbons, methane, ethane, and propane. The presence of COS and CS_2 is particularly interesting because these gases have not been reported from other geothermal systems. Both COS and CS_2 have, however, been identified in soil gases collected over fossil hydrothermal deposits and appear to result from weathering of sulfides (Gardner et al., 1984). Their presence in the Salton Sea samples suggests that these gases may also form where hot waters contact organic-rich sedimentary rock. Unsaturated hydrocarbons and NH_3 were not detected. The compositions of the gases in terms of their molecular proportions are presented in Table 1.

Despite the overall similarities in the alteration patterns in the two wells, the gas compositions indicate that the fluid chemistries varied both within and between the wells. In well A carbon and sulfur vary inversely (Table 1) while the total carbon content increases with increasing total gas, suggesting that at least two populations of inclusions are present. The two populations can be distinguished on the basis of $\Sigma C/\Sigma S$ ratios. In contrast, carbon and sulfur vary proportionally in well B and the gases contain H_2S, indicating that different fluids or a third fluid was involved in the alteration here.

Figures 1a and 1b summarize the distribution of hydrocarbons in the two wells. A significant feature of these data is the relatively low ratio of methane to the total hydrocarbon concentration in well A. These data are at variance with the "usual" hydrocarbon ratios of both geothermal steam (Ellis, 1979) and naturally occurring hydrothermal solutions. Fluid inclusions have been analyzed for hydrocarbons in volcanic (Petersil'ye and Pavlova, 1976; Sommer, 1974), igneous (Konnerup-Madsen et al., 1979; Andreeva and Molchanov, 1978), and metamorphic rocks (Voytov et al., 1971), and in hydrothermal quartz (Murray, 1957; Naumov et al., 1976; Kvenvolden and Roedder, 1971). These studies have shown that methane is the dominant hydrocarbon and that the hydrocarbons were produced by reduction of CO_2 and pyrolysis of methane rather than by degradation of organic matter. While the reasons for the low methane ratios in the Salton Sea samples are not yet clear, the consistency of our data suggests that they are not simply a result of analytic errors or gas

TABLE 1

WELL A - MOLECULAR FRACTIONS OF TOTAL GAS

($x\ 10^{-3}$)

Depth	CS_2	SO_2	COS	H_2S	C_1	C_2	C_3	CO_2
790-820	12	108	15	0	59	48	96	364
820-850	371	0.2	0	0	89	50	83	408
1120-1150	17	43	0	0	94	150	246	449
1180-1210	26	66	0	0	50	116	105	638
2000-2020	28	28	0	0	42	270	178	454
2020-2040	16	6	4	0	111	167	75	620
2220-2240	35	51	0	0	64	208	122	527
3160-3180	40	164	29	0	24	43	40	660
3200-3220	43	22	0	0	86	194	184	472
3440-3460	26	164	0	0	26	126	120	538
3900-3920	36	133	22	0	2	21	16	770
3920-3940	30	85	23	0	60	91	120	581
4060-4080	13	55	24	0	20	118	103	667
4160-4180	31	53	15	0	58	166	135	542
4520-4540	7	123	31	0	148	211	144	337
4660-4680	17	54	15	0	16	152	150	537
4960-4980	18	35	16	0	82	136	118	594
5100-5120	58	54	0	0	8	80	55	746

WELL B - MOLECULAR FRACTIONS OF TOTAL GAS

($x\ 10^{-3}$)

Depth	CS_2	SO_2	COS	H_2S	C_1	C_2	C_3	CO_2
100-130	1	1	0	23	39	7	17	912
560-610	2	0	0	0	37	7	69	885
790-820	0	0	0	0	0	0	13	987
910-940	0	442	0	0	0	0	205	353
1060-1090	67	1	12	0	28	15	12	65
1060-1090	70	1	13	0	2	0.2	1	910
1360-1390	22	0	3	2	30	2	18	923
1660-1690	0	0	0	0	296	70	240	390
1960-1990	49	15	11	0	0	19	9	897
2380-2410	0	148	0	0	59	110	22	660
2590-2620	15	0	3	2	11	1	3	966
2740-2770	44	51	19	0	3	10	66	859
2890-2920	12	7	12	12	8	40	46	864
3010-3040	86	23	164	134	17	88	107	381
3190-3220	0	0	0	0	159	42	58	742
3400-3420	21	28	19	0	2	12	14	903
3600-3660	105	14	3	0	79	2	32	164
3820-3840	42	14	17	0	0	21	10	896
3940-3960	15	50	30	43	1	12	11	841
4220-4240	16	73	12	0	0	6	0	945

WELL A

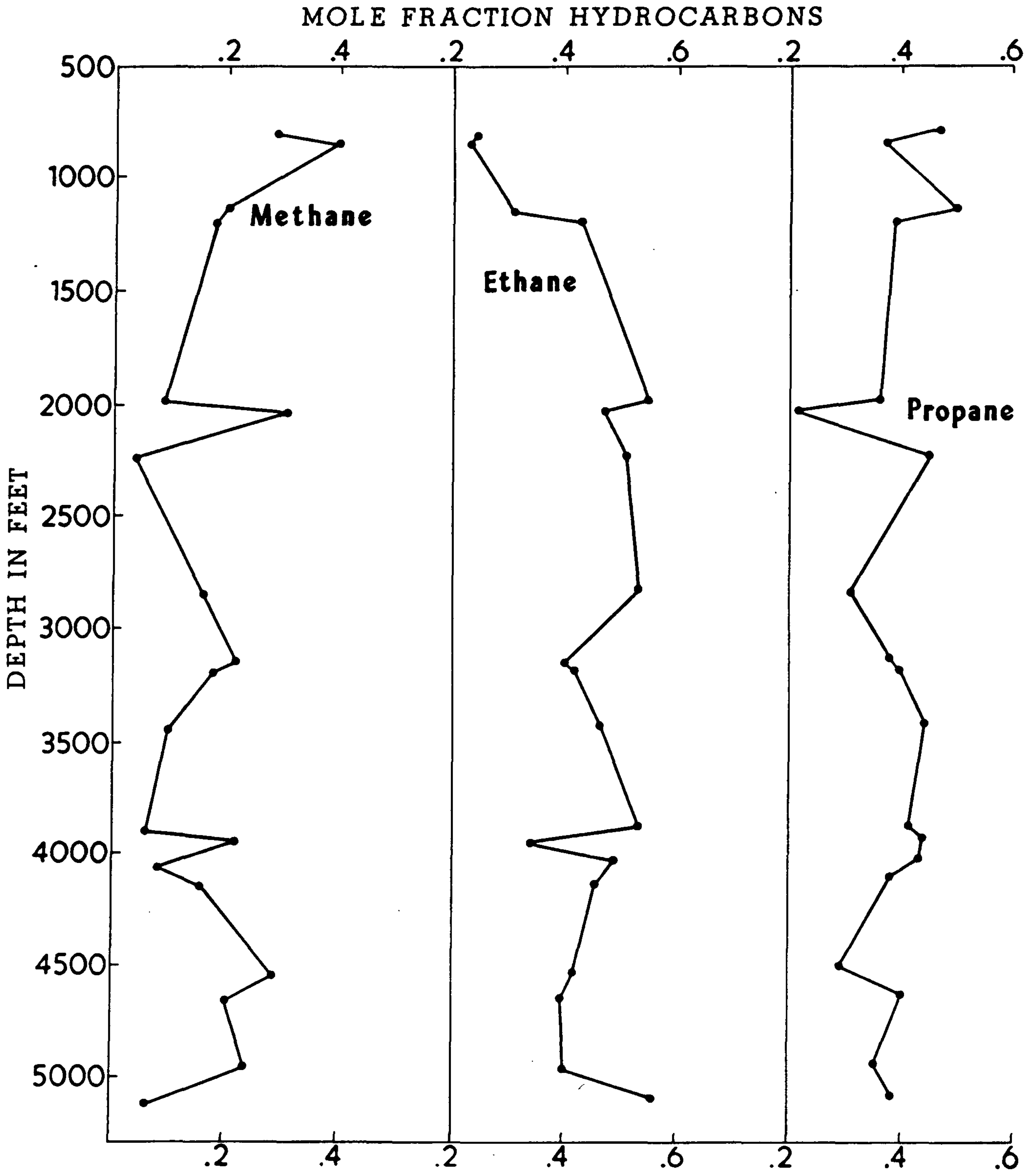


Figure 1a

WELL B

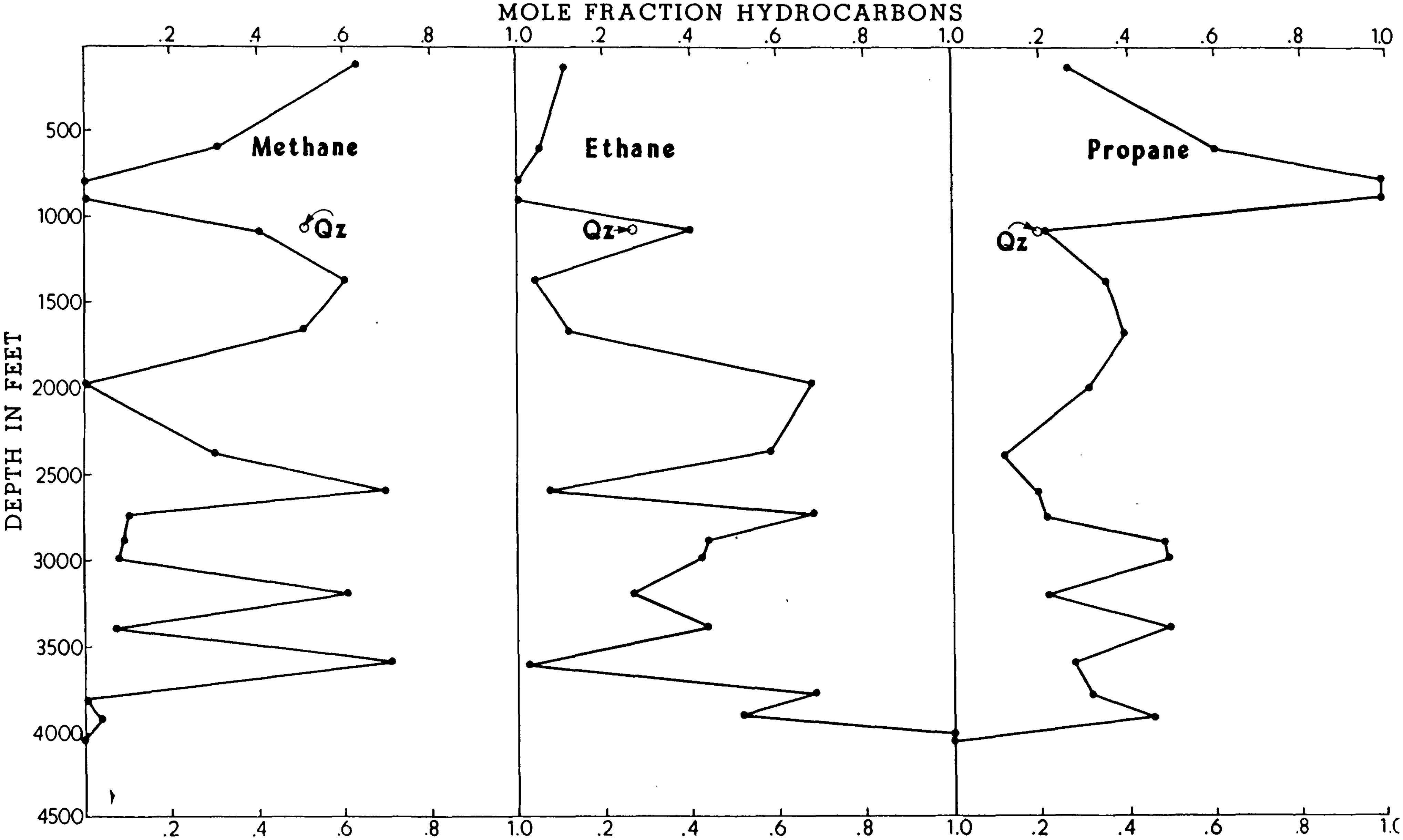


Figure 1b

loss. We are currently investigating other possibilities.

Proposed Research

The data we have collected to date indicate that fluid inclusion studies do indeed offer a promising approach to unraveling the chemical evolution of active geothermal systems. These data, however, also emphasize the need for detailed microscopic studies of the inclusions in the altered rocks as well as a better understanding of the relationship between gas chemistry, temperature, mineralogy, abundance and maturation of organic material and fluid chemistry.

The investigations proposed here are directed toward this goal and will include both petrographic and chemical investigations. It is our intention to take additional samples from the Salton Sea wells for this work. However, other thermal systems, such as Los Azufres or Meager Creek, where core is available would be equally suitable.

To help further this research, we are requesting funds to purchase a petrographic microscope and heating stage specifically suited to fluid inclusion work. The equipment would cost $14,900, and this amount is included in the budget presented here.

References

Andreeva, T. A., and Molchanov, V. I., 1978, Hydrogen and hydrocarbon gases in the composition of the gaseous inclusions in rocks: Sov. Geol. Geophys., v. 19, p. 24-29.

Aleksandrova, E. S., Bannikova, L. A., and Sushchevskaya, T. M., 1980, Errors in gas analysis in thermal explosion of inclusions: Geochem. Int., v. 17, p. 66-71.

Bird, D. K., Schiffman, P., Elders, W. A., Williams, A. E., and McDowell, S. D., 1984, Calc-silicate mineralization in active geothermal systems: Econ. Geol., v. 79, p. 671-695.

Capuano, R. M., and Cole, D. R., 1982, Fluid-mineral equilibria in a high temperature geothermal system, Roosevelt Hot Springs, Utah: Geochim. Cosmochim. Acta, v. 46, p. 1353-1364.

Christensen, O. D., Capuano, R. M., and Moore, J. N., 1983, Trace element distribution in an active geothermal system, Roosevelt Hot Springs Thermal Area, Utah: J. Volcanol. Geotherm. Research, v. 16, p. 99-129.

Ellis, A. J., 1979, Explored geothermal systems, in Geochemistry of Hydrothermal Ore Deposits, H. L. Barnes ed., Wiley, New York, p. 632-683.

Gardner, M. D., Kelser, S. E., Creech, M., and Cloke, P. L., 1984, Factors affecting sulfur gas anomalies in overburden: Exploration for ore deposits of the North American Cordillera: Symposium of the Assoc. of Exploration Geochemists, Abstracts with Program, p. 40.

Gunter, B. D., 1978, C1-C4 hydrocarbons in hydrothermal gases: Geochim. Cosmochim. Acta, v. 42, p. 137-139.

Gutierrez, A., and Aumento, F., 1982, The Los Azufres, Michoacan, Mexico, geothermal field, in J. Lavigne and J. B. W. Day (guest editors), Hydrogeothermal studies, 26th International Geological Congress, Jour. Hydrology, v. 56, p. 137-162.

Helgason, H. C., 1967, Solution chemistry and metamorphism, in Researches in Geochemistry, Vol. 2, P. H. Abelson, ed., New York, Wiley, p. 362-402.

Konnerup-Madsen, J., Larsen, E., and Rose-Hansen, J., 1979, Hydrocarbon-rich fluid inclusions in minerals from the alkaline Ilimaussag intrusion, South Greenland: Bull. Mineral., v. 102, p. 642-653.

Kvenvolden, K. A., and Roedder, E., 1971, Fluid inclusions in quartz crystals from Southwest Africa: Geochim. Cosmochim. Acta, v. 35, p. 1209-1229.

McKibben, M. A., 1979, Ore minerals in the Salton Sea geothermal system, Imperial Valley, California, U.S.A.: Inst. of Geophys. and Planet. Phys. Univ. of California, Riverside, UCR/IGPP-79/17, 90 p.

Moore, J. N., Adams, M. C., and Stauder, T., 1983, Geochemistry of the Meager Creek geothermal field, British Columbia, Canada: Geotherm. Res. Council, Trans., v. 7, p. 315-319.

Murray, R. C., 1957, Hydrocarbon fluid inclusions in quartz: Bull. Am. Ass. Pet. Geol., v. 41, p. 950-956.

Naumov, G. B., Mironova, O. F., and Naumov, V. B., 1976, Carbon compounds in inclusions in hydrothermal quartz: Geochem. Int., v. 13, p. 164-171.

Nehring, N. L., and Truesdell, A. H., 1979, Hydrocarbon gases in some volcanic and geothermal systems: Geotherm. Res. Council, Trans., v. 2, p. 483-486.

Nehring, N. L., Des Marais, D. J., and Truesdell, A. H., 1982, Thermal decomposition of hydrocarbons in the Cerro Prieto, Mexico, geothermal reservoir: Geotherm. Res. Council, Trans., v. 6, p. 305-307.

Pezersil'ye, N. A., and Pavlova, M. A., 1976, Organic compounds in volcanic and metamorphic rocks: Int. Geol. Rev., v. 20, p. 339-344..

Roedder, E., 1972, Composition of fluid inclusions: U.S. Geol. Surv. Prof. Paper 440 JJ, 164 p.

Sommer, M. A. II, 1974, Analysis and interpretation of the gases released from various sites in rocks and minerals: Diss. Abstr. Int., v. 35, p. 897b.

Stoiber, R. E., Leggett, D. C., Jenkins, T. F., Murrman, R. P., and Rose, W. I., Jr., 1971, Organic compounds in volcanic gas from Santiaquito Volcano, Guatemala: Geol. Soc. Amer. Bull., v. 87, p. 2299-2302.

Voytov, G. I. Shirokova, I. Y, Pinisenko, V. Y., Katsonis, A. N., and Spektor, I. L., 1971, Gas composition in quartz veins of the Krivay Rog amphibolite series: Acid. Sci. UUSR, Dakl., Earth Sci. Sect., v. 207, p. 233-236.

Scope of Work

Task 2.1 Sample Preparation and Analyses. The minerals selected for study will be carefully cleaned of organic material and crushed prior to analysis. The samples will be analyzed for alkane and alkene hydrocarbons, H_2O, CO_2, CS_2, COS, SO_2 and H_2S using a helium carrier gas. In addition, the concentrations of long chain hydrocarbons (C_5-C_{20}), aromatics, carboxylic acids, NH_3 and N_2, will be determined in selected samples. These analyses will help to evaluate any hydrocarbon decomposition reactions. The gas analyses will be conducted by Mr. David Osborne of MIDECO using a combined gas chromatograph/mass spectrometer. These facilities are housed in Salt Lake City.

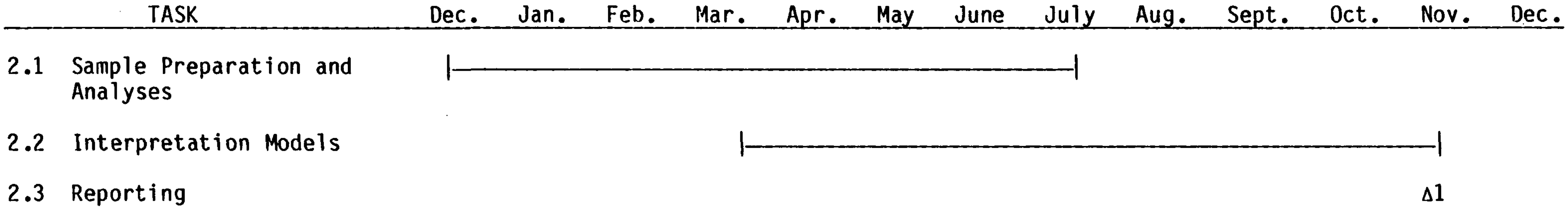
Task 2.2 Interpretation. The data obtained from this work will be evaluated for its exploration significance and integrated with petrologic and thermal data to develop an evolutionary model of the thermal system.

Task 2.3 Reporting. A technical report will be written on the work and at least one presentation will be made before a professional society. The material would be submitted to a journal for publication.

2. GEOCHEMICAL STUDIES OF DRILL CHIP SAMPLES FROM GEOTHERMAL AREAS

SCHEDULE AND DELIVERABLES

FY 1985



Deliverables

1. Technical report or journal publication

GEOCHEMICAL STUDIES OF DRILL CHIP SAMPLES FROM GEOTHERMAL AREAS

BUDGET

	Days		Amount
A. Salaries and Wages:			
1. Senior Personnel		$15,223	
M. C. Adams	62		
J. N. Moore	54		
2. Other Personnel		2,394	
Staff Analyst	3		
Draftsperson	5		
Secretary	5		
Technician	5		
3. Wages - Professional		7,798	
Research Assistant	163		
Total Salaries and Wages			$25,415
B. Employee Benefits:			
1. 39.0% of A.1 and A.2		$6,871	
2. 9.5% of A.3		741	
Total Employee Benefits			7,612
C. Permanent Equipment: (See Attachment 1 - Equipment Request)			-0-
D. Expendable Supplies and Equipment:			
1. Drafting Supplies		$185	
2. Office Supplies		50	
Total Expendable Supplies and Equipment			235
E. Travel:			
1. Two trips to DOE/SAN			1,230
F. Reports and Publications:			
1. Printing, Binding and Distribution Costs			475
G. Data Processing:			
1. PRIME 400 Computer			600

H. Other Costs:	
1. Gas Analyses	4,000
I. Total Direct Costs:	$39,567
J. Indirect Costs:	
1. 45.0% of "I"	17,805
K. General and Administrative:	
1. 14.5% of "I"	5,737
L. Total Direct, Indirect and G & A Costs:	$63,109
M. Fee:	
1. 6.5% of "L"	4,101
N. Total Project Costs:	$67,210

ATTACHMENT 1

Equipment Request

The following equipment is requested to support the task: "Geochemical Studies of Drill Chip Samples from Geothermal Areas".

Fluid Inclusion Microscope	$14,900*

* Includes 6.5% Fee

PROJECT 3

FRACTURE DETECTION USING BOREHOLE ELECTRICAL GEOPHYSICAL TECHNIQUES

Cost: $67,305 Equipment: $50,320

Background

In FY 84, we stated the background for our studies under this project as follows:

"The most formidable problem in exploration for geothermal resources is precise location of fractures and fracture zones. Dry holes which have missed fractures or fracture zones are expensively plentiful throughout the geothermal industry. To attempt to alleviate this problem, we propose an exploratory study of means to detect fractures and fracture zones via electrical systems deployed in a single well, deployed partly in one well and partly in another, and deployed partly on surface and partly in one well. This class of systems is referred to as borehole geophysics and is distinct from well logging in that a large separation between transmitter and receiver permits exploration to hundreds of meters from a well."

We addressed the problem of detection of fracture zones by conducting numerical model studies of the anomalies to be expected with the following techniques:

1) single-borehole and cross-borehole resistivity,
2) borehole-to-surface resistivity,
3) borehole-to-surface and borehole-to-borehole mise-à-la-masse, and
4) surface-to-borehole time-domain electromagnetics.

We have, via a thorough literature survey, ruled out the radar and induced-polarization techniques. Manpower and financial resources did not permit study of the magnetometric resistivity (MMR) technique beyond the literature survey. We did identify, via our literature survey, another technique that warrants study, and that is the VLF frequency-domain electromagnetic technique.

Accomplishments in FY 1984

Literature Survey. Our first concern was early completion of a literature survey of all borehole electrical geophysical techniques regardless of application. The report by Ross and Ward (1984) documents our findings. Minor updates to that document appear in the more detailed reports referenced below.

Single-Borehole and Cross-Borehole Resistivity Modeling. Prior to award of the subject contract, (using in-house funds) Yang and Ward (1985a) released a study of single-borehole and cross-borehole numerical resistivity modeling. Their abstract follows.

"Hole-to-hole resistivity measurement is a useful method of detecting deeply buried fractures and ore deposits in the subsurface. With drilling costs continually rising, there is a growing need for developing methods of borehole geophysics such as this. In this study, we present theoretical results relating to detection of thin oblate spheroids and ellipsoids with arbitrary attitude.

If we assume that individual fractures within a fracture zone are connected to each other and are of finite lateral and vertical extent, then we can model the fracture zone as a thin conductive oblate ellipsoid or spheroid with arbitrary orientation of the major axis. Detection of such deeply buried fracture zones is the object of this study. In this study, the effects of the surface of the earth are neglected and the body is assumed to be enclosed within an infinite homogeneous mass. The surface of the body is divided into a series of subsurfaces, and a numerical solution of the Fredholm integral equation is applied. Once a solution for the surface charge distribution is determined, the potential can be specified anywhere by means of Coulomb's law. The theoretical model results indicate that cross-borehole resistivity measurements are a more effective technique than single-borehole measurements for delineating resistivity anomalies in the vicinity of a borehole. In some cases, the depth to the center of the body and the dip and strike of the major axes of the body can be estimated."

Borehole-to-Surface Resistivity Modeling. Subsequent to the award of the subject contract, Yang and Ward (1985b) released a study of borehole-to-surface numerical modeling. They found that this method could provide useful information on the attitude and the depth to the center of a conductive oblate spheroid. Only crude information could be provided on the lateral location of the center of the spheroid.

Borehole-to-Surface and Borehole-to-Borehole Mise-à-la-masse . Beasley and Ward (1984) recorded a study of the mise-à-la-masse method applied to the detection of conductive fracture zones when potential measurements are made either on the surface or in adjacent boreholes. We quote from their abstract.

"A numerical scheme applying the method of integral equations has been developed for borehole-to-borehole and borehole-to-surface modeling of the apparent resistivity (ρ_a) response of a thin conductive body in a half-space; the inhomogeneity simulates a geothermal fracture zone. The algorithm is applicable for the direct current case when the buried electrode is either inside (mise-à-la-masse) or outside (near-miss) of the body. In implementing the scheme, the integral equation is transformed into a matrix equation as a result of discretizing the inhomogeneity into rectangular subcells. All properties are assumed to be constant within each subcell. The rectangular subcells are used throughout execution of the algorithm.

The computed surface and subsurface apparent resistivity responses are examined for similar bodies with different orientations: (1) vertical, (2) horizontal, (3) dipping at 60°, and (4) dipping at 30°. The different bodies produce apparent resistivity cross-section plots which differ little from each other with the exception of orientation. In plan view, estimates of orientation, areal extent, and dip can often be made. The maximum depth at which a body can be located and still produce a detectable surface anomaly is dependent upon the buried electrode position and contrast in conductivity. Locating the buried electrode just outside of the body does not significantly alter the results from those of when the electrode is embedded in the inhomogeneity."

Surface-to-Borehole Time-Domain Electromagnetics. West and Ward (1984) analyzed the application of the time-domain electromagnetic (TEM) method to detection of fracture zones. The transmitting coil, of necessity, was restricted to the surface of the earth but the receiver was placed in boreholes adjacent to the fracture zone. Their abstract follows.

"Borehole geophysical methods can be very useful in the detection of subsurface fracture zones and mineral deposits which are nearby, but not intersected by boreholes. One electrical borehole technique which can be applied to this problem is the surface-to-borehole transient electromagnetic (TEM) method. This study provides modeling results of the borehole TEM responses of a fracture zone that is contained in a conductive host and energized by a large-loop transmitter. A preliminary assessment of the detectability of the fracture zone is presented and directions for future research efforts are defined.

A conductive, horizontal, tabular body in a homogenous half-space was chosen to simulate a 3-D fracture zone composed of individual, interconnected fractures. Theoretical borehole TEM responses for several models of practical interest were computed using a direct integral-equation formulation. The anomalous TEM response (secondary response) is the result of a complex interaction between vortex and galvanic currents within the body. Distortion of the secondary response by the conductive host effects does not affect the interpretation of the body depth but it does lead to erroneous estimates of the conductivity and the size of the body. Increasing the host resistivity decreases the host effects and increases the response of the body, while decreasing body-borehole separation and body depth increase the secondary response. The decrease in the vortex response due to decreasing transmitter-body coupling is offset by an increase in the galvanic response at late times; however this phenomenon is model-dependent.

This study indicates much promise for the borehole TEM method but the application of the technique for fracture detection in a geothermal environment is limited by the lack of existing hardware and limited modeling capabilities. Future research should concentrate on resolving these problems by developing: (1) high-temperature, large-moment borehole magnetic sensors which can withstand the harsh geothermal environment, (2) high-power, rapid turn-off transmitters to increase the ratio of signal to natural noise, thereby increasing the radius of detection of the tool, and (3) efficient computational schemes capable of modeling arbitrarily-oriented, 3-D bodies in a multi-layered earth in order to improve the interpretational capability of the TEM technique."

Problems Identified, FY 84

In the above studies, we found that the anomalies with borehole-to-surface and cross-borehole methods were not always large. Anomalies with the mise-à-la-masse and TEM borehole geophysical methods were sometimes larger.

We have not, however, analyzed the ratio of signal to noise for any of the methods and this needs to be done before the feasibility of application of any one of the techniques can be evaluated. Noise here must include effects of topography and random or ordered variations in the resistivity of the host medium in which the fracture zones occur. It must also include the effects of drill casing plus natural and artifical field electromagnetic noise.

Sensors capable of withstanding the hostile environment of a high-temperature geothermal well have not been identified for any of the methods, although we believe this to be much less of a problem for resistivity techniques than for electromagnetic techniques which include TEM, VLF, and MMR.

Significant Technology Invented

We believe that our research has led to a potentially patentable multi-array borehole resistivity method which is described in the following pages.

Multi-Array Borehole Resistivity System

The potential invention relates to a means of converting a conventional long lateral array used in well logging (current electrodes A_B and B_∞) to a multi-array system capable of providing hole-to-surface ($A_B B_\infty M_S N_S$), and surface-to-borehole ($A_S B_\infty M_B N_B$) measurements. Rapid sequencing of electrode combinations is necessary so that all measurements are made before the logging sonde has moved significantly down the borehole.

The following sequence of measurements is envisioned:

1. $B_\infty A_B M_B N_B$ long lateral
2. $B_\infty A_B M_S(-4) N_S(-3)$ borehole-to-surface
3. $B_\infty A_B M_S(-3)(N_S)(-2)$ borehole-to-surface
4. $B_\infty A_B M_S(-2) N_S(-1)$ borehole-to-surface

5. $B_\infty A_B M_S(-1)N_S(0)$ borehole-to-surface
6. $B_\infty A_B M_S(0)N_S(1)$ borehole-to-surface
7. $B_\infty A_B M_S(1)N_S(2)$ borehole-to-surface
8. $B_\infty A_B M_S(2)N_S(3)$ borehole-to-surface
9. $B_\infty A_B M_S(3)N_S(4)$ borehole-to-surface
10. $B_\infty A_S(-4)M_B N_B$ surface-to-borehole
11. $B_\infty A_S(-3)M_B N_B$ surface-to-borehole
12. $B_\infty A_S(-2)M_B N_B$ surface-to-borehole
13. $B_\infty A_S(-1)M_B N_B$ surface-to-borehole
14. $B_\infty A_S(0)M_B N_B$ surface-to-borehole
15. $B_\infty A_S(1)M_B N_B$ surface-to-borehole
16. $B_\infty A_S(2)M_B N_B$ surface-to-borehole
17. $B_\infty A_S(3)M_B N_B$ surface-to-borehole
18. $B_\infty A_S(4)M_B N_B$ surface-to-borehole

Because logging speeds are typically 10 m/minute, it is necessary to switch through all of these 18 electrode connections in less than 6 seconds so that the logging sonde has not moved through more than 0.1 m during a sequence.

Referring to Figure 2, the electrodes A_S, M_S, and N_S can be in a single section through the borehole for section surveys (electrode locations -4 through +4) or deployed offset from the borehole for azimuth surveys (electrode locations a through h). The section survey in the surface-to-hole measuring mode is especially useful for determining depth to the center of the body while the azimuth survey is useful for determining the direction to the body from the borehole and the attitude of the body. The hole-to-surface measurement is best for locating the lateral position of the body.

The mise-a-la-masse method is also accomodated by the multi-array. When the electrode A_B lies in the body, the body is directly energized. Then measurements of potential via $M_S N_S$ yield the conventional mise-à-la-masse result.

If more than one borehole is available, then cross-borehole measurements are also facilitated and mise-à-la-masse potential measurements can then be made subsurface as well as surface. Figure 3 illustrates a two borehole multi-array. Rapid switching between all electrode pairs is then generalized from that presented earlier.

With all of the electrode positions used, electrical geotomography can be used in interpretation. We visualize three-dimensional data inversion to effect geotomographic interpretation.

The invention is the concept of a multi-array borehole geophysical survey, the layout of electrodes at surface each connected to a switch at the logging truck, and the concept of rapid switching of current and potential electrodes. These items are considered to be new and patentable.

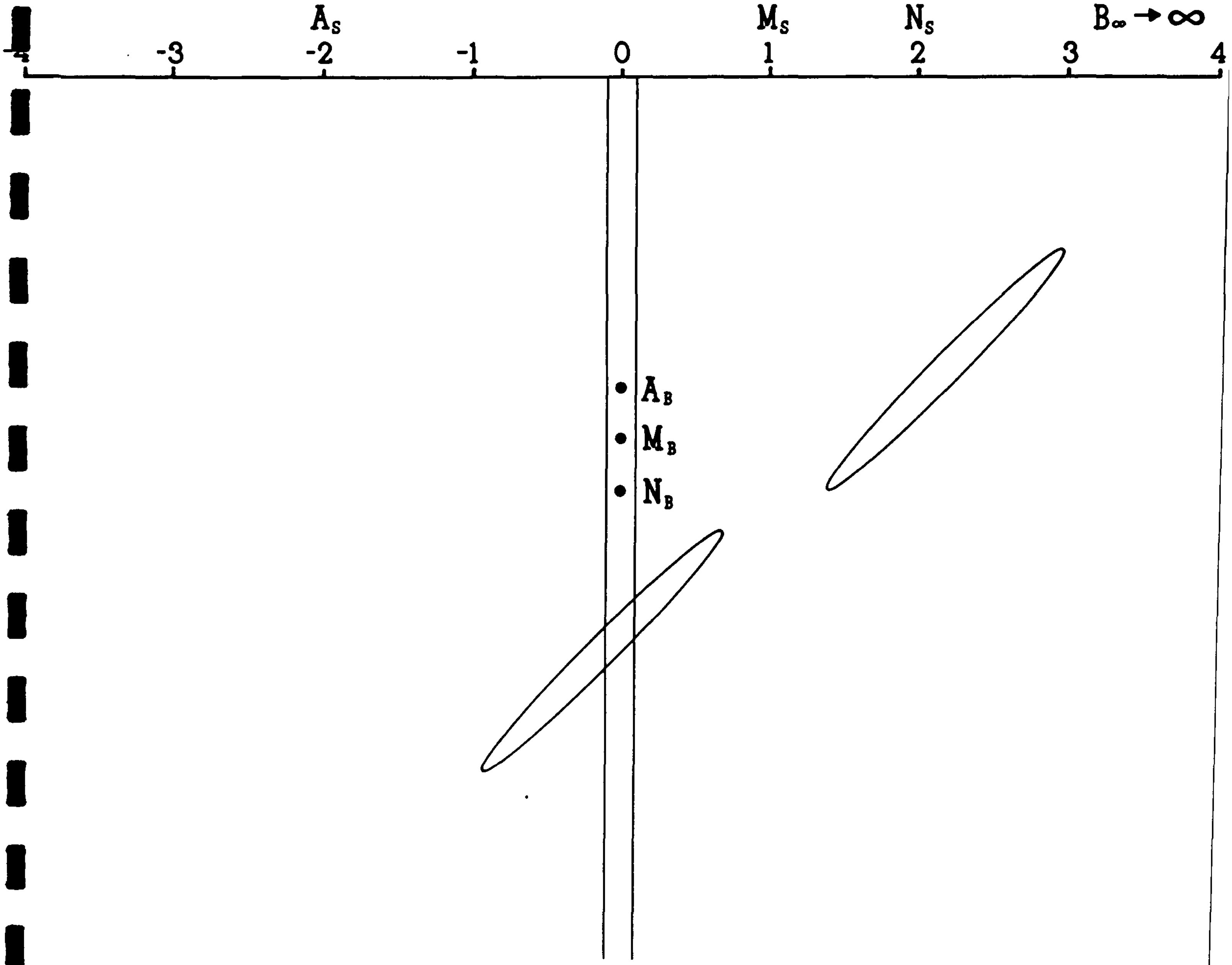
Methods Which Require Further Study

The following is our prioritized list of methods which warrant further study.

1. Multi-Array Borehole Resistivity Method

Compute borehole-to-surface, surface-to-borehole, cross-borehole, and mise-à-la-masse forward anomalies for a concise set of subsurface models. Use available computations whenever possible, but extend to application of the finite-element method so that the effects of topography, overburden, buried topography, random geological noise, and ordered geological noise (contacts and layering) may be evaluated. Attempt to develop an inverse scheme for the multi-array borehole resistivity system, using all available data sets, which could lead to development of a surface-subsurface geotomographic method of

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



- ●LONG LATERAL ARRAY — $A_B B_\infty M_B N_B$
- ●SURFACE-TO-BOREHOLE — $A_S B_\infty M_B N_B$
- ●BOREHOLE-TO-SURFACE — $A_B B_\infty M_S N_S$
- ●MISE-A-LA-MASSE — A_B in fracture zone; $M_B N_B$ or $M_S N_S$

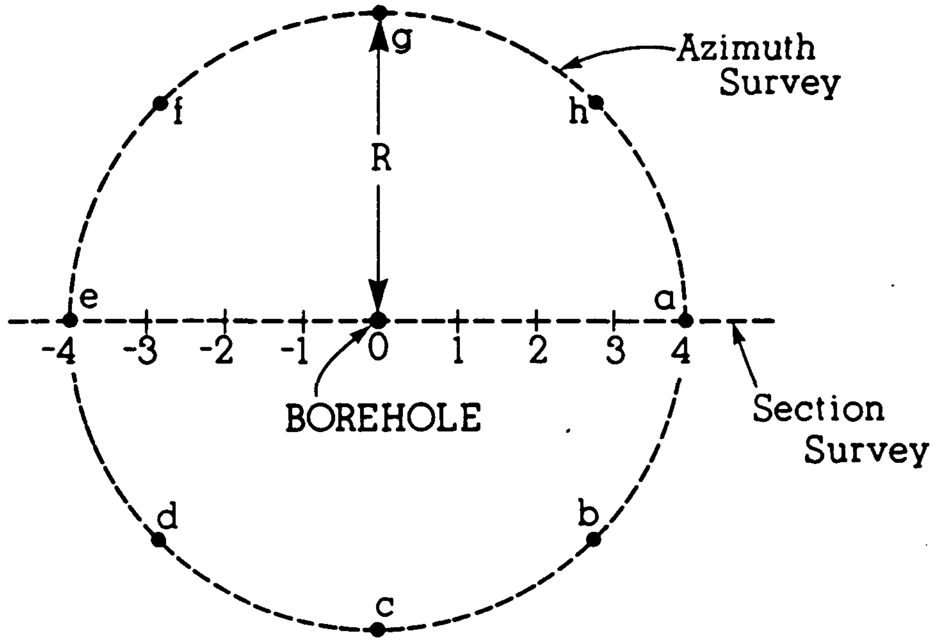
*CONVENTIONAL LOGGING TRUCK

*POTENTIAL AND CURRENT ELECTRODES ON SURFACE AND DOWNHOLE

*RAPID SEQUENCING THROUGH ELECTRODES

FIGURE 1

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



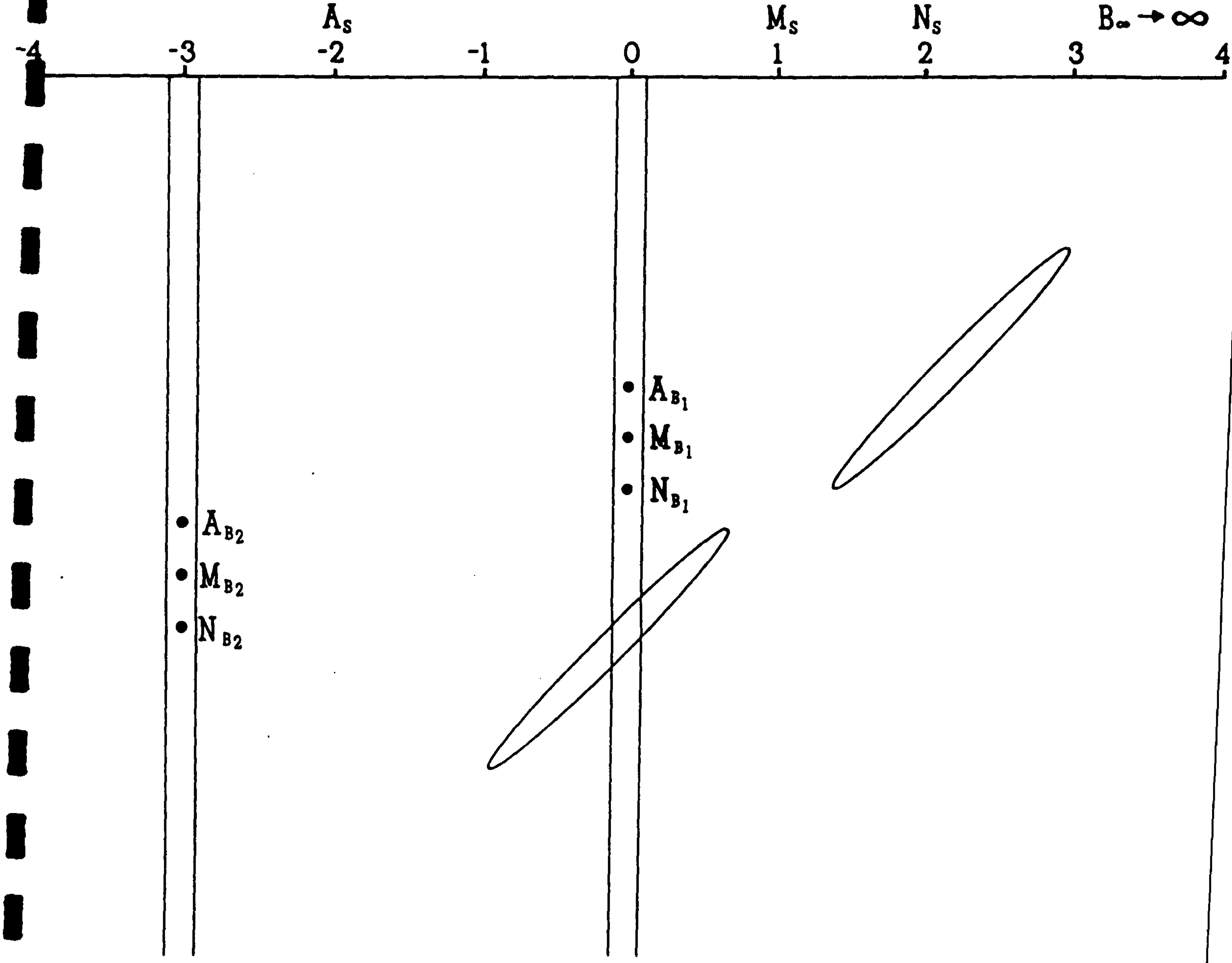
PLAN VIEW

LOCATIONS OF A_s : -4,-3,-2,-1,0,1,2,3,4 SECTION SURVEY

a,b,c,d,e,f,g,h AZIMUTH SURVEY

FIGURE 2

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



- ● LONG LATERAL ARRAY — $A_B B_\infty M_B N_B$
- ● SURFACE-TO-BOREHOLE — $A_S B_\infty M_B N_B$
- ● BOREHOLE-TO-SURFACE — $A_B B_\infty M_S N_S$
- ● MISE-A-LA-MASSE ——— A_B in fracture zone
  $M_B N_B$ or $M_S N_S$

*CONVENTIONAL LOGGING TRUC

*POTENTIAL AND CURRENT ELECTRODES ON SURFACE AND DOWNHOLE

*RAPID SEQUENCING THROUGH ELECTRODES

FIGURE 3

interpretation of electrical geophysical data. Evaluate the ratio-of-signal to noise for each method, including the effects of casing, natural and artificial field noise, as well as geological noise. Identify downhole probes suitable for the above task and state their current and projected temperature ranges. (State-of-the-art probes are available for temperatures to 250°C).

2. Evaluate via studies similar to those listed in 1) above of the ratios of signal to noise, the probable relative feasibilities of application of the TEM, VLF, and MMR methods to detection of fracture zones in geothermal exploration. No electromagnetic detection probes are known to have been used at temperatures above 100°C.

3. It is probable that a prototype multi-array borehole resistivity system can be defined and recommended for test surveys in FY 85. In order to begin test work, we will require a relatively simple wellbore logging capability. We are therefore requesting equipment funds, as shown on the attached budget, of $50,320 for purchase of wellbore resistivity logging equipment. We would modify this equipment so that we could perform multiple-electrode surveys with electrodes in both the wellbore and on the surface.

References

Beasley, C. W., and Ward, S. H., in preparation, Theoretical borehole-to-borehole and borehole-to-surface resistivity anomalies of geothermal fracture zones.

Ross, H. P., and Ward, S. H., 1984, Borehole electrical geophysical methods: A review of the state-of-the-art and preliminary evaluation of the application to fracture mapping in geothermal systems: Univ. of Utah Research Inst., Earth Science Lab. Rept. DOE/SAN/12196-2.

West, R. C., and Ward, S. H., in preparation, The borehole transient EM response of a 3-D fracture zone in a conductive half-space.

Yang, F. W., and Ward, S. H., 1985, Single- and cross-borehole resistivity anomalies of thin ellipsoids and spheroids: Geophysics, **50**, April.

Yang, F. W., and Ward, S. H., 1985, On sensitivity of surface-to-borehole resistivity measurements to the attitude and the depth to the center of a 3-D oblate spheroid: Geophysics, **50**, in press.

Scope of Work

3.1 Develop Interpretation. Perform forward modeling of the borehole-to-surface, surface-to-borehole, cross-borehole, and mise-à-la-masse methods to evaluate the feasibility of a multi-array borehole resistivity system. Include the effects of topography, overburden, buried topography, random geological noise, ordered geological noise, cultural noise, and natural field noise.

Commence development of an inverse scheme with the goal of developing electrical geotomography.

3.2 Electromagnetic Borehole System. Perform forward modeling of the TEM, VLF, and MMR methods so as to evaluate the ratio of signal to noise. Noise sources to be considered for study include topography, overburden, buried topography, random geological noise, ordered geological noise, cultural noise, and natural field noise.

3.3 Initial Testing. Begin field test work by modeling a commercial wellbore resistivity logger for use with a multiple array of electrodes in the wellbore and on surface.

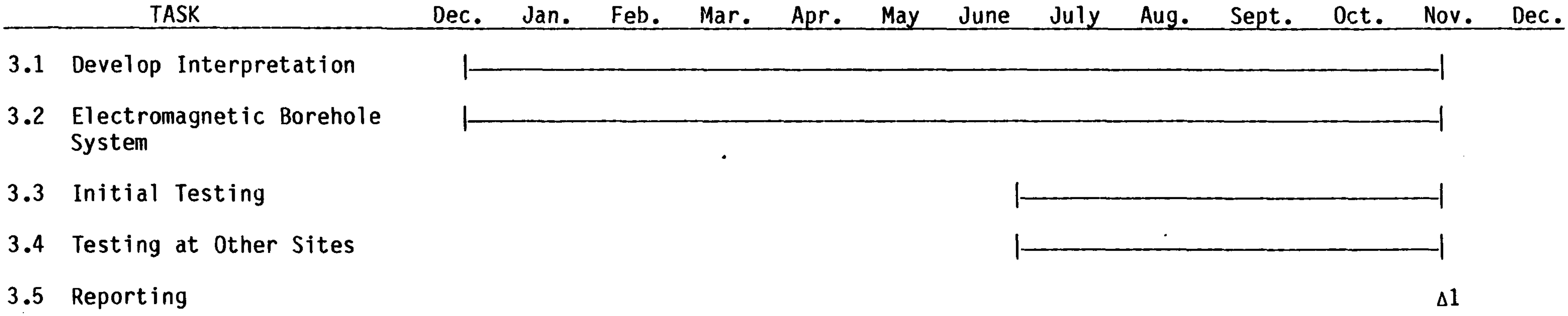
3.4 Testing at Other Sites. If additional funds become available, beyond the amount requested herein, initiate development of a prototype and plan for testing it at such sites as Valles caldera and Los Azufres.

3.5 Reporting. At least one technical report would result from this work.

3. FRACTURED DETECTION USING BOREHOLE ELECTRICAL GEOPHYSICAL TECHNIQUES

SCHEDULE AND DELIVERABLES

FY 1985



Deliverables

1. Technical report

FRACTURE DETECTION USING BOREHOLE ELECTRICAL GEOPHYSICAL TECHNIQUES

BUDGET

	Days		Amount
A. Salaries and Wages:			
1. Senior Personnel			
P. E. Wannamaker	5	$ 678	
2. Other Personnel		3,318	
Staff Analyst	5		
Draftsperson	22		
Secretarial	22		
Technician	115		
3. Wages - Professional		24,125	
S. H. Ward	25		
Research Assistants (2)	326		
Total Salaries and Wages			$28,121
B. Employee Benefits:			
1. 39.0% of A.1 and A.2		$ 1,558	
2. 9.5 % of A.3		2,292	
Total Employee Benefits			3,850
C. Permanent Equipment: (See Attachment 2 - Equipment Request)			-0-
D. Expendable Supplies and Equipment:			
1. Drafting Supplies		$ 200	
2. Office Supplies		75	
Total Expendable Supplies and Equipment			275
E. Travel:			-0-
F. Reports and Publications:			
1. Printing, Binding and Distribution Costs			575
G. Data Processing:			
1. PRIME 400 Computer			6,800
H. Other Costs:			-0-
I. Total Direct Costs:			$39,621

J. Indirect Costs:	
1. 45.0% of "I"	$17,829
K. General and Administrative:	
1. 14.5% of "I"	$ 5,745
L. Total Direct, Indirect and G & A Costs:	$63,195
M. Fee:	
1. 6.5% of "L"	$ 4,110
N. Total Project Costs:	$67,305

ATTACHMENT 2

Equipment Request

The following equipment is requested to support the task: "Fracture Detection Using Borehole Electrical Geophysical Techniques".

Wellbore Resistivity Logger	$50,320*

* Includes 6.5% Fee

RESUMES OF KEY PERSONNEL

RESUME

Joseph N. Moore

DATE OF BIRTH: January 21, 1948

POSITION: Geologist/Project Manager and Section Manager of Geochemical Group, Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah

EDUCATION:
B.S., Geology, 1969, City College of New York
M.S., Geology, 1972, Pennsylvania State University
Ph.D., Geology, 1975, Pennsylvania State University

SOCIETY AFFILIATIONS:
Geological Society of America
Geothermal Resources Council

HONORS AND AWARDS:
1971, Sigma Xi Grant
1971, Paul D. Krynine Fund Award
1972, Sir William Logan Medallion
1973, Phi Kappa Phi Honor Society
1978, American Men and Women in Science

PROFESSIONAL EXPERIENCE:

1979-present	Section Manager, the Geochemistry group, Earth Science Laboratory. Responsibilities include management of ESL geochemical programs and analytical facilities as well as the development of new geochemical techniques for use in geothermal exploration.
1977-1979	Geologist, Earth Science Laboratory. Conduct and supervise geologic programs in known geothermal resource areas of the Basin and Range.
1975-1977	Staff geologist, Uranium Division/The Anaconda Co. Primary responsibilities included developing an exploration program in volcanic terrains for hydrothermal uranium deposits and detailed and reconnaissance mapping in the Basin and Range.
1972-1975	Graduate Teaching Assistant, Pennsylvania State University. Duties included preparation of laboratories and laboratory lectures for basic physical geology and mineralogy courses.
1970-1972	Graduate Research Assistant, Pennsylvania State University. Research involved a comparison of igneous and impact breccias.
1971 summer	Geologist, Johns-Manville Ltd. Detailed mapping in the Stillwater Complex, Montana.
1968-1969 summers	Geologic Field Assistant, U.S.G.S., Dr. Nicholas Ratcliffe, party chief. Assist in detailed bedrock mapping of Taconic geology in southwestern Massachusetts.

1968 Part-Time Laboratory Assistant, Lamont Geological Observatory, Paleomagnetism Section, Dr. Neil Opdyke, supervisor. Duties included cutting, preparation, and magnetic analysis of deep sea drill cores.

PUBLICATIONS:

"Northeast Breccia Pipes and Dikes," Moore, J. N. and Gold, D. P., *International Geologic Congress (24th Session) Guidebook, Monteregian Hills: Diatremes, Kimberlites, Lamprophyres, and Intrusive Breccias West of Montreal* (1972).

"Mixed-Volatile Equilibria in Calcareous Rocks from the Alta Aureole, Utah," Moore, J. N. and Kerrick, D. M., Am. Jour. Sci., *276*, 502-524 (1976).

"Geology of Roosevelt Hot Springs KGRA Beaver Co., Utah," Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore J. N. and Samberg, S. M., University of Utah Research Institute, Earth Science Laboratory Report (IDO/78-1701.b.1.1.3), 120 p. (1978).

"Geology of the Cove Fort-Sulphurdale KGRA," Moore, J. N. and Samberg S. M., Bibliographic Annotations and Petrographic Descriptions by B. Sibbett, University of Utah Research Institute, Earth Science Laboratory (IDO/78-1701.b.1.1.5), 44 p. (1979).

"Geology Map of the San Emidio Geothermal Area," University of Utah Research Institute, Earth Science Laboratory (EG-78-C-07-1701) 8 p. (1979).

"Geology, Geochemistry, and Geophysics of the Roosevelt Hot Springs KGRA, Utah," *Basic Geology for the Exploration of Geothermal Systems*, GRC Technical Training Course #5, 24 p. (1980).

Geochemistry of solids in geothermal systems, Moore, J. N., National Conference on renewable energy resources technologies, Honolulu, 1980.

"Trace Element Geochemical Zoning in the Roosevelt Hot Springs Thermal Area, Utah," Christensen, O. C., Moore, J. N. and Capuano, R. M., Geothermal Resources Council Trans., *4*, 149-152 (1980).

"A Summary of the Geology and Geophysics of the San Emidio KGRA, Washoe County, Nevada," Mackelprang, C. E., Moore, J. N. and Ross, H. P., Geothermal Resources Council Transaction, *4*, 221-224 (1980).

Road log to geothermal systems in central Utah, Nielson, D. L., Moore, J. N., and Forrest, R. J., 1980, *in* Nielson, D. L. (ed.), Geothermal Systems in Central Utah, Geothermal Resources Guidebook to Field Trip No. 7, p.44

"Hg and As soil geochemistry as a technique for mapping permeable structure over a hot-water geothermal system", Capuano, R. M., and Moore, J. N., [abs.] Geol. Society America, Rocky Mt. Section *12*, no. 5, 269 (1980).

"K/Ar Ages of the Pyramid Sequence in the Vicinity of the San Emidio Geothermal Area, Washoe County, Nevada," Evans, S. H., Moore, J., Adams, M., Isochron/West, No. 31, 19-21 (1981).

"The Roosevelt Hot Springs, Utah Geothermal Resource - An Integrated Case Study," Ross, H. P., Nielson, D. L., Glenn, W. E, Moore, J. N., Smith, Christian and Christensen, O. D., 66th Annual AAPG Meeting, San Francisco, June (1981).

"Geochemical Indicators of a High-Temperature Geothermal System" [abs.], Moore, J. N., Capuano, R. M., and Christensen, O. D., 9th International Geochemical Exploration Symposium, Saskatoon, Canada, May 12-14 (1982).

"An Exploration Case Study of the Roosevelt Hot Springs Geothermal System, Utah, Ross, H. P., Nielson, D. L., and Moore, J. N., Amer. Assoc. of Petrol. Geologists Bulletin, v. 66, p. 879-902 (1982).

"The Cove Fort-Sulphurdale KGRA - A Geological and Geophysical Case Study" Ross, H. P., Moore, J. N. and Christensen, O. D., ESL Report 90, 29 p. (1982).

"Mercury as a Pathfinder Element in the Exploration of Vapor Dominated Geothermal Systems" Moore, J. N., Christensen, O. D., and Bamford, R., Geothermal Resources Council Transactions, v. 6, p. 99-102, (1982).

"Geologic map of the McCoy geothermal prospect, Adams, M. C., Moore, J. N., and Struhsacker, E., ESL Report 111 (DOE/ID/12019-92), (1982).

"Trace Element Distribution in an Active Hydrothermal System, Roosevelt Hot Springs Thermal Area, Utah," Christensen, O. D., Capuano, R., Moore, J. N., J. Volcanology and Geothermal Research, v. 16, p. 99-129 (1983).

"Nevada Geothermal Areas; Steamboat Springs, Brady Hot Springs, Humbolt House Colado, Beowawe," Moore, J. N. and Cerling, B. W., eds., Guidebook for Field Trip #2, GRC, 1980 Annual Meeting, 95 p. (1983).

"Preliminary geothermal assessment of the Tuttapani thermal area, Madhya Prodesh, India: Geothermal Resources Council Transactions, in press.

"Geochemistry of the Meager Creek geothermal field, Moore, J. N., Adams, M. C., and Stauder, J. J., British Columbia Geothermal Resources Council, in press.

RESUME

Dennis L. Nielson

POSITION: Section Manager - Geology, Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah

EDUCATION:
B.A., Geology, 1970, Beloit College, Beloit, Wisconsin
M.A., Geology, 1972, Dartmouth College, Hanover, New Hampshire
Ph.D., Geology, 1974, Dartmouth College, Hanover, New Hampshire

SHORT COURSES:
Volcanic Rocks and Their Vent Areas, University of Nevada, Reno, 1977
Engineering Management by Objectives for Improving Productivity, University of Utah, 1978
Geothermal and Hydrothermal Systems, Yellowstone Institute, 1978
Economics of Minerals and Energy Projects, AIME, 1981

SOCIETY AFFILIATIONS:
American Geophysical Union
Geological Society of America
Geothermal Resources Council
Society of Economic Geologists
Utah Geological Association

HONORS AND AWARDS:
Haven Science Prize, Beloit College (1970)
NDEA Title IV Fellowship - Dartmouth College (1971-1974)
American Men and Women of Science
President, Basin and Range Section, Geothermal Resources Council (1979)

PROFESSIONAL EXPERIENCE:

7/80-present	Section Manager - Geology. Earth Science Laboratory, University of Utah Research Institute. Responsible for overall technical quality of geologic work and management of the geologic staff.
7/79-present	Geologist/Project Manager, Earth Science Laboratory, University of Utah Research Institute. Project manager for the following programs under Department of Energy contracts: Geothermal Exploration and Assessment Technology Program, Industry Coupled Program, M-X/Renewable Energy Systems Program. Responsible for coordinating technical work at Roosevelt Hot Springs KGRA, Utah; and Beowawe; Tuscarora; Colado; McCoy; Soda Lake-Stillwater KGRAs, NV. Formulation and technical review of procurements, contract monitoring , and program design. Principal investigator for the geothermal exploration of Ascension Island, South Atlantic Ocean, under contract to U.S. Department of Energy and U.S. Air Force. Participated in a program to assess the state-of-the-art and recommend needed research in an industry sponsored program in solution mining and

	hydrometallurgy. Have participated in numerous DOE advisory committees including those concerned with the Baca Geothermal Demonstration Power Plant, Deep Continental Scientific Drilling Program, and the Hot Dry Rock Project.
1979-present	Instructor, Yellowstone Institute, for a course on Calderas and Hydrothermal Systems which concentrates on the formation of calderas, ash-flow tuff stratigraphy, and the geology of hydrothermal systems in the caldera environment.
4/78-7/79	Geologist, Earth Science Laboratory, University of Utah Research Institute. Develop case studies for geothermal resource areas in western U.S. Responsibilities include supervision of geologic programs, geologic mapping, synthesis and publication of exploration data, and formation of exploration criteria.
6/74-4/78	Staff Geologist, The Anaconda, Co., Salt Lake City, Utah. Uranium exploration in frontier project areas in the United States. Responsible for generating and supervising projects through the initial drilling stages. Experience in Precambrian plutonic and metasedimentary environments and Tertiary volcanic and sedimentary environments. Activities included detailed mapping, quadrangle mapping, regional reconnaissance, interpreting geophysical and geochemical data, supervising rotary and diamond drilling, and land acquisition through leasing and claim staking.
1971 summer	Field Geologist, Great Lakes Exploration Co. (subsidiary of Bear Creek Mining Co.). Reconnaissance mapping in the Precambrian Shield of the Upper Peninsula of Michigan and northern Wisconsin. The mapping was designed to locate areas having potential for massive sulfide deposits.
1970 summer	Field Geologist, Great Lakes Exploration Co. (subsidiary of Bear Creek Mining Co.). Quadrangle mapping and geochemical surveys of water wells and soils in conjunction with a massive sulfide exploration program in northern Wisconsin.
1968 fall	Field Assistant, Bear Creek Mining Co. Base metal exploration in the Upper Peninsula of Michigan and northern Wisconsin. Duties included drafting, supervising diamond drilling, and assisting with field mapping.

PUBLICATIONS:

PAPERS AND TECHNICAL REPORTS

Nielson, D. L., 1973, Silica diffusion at Ascutney Mountain, Vermont: Contributions to Mineralogy and Petrology, v. 40, p. 141-148.

Nielson, D. L., Clark, R. G., Lyons, J. B., Englund, E. J., and Borns, D. J., 1976, Gravity models and mode of emplacement of the New Hampshire Plutonic Series, in Lyons, P. C., and Brownlow, A. H. (eds.) Studies in New England Geology: Geological Society of America Memoir 146, 301-318.

Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S. M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 12, 121 p.

Nielson, D. L., 1978, Radon in geothermal exploration, theory and an example from Roosevelt Hot Springs KGRA, Utah: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 14, 31 p.

Nielson, D. L., and Moore, J. N., 1979, The exploration significance of low-angle faults in the Roosevelt Hot Springs and Cove Fort-Sulphurdale Geothermal Systems, Utah: Geothermal Resources Council Transactions, v. 3, p.503-506.

Nielson, D. L. (ed.) 1979, Program Review: Geothermal Exploration and Assessment Technology Program including a report of the Reservoir Engineering Technical Advisory Group: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 29, 128 p.

Foley, D., Nielson, D. L., and Nichols, C. R., 1980, Geothermal systems of the Yellowstone Caldera: Geothermal Resources Council Field Trip No. 1, 69 p.

Glenn, W. E., Hulen, J. B., and Nielson, D. L., 1980, A comprehensive study of LASL Well C/T-2 Roosevelt Hot Springs KGRA, Utah and application to geothermal well logging: Los Alamos Scientific Laboratory, Rept. LA-8686-MS, 175 p.

Nielson, D. L. (ed.) 1980, Geothermal Systems in Central Utah: Geothermal Resources Council Guidebook to Field Trip No. 7, 54 p.

Nielson, D. L., 1980, Summary of the geology of the Roosevelt Hot Springs Geothermal System, Utah: in Nielson, D. L. (ed.), Geothermal Systems in Central Utah, Geothermal Resources Council Guidebook to Field Trip No. 7, p.25-29.

Nielson, D. L., Moore, J. N., and Forrest, R. J., 1980, Road log to geothermal systems in central Utah: in Nielson, D. L. (ed.), Geothermal Systems in Central Utah, Geothermal Resources Guidebook to Field Trip No. 7, p.44-54.

Sibbett, B. S., and Nielson, D. L., 1980, Geology of the central Mineral Mountains, Beaver County, Utah: University of Utah Research Institute, Earth Science Laboratory, Rept. No. 33, 42 p.

Ward, S. H., Ross, H. P., and Nielson, D. L., 1981, Exploration strategy for high-temperature hydrothermal systems in the Basin and Range Province: Am. Assoc. Petroleum Geologists Bull., 65/1 p.86-102. Reprinted in Energy Minerals, AAPG reprint Series No. 25, p. 232-248.

Nielson, D. L., 1981, The bedrock geology of the Hillsboro quadrangle, New Hampshire: N. H. Dept. of Resources and Economic Development Bull. No. 8, 76 p.

Ross, H. P., Nielson, D. L., and Moore, J. N., 1982, Roosevelt Hot Springs geothermal system, Utah-Case Study: Am. Assoc. Petroleum Geologists Bull., v. 66, no. 7, p. 879-902.

Nielson, D. L., (ed.), 1982, Overthrust belt of Utah: Utah Geological Association Publication 10, 335 p.

Hulen, J. B. and Nielson, D. L., 1982, Stratigraphic permeability in the Baca geothermal system, Redondo Creek area, Valles Caldera, New Mexico: Geothermal Resources Council Transactions, v. 6, p. 27-30.

Evans, S. H. and Nielson, D. L., 1982, Thermal and tectonic history of the Mineral Mountains intrusive complex: Geothermal Resources Council Transactions, v. 6, p. 15-18.

Foley, D., Nielson, D. L., and Nichols, C. R., 1982, Road Logs: West Yellowstone to Canyon Junction, Canyon Junction to Mud Volcano - Sulphur Cauldron Area, Canyon Junction to Tower Junction, Tower Junction to Mammoth Hot Springs, Mammoth Hot Springs to Norris Junction, Madison Junction to Old Faithful, *in* Reid, S. G. and Foote, D. J. (eds.) Geology of Yellowstone Park Area: Wyoming Geological Association Guidebook.

Hulen, J. B. and Nielson, D. L., 1983, Stratigraphy of the Bandelier Tuff and characterization of high-level clay alteration in borehole B-20, Redondo Creek area, Valles Caldera, New Mexico: Geothermal Resources Council Transaction, v. 7, p. 163-168.

Nielson, D. L., and Hulen, J. B., 1983, Geologic model of the Baca geothermal reservoir, Valles caldera, New Mexico: Proceedings Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, p. 145-150.

Nielson, D. L., and Hulen, J. B., 1984, Internal geology and evolution of the Redondo Dome, Valles caldera, New Mexico: Jour. Geophys. Research Special volume on calderas and associated igneous rocks, in press.

ABSTRACTS

Nielson, D. L., 1973, Contact metamorphism and molecular diffusion at Ascutney Mountain, Vermont: Geological Society of America, Abstracts with Programs, Northeastern Section, p.203.

Nielson, D. L., Lyons, J. B., and Clark, R. G., 1973, Gravity and structural interpretations of the mode of emplacement of the New Hampshire Plutonic Series: Geological Society of America, Abstracts with Programs 1973 Annual Meetings, p.750.

Nielson, D. L., Sibbett, B. S., and McKinney, D. B., 1979, Geology and structural control of the geothermal system at Roosevelt Hot Springs KGRA, Beaver County, Utah (abs.): American Association of Petroleum Geologists Bull., v. 63/5, p.836.

Ward, S. H., Chapman, D. S., Evans, S. H., Nielson, D. L., Wannamaker, P. E., and Wilson, W. R., 1979, Roosevelt Hot Springs Geothermal System: Geologic and geophysical models: IAVCEI Abstracts and timetables, IUGG XVII General Assembly, Canberra, Australia.

Nielson, D. L, 1980, Geology of low- and intermediate-temperature hydrothermal systems: National Conference on Renewable Energy Technologies, Proceedings, Honolulu, p.8-3 to 8-4.

Sibbett, B. S., and Nielson, D. L.,1980, The Mineral Mountains intrusive complex, Utah: Geological Society of America, Abstracts with Programs, Rocky Mountain Section, v. 12, No. 6, p.305.

Ward, S. H., Ross, H. P., and Nielson, D. L., 1980, Strategy of exploration for high temperature hydrothermal systems in the Basin and Range Province (abs.): Am. Assoc. Petroleum Geologists Bull., v. 64/5, p.799.

Ross, H. P., Nielson, D. L., and Glenn, W. E., et al., 1981, Roosevelt Hot Springs, Utah geothermal resource-integrated case study (abs.): Am. Assoc. Petroleum Geolgists Bull., v. 65/5, p. 982.

Nielson, D. L., and Hulen, J. B., 1984, Results of deep drilling in the Valles caldera, New Mexico (abstract): Invited paper, International Symposium on Continental Drilling, Tarrytown, N.Y.

RESUME

Stanley H. Ward

BIRTHPLACE AND DATE: Vancouver, B.C., Canada, January 16, 1923

POSITION: Professor, Department of Geology and Geophysics, College of Mines and Mineral Industries, University of Utah, Salt Lake City, Utah
Director, University of Utah Research Institute, Earth Science Laboratory, Salt Lake City, Utah

EDUCATION: 1940, John Oliver High School, Vancouver, Canada
B.A.Sc., Engineering Physics, 1949, University of Toronto, Toronto, Ontario, Canada
M.A., Geophysics, 1950, University of Toronto
Ph.D., Geophysics, 1952, University of Toronto

SOCIETY AFFILIATIONS:
Fellow, Royal Astronomical Society
Fellow, Institute of Electrical and Electronic Engineers
Fellow, Geological Society of America
Member, Society of Exploration Geophysicists
Member, Geothermal Resources Council

Member, European Association of Exploration Geophysicists
Member, Canadian Institute of Mining and Metallurgy
Member, American Geophysical Union
Member, International Union of Geodesy and Geophysics
Member, Society of Sigma Xi
Member, Professional Engineers of the Province of Ontario
Member, Australian Society of Exploration Geophysicists

PROFESSIONAL EXPERIENCE:

4/78-present	Director, Earth Science Laboratory, University of Utah Research Institute. Responsible for the management of research activities of a professional staff of 29 and a support staff of 30. Responsible for administration of funds totalling $10,000,000.
7/73-6/80	Director, University of Utah Seismograph Stations. Responsible for the management of research activities of a professional staff of 6 and a support staff of 8. Responsible for administration of funds totalling $132,000.
7/70-6/80	Professor, Department of Geology and Geophysics, University of Utah. Research and teaching concerned with electromagnetic exploration with the objectives including the search for minerals, oil and gas, and geothermal energy, deep probing of the earth's crust, and study of the lunar interior.
1959-1970	University of California, Berkeley, Professor of Geophysical

Engineering. Research and teaching concerned with electromagnetic exploration with the objectives including the search for minerals and oil, deep probing of the earth's crust, study of the earth's magnetosphere, and study of the lunar interior.

1958-present Consulting Geophysical Engineer. Consults to mining, petroleum, geothermal, aerospace and instrument companies and to governmental agencies; designs, supervises, and interprets data from exploration campaigns; originates, invents, advises regarding hardware and software utilized in mining exploration, petroleum exploration, and geothermal exploration; primarily concerned with electromagnetic exploration; consults on special government problems; clients have included:

Phelps Dodge Corporation
Kennecott Copper Corp.
Noranda Mines Ltd. - Canada
Placer Development Ltd. - Canada
Brenda Mines Ltd. - Canada
Craigmont Mines Ltd. - Canada
Endako Mines Ltd. - Canada
Scurry Rainbow Oil Co. - Canada
Pure Oil Company
Amax Exploration, Inc.
Commonwealth Scientific and Industrial Research Organization, Australia
Colonial Sugar Refining Co., Australia
Sinclair Oil and Gas Co.
United States Steel Corp.
Varian Associates
The Bunker Hill Co.
Peerless Gas and Oil Co.
The U.S. Dept. of Justice
Cyprus Mines Corp.
Morrison-Knudson Co., Inc.
The National Aeronautics and Space Administration
Westinghouse Electric Corp.
Universidade Federal Do Bahia Instituto de Geosciencias E Instituto de Fisico-Brazil
Engenheiros Consultores Associados, S.A. - Brazil
Exxon Corporate Research Laboratory, Newark
Atlantic Richfield Co., Dallas
Greatland Exploration Ltd., Anchorage
McPhar Instrument Corporation, Toronto
Exxon Production Research Laboratory, Houston
Quintana Minerals Corp. Houston
General Electric Corporate Laboratory, Schnectady
CRA Exploration Pty. Ltd., Melbourne
Royal Dutch Shell, Amsterdam
Houston Oil and Gas Corporation, Denver
SERU Nucleaire (Canada) Limitee, Montreal, Canada
Getty Oil Co., Salt Lake City
Anglo American of South Africa, Johannesburg
BP Minerals, Vancouver

1953-1958 Managing Director and Chief Geophysicist, Nucom Ltd. (subsidiary of American Metal Climax Inc.). Supervised geophysical aspects of exploration program involving as many as 275 men; supervised operation of three helicopter-borne electromagnetic prospecting units; supervised gravity, magnetic, electromagnetic surveys; prepared budgets of $500,000 yearly for research and operations; interpreted data from mining geophysical surveys; collaborated in design of airborne, ground and drill hole prospecting systems; prepared reports on surveys and papers for publication in scientific and professional journals.

1949-1953 Managing Director and Chief Geophysicist, McPhar Geophysics Ltd. Directed operations and research of geophysical contracting firm; interpreted data from mining geophysical surveys; supervised staff of forty engineers, technicians, clerical staff; prepared cost estimates for surveys; collaborated in design of airborne, ground and drill hole electromagnetic prospecting systems; prepared reports on surveys and papers for publication in scientific and professional journals.

PUBLICATIONS AND REPORTS:

113 Publications
31 Abstracts
14 Contract Reports

Mainly in geophysical exploration and exploration strategies for minerals and geothermal energy.

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