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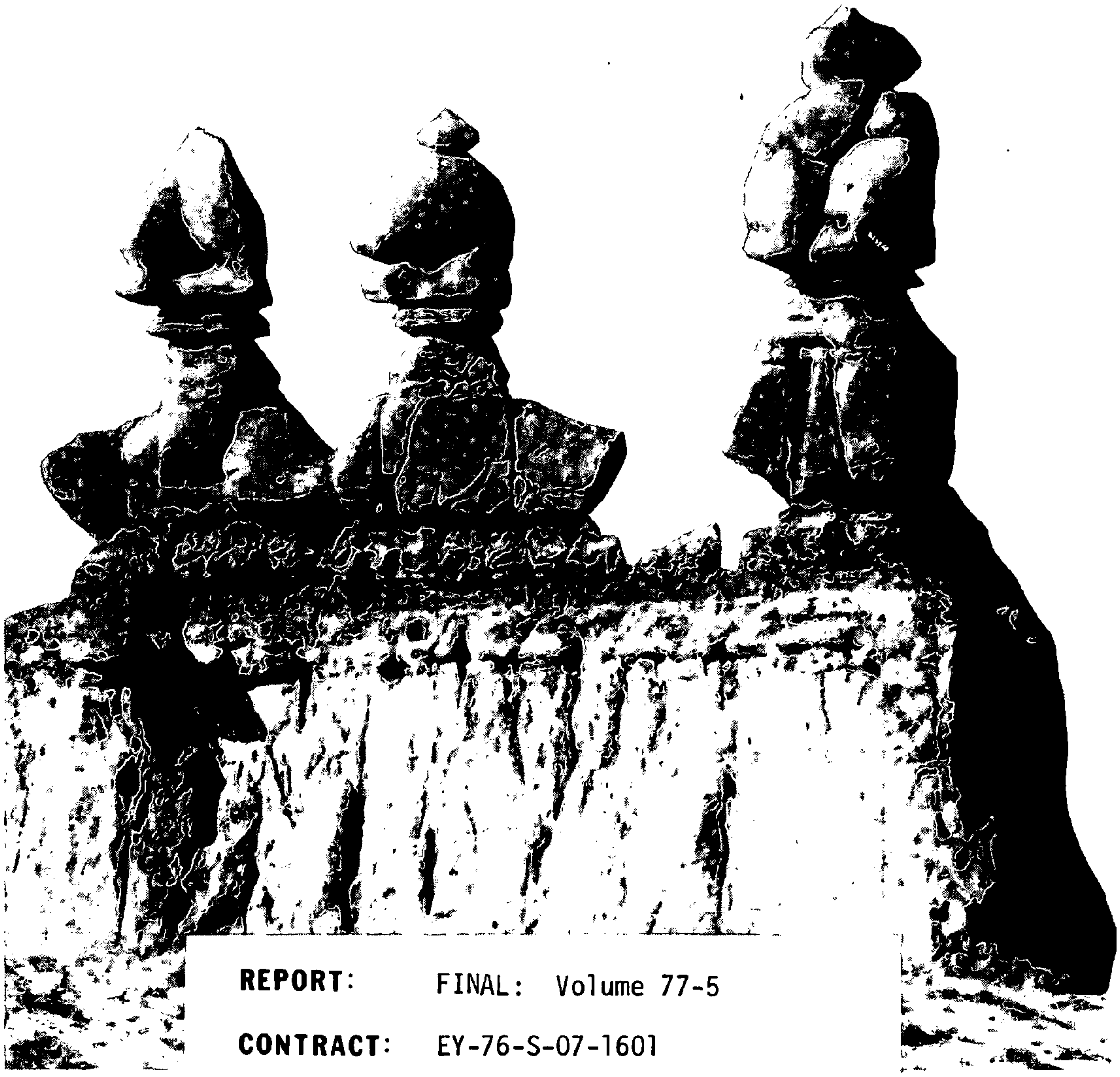
DEPARTMENT OF GEOLOGY AND GEOPHYSICS



REPORT: FINAL: Volume 77-5

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AGENCY: DOE/DGE

TITLE: Final Report, Volume 77-5

AUTHORS: S. H. Ward, J. A. Whelan, and others

DATE: December 1977

UNIVERSITY OF UTAH SALT LAKE CITY, UTAH 84112

FINAL REPORT

VOLUME 77-5

EY-76-S-07-1601

I. Introduction

The final report under contract EY-76-S-07-1601 is being submitted as a series of volumes as follows:

Volume 77-0	*October, 1977
Volume 77-1	*September, 1977
Volume 77-2	December, 1977
Volume 77-3	December, 1977
Volume 77-4	December, 1977
Volume 77-5	December, 1977
Volume 77-6	December, 1977
Volume 77-7	January, 1978
Volume 77-8	January, 1978

*Submitted

Other volumes will be submitted in accordance with the contractual reporting schedule.

II. Reports Delivered

Task 76.1.21 Color photos

Stereo color aerial photographs were made available to industry for copying at industry's expense on November 28, 1977 at 11:00 a.m. This final report on this task merely records that fact.

Task 77.1.14 Proposal Review (MOD A002)

All activities under this task have been completed. No tangible deliverables were required.

Task 76.1.14 Simultaneous modeling of multiple data sets

A technique for simultaneous inversion of MT and Schlumberger data was developed and tested on some available deep crustal data from

South Africa. The publication resulting and included herewith is:

> Petrick, W. R., W. H. Pelton, and S. H. Ward, 1977, Ridge Regression Inversion Applied to Crustal Resistivity Sounding Data from South Africa, Geophysics, vol. 42, no. 5, p. 995-1005.

Joint inversion of Schlumberger and electromagnetic sounding data was developed and applied to geothermal data from Roosevelt Hot Springs KGRA. The publication resulting and included herewith is:

> Tripp, A. C., S. H. Ward, W. R. Sill, C. M. Swift, Jr., W. R. Petrick, 1978, Electromagnetic and Schlumberger Resistivity Sounding in the Roosevelt Hot Springs KGRA, Geophysics, in press.

To utilize multiple inversion schemes at a convective hydrothermal system in the Eastern Great Basin will require applications of three-dimensional forward algorithms now available for gravity, magnetics, and AMT/MT. Unfortunately the pertinent data sets available for Roosevelt Hot Springs KGRA (or Monroe Hot Springs KGRA, for that matter) are not compatible since the physical property distributions giving rise to the gravity field is not coincident with that giving rise to the magnetic field, and so on.

Thus, we have turned to interpreting each data set independently and then drawing a schematic model of the subsurface which accepts all data sets. An example of this procedure is contained in "Ward, S. H., J. M. Bodell, W. D. Brumbaugh, J. A. Carter, K. L. Cook, T. J. Crebs, T. L. Olsen, W. T. Parry, W. R. Sill, R. B. Smith, I. Thangsuphanich, and A. C. Tripp, 1978, Geophysics of the Roosevelt Hot Springs Thermal Area, Utah", submitted to Geology and included in Final Report Volume 77-2.

Task 76.1.11 Drill and Log 10 Heat Flow Holes

All thermal gradients and heat flows appear in Technical Report 77-3. The summary of drilling progress, costs, and lithologs is enclosed.

Cost Analysis and Drilling Data
Thermal Gradient and Heat Flow Holes, 1976

by

J. A. Whelan

Cost Analysis and Drilling Data
Thermal Gradient and Heat Flow Holes, 1976

1.0 Introduction and Summary

1.1 This report summarizes the summer 1976 drilling program in the Roosevelt KGRA near Milford. Results of geologic, hydrothermal alteration, thermal gradient, heat flow, and rock properties made with cores or cuttings from these holes will be published in other reports.

Ten holes were drilled, totaling 2732 feet. Total funds expended, not including University of Utah supervision, or supplies, chiefly black-iron pipe, were $29,320. Cost per foot for NX-core drilling, on holes was $15.08. Cost per foot for rotary drilling in alluvium was $4.98 per foot.

Locations of the holes are shown in Figures 1 through 5.

Summary data on individual holes is given in Appendix (A). Detailed logs are available at the University of Utah to interested parties. Cores and cuttings may be examined there.

2.0 Administration

2.1 Permission to Drill. On Federal Lands permission to drill was requested on Notice of Intent to Conduct Geothermal Resource Exploration Operations (Form 3200-9, December, 1973). On state lands, permission to drill was obtained from the Division of State Lands, Department of Natural Resources. If state lands were leased, permission was also obtained from the leasees. On private land, permission was obtained from the owners.

2.2 Two drilling contracts were utilized. General features are described below:

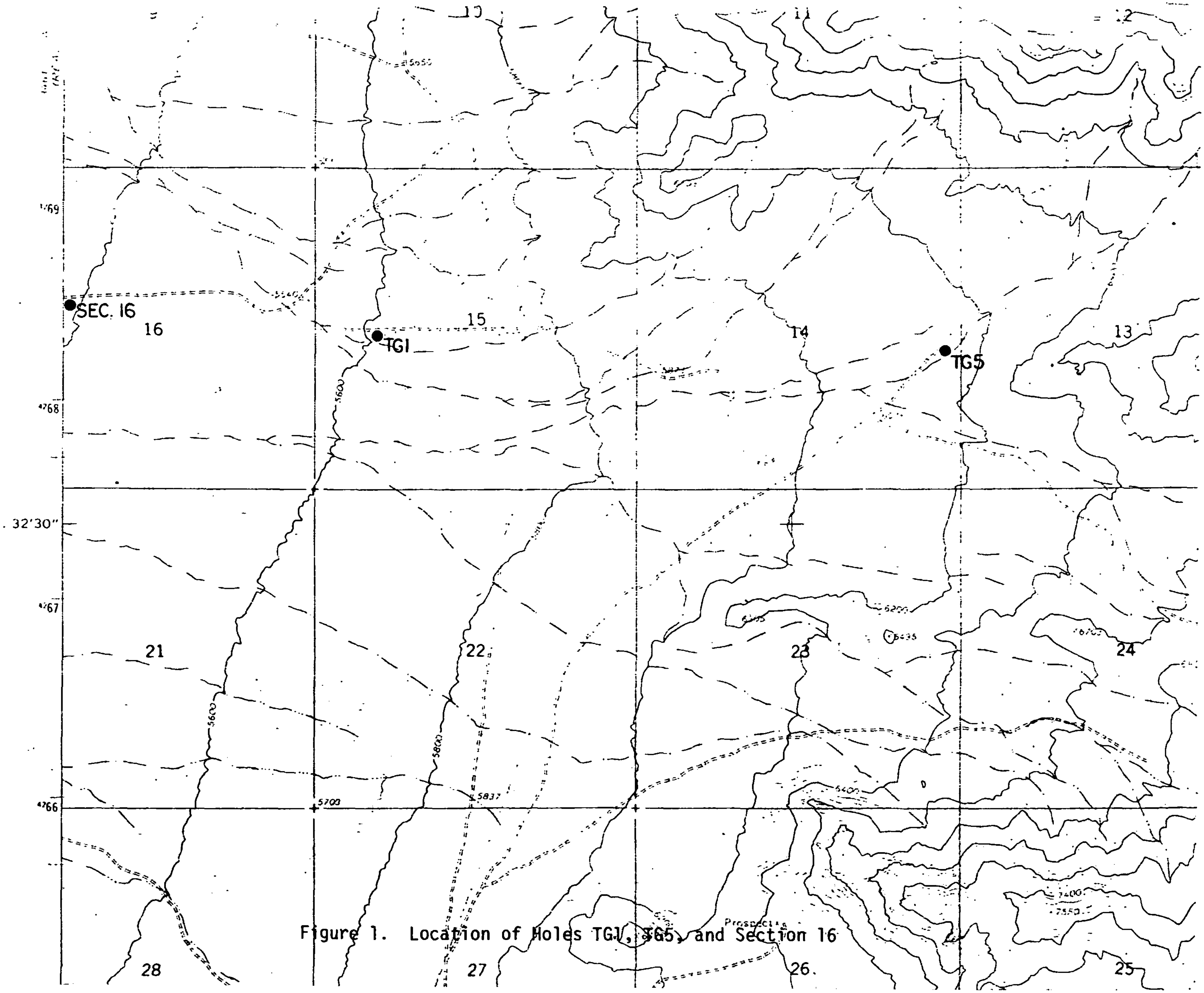

Figure 1. Location of Holes TG1, TG5, and Section 16

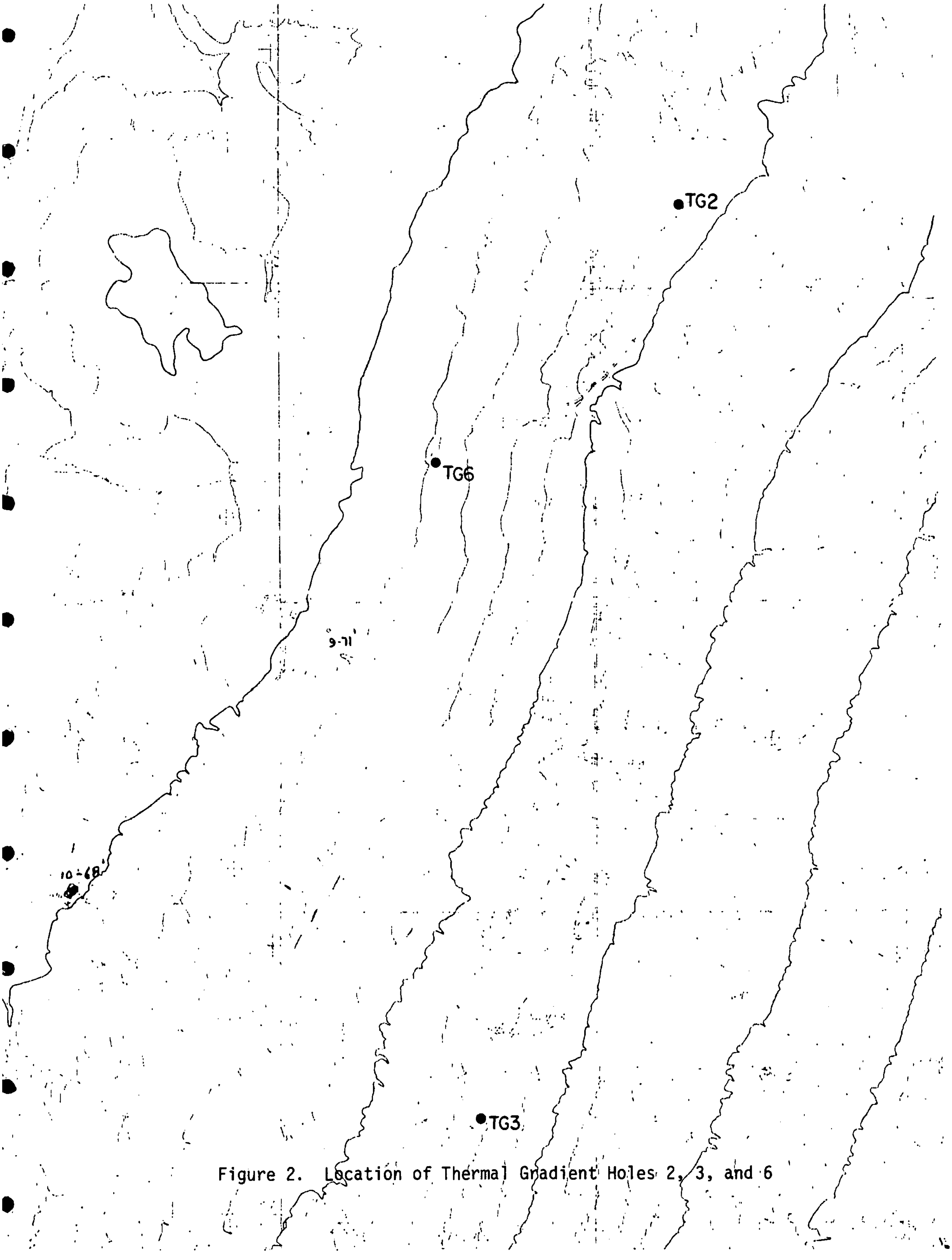

Figure 2. Location of Thermal Gradient Holes 2, 3, and 6

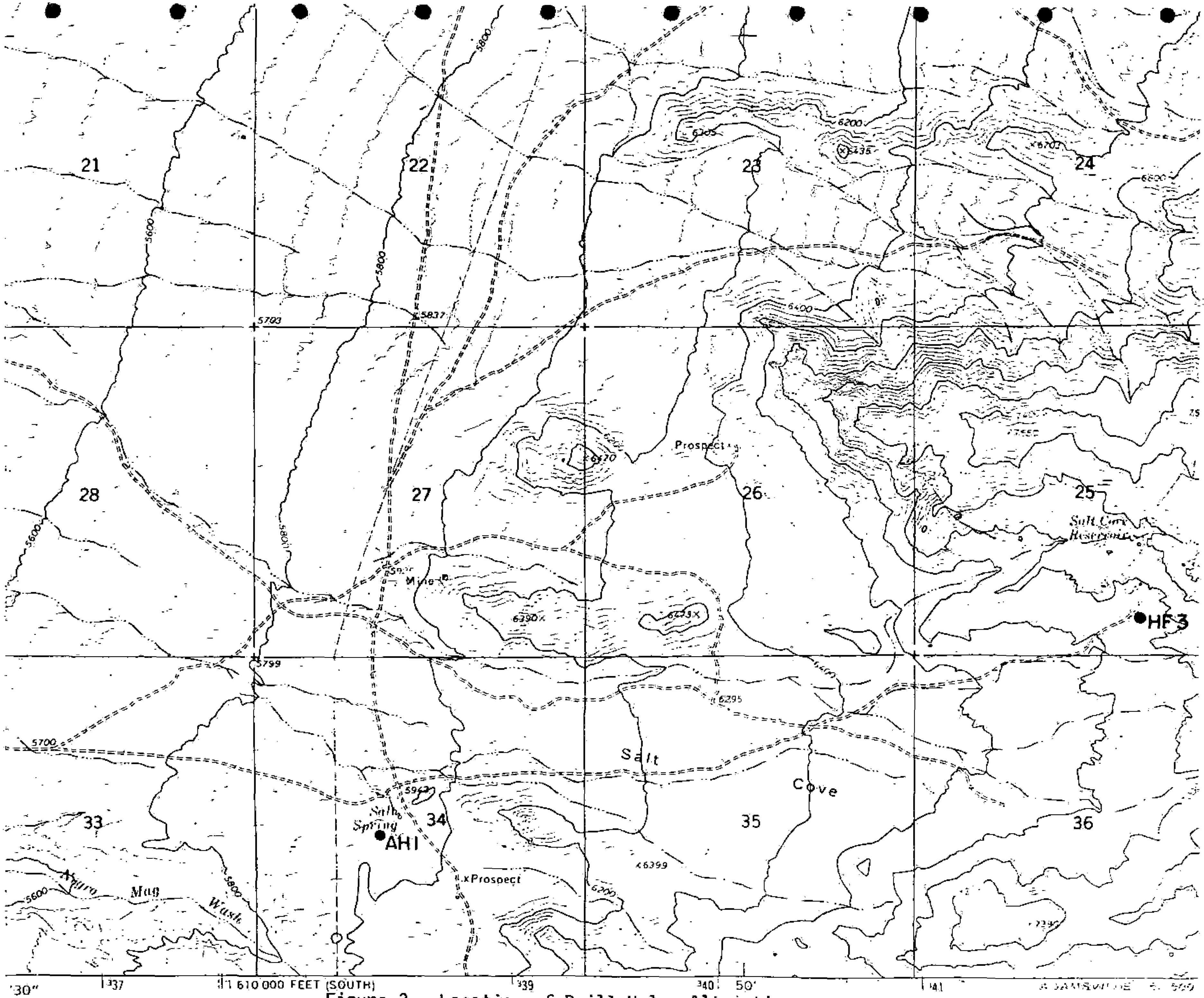

Figure 3. Location of Drill Holes Alteration and Heat Flow 3

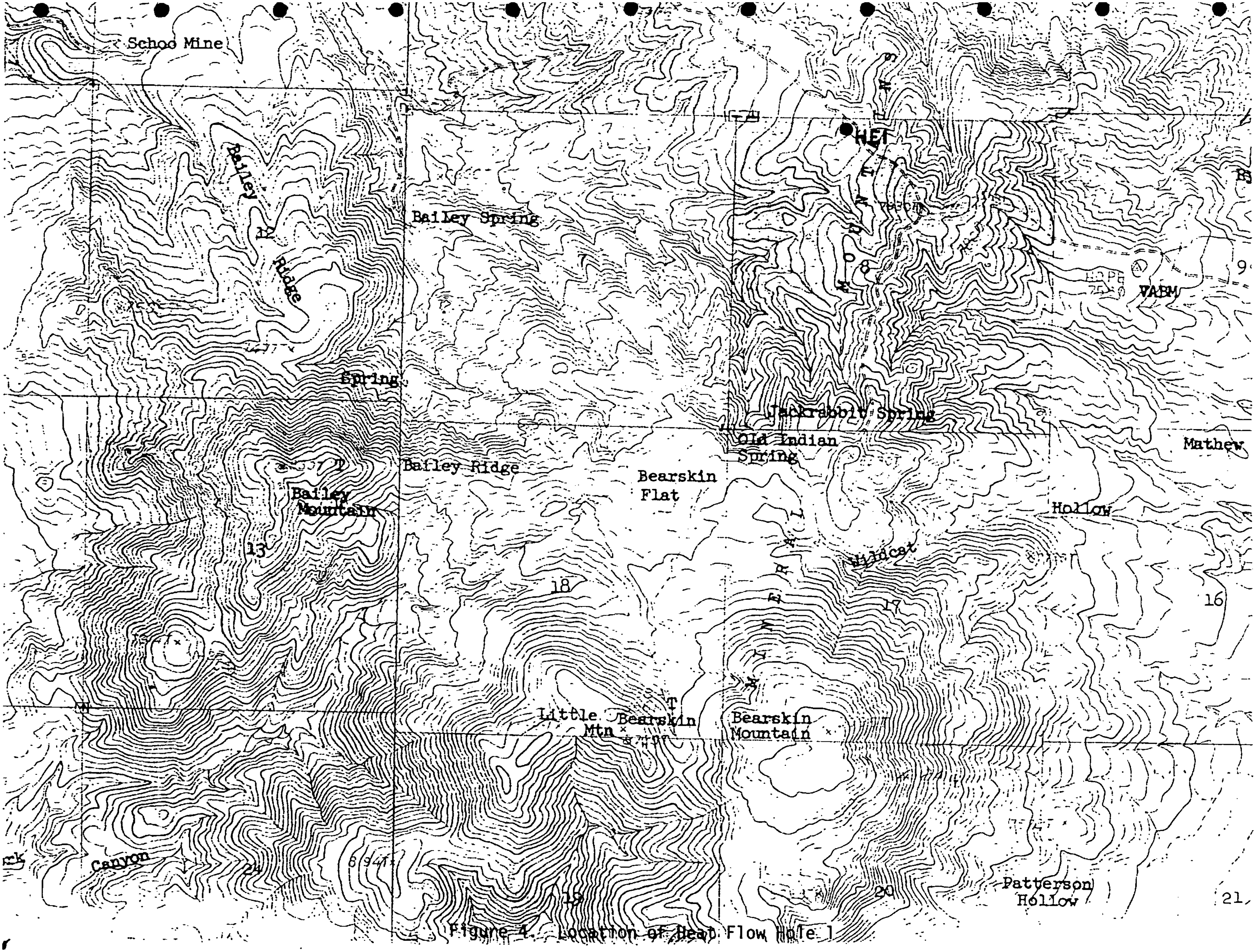

Figure 4. Location of Heat Flow Hole 1

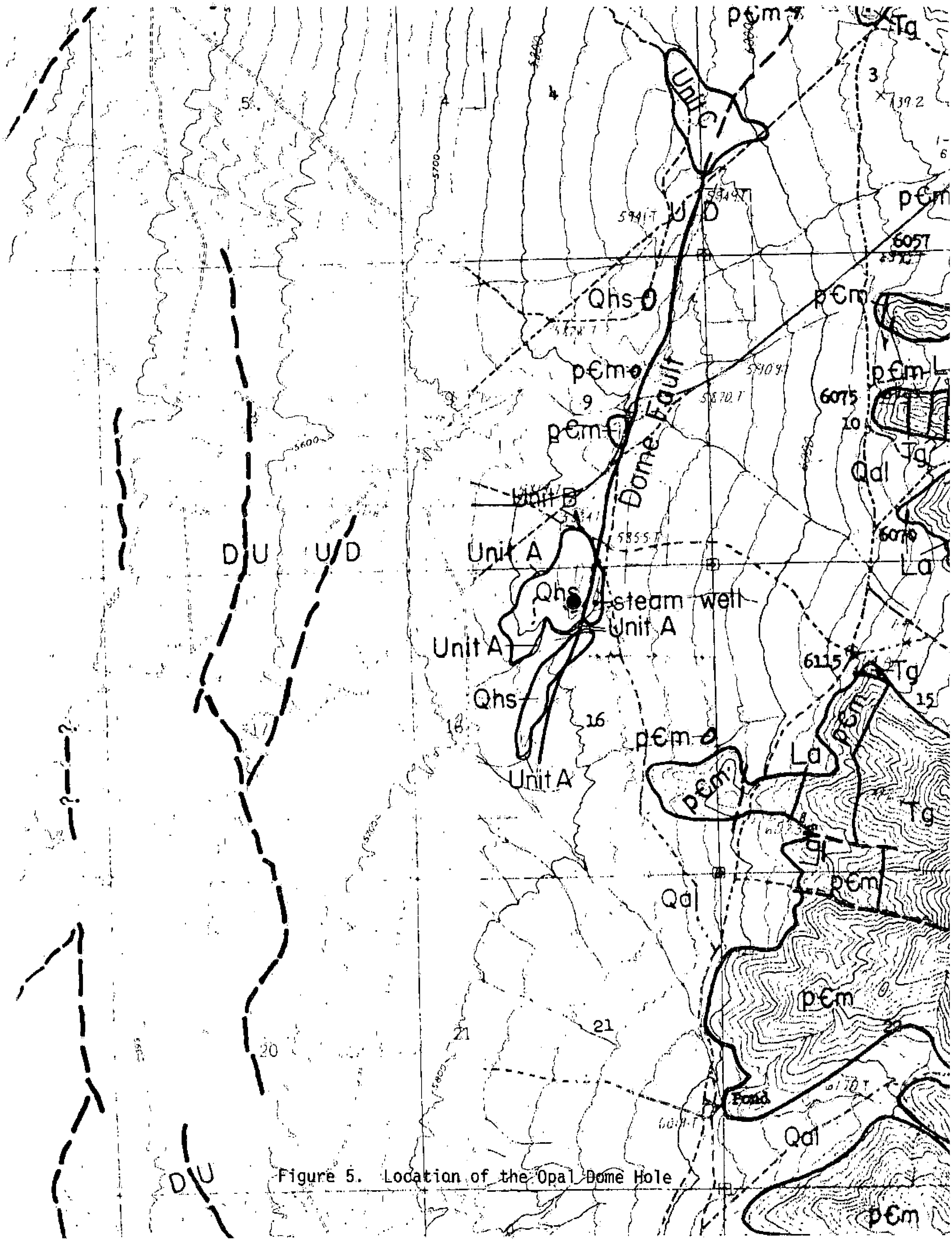

Figure 5. Location of the Opal Dome Hole

2.2.1 Jensen Construction and Drilling Company. The basic features of this contract were as follows:

(a) Mobilization and moving were at $1.50 per mile per unit (drill, water truck, pickup truck).

(b) Rig time, including the drill, a 1966 Hyarth, driller and helper, water truck and pickup truck was $45.00 per hour.

(c) Water truck driver, when needed was furnished at $70.00 per day.

(d) Bits were furnished at cost. Credit was given for diamond salvage.

(e) Core boxes and casing lost in the hole were paid for at cost.

(f) Other supplies - cement, drilling mud, casting plaster were charged for at cost plus 10 percent delivery charge.

2.2.2 The Wortley Engineering contract had the following features:

(a) No mobilization charge.

(b) Moves were at hourly "rig time" rate.

(c) Rig time was charged at $24 per hour which included a driller and helper, pickup truck, a Joy 12 drill, an air compressor, and a water pump tank combination.

(d) Supplies were furnished at cost.

3.0 Procedure

3.1 Site Preparation. No holes required site preparation.

3.2 Surveying. All holes were tape and compass surveyed to the nearest land survey monument. Surveys are provided in hole data, Appendix (A).

3.3 Geologist. A geologist was present on the drill coring.

3.4 Hole completion. Thermal gradient holes and the alteration hole were completed by setting bottom capped one-inch black iron pipe in the hole, back filling with cuttings or sand to within 10 feet of the surface and from 10 feet to the surface with concrete. The heat flow holes were completed by setting one-inch black iron pipe with a check valve on the bottom. Water was circulated until good returns were obtained, followed by grout until it returned. Then a swabber, consisting of three tight fitting rubber stoppers on a threaded rod was forced into the check valve. After the grout or cement set, the black iron pipe was filled with water. All sites were raked or tilled and were seeded with 83 percent by weight crested wheat grass and 17 percent bitter brush between 15 September and December 1.

4.0 Costs

4.1 Costs for individual holes for Wortley Engineering are given in Appendix A. Costs for individual holes are not available for Jensen Drilling and Construction. Average costs for Jensen Drilling and Construction are given in Table 1 and for Wortley Engineering in Table 2.

TABLE 1 Average Costs, NX Core Drilling

Year	1975	1976	1976
Contract Agency	NSF	ERDA	USGS
Company	Boyles Brothers	Jensen	Jensen
Company Location	Salt Lake City, UT	Springville UT	Springville UT
Number of Holes	7	4	6
Total Footage	1727	1255	1589
Cost Per Foot			
Mobilization Move in, move out	2.81	0.57	1.04
Rig Time	11.68	11.05	9.58
Bits (Net)	1.59	3.16	3.07
Supplies & Materials	1.50	0.30	0.51
Casing and Shoes lost in hole	0.07	--	0.42
	17.65	15.08	14.62

TABLE 2 Average Costs, Rotary Drilling, Wortley Company, Summer, 1976

	Cost Per Foot
Rig Time	$3.67
Diamond Bits	0.08
Rotary Bits	0.78
Surface Pipe	0.14
Supplies & Materials	0.31
Average Cost Per Foot	$4.98

APPENDIX A - Descriptions of Holes

Thermal Gradient Hole 1

LOCATION: NW 1/4, SW 1/4, Sec. 15,T26S,R9W. (SLB & M)
994.8 Ft. S85°E from quarter corner 16/15.

LAND STATUS: Public Domain (BLM).

DATES OF DRILLING: July 12, 1976 - July 15, 1976

DEPTH: 185 Feet

COST ANALYSIS

	Total Cost $	Cost Per Foot $
Rig Time	614.00	3.32
Rotary Bits (2)	152.00	0.82
Supplies and Materials	68.40	0.37
Totals	834.40	4.51

SUMMARY OF DRILLERS LOG: 0-20 drilled and cemented surface, pipe. 0-205 feet. Drilled ahead of coring hole. Final effective depth 185 feet.

SUMMARY OF LITHOLOGIC LOG: Alluvium. Poorly sorted subangular granite wash, sand to gravel size. Contains streaks of magnetite.

WATER: None encountered

COMPLETION DATA: Set black iron pipe to 185 feet. Backfilled with cuttings to 10 feet from the surface. Cemented top 10 feet. Site tilled and reseeded with crested wheat grass and bitter brush, 10:2 by weight.

Thermal Gradient Hole 2

LOCATION: SW 1/4 Sec. 5, T6S, R9W (SLB & M)
2469 Ft. East and 1108 Ft. North of $\frac{6|5}{7|8}$

LAND STATUS: Public Domain (BLM).

DEPTH: 232 Feet

COST ANALYSIS

	Total Cost $	Cost Per Foot $
Rig Time	870.00	3.75
Rotary Bits (2)	152.00	0.66
30-ft. of 2.5-inch casing @ $1.50/foot	45.00	0.19
Supplies and Materials	68.00	0.29
Totals	1135.00	4.89

DRILLERS LOG:
0-15 feet. Drilled and cemented.
0-50 feet. Set casing to 30 feet. Hole coring.
50-125 feet. Drilling.
125-220 feet. Soft with small boulders.
220-232 feet. Set black iron pipe to 212 feet because of coring.

SUMMARY OF LITHOLOGIC LOG: Granite wash (cuttings from boulders), coarse sand with magnetite streaks.

WATER: None encountered.

COMPLETION DATA: Set capped black iron pipe to 212 feet. Backfilled with sand and cuttings to 10 feet from the surface. Cemented to surface. Site tilled and reseeded with crested wheat grass and bitter brush, 10:2 by weight.

Thermal Gradient Hole 3

LOCATION: SE 1/4 Sec. 19, T26S, R9W (SLB & M).
2670 feet N54°W from Sec. Corner 19 | 20
30 | 29

LAND STATUS: Private

DATES OF DRILLING: 24 June 1976 to 11 July 1976

COST ANALYSIS

	Total Cost $	Cost per Foot $
Rig Time	1194.00	3.67
Rotary Bits (3)	228.00	0.70
Surface Pipe 10'-3" iron	36.61	0.11
Supplies and Materials	77.00	0.24
Totals	1535.61	4.72

SUMMARY OF DRILLERS LOG:
0-10 feet. Set Casing. Cemented.
10-45 feet. Drill and cement each day.
45-132 feet. Drilled ahead with casing.

SUMMARY OF LITHOLOGIC LOG:
0-20 feet. Granite wash, gravely sand.
20-45 feet. Silt
45-85 feet. Granite wash. Gravely sand
85-95 feet. Gravel
95-325 feet. Granite wash sand.
Magnetite present through entire hole.

WATER: None encountered

COMPLETION DATA: Set capped black iron pipe to 305 feet. Backfilled with cuttings and sand to within 10 feet of the surface. Cemented top 10 feet. Cleaned and reseeded site with crested wheat grass and bitter brush (10:2 by weight).

Thermal Gradient Hole 5

LOCATION: SE 1/4, Sec. 14, T26S, R9W (SLB & M).
3047.4 feet N53E° of $\frac{S14}{S22}$ 1/4

LAND STATUS: Public Domain (BLM)

DATES DRILLED: 2 September 1976 - 7 September 1976

DEPTH: 170 Feet

COST ANALYSIS

	Total Cost $	Cost Per Foot $ (overall)
Rig Time	1158.00	6.81
Rotary Bits (3)	228.00	1.34*
Diamond Bits (1) 20' - 3 inch	100.00	0.53**
Casing	30.00	0.18
Supplies and Materials	129.10	0.76
Totals	1645.10	9.68

*150 feet drilled. $1.52 per foot
**20 feet drilled. $5.00 per foot.

SUMMARY OF DRILLERS LOG: 0-20 feet. Drilled. Set 20-feet casing.
20-150 feet. Rotary drilling. Lost circulation.
150-170 feet. Changed to Diamond Bit. Lost circulation.

SUMMARY OF LITHOLOGIC LOG: 0-150 feet. Granite wash with magnetite streaks.
150-170 feet. Fractured granite. Biotite altered to chlorite. Abundant iron and manganese staining.

WATER: None encountered

COMPLETION DATA: Ran capped PVC pipe to 162 feet. Backfilled to 10 feet from the surface. Cemented 10 feet to surface. Cleaned and reseeded site.

Thermal Gradient Hole 6

LOCATION: SE 1/4, Sec. 7 T26S, R9W (SLB & M)
3710 feet N 54° W of
7 | 8
18 | 17

LAND STATUS: Private.

DATES DRILLED: 20 August 1976 to 24 August 1976

DEPTH: 315 feet

COST ANALYSIS: Details not available. Total cost $1065.45, or $3.38 per foot.

SUMMARY OF DRILLERS LOG: Not available.

SUMMARY OF LITHOLOGIC LOG: Granite wash with streaks of magnetite.

WATER: None encountered

COMPLETION DATA: Set 305 feet of capped, one-inch PVC pipe in the hole. Back filled to 10 feet of surface. Cemented top 10 feet. Raked and reseeded drill site.

Thermal Gradient Sec. 16

LOCATION: NW 1/4, Sec. 16, T26S, R9W (SLB & M)
4483 ft. S41W from
9 | 10
16 | 15

LAND STATUS: State

DATES DRILLED: 2 September 1976 through 7 September 1976

DEPTH: 250 feet

COST ANALYSIS:

	Total Cost $	Cost Per Foot $
Rig Time	816.00	3.26
Rotary Bits (3)	228.00	0.91
Surface pipe 15'-3-inch	37.00	0.15
Supplies and Materials	52.60	0.21
Totals	1133.60	4.53

SUMMARY OF DRILLERS LOG:
0-15 feet. Drilled, set 3-inch steel casing, cemented.
15-55 feet. Drilling, hole coring.
55-250 feet. Drilling.

SUMMARY OF LITHOLOGIC LOG:
0-25 feet. Gravel of granitic composition.
25-185 feet. Granite wash with magnetite streaks.
185-215 feet. Quartz sand.
215-250 feet. Granite wash with magnetite streaks.

WATER: None encountered.

COMPLETION DATA: Ran 235 feet of capped one-inch black iron pipe. Backfilled to ten feet from surface, cemented ten feet to surface. Cleaned and reseeded site with 10:2 by weight crested wheat grass and bitter brush.

Alteration Hole 1-76

LOCATION: NE 1/4, SW 1/4, Sec. 34, T26S, R9W (SLB & M).
East 1926 feet and south 2756 feet from

28	27
33	34

LAND STATUS: Private

DATES DRILLED: 21 June 1976 - 25 June 1976

DEPTH: 201.8 feet.

COST ANALYSIS: Not available.

DRILLERS LOG: 0-10.8 feet. Rotary drilling.
10.8-201.8 feet. Core drilling.
Lost circulation at 150.8 feet, added cement.
Lost circulation at 188.0 feet, changed from water to bentonite drilling mud.

CORE RECOVERY: 74 percent

SUMMARY OF LITHOLOGIC LOG: 0-10.8 feet. Granite wash
10.8-61.4 feet. Silica cemented granite wash alluvium.
61.4-201.8 feet. Altered and fractured granite containing some pyrite, chlorite, and sphene.

WATER: None encountered

COMPLETION DATA: Set capped one-inch black iron pipe to 200 feet. Backfilled with cuttings to 10 feet from the surface. Site cleaned and reseeded with 10:2 by weight crested wheat grass and bitter brush.

Heat Flow Hole No. 1

LOCATION: NW 1/4, Sec. 8, T27S, R8W (SLB & M)
1620 feet East and 162 feet south of $\frac{6|5}{8}$

LAND STATUS: Public domain (BLM).

DATES DRILLED: 28 June 1976 - 15 July 1976; 2 August 1976 - 9 August 1976

DEPTH: 508.4 feet.

COST ANALYSIS: Not available

DRILLERS LOG: 0-101.7 feet. Rotary drilling.
101.7-508.4 feet. Coring.
Continuous sanding in hole. Lost circulation at 432.0 feet. Wide crevice at 450 feet. Tried regaining circulation from top and bottom. Failed. Cemented. Cased hole to 467.0 feet with NX drill rods. Commenced drilling with BX rods. Extreme difficulty in recovering NX rods.

LITHOLOGIC LOG: 0-101.7 feet. Muddy top soil.
101.7-316.5 feet. Altered granite, chlorite prominent.
316.5-318.0 feet. Basic dike.
316.5-508.4 feet. Intermittent aplite dikes in granite containing biotite and chlorite. Iron, manganese, and chlorite staining on fractures.

PERCENT CORE RECOVERY: 65 percent.

COMPLETION DATA: Set one-inch black iron pipe to 504 feet. Pumped cement into pipe until surface returns were obtained and pushed it out with a swabber. Cleaned site and reseeded site with crested wheat grass and bitter bush (10:2 by weight).

Hole Number 3 Heat Flow

LOCATION: SE 1/4, Sec. 25, T26S, R9W
3432 ft. N79E from 26|25
35|36

LAND STATUS: Public Domain (BLM).

DATES DRILLED: 9 August 1976 - 27 August 1976

DEPTH: 489.3 feet.

COST ANALYSIS: Not available

DRILLERS LOG: 0-29.0 feet. Rotary drilling.
29.0-489.3 feet. Core drilling.

LITHOLOGIC LOG: 0-29.0 feet. Granite wash.
29.0-106.6 feet. Fractured granite with biotite and chlorite.
74.0-81.0 feet. Basic dike.
81.2-82.7 feet. Basic dike.
106.6-489.3 feet. Intermittent aphite dike in granite containing biotite and chlorite. Some sphene, hemitic, manganuferous, and chloritic staining in fractures.

PERCENT CORE RECOVERY: 96

COMPLETION DATA: Set one-inch black iron pipe to 487 feet. Pumped cement into pipe until surface returns were obtained and pushed cement out of pipe with a swafter. Cleaned site and reseeded it with crested wheat grass and bitter bush (10:2 by weight).

Opal Dome Hole

LOCATION: NE 1/4 Sec. 16, R9W, T26S (SLB & M)
2548 feet S77W of 9 | 10
16 | 15

LAND STATUS: State opal lease to A. & L. McDonald

DATES DRILLED: 9 August 1976

DEPTH: 55.2 feet

COST ANALYSIS: Not available

DRILLERS LOG: 0-4.7 feet. Rotary drilling.
4.7-55.2 feet. Core drilling.

LITHOLOGIC LOG: Coring began just below 5 feet. The first 23 feet consists dominantly of massive or banded opal with some clay interbeds, which become more abundant near the bottom of this section of the core. From 23 to 33 feet the core consists mainly of silicified sediment with minor opal layers. Below this to the bottom the core is made of cemented alluvium, either brown or light green, and varying considerably in its coherence.

COMPLETION: Abandoned.

FOR DETAILS SEE: Brown, F. H. (1977). Attempt at Paleomagnetic Dating of Opal, Roosevelt Hot Springs KGRA. Technical Report, vol. 77-1, Contract EY-76-S-07-1601, ERDA, 13 p.

ELECTROMAGNETIC AND SCHLUMBERGER RESISTIVITY SOUNDING IN THE ROOSEVELT HOT SPRINGS KGRA

by

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Paper presented at the 46th Annual International SEG Meeting, Houston, Texas, October 28, 1976.

ABSTRACT

One- and two-dimensional modeling of the Schlumberger soundings at the Roosevelt Hot Springs KGRA have indicated a low-resistivity zone of approximately 5 Ω-m paralleling the Dome Fault. The low resistivity of this zone is probably due to intensely fractured and altered rock. A zone of resistivity 12 Ω-m extending to the west of the Dome Fault is probably due to leakage of brine away from the geothermal system. A resistive basement underlies the conductive zones and is believed to be unaltered rock.

A major problem in the application of one-dimensional modeling of Schlumberger data in the Roosevelt Hot Springs KGRA is poor resolution of the one-dimensional model parameters. The joint inversion of Schlumberger and electromagnetic sounding data gives a least-squares one-dimensional conductivity model in which parameters are much better resolved than the model parameters estimated by the inversion of Schlumberger data alone.

One-dimensional modeling of Schlumberger soundings along a traverse does indicate the presence of a two-dimensional inhomogeneity but it gives no hint of the possible complexity of that inhomogeneity even though the parameters of the models fitting each sounding have acceptable standard deviations when constrained by electromagnetic sounding data. The model parameter standard deviations are a function of the partial derivatives of the model

values of apparent resistivity with respect to the one-dimensional model parameters evaluated at the model parameter values. Thus, good resolution of one-dimensional model parameters does not indicate that the assumption of a one-dimensional model is valid. On the other hand, the possible complexity of structure is brought out by two-dimensional modeling of the same data, but with no estimates of parameter reliability whatsoever. Since the degrees of freedom for complex two-dimensional models is large, a thorough study of the resolution of such models is prohibitively costly at present. In these circumstances, the best we can do is to constrain the two-dimensional models with independent geological or geophysical data and then take the subsequent best-fit model with an intuitive grain of salt.

INTRODUCTION

Since 1974, the University of Utah has done extensive geological, geochemical, and geophysical investigations of the Roosevelt Hot Springs KGRA, near Milford, Utah. A part of this investigation was the collection and interpretation of approximately 50 oscillating magnetic dipole soundings and 21 Schlumberger resistivity soundings. We shall report on these soundings here.

Investigation of geothermal areas via Schlumberger sounding has been extensive and worldwide (Breusse and Mathiez, 1956; Cheng, 1970; Duprat, 1970; Zohdy et al., 1973; Stanley et al., 1976). These investigations have invariably utilized one-dimensional modeling of individual soundings, with subsequent synthesis, to predict relevant geologic structure. Previous investigations of geothermal regions via artificial source electromagnetic methods include time-domain investigations by Keller (1970) and Stanley et al.,(1976) and frequency-domain measurements by Keller (1970), Lumb and MacDonald (1970), and MacDonald and Muffler (1972).

The Schlumberger method was used in the Roosevelt Hot Springs KGRA for three reasons. First, finer resolution of the vertical geoelectric section was desired along traverse lines where extensive reconnaissance dipole-dipole sounding-profiling had been done. In particular, accurate estimates of the depth to crystalline bedrock were desirable, both as a counter-check of the gravity and magnetic interpretation of the area (Crebs, 1976) and as a complement to the dipole-dipole interpretation (Ward and Sill, 1976). Second, the Roosevelt Hot Springs environment provided a field test of the utility of joint electromagnetic-resistivity one-dimensional least-squares inversion. Third, a test of the utility of the Schlumberger method in two-dimensional laterally inhomogeneous regions was desired. By use of a two-dimensional transmission surface analogy modeling program, a judgment of the merits of lumping one-dimensional interpretations to deduce a two-dimensional structure of dimensions comparable to those of the soundings was possible. Conversely, the relative effects of lateral conductivity inhomogeneities of the scale encountered at Roosevelt Hot Springs on one-dimensional interpretation schemes could be judged.

The electromagnetic method was used to detect shallow (depths to 100 meters) conductivity layering and to complement the resistivity data, as mentioned above.

The location of both Schlumberger and electromagnetic sounding sites was based on geological considerations and previous dipole-dipole resistivity surveys. Actual location of the Schlumberger and electromagnetic sounding-profiling is illustrated in Figure 1. Figure 1 also illustrates fractures previously delineated by several other geophysical and geological methods.

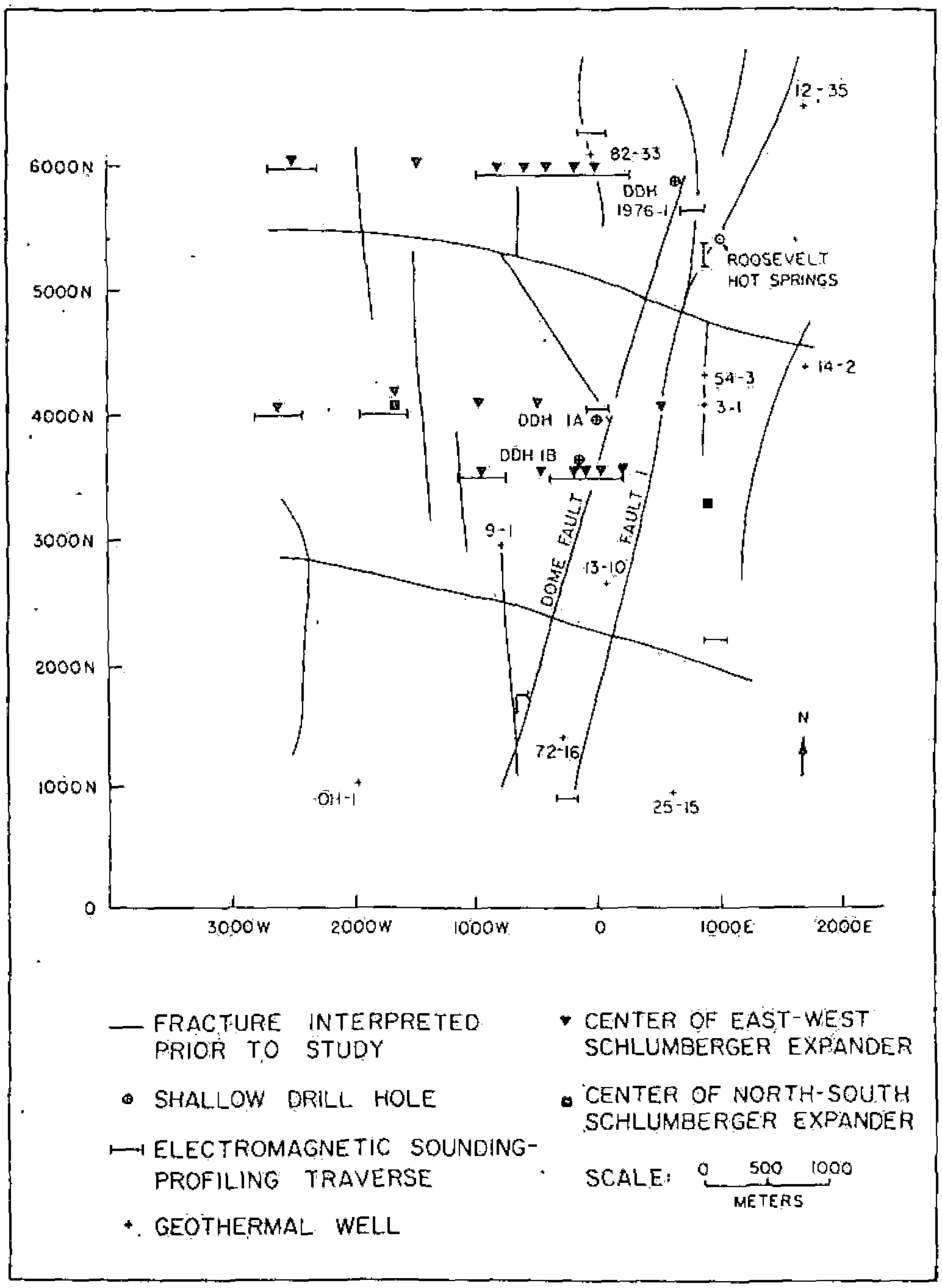
GEOLOGICAL SETTING

The Roosevelt Hot Springs KGRA lies to the immediate west of the Mineral Range. The major unit of the Mineral Range is a granitic pluton 32 km long and 8 km wide. This pluton is flanked by sedimentary units, basalt flows and Precambrian (?) metamorphics to the west. Rhyolitic volcanics, between 500,000 and 700,000 years old (Nash, 1976), are exposed in the central part of the range. North-south faulting paralleling the Mineral Range is extensive (Petersen, 1975; Crebs, 1976).

The survey area is mostly covered with alluvium of Tertiary and Quaternary age. Hot spring deposits occur along the north-south Dome fault which is upthrown on the west and is thought to be a major structural control for the geothermal activity (Petersen, 1975). Core from shallow drill hole DDH 1A (Figure 1) and analysis of aeromagnetic data indicates that the alluvium to the west of the Dome Fault is underlain by Precambrian bedrock while bedrock is granite east of the fault (Ward and Sill, 1976). Extensive clay alteration has been found in drill-holes DDH 1A (Parry et al., 1976) and DDH 1B.

The major conductivity changes sought in the survey region occur at bedrock, at the water table, and at alteration zones and brine-filled fractures.

Figure 1. Map of previously interpreted fractures, showing the location of Schlumberger and electromagnetic soundings.

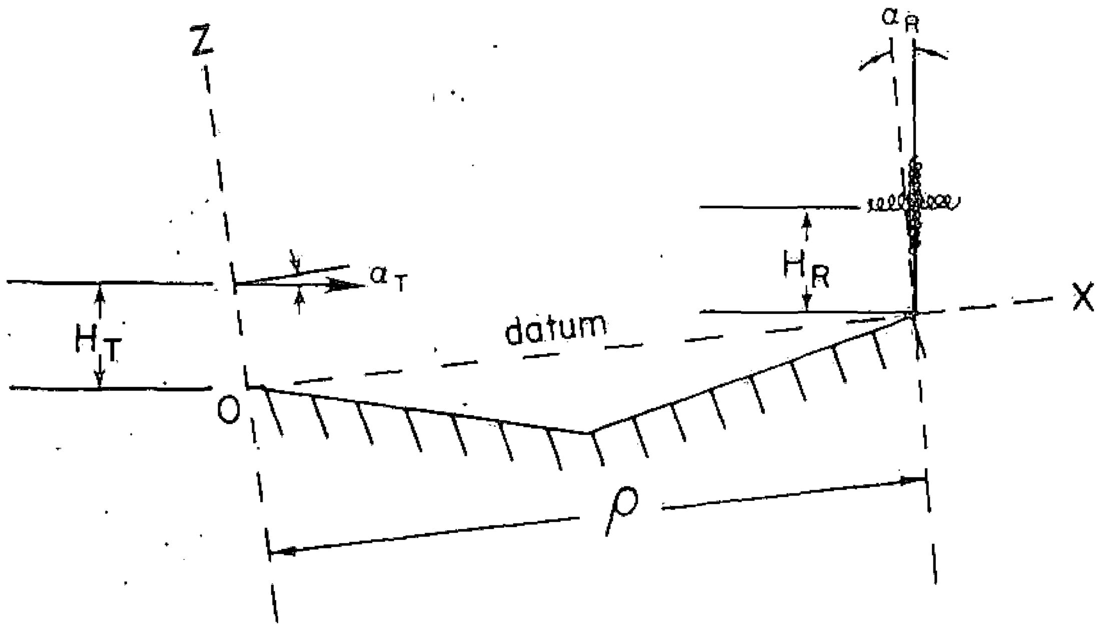

12-35
82-33
DDH
1976-1
ROOSEVELT
HOT SPRINGS
14-2
54-3
3-1
DDH 1A
DDH 1B
9-1
DOME FAULT
FAULT
13-10
72-16
25-15
OH-1
N
6000N
5000N
4000N
3000N
2000N
1000N
0
3000W
2000W
1000W
0
1000E
2000E
FRACTURE INTERPRETED PRIOR TO STUDY
SHALLOW DRILL HOLE
ELECTROMAGNETIC SOUNDING-PROFILING TRAVERSE
GEOTHERMAL WELL
CENTER OF EAST-WEST SCHLUMBERGER EXPANDER
CENTER OF NORTH-SOUTH SCHLUMBERGER EXPANDER
SCALE: 0 500 1000
METERS

ELECTROMAGNETIC MEASUREMENTS AND INVERSION

The electromagnetic measurements at Roosevelt Hot Springs were made with the University of Utah's 14 frequency two-loop electromagnetic system. The system is designed to measure the tilt angle and ellipticity of the polarization ellipse of the magnetic field scattered by a conductive earth. The soundings utilized a transmitting coil of 10 m diameter, vertically suspended from an aluminum mast. The receiver used two tunable orthogonal ferrite-cored coils. The coils were supported by a vertical yoke, which enabled the operator to make the axes of the coils coplanar with the oscillating dipole and then align the coils with the major and minor axes of the polarization ellipse. Figure 2 illustrates the general transmitter-receiver configuration. A detailed description of the field technique and the system design is contained in Ward et al. (1974).

At the beginning of the field measurements for each traverse, it was necessary to establish the optimal transmitter-receiver separations. The transmitter-receiver separation was varied until low and high frequency asymptotes appeared in the tilt angle curves. The low-frequency asymptote, combined with ellipticity values very close to 0, indicated that the scattered field, to the resolving power of the polarization ellipse parameters, was zero. The high frequency asymptote indicated that the field was entirely reflected

Figure 2. Illustration of electromagnetic transmitter and receiver geometry.



α_T = TRANSMITTER ANGLE

H_T = TRANSMITTER HEIGHT

α_R = RECEIVER ANGLE

H_R = RECEIVER HEIGHT

ρ = TRANSMITTER-RECEIVER SEPARATION at the air-earth interface. Thus the full resolving capabilities of the system could be utilized. This empirical technique gave transmitter-receiver separations which were optimal in the sense of Glenn and Ward (1976). In some cases, multiple separation soundings were performed to accentuate the resolution at depth.

Accurate interpretations of the soundings required that the effects of terrain be removed. Figure 2 illustrates the geometric parameters which must be taken into account in the terrain correction. H_T and H_R are the vertical elevations of the transmitting magnetic dipole and the receiving coils respectively while ρ is the distance between the transmitter and the receiver. These three parameters are measured directly. α_T is the angle between the transmitting dipole and the horizontal direction with respect to the "datum" while α_R is the angle between the receiver vertical axis and the vertical direction with respect to the datum. α_T and α_R are determined from a knowledge of the relative elevation of the transmitter base with respect to the receiver base. Since low frequency magnetic field tilt angles are solely dependent on the relative geometry of the transmitter and the receiver, theoretical low-frequency field tilt angles, computed using the measured values of H_T, H_R and ρ and the computed values of α_T and α_R, should agree with the measured low-frequency tilt angles. In practice, the average variance of these quantities is approximately 1°, which is significantly larger than any expected measurement error. Misorientation of the transmitting dipole with respect to the true horizontal direction is responsible for this discrepancy, since H_T,

H_R, and ρ are measured precisely and since any orientation error of the receiver axis with respect to the vertical is eliminated by the measurement technique (Ward et al., 1974). Thus the angle α_T is adjusted to correct any low frequency mismatch between theoretical and observed tilt angles. Appendix A contains a short discussion of the actual computation of tilt angle and ellipticity when the transmitting dipole and the receiver axis are inclined with respect to a one-dimensional earth, whose surface in this case is the "datum".

After the low frequency tilt angle asymptotes were matched, the soundings were inverted to a layered geoelectric section using a generalized linear inversion routine, developed by Smith and Glenn and described by Glenn et al. (1973). Of course, the model earth surface is taken to be the "datum".

We have not made an a priori estimate of the data variance for ellipticity and tilt angle measurements. An empirical estimate of data variance is possible however. We have found that the electromagnetic soundings over approximately layered earths may be inverted to models which match the observed data to the extent illustrated in Figure 4. Assuming that the misfit in the curves of Figure 4 are indicative of the data noise, we will consider an inversion successful if the observed-theoretical data match is comparable, in a square residual sense, to those illustrated in Figure 4.

SCHLUMBERGER MEASUREMENTS AND INVERSION

The Schlumberger measurements were made using a non-coherent detector and a transmitting frequency of 0.1 hz. The received rectified voltage was averaged over at least 120 seconds, or 12 current cycles. A reading was made when the percent standard deviation of the time-averaged measurement indicated by the receiver was less than 2%. The transmitted current was electronically controlled by the transmitter to 3% of the specified current. Assuming that the distance AB/2 from the center of the Schlumberger expander to either current electrode and the distance MN between the potential electrodes both have 3% standard deviations, the percent standard deviation for the geometric factor $K = \pi[(AB/2)^2 / MN - MN/4]$ was found to be approximately 7% by the standard error propagation approximation (Bevington, 1969). Assuming these percent standard deviations for voltage drop, transmitted current, and geometric factor, and assuming that the time-averaged voltage deviation and the current deviation are uncorrelated, error propagation analysis gives a percent standard deviation for the apparent resistivity measurement of 8%.

Three soundings (Figure 1) centered at 4000N, 2700W; 3500N, 1000W; and 5950N, 2500W had maximum AB/2 values of 2000 meters. Soundings centered at 3500N, 200E; and 3500N, 00E had maximum AB/2 values of 1500 meters. The fifteen remaining soundings had maximum AB/2 values of 1000 meters.

All soundings were inverted to plane-layered conductivity models using ridge regression least-squares inversion, developed and described by Rijo et al. (1977). The starting model for each inversion was determined using a forward problem routine by manually varying model parameters until a close theoretical - observed data match was obtained. In all cases, discontinuities in apparent resistivity versus AB/2 introduced by expansion of the MN distance were left in the data during the inversion. However, in most cases, these discontinuities were minor.

GENERAL INVERSION PROCEDURE

In the inversion of the electromagnetic and the Schlumberger data to one-dimensional conductivity models, a fixed procedure was followed. If a data point was suspect in any of the sounding curves, it was excluded before the inversion. All data points retained for an inversion were given the weight 1. This assignment of weights is equivalent to the assumption that the variance of each observation is the same (Glenn et al, 1973). The final variance for the data was estimated via the reduced chi-square measure (Rijo et al., 1977; Glenn et al., 1973).

As a test of the stability of the inversion process, in numerous instances the inversion was begun using as initial guess a random model that did not fit the observed data at all well. In all cases, the model obtained by inversion was the same as that obtained from an initial model fitting the data very well, as long as the number of layers for the two models was the same. Thus, for the classes of models encountered in this study, there does not seem to be a problem with multiple minima in least squares residual space for either the Schlumberger or the electromagnetic soundings. Such stability also indicates that the programs which were used successfully dealt with convergence problems arising in non-linearity in the forward problem.

In considering the results of an inversion, three quantities are taken into account. The reduced chi-square measure indicates whether a particular model is consistent with the data, the parameter variances give a measure of the range of possible parameter values, while the parameter correlation matrix estimates the interdependence of the parameter variances. Thus the reduced chi-square measure and the parameter variances are enlisted in judging the reliability of a particular best-fit model, while the correlation coefficient of two parameters, say X_1 and X_2, indicates whether an independent estimate of one parameter will constrain the value of the other parameter. Note that an estimated correlation coefficient which is close to 1 in absolute value does not by itself indicate that only a product or quotient of X_1 and X_2 may be resolved. It is simply a measure of the tilt relative to the X_1 and X_2 axes and the ellipticity of the ellipse of standard deviation in the X_1-X_2 plane for the two estimated parameters (Hamilton, 1964). Only when the standard deviations for X_1 and X_2 are large will the ellipse of standard deviation enclose an important area of the X_1-X_2 plane.

The statistical estimates of parameter variance and parameter correlation assume that the forward problem theory is linear. Since this is only true locally, in the mathematical sense, the statistical estimates must only be used in a qualitative manner.

It was necessary to determine the number of conductivity layers to be included in the models. We believe the optimal number of layers to be the smallest number necessary to fit the data within the predetermined data variance. If the model has fewer layers, information contained in the data will be ignored. Adding more layers does not significantly reduce the least-square residual, as judged by the F-test (Davis, 1973), while the added parameters are often unresolvable.

TWO-DIMENSIONAL MODELING

One of the Schlumberger soundings had a curve with a positive slope greater than 45°. The thorough interpretation of this sounding required a consideration of two-dimensional effects. It will be shown later that consideration of two-dimensional effects is quite important for an adequate interpretation of all the Schlumberger soundings on lines 3500N and 5950N (see Figure 1 for locations). For this reason, we utilized a two-dimensional transmission surface forward algorithm to model the soundings along lines 3500N and 5950N. This algorithm gives the apparent resistivities for various values of AB/2 and MN due to a previously specified two-dimensional model. Each change in the conductivity structure must be user-specified. We began with a model "compatible" with the one-dimensional resistivity and electromagnetic best-fit models. The position of lateral contacts between blocks of different resistivities was constrained to be compatible with the faults mapped by a gravity survey (Crebs, 1976) and by reconnaissance dipole-dipole resistivity (Ward and Sill, 1976). A trade-off between resolution of conductivity features and the ability to model a large area was necessary. Since we were not interested in shallow or localized effects, we modeled the resistivity soundings only for values of AB/2 greater than or equal to 50 meters. We made the vertical magnitude of the individual conductivity grid boxes greater than or equal to 15 meters.

Recall that a measure of model non-uniqueness for one-dimensional modeling is provided by the model parameter statistics and correlations calculated by the inversion program. Since the two-dimensional model program used did not give the derivatives of the data with respect to the model parameters, two-dimensional model parameter statistics are not given. Although the models were made as simple as was conducive to a good data fit, it is likely that model equivalence problems are present. Since the degrees of freedom for such models is large, a thorough study of the resolution of such models by utilizing the forward problem is prohibitively costly. In these circumstances, the best we can do is to constrain the modeling with independent geological or geophysical data whenever possible, and then take the subsequent best-fit model with an intuitive grain of salt.

MODELING RESULTS

Line 3500N

Electromagnetic soundings. - Figure 3 illustrates the least-squares models and model parameter standard deviations for the one-dimensional inversion of the electromagnetic data along line 3500N. Figure 4 illustrates the match obtained between theoretical and observed values of tilt angle and ellipticity for the soundings 1.2, 2.2, and 3.3 of Figure 3. These theoretical-observed data matches are typical of the matches obtained throughout the study.

The models in Figure 3 indicate a simple conductivity structure. West of 150W, the upper layer has a resistivity of approximately 100 Ω-m; this upper layer is underlain by a unit with a resistivity of approximately 10 Ω-m, which seems to surface at 50W. The interface between these two units dips approximately 10° to the west. To the east of 50W as far as 200E there are two conductive units. The surface unit has a resistivity in the range 35 Ω-m to 107 Ω-m. The lower unit has a resistivity of approximately 5 Ω-m. The interface between the two units has a fairly constant depth of, say, 25m.

Schlumberger soundings. - Figure 5 depicts models and model parameter standard deviations for the one-dimensional inversion of the Schlumberger data along line 3500N. During the inversions, all model parameter values were unconstrained. The parameter standard deviations in Figure 5 reveal that the resistivities and thicknesses

Figure 3. Least-squares one-dimensional models and subsequent percent parameter standard deviations for electromagnetic soundings along line 3500N. The values in the layers are layer resistivities in ohm-meters and percent standard deviations. The value beneath each interface is the percent standard deviation for the thickness of the layer above. The vertical exaggeration is 4:1.

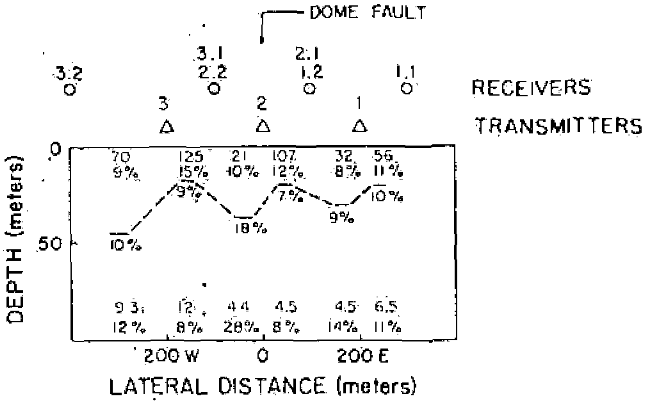
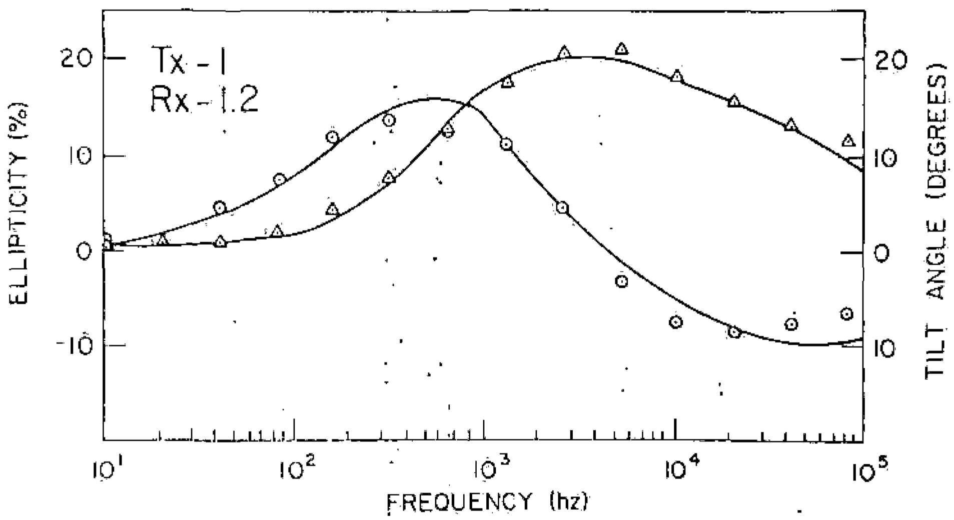
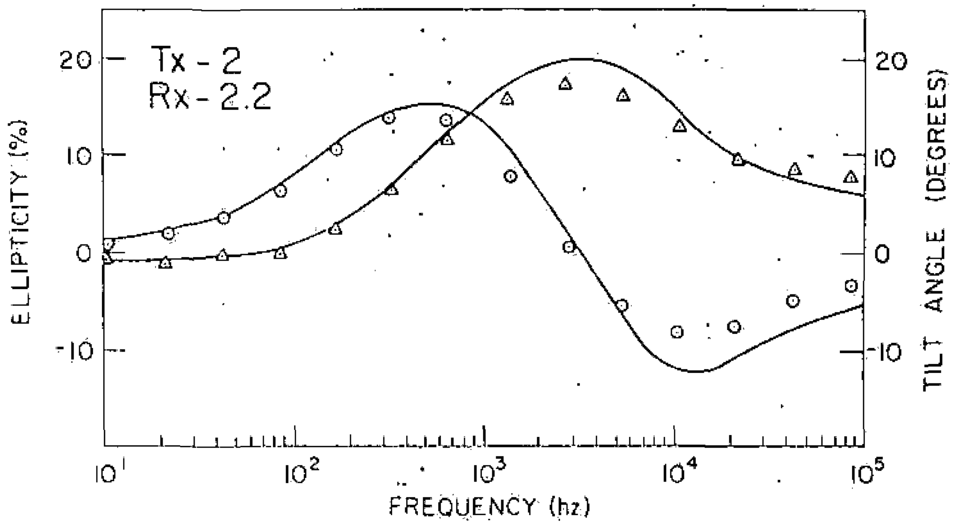

DOME FAULT
3.2
3.1
2.2
2.1
1.2
1.1
RECEIVERS
3
2
1
TRANSMITTERS
0
50
DEPTH (meters)
70
9%
125
15%
21
40%
107
12%
32
8%
56
11%
9%
7%
10%
18%
9%
10%
9.3
12%
12
8%
4.4
28%
4.5
8%
4.5
14%
6.5
11%
200 W
0
200 E
LATERAL DISTANCE (meters)

Figure 4. Fit for three electromagnetic soundings obtained from the one-dimensional models illustrated in Figure 3. Dotted circles or triangles are data points while the solid lines are the theoretical curves.


Tx - 1
Rx - 1.2
ELLIPTICITY (%)
20
10
0
-10
TILT ANGLE (DEGREES)
20
10
0
10
10¹
10²
10³
10⁴
10⁵
FREQUENCY (hz)


Tx - 2
Rx - 2.2
ELLIPTICITY (%)
20
10
0
-10
TILT ANGLE (DEGREES)
20
10
0
-10
10¹
10²
10³
10⁴
10⁵
FREQUENCY (hz)

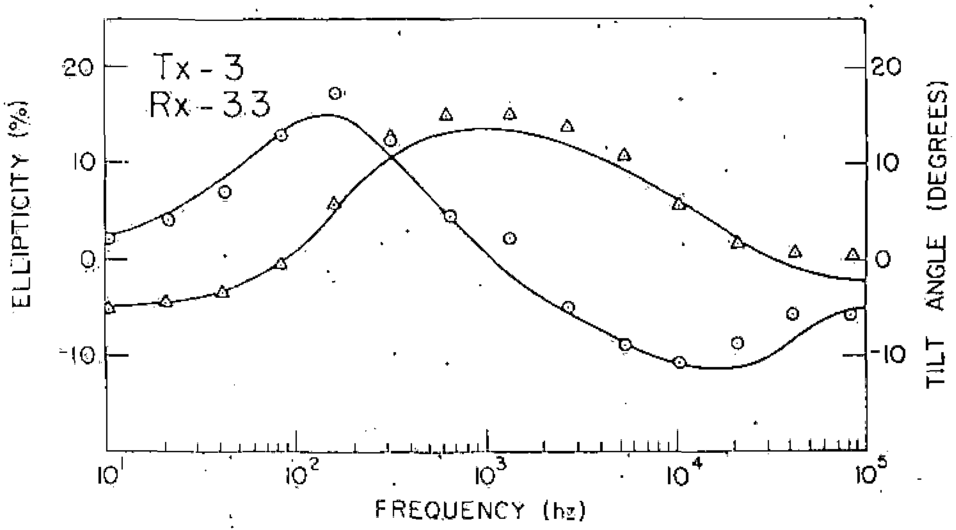
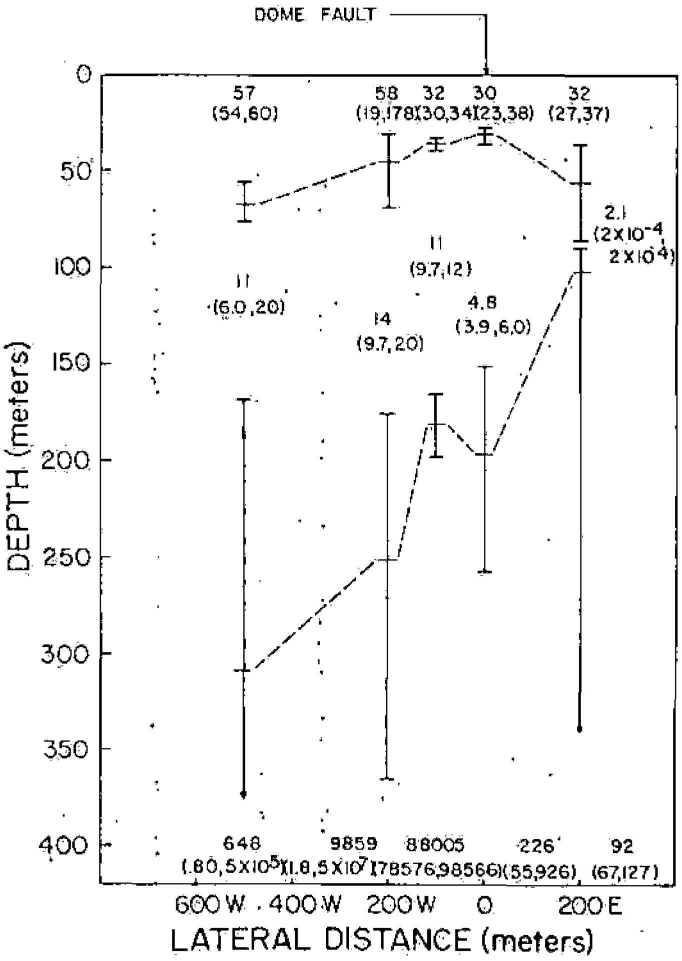

Tx - 3
Rx - 3.3
ELLIPTICITY (%)
20
10
0
-10
TILT ANGLE (DEGREES)
20
10
0
-10
10¹
10²
10³
10⁴
10⁵
FREQUENCY (hz)

Figure 5. Least-squares one-dimensional models and subsequent parameter standard deviations for Schlumberger soundings along line 3500N. The vertical exaggeration is 4:1. Superficial top layers are not depicted.

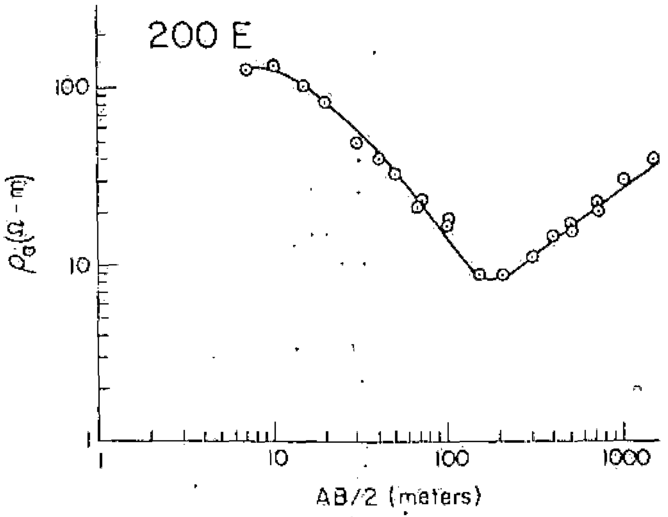

DOME FAULT
0
50
100
150
200
250
300
350
400
DEPTH (meters)
57
(54,60)
58
(19,178)
32
(30,34)
30
(23,38)
32
(27,37)
2.1
(2x10^-4, 2x10^4)
11
(6.0,20)
14
(9.7,20)
11
(9.7,12)
4.8
(3.9,6.0)
648
(.80,5x10^5)
9859
(1.8,5x10^7)
88005
(78576,98566)
226
(55,926)
92
(67,127)
600 W
400 W
200 W
0
200 E
LATERAL DISTANCE (meters)

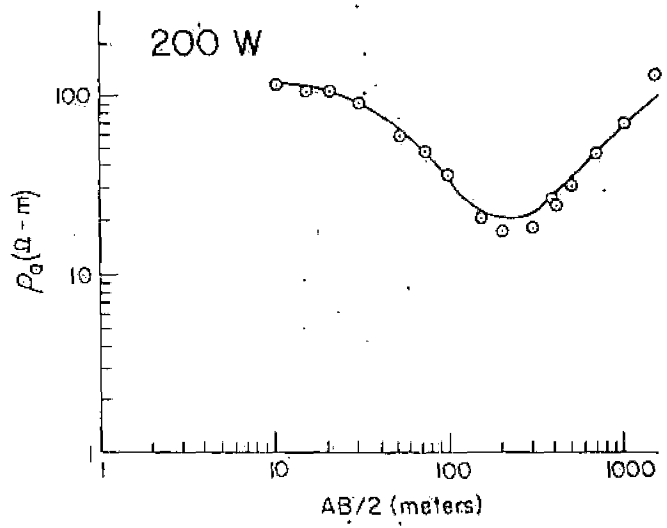
of the layers overlying the most conductive layer are in general well-resolved. The resistivities and thicknesses of the most conductive layer range from well-resolved to unresolved. The parameters of the resistive basement are mostly unresolved. Figure 6 depicts the small residuals obtained between theoretical and observed values of apparent resistivity for the soundings 500W, 200W, and 200E, which are representative of the residuals obtained for all of the soundings throughout this study.

Figure 7 depicts the one-dimensional models obtained from the inversion of the Schlumberger soundings when the basement resistivity is constrained to the value 300 Ω-m everywhere. The inversions with this constraint were done to facilitate comparison of one-dimensional and two-dimensional interpretations of the Schlumberger soundings. As is evident from Figures 5 and 7 the estimated parameters for the inversions with the basement resistivity constrained are comparable to the estimated parameters with the basement resistivity unconstrained for the four soundings east of 300W. For the sounding at 500W, the "constrained" basement depth is shallower than the "unconstrained" depth.

Two-Dimensional Modeling. - Heretofore, the interpretation of the Schlumberger soundings along line 3500N has assumed that the earth sampled by the soundings is locally one-dimensional. However, the marked lateral variation in the conductivity-thickness product of the conductive layer across the Dome Fault shown in Figure 5 is indicative of lateral conductivity inhomogeneity. Lateral inhomogeneity is also indicated by the sounding centered at 1000W, which

Figure 6. Fit for three Schlumberger soundings obtained from the one-dimensional models illustrated in Figure 5. Dotted circles are data points while the solid lines are the theoretical curves.


200 E
100
10
1
$\rho_a(\Omega - m)$
1
10
100
1000
AB/2 (meters)


200 W
100
10
1
$\rho_a(\Omega - m)$
1
10
100
1000
AB/2 (meters)

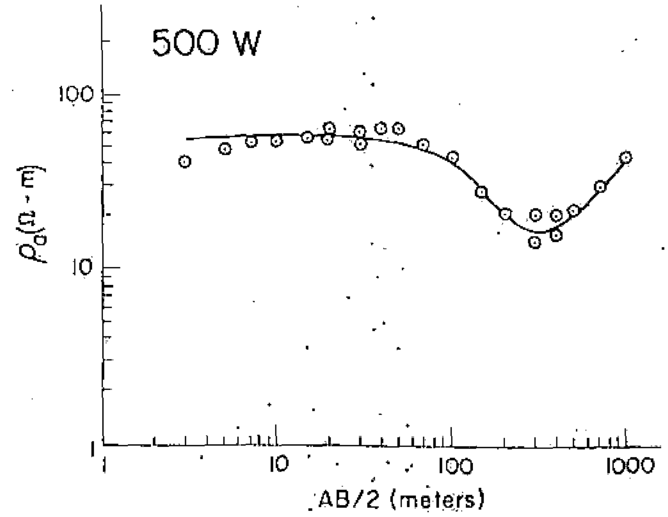
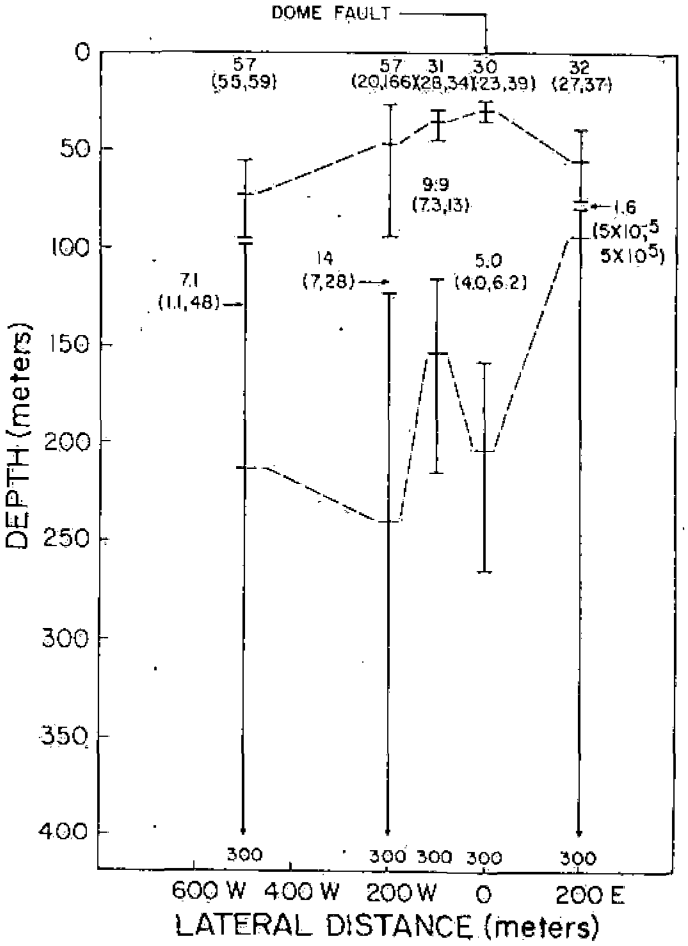

500 W
100
10
1
$\rho_a(\Omega - m)$
1
10
100
1000
AB/2 (meters)

Figure 7. Least-squares one-dimensional models and subsequent parameter standard deviations for Schlumberger soundings along line 3500N, obtained when basement resistivity is constrained to 300 Ω-m everywhere. The vertical exaggeration is 4:1. Superficial top layers are not depicted.


DOME FAULT
57
(55,59)
57
(20,166)
31
(28,34)
30
(23,39)
32
(27,37)
9.9
(7.3,13)
1.6
(5X10-5,
5X105)
14
(7,28)
7.1
(1.1,48)
5.0
(4.0,6.2)
300
300
300
300
300
0
50
100
150
200
250
300
350
400
DEPTH (meters)
600 W
400 W
200 W
0
200 E
LATERAL DISTANCE (meters)

has a greater than 45° ascending slope for AB/2 values greater than 1000 meters (Figure 8). Since reconnaissance dipole-dipole resistivity sounding-profiling in the area of line 3500N indicates a two-dimensional conductivity structure roughly paralleling the Dome Fault (Ward and Sill, 1976), the use of the two-dimensional resistivity forward algorithm to test the conjectured one-dimensional interpretation is justified. Note that the model parameter standard deviations are functions of the partial derivatives of the model values of apparent resistivity with respect to the one-dimensional model parameters evaluated at the model parameter values. Thus, good resolution of one-dimensional model parameters does not indicate that the assumption of a one-dimensional model is valid.

For the two-dimensional modeling, we fixed the Dome Fault at 0, a location compatible with the one-dimensional interpretations of both Schlumberger and electromagnetic data. East of 500E, conductivities of the blocks overlying the basement were chosen to be roughly compatible with a dipole-dipole profile which utilized 100 meter dipoles. This was necessary because of the absence of Schlumberger sounding centers east of 200E. The resistivity of the basement was constrained to 300 Ω-m. This resistivity value is compatible with deep dipole-dipole sounding and with laboratory measurements on Precambrian gneiss saturated with brine of the same salinity as brine sampled in the Roosevelt Hot Springs area.

The two-dimensional conductivity model for line 3500N is illustrated in Figure 9. As shown, in Figure 10, the match between the observed and the model apparent resistivity values is good for

Figure 8. Data curve for Schlumberger sounding centered at 3500N, 1000W. The break in the curve at AB/2 = 1000 corresponds with the crossing of the Dome Fault by the east current electrode.

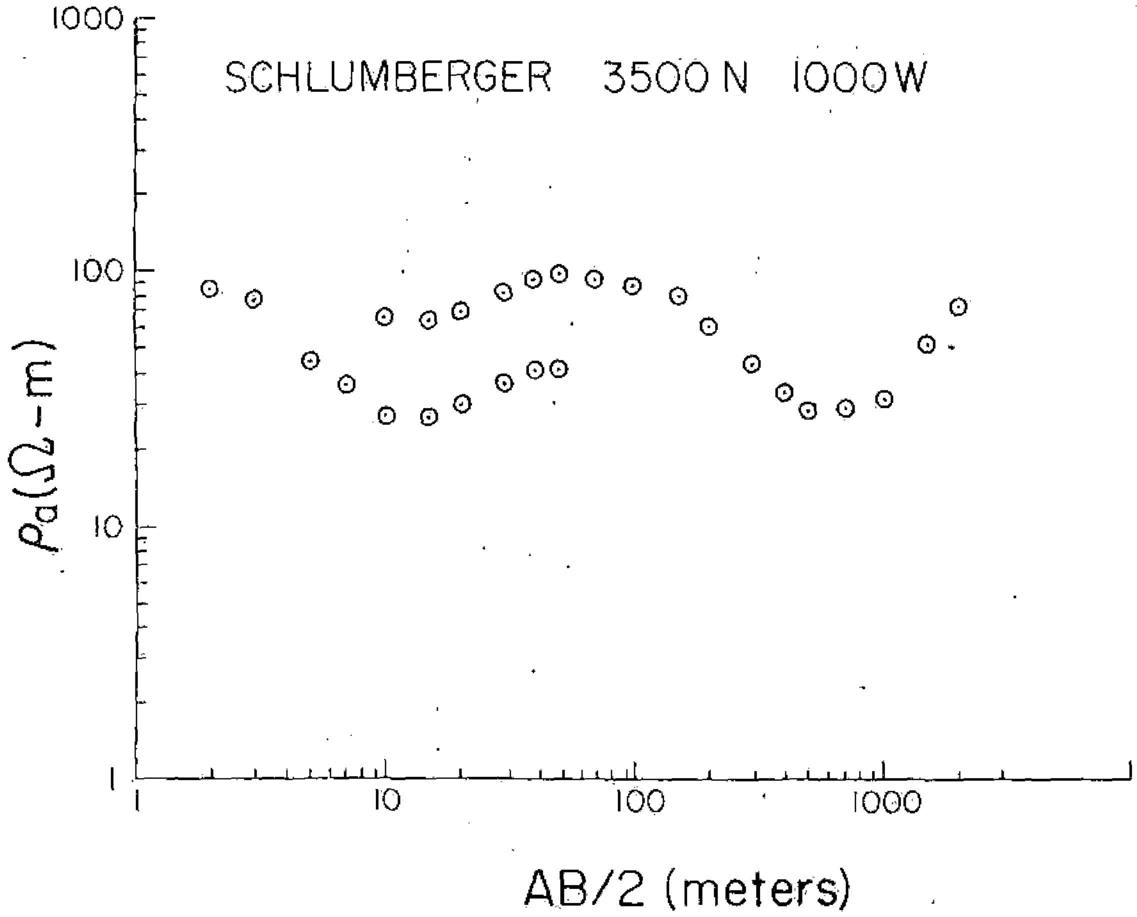

SCHLUMBERGER 3500 N 1000 W
1000
100
10
1
$\rho_a(\Omega\text{-m})$
1
10
100
1000
AB/2 (meters)

Figure 9. Two-dimensional resistivity model for Schlumberger soundings along line 3500N. Block resistivities are in ohm-meters. The vertical exaggeration is 4:1.

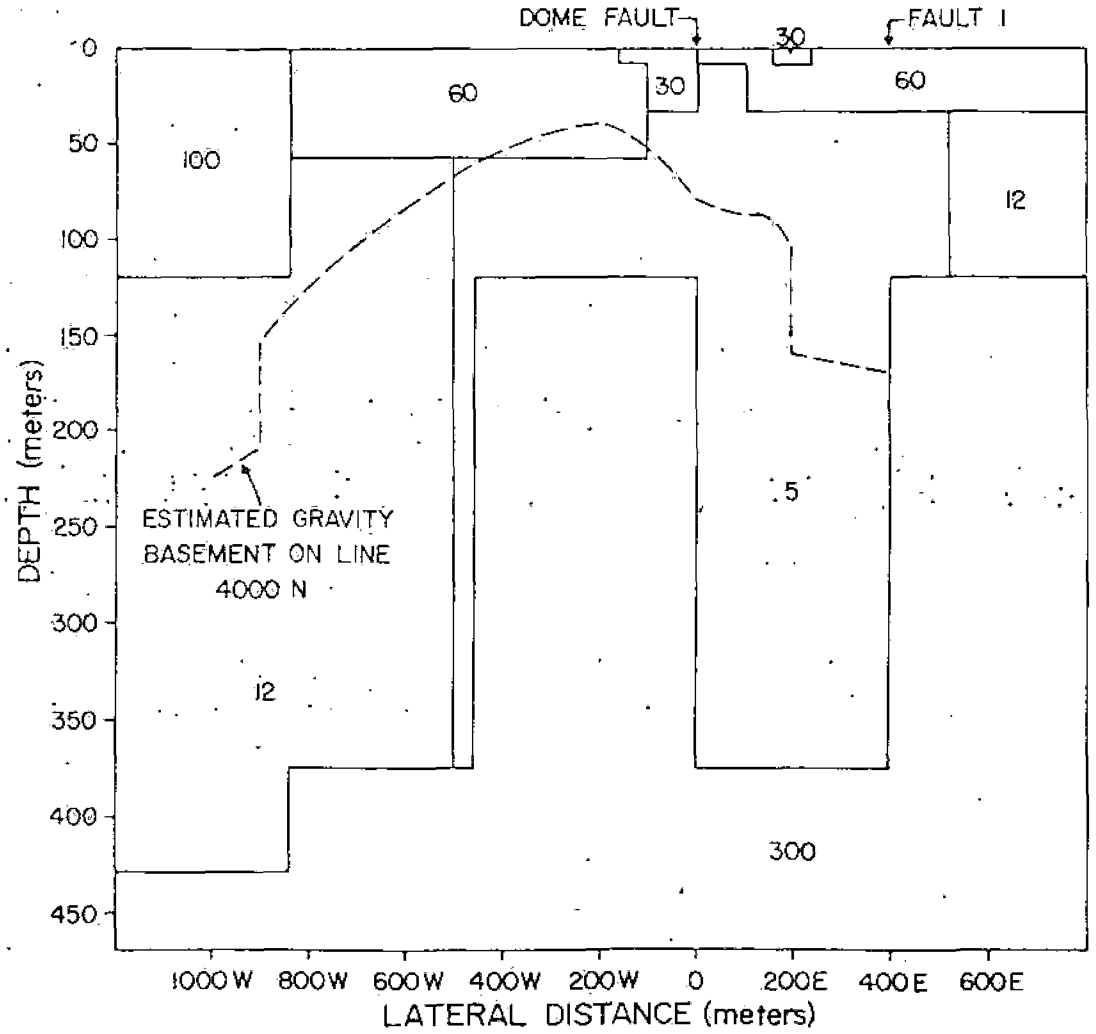
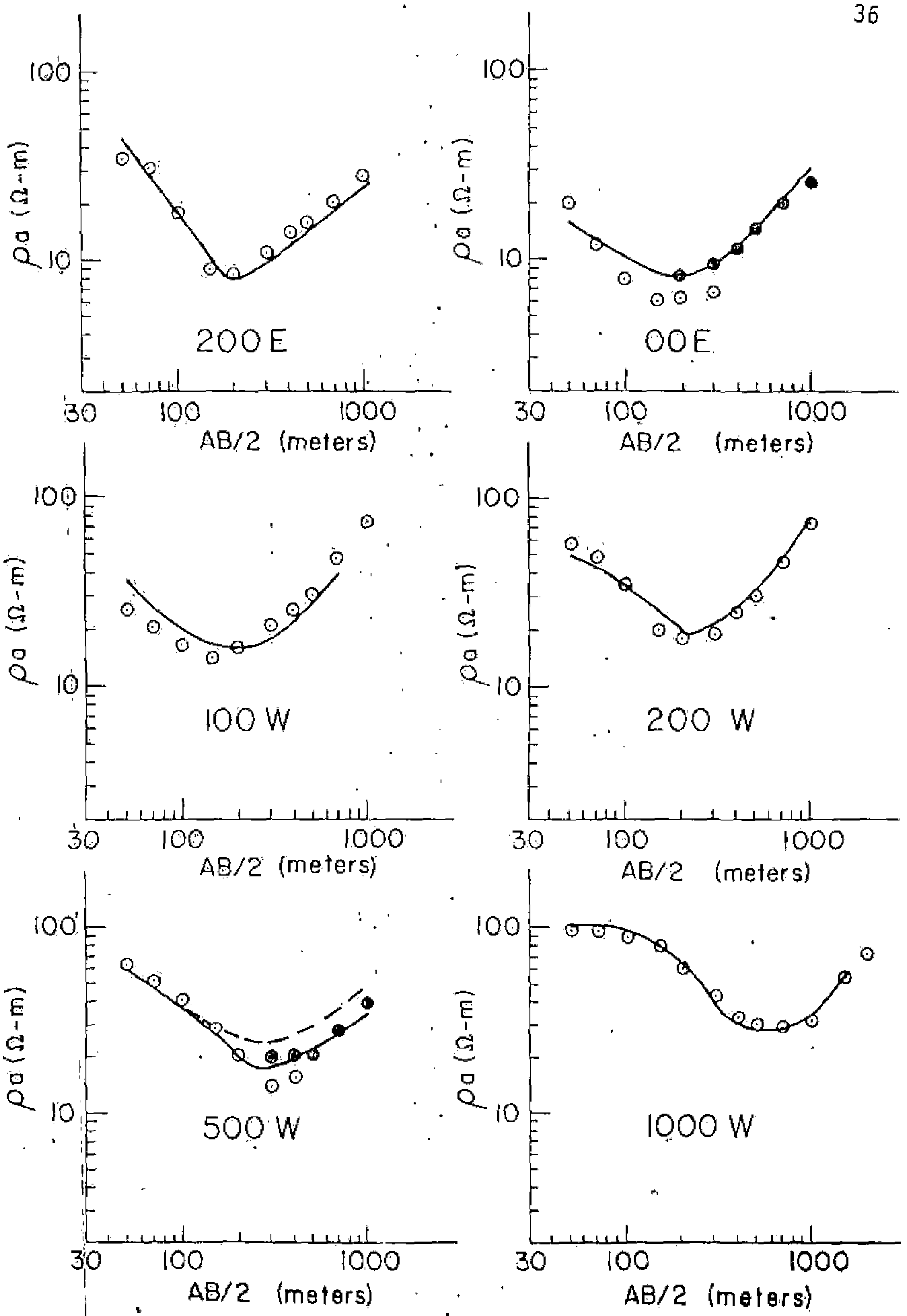

DOME FAULT
FAULT I
30
30
60
60
100
12
5
12
300
ESTIMATED GRAVITY BASEMENT ON LINE 4000 N
DEPTH (meters)
0
50
100
150
200
250
300
350
400
450
1000 W
800 W
600 W
400 W
200 W
0
200 E
400 E
600 E
LATERAL DISTANCE (meters)

Figure 10. Fit for Schlumberger soundings obtained from the two-dimensional model illustrated in Figure 9. Dotted circles and solid circles are data points for MN=4 meters and MN=80 meters respectively, when a sizable variance occurs, while the solid lines are the theoretical curves. The dotted line for the sounding curve at 500W is the theoretical curve obtained by removing the thin 5 Ω-m strip from the model of Figure 9.


100
10
ρa (Ω-m)
200 E
30
100
1000
AB/2 (meters)
100
10
ρa (Ω-m)
00 E
30
100
1000
AB/2 (meters)
100
10
ρa (Ω-m)
100 W
30
100
1000
AB/2 (meters)
100
10
ρa (Ω-m)
200 W
30
100
1000
AB/2 (meters)
100
10
ρa (Ω-m)
500 W
30
100
1000
AB/2 (meters)
100
10
ρa (Ω-m)
1000 W
30
100
1000
AB/2 (meters)

each Schlumberger sounding.

As mentioned above, the two-dimensional modeling program used does not give an estimate of model parameter standard deviations. A poor alternative is varying the model parameters and comparing the various results. Since this is clearly a quixotic undertaking, we will confine ourselves to comments on a few of the more problematic aspects of the model presented.

The several small features of the model between 200E and 300W and shallower than 25 meters were necessary to model the data. However, since the two-dimensional modeling mesh was coarse and since the data for AB/2 values smaller than 50 meters was not modeled, these small features represent only a rough approximation to the actual conductivity structure. The narrow strip of 5 Ω-m conductivity located at 500W and running from a depth of 50 meters to a depth of 350 meters seems to be necessary to fit the sounding curve centered at 500W. Figure 10 shows the observed-theoretical data fit obtained by removing the 5 Ω-m strip. As is evident, the observed-theoretical data fit is markedly worsened.

The two-dimensional estimates of depth to the highly conductive zones and the resistivities of these zones are in close agreement with the one-dimensional estimates, depicted in Figure 7. However, the two-dimensional estimate of the depth to the resistivity basement is at variance with the one-dimensional estimate by as much as 200 meters.

The north-south sounding centered at 4000N, 1700W supports the two-dimensional interpretation; it gave a depth to the conductive zone of approximately 120 meters, a value extremely close to the two-dimensional estimate.

Figure 11 illustrates the two-dimensional modeling for 300m and 1 km dipole-dipole data taken along line 4000N (Ward and Sill, 1976). The observed-theoretical data match is shown in Figure 12. The dipole-dipole two-dimensional modeling indicates a shallow zone of high conductivity between 900E and 900W. This zone, of 5-20 Ω-m resistivity, corresponds to the zone of 5-12 Ω-m shown by the Schlumberger two-dimensional modeling (compare Figures 9 and 11). The depth to the 300 Ω-m zone indicated by the dipole-dipole modeling, which is not shown in the figure, is 600m, which is much greater than the depth indicated by the Schlumberger modeling. Although this difference in the two-dimensional models may be due in part to real variances in the conductivity structure between lines 4000N and 3500N, it is likely that lack of model uniqueness of the dipole-dipole or the Schlumberger models is also responsible.

Line 5950N

Electromagnetic soundings. - Figure 13 depicts the least-square residual models and model parameter standard deviations for the one-dimensional inversion of the electromagnetic data along line 5950N.

The soundings to the east of 600W were modeled exclusively by two-layer models. The two soundings west of 600W could not be fitted by two-layer models, while the three-layer models gave small theoretical-observed data residuals and small model parameter standard deviations.

Figure 11. Two-dimensional resistivity model for dipole-dipole sounding-profiling data along line 4000N (after Ward and Sill, 1976). The vertical exaggeration is 4:1.

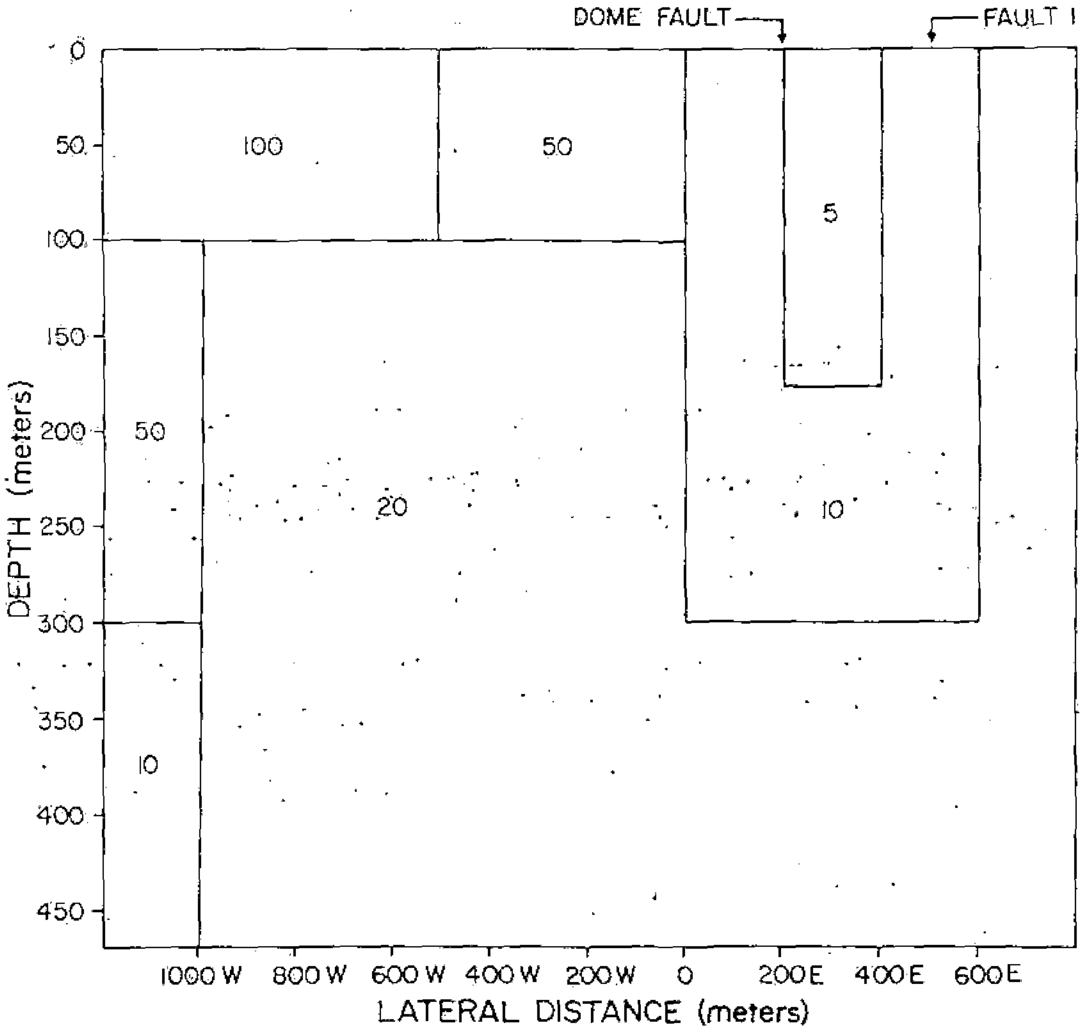

DOME FAULT
FAULT I
100
50
5
50
20
10
10
DEPTH (meters)
0
50
100
150
200
250
300
350
400
450
1000 W
800 W
600 W
400 W
200 W
0
200 E
400 E
600 E
LATERAL DISTANCE (meters)

Figure 12. Theoretical-observed data fit obtained for the model of Figure 11. Solid lines are observed data contours while the dotted lines are theoretical contours.

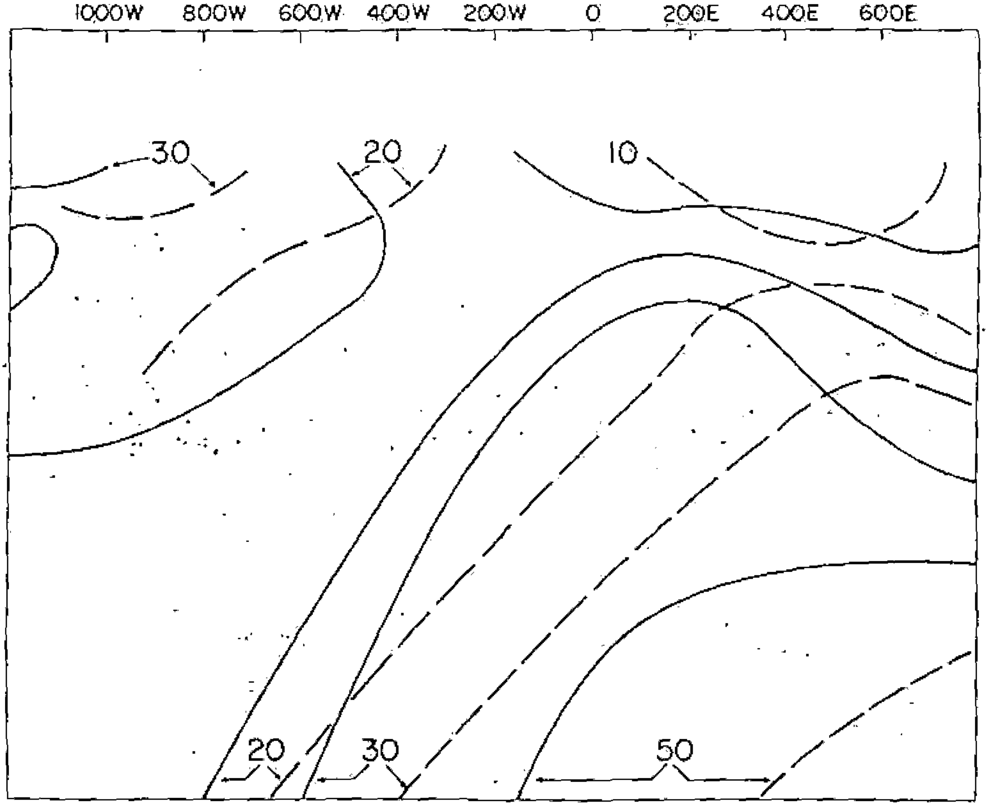
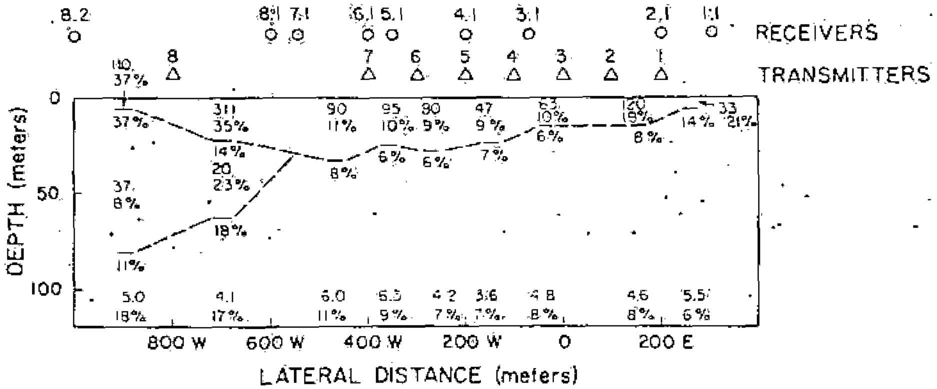

1000W
800W
600W
400W
200W
0
200E
400E
600E
30
20
10
20
30
50

Figure 13. Best fit one-dimensional models and subsequent percent parameter standard deviations for electromagnetic soundings along line 5950N. The vertical exaggeration is 4:1.


8.2
8.1
7.1
6.1
5.1
4.1
3.1
2.1
1.1
RECEIVERS
8
7
6
5
4
3
2
1
TRANSMITTERS
110
37%
37%
311
35%
14%
20
23%
18%
37
8%
11%
90
11%
8%
95
10%
6%
80
9%
6%
47
9%
7%
63
10%
6%
120
19%
8%
33
21%
14%
5.0
18%
4.1
17%
6.0
11%
6.5
9%
4.2
7%
3.6
7%
4.8
8%
4.6
8%
5.5
6%
0
50
100
DEPTH (meters)
800 W
600 W
400 W
200 W
0
200 E
LATERAL DISTANCE (meters)

On line 5950N, the electromagnetic method was able to resolve the depth and the resistivity of the lower conductive half-space even through 80 meters of fairly conductive overburden, as in the case of sounding 8.2. The estimated depth to the lower conductive half-space seems to have a definite trend.

Schlumberger soundings. - Figure 14 presents the least-squares models obtained by the one-dimensional inversion of Schlumberger resistivity data taken along line 5950N. As is apparent from the figure, the soundings centered at 800W and at 200W do not resolve the highly conductive layer. None of the soundings resolves the resistivity of the basement.

Two-Dimensional Modeling. - It may be seen from Figure 14 that the one-dimensional model parameters seem to be self-consistent in indicating a surface layer of 50-120 Ω-m, a conductive second layer of 5-10 Ω-m, and a resistive basement. The first two layers are totally consistent with the model derived from the electromagnetic soundings. The large variation in the basement resistivities could be an effect of noise in measurements. However, since dipole-dipole resistivity reconnaissance surveying (Ward and Sill, 1976) indicates a two-dimensional structure paralleling the mapped fault in the area (Figure 1), two-dimensional conductivity modeling is justified.

The final two-dimensional model is shown in Figure 15. Figure 16 illustrates the agreement obtained between the sounding data and the two-dimensional model data. Since the soundings exhibit large discontinuities in observed apparent resistivity when the potential

Figure 14. Best fit one-dimensional models and parameter standard deviations for Schlumberger soundings along line 5950N. The vertical exaggeration is 4:1. Superficial top layers are not depicted.

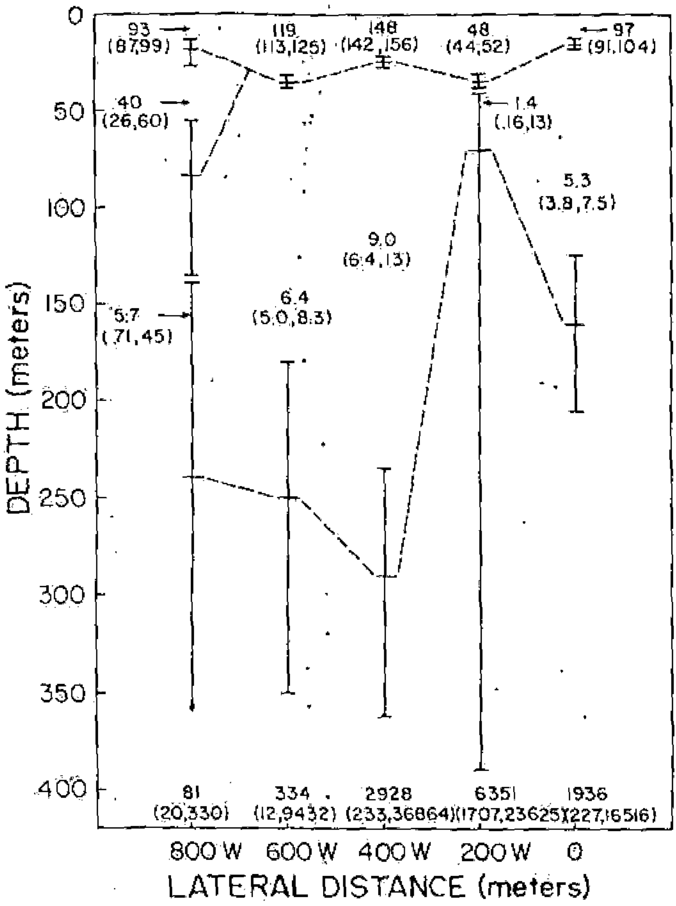

0
50
100
150
200
250
300
350
400
DEPTH (meters)
93
(87,99)
119
(113,125)
148
(142,156)
48
(44,52)
97
(91,104)
40
(26,60)
1.4
(.16,13)
5.3
(3.8,7.5)
9.0
(6.4,13)
6.4
(5.0,8.3)
5.7
(.71,45)
81
(20,330)
334
(12,9432)
2928
(233,36864)
6351
(1707,23625)
1936
(227,16516)
800 W
600 W
400 W
200 W
0
LATERAL DISTANCE (meters)

Figure 15. Two-dimensional resistivity model for Schlumberger soundings along line 5950N. Block resistivities are in ohm-meters. The vertical exaggeration is 4:1.

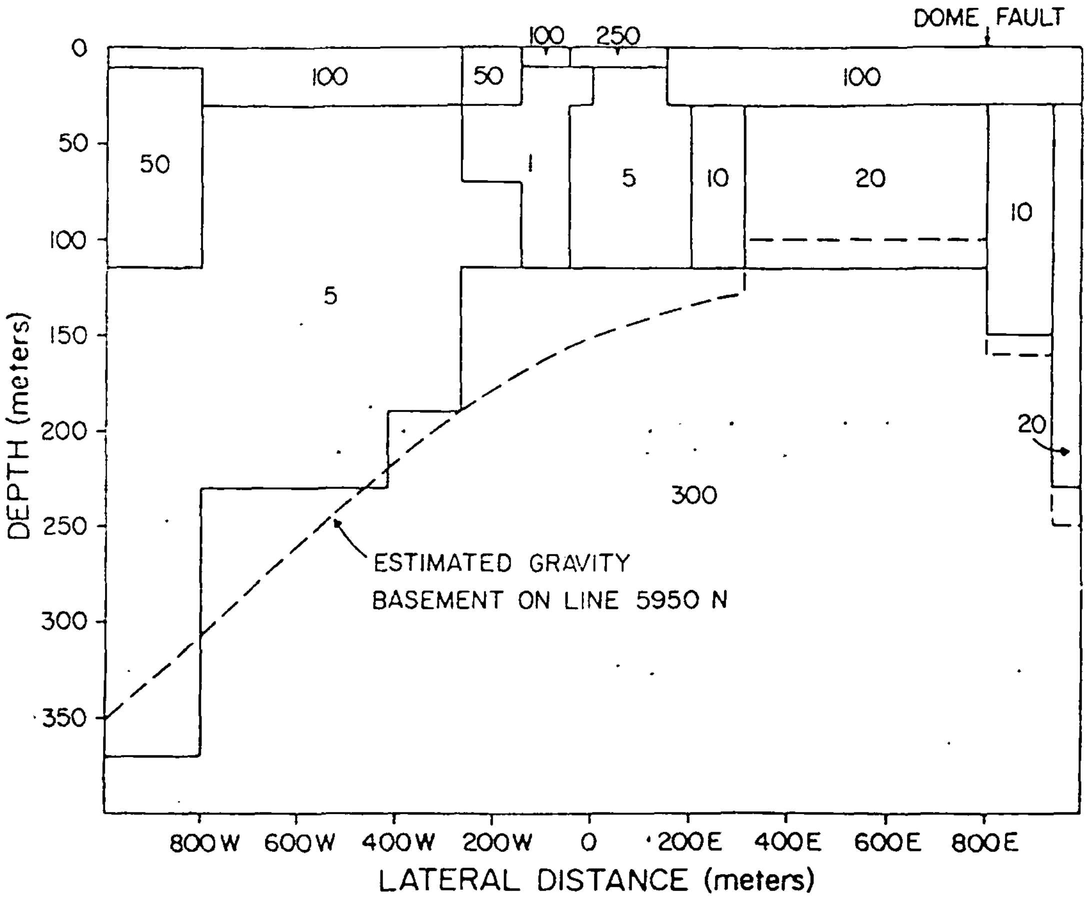
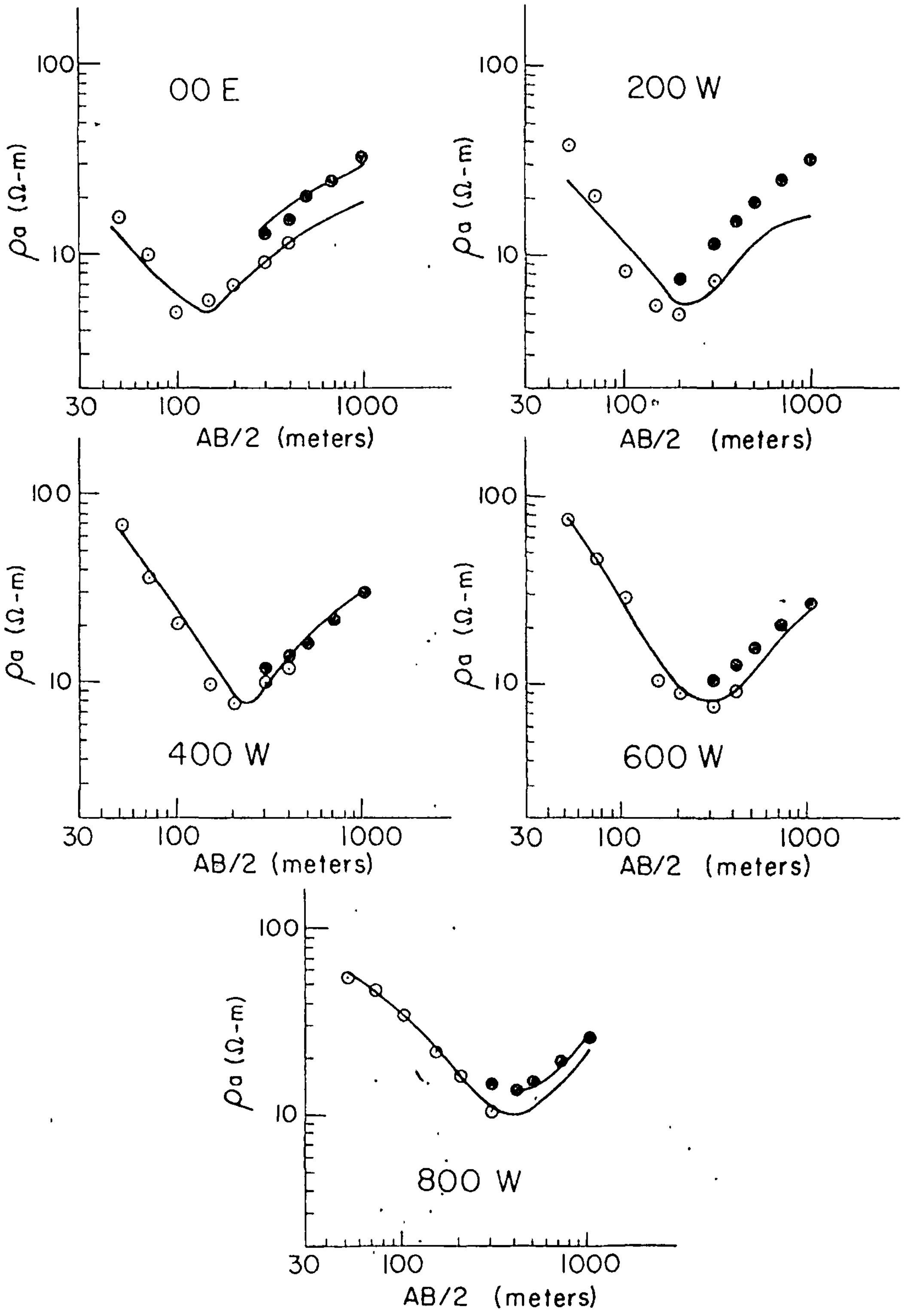

DOME FAULT
100
250
0
50
100
150
200
250
300
350
DEPTH (meters)
50
100
50
100
1
5
10
20
10
5
20
300
ESTIMATED GRAVITY
BASEMENT ON LINE 5950 N
800W
600W
400W
200W
0
200E
400E
600E
800E
LATERAL DISTANCE (meters)

Figure 16. Fit for Schlumberger soundings obtained from the two-dimensional model illustrated in Figure 15. Change in ρ_a due to expansion of MN distance is modeled. Dotted circles and solid circles are data points for MN=4 meters and MN=80 meters respectively.


00 E
200 W
400 W
600 W
800 W
ρa (Ω-m)
10
100
30
100
1000
AB/2 (meters)

electrode distance MN is expanded, the theoretical discontinuities due to the two-dimensional model were calculated for comparison. In three of the five soundings the theoretical and the observed discontinuities match exactly, as is shown in Figure 16. This suggests that the "clutch" can contain useful information and should be retained during modeling.

A comparison of Figure 14 and 15 reveals that the one-dimensional models provide a good first approximation of the two-dimensional model. The estimated depth to basement and the estimated resistivity of the very conductive units are in reasonable agreement. The two-dimensional model retains the shallow 20 to 50 Ω-m unit introduced by the one-dimensional inversion of the sounding at 800W. This unit has a counterpart in the third layer introduced by the electromagnetic modeling west of 600W.

SIMULTANEOUS ELECTROMAGNETIC - SCHLUMBERGER INVERSION

As has been observed throughout the study, a number of the one-dimensional Schlumberger models have had large percent standard deviations for the thickness and resistivity of the most conductive layer. Finer resolution of these model parameters utilizing the Schlumberger method is limited by the accuracy of the measurements, the finite number of data points, and the limited AB/2 distance used. Thus an independent source of model information is necessary to achieve finer resolution of conductivity model parameters.

It was noted during the study that in locations having both electromagnetic and Schlumberger soundings, the conductive layer resistivities for the electromagnetic sounding models were comparable to those of the Schlumberger models, but had smaller standard deviations. Since the conductive layer resistivity is usually highly correlated with the conductive layer thickness in the Schlumberger inversion, simultaneous inversion of the electromagnetic and Schlumberger data should resolve both parameters. In order to test this hypothesis, an existing simultaneous one-dimensional electromagnetic dipole-dipole resistivity least-squares inversion program was modified for the Schlumberger configuration.

At this juncture, it would be well to discuss briefly the actual joint inversion procedure used. It was found in the Roosevelt Hot Springs KGRA that the one-dimensional models for the Schlumberger and electromagnetic soundings were often dissimilar for the layers above the most conductive zone, even though the depth and conductivity of this zone were similar. This diversity between models is to be expected, because of the difference in the scale of exploration of the two methods. Since such diversity is not germane to the problem at hand, the high frequency electromagnetic data was not used in the inversion. The choice of cutoff frequency was subjectively determined by inspection of the derivative matrix, evaluated at the electromagnetic model parameters. Suppose that the partial derivatives of ellipticity and tilt angle, with respect to the model parameters of the deep or interesting layers, are small at one frequency relative to the partial derivatives at other frequencies. Then discarding the data points at the first frequency will not greatly affect the resolvability of the interesting layers. An alternative approach would be to discard resistivity measurements for small AB/2 values. Note that a trade-off between the amount of useful information and contradictory information included in the inversion process is inescapable.

Once the data to be included in the inversion is specified, it is necessary to choose an appropriate scale for the data. For example, we must decide whether we wish to minimize the square residual of apparent resistivity or the square residual of log apparent resistivity. It is also necessary to decide what data weighting matrix is appropriate for the problem. Finally, it is necessary to decide upon the model parameterization used during the inversion.

The weighted data difference vector, $\Delta\mathbf{G}$, may be written as:

$$\Delta\mathbf{G} = \mathbf{W}\begin{pmatrix} \mathbf{G}_s \\ \mathbf{G}_\varepsilon \\ \mathbf{G}_t \end{pmatrix}$$

where $\Delta\mathbf{G}_s$, $\Delta\mathbf{G}_\varepsilon$, and $\Delta\mathbf{G}_t$ are the observed-theoretical data difference vectors for the Schlumberger apparent resistivity data, the ellipticity data, and the tilt angle data respectively, and $\mathbf{W}$ is the data weighting matrix. Since the apparent resistivity data has a large range of values, $\Delta\mathbf{G}_s$ is taken to be the column vector of the log apparent resistivity residuals $(\ln(\rho_a)_T - \ln(\rho_a)_0)$ where $(\rho_a)_T$ is the theoretical apparent resistivity and $(\rho_a)_0$ is the observed apparent resistivity. The elements of the ellipticity and tilt angle residual vectors, $\Delta\mathbf{G}_\varepsilon$ and $\Delta\mathbf{G}_t$, will be in decimal fractions and radians respectively.

We take the weighting matrix $\mathbf{W}$ to be the diagonal matrix whose terms are the values necessary to scale the standard deviations for the ellipticity and tilt angle data to the same magnitude as the standard deviation of the log apparent resistivity data. This weighting scheme enables the inversion algorithm to fit each data point to within one standard deviation. This weighting is appropriate in our case since care is taken to assure that the data included in each inversion is self-consistent. For simplicity, we assumed that the standard deviation of the ellipticity data was approximately 1%, while the standard deviation of the tilt angle data was taken to be .5°. We believe these values to be reasonable.

The plane-layered conductivity model was parameterized in terms of log conductivities and log layer thicknesses to avoid the occurrence of negative layer conductivities and thicknesses. The estimated model parameter covariance matrix **cov (P)** is:

$$\mathbf{cov}(\mathbf{P}) = \chi_\nu^2 \, (\mathbf{A}^T \mathbf{W}^T \mathbf{W} \mathbf{A})^{-1}$$

where **A** is the system derivative matrix, ν is the arithmetic difference between the number of observations and the number of model parameters, and

$$\chi_\nu^2 = \frac{\Delta \mathbf{G}^T \Delta \mathbf{G}}{\nu} .$$

As seen in Figure 5, the values of ρ and t of the conductive layer for the Schlumberger sounding centered at 3500N, 200E are unresolved. However, the conductive layer resistivity of the least-squares model for the magnetic dipole sounding 1.1 is well-resolved, as is shown in Figure 3. Thus, this electromagnetic sounding and Schlumberger sounding are well adapted to joint one-dimensional inversion.

The electromagnetic data values for frequencies greater than 2 Khz were discarded for the purposes of the joint inversion because the data points did not markedly contribute to the resolution of the conductive zone resistivity.

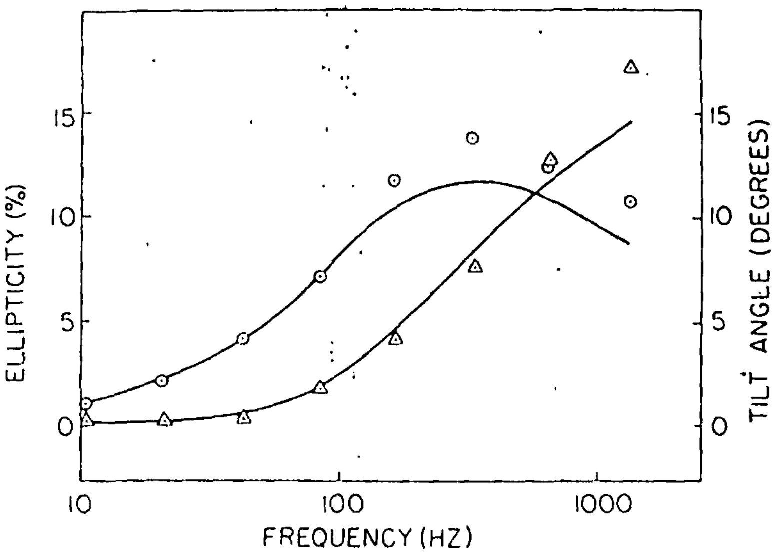
The least-squares model, the model parameter standard deviations, and the theoretical-observed data residual for the joint inversion are shown in Figure 17. The percent standard deviations for ρ_3 and t_3 are greatly reduced, as was predicted. This example demon-

Figure 17. A) Best fit one-dimensional model and parameter standard deviations for the joint inversion of the electromagnetic and Schlumberger soundings at 3500N, 200E. B) Fit between theoretical ellipticity and tilt angles (solid lines) and observed ellipticitiy (dotted circles) and observed tilt angles (dotted triangles). C) Fit between theoretical ρ_a (solid lines) and observed ρ_a (dotted circles).

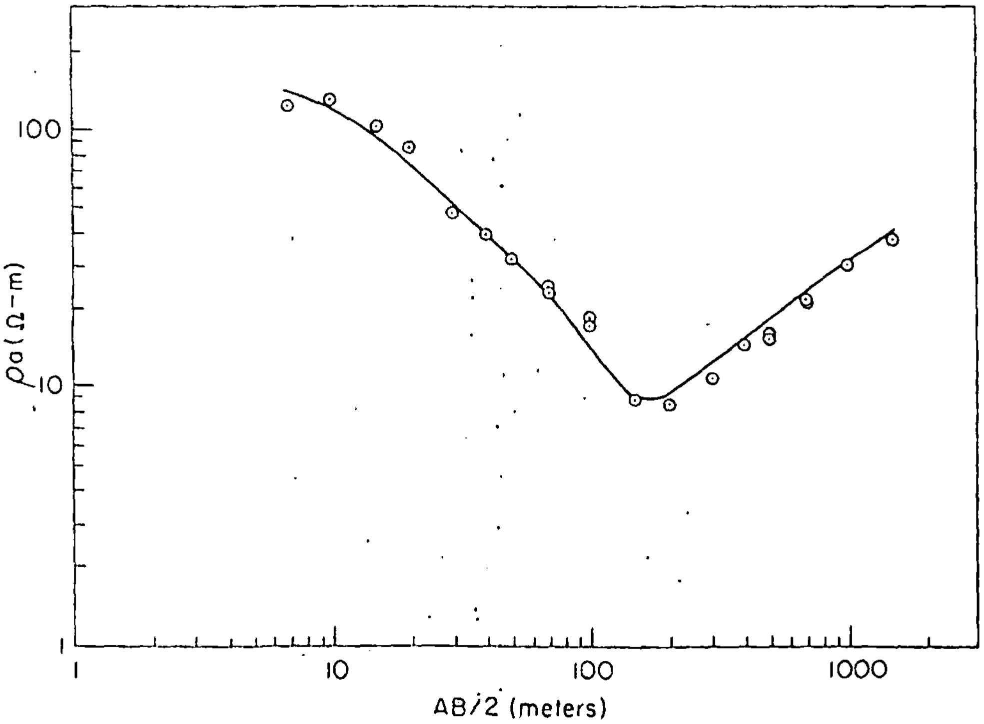
A)

ρ_1 = 151 Ω-m(128,178)	t_1 = 7.4 m(5.8,9.4)
ρ_2 = 39 Ω-m(32,47)	t_2 = 36 m (32,41)
ρ_3 = 2.4 Ω-m(1.8,3.2)	t_3 = 46 m (35,61)
ρ_4 = 73 Ω-m(52,103)	

B)



C)



strates that electromagnetic data does contain useful information not contained in the Schlumberger data. In the present case, this information has been used to gain confidence in the model advanced by the Schlumberger method.

GEOLOGICAL INTERPRETATION

We will now present interpretations of the two-dimensional conductivity structures advanced for line 3500N, depicted in Figure 9, and the two-dimensional conductivity structure advanced for line 5950N, depicted in Figure 15.

Rocks which do not contain massive amounts of semi-conducting minerals owe their conductivity almost solely to intersitial water and to water-saturated clay minerals. Thus we would expect a radical decrease in model resistivity for moderate depths to correspond to the water table wherever the water is saline. Thus, on lines 3500N and 5950N the interface between the shallow units with resistivity of order 30 Ω-m to 250 Ω-m and the conductive units of resistivity between 1 Ω-m and 12 Ω-m corresponds to the water table. Unfortunately, the water table was not noted during the drilling of DDH 1B, nor does the core give geochemical evidence of the depth to water table (Parry, pers. comm.). However, extrapolation of the depth to water table noted at DDH 1A (Parry et al., 1976) gives a depth to water table on line 3500N of approximately 40 meters. This is in good agreement with the depth predicted by the modeling on line 3500N at the site of DDH 1B (see Figure 9).

The two-dimensional modeling resolved zones of anomalously low resistivity within the main water-saturated zone. On line 3500N, the zone of resistivity 5 Ω-m is fairly localized between the Dome

Fault and Fault 1 (Figure 9). On line 5950N, the anomalous zone with a resistivity of 1 Ω-m, situated at 0, is associated with a previously mapped fracture (Figure 15). The possible and by no means mutually exclusive causes of these conductivity anomalies are increased fracturing and increased clay alteration. Ward and Sill (1976) showed that the presence of clay in typical amounts at the Roosevelt Hot Springs KGRA can lower the resistivity by a factor of four. Since the clay is undoubtedly associated with the fracturing, discrimination between clay conduction effects and fracture conduction effects seems unlikely.

The 12 Ω-m zone west of 500W and the 5 Ω-m zone west of 200W on line 3500N (Figure 9) are certainly water-saturated units. These low resistivity zones are compatible with the conclusion of Ward and Sill (1976) that brine is leaking from the vicinity of the Dome Fault westward and is saturating alluvium or altered bedrock.

If the saturated units are wholly alluvium, we would expect the bottom of the units to correspond with the gravity basement. While this correspondence is true on line 5950N (Figure 15) it does not appear to be true on line 3500N (Figure 9). On line 3500N, west of 400E, the gravity basement, extrapolated from the traverse along line 4000N (Crebs, 1976), is much shallower than the resistivity basement. There are several possible explanations of such a variance. It is likely that the depth to basement estimated by the two-dimensional Schlumberger method has a large associated standard deviation. If the depth to basement estimated by gravity lies within a standard deviation of the resistivity estimate, the variance between the two estimates would not be statistically significant. Unfortunately, this hypothesis cannot be tested at present. The gravity modeling for line 4000N assumed that the density contrast between the alluvium and the bedrock is .5 gm/cc. This contrast is substantiated by Crebs' density profile measurements on dry alluvium. If we assume that the alluvial constituent material has a density of 2.67 gm/cc, Crebs' estimate of dry alluvium density gives an alluvial porosity of 20%. Saturating the alluvium thus reduced the density contrast between alluvium and bedrock to .3 gm/cc. Talwani gravity modeling indicates that between 500W and 1500W, the estimated depth to bedrock for a gravity model containing a saturated alluvium unit will be 40m to 120m greater than the depth estimated by Crebs.

We believe that part of the discrepancy in the gravity and resistivity depth estimates may also be due to high density, low resistivity altered rock. Densities for dried samples of the low resistivity altered core from DDH #1A range from 1.80 gm/cc to 2.48 gm/cc. The estimated wet density of these samples ranges from 2.1 gm/cc to 2.63 gm/cc. These values suggest that high density, low resistivity altered rock is present at Roosevelt Hot Springs.

Available heat-flow and geochemical data at Roosevelt Hot Springs support the notion that the depth of the resistive basement corresponds with the maximum depth of alteration. The K-feldspar stable temperature for values of pH and K^+ activity measured at Roosevelt Hot Springs (Parry et al., 1976) is approximately 150°C. Assuming a thermal gradient of 460°C/km measured in DDH 1B (Sill, pers. comm.), this temperature is reached at a depth of 325 meters. This is in good agreement with the model depth to resistive basement found for line 3500N west of 500W (Figure 9). It is also in good agreement with the depth to resistive basement for the zone between the Dome Fault and Fault 1 on line 3500N. Assuming a thermal gradient of 800°C/km measured in drill hole DDH 1976, #1 (Sill, pers. comm.), the 150°C transition temperature is reached at a depth of 186 meters. This agrees well with the depth to resistive basement predicted due north from DDH 1976 #1, on line 5950N.

The final geological interpretations of the two-dimensional modeling along lines 3500N and 5950N are illustrated in Figures 18 and 19 respectively.

Figure 18. Geological interpretation for line 3500N.

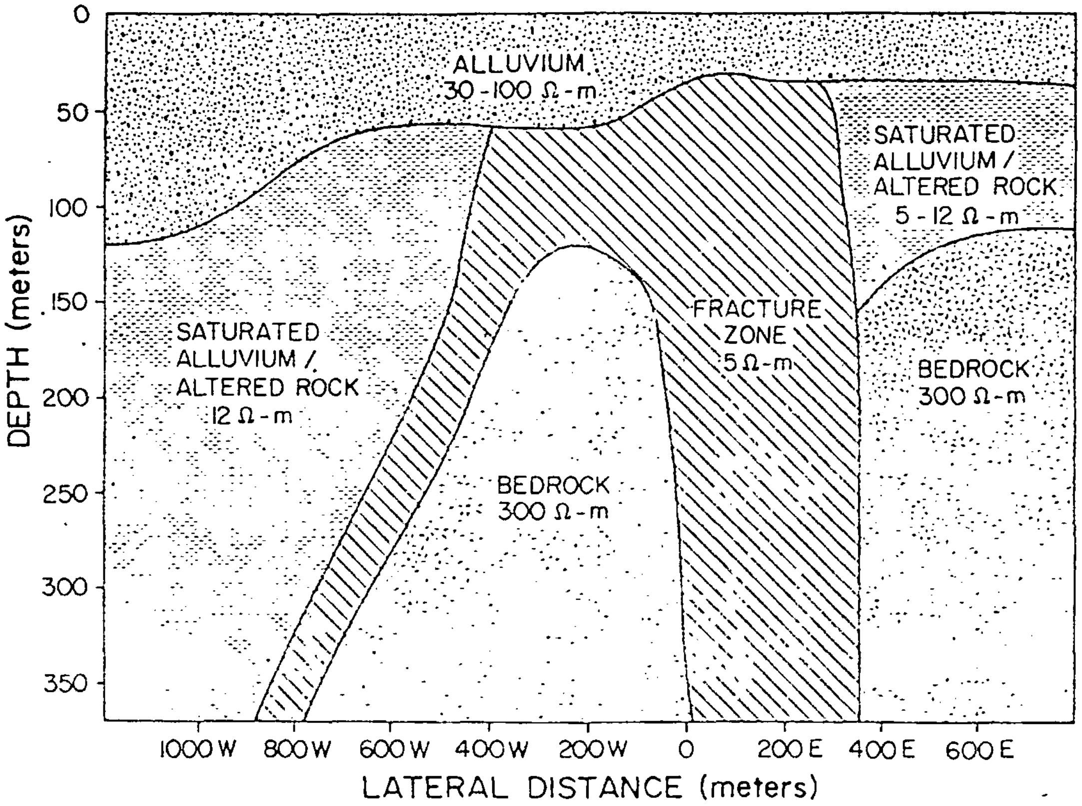
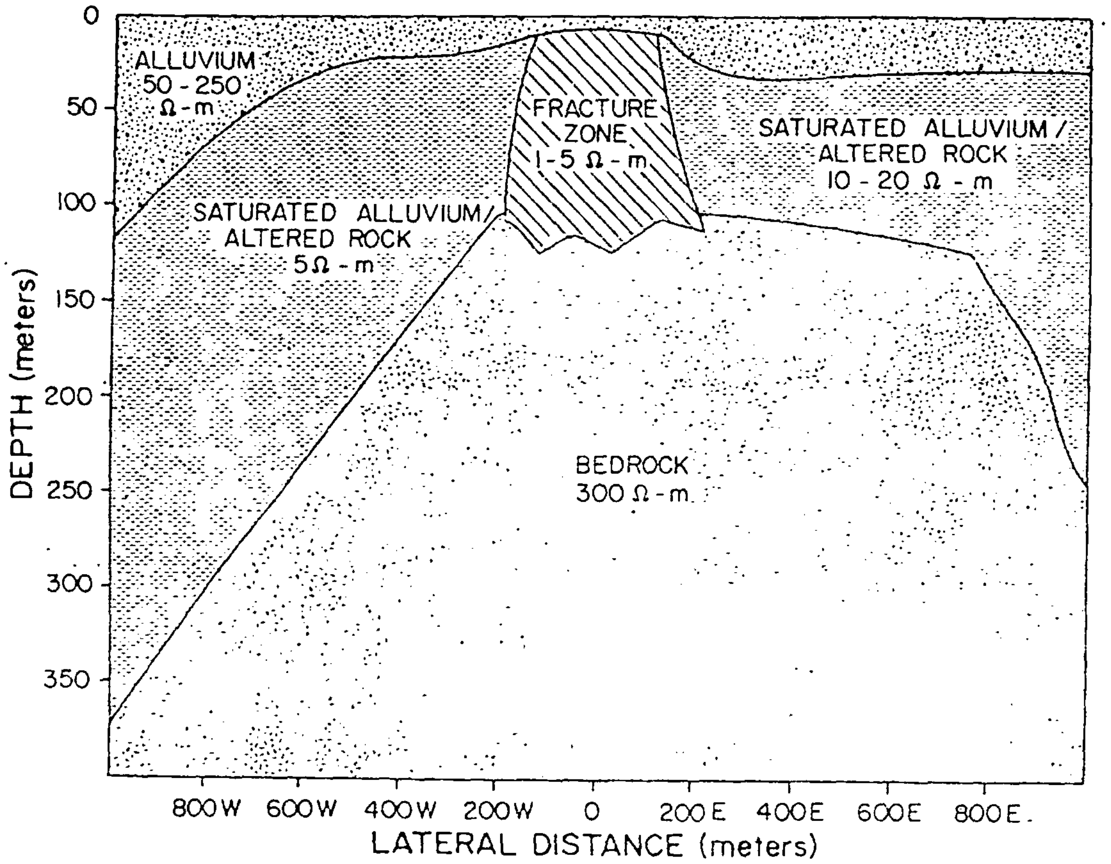

ALLUVIUM
30 - 100 Ω - m
SATURATED
ALLUVIUM /
ALTERED ROCK
5 - 12 Ω - m
SATURATED
ALLUVIUM /
ALTERED ROCK
12 Ω - m
FRACTURE
ZONE
5 Ω - m
BEDROCK
300 Ω - m
BEDROCK
300 Ω - m
DEPTH (meters)
0
50
100
150
200
250
300
350
1000 W
800 W
600 W
400 W
200 W
0
200 E
400 E
600 E
LATERAL DISTANCE (meters)

Figure 19. Geological interpretation for line 5950N.


ALLUVIUM
50 - 250
Ω - m
FRACTURE
ZONE
1-5 Ω - m
SATURATED ALLUVIUM /
ALTERED ROCK
10 - 20 Ω - m
SATURATED ALLUVIUM/
ALTERED ROCK
5 Ω - m
BEDROCK
300 Ω - m
DEPTH (meters)
0
50
100
150
200
250
300
350
800 W
600 W
400 W
200 W
0
200 E
400 E
600 E
800 E
LATERAL DISTANCE (meters)

CONCLUSIONS

Schlumberger and electromagnetic soundings have detected a large conductive zone which parallels the Dome Fault, thought to be a major structural control for the geothermal system at the Roosevelt Hot Springs, KGRA. This zone consists, we believe, of extensively fractured and altered rock. An extensive conductive zone to the west of the Dome Fault seems to indicate that brine is leaking from the geothermal system. This zone bottoms in a high resistivity unit, believed to be Precambrian (?) basement.

We have found that two-dimensional Schlumberger modeling is essential for adequate modeling of the geothermal system at Roosevelt Hot Springs; one-dimensional inverse modeling only provides a starting point for the two-dimensional forward modeling. The two-dimensional models appear to satisfy all of the demands placed on them by geological, heat flow, and gravity data. However, a method of estimating the uniqueness of the two-dimensional models advanced is needed. We have also found that the joint one-dimensional inversion of Schlumberger and electromagnetic data is superior to the inversion of Schlumberger data alone in resolving the vertical geoelectric section at Roosevelt Hot Springs at any single sounding site.

ACKNOWLEDGEMENTS

The authors wish to thank Drs. Bruce Smith and Lindsay Thomas for providing the electromagnetic inversion algorithm used throughout this study and Mr. Luiz Rijo for valuable discussions. The support of the National Science Foundation, RANN division under grant GI-43741, and ERDA, under contract EY-76-S-07-1601, for performance of this research is gratefully acknowledged.

APPENDIX A

We have mentioned that in the presence of terrain the transmitting magnetic dipole is rarely perfectly horizontal or vertical with respect to the "datum", as illustrated in Figure 2. Likewise, the receiver axis is rarely vertical with respect to the datum. Thus an algorithm is needed for computing the ellipticity and tilt angle of the magnetic field polarization ellipse which would be measured when the transmitter and receiver are inclined with respect to the datum. The presentation follows Thomas (1975).

We assume that the angle α_T between the transmitting dipole and the X-axis, as shown in Figure 2, is measured anticlockwise from the Ox direction. When the receiver is uphill from the transmitter, the receiver angle α_R is measured clockwise from the Oz direction. When the receiver is downhill from the transmitter, α_R is measured anticlockwise from the Oz direction.

Suppose that the magnetic field response of a one-dimensional earth to a vertical magnetic dipole of unit dipole moment has the components H_z^v and H_x^v, while the response to a horizontal magnetic dipole of unit moment has the components H_z^h and H_x^h. Now the field components $H_z^{'}$ and $H_x^{'}$ for a unit moment dipole inclined an angle α_T with respect to the x axis may be computed by superposition of the fields due to a vertical dipole of moment sin α_T and a horizontal dipole of moment cos α_T. Assuming the angle sign conventions advanced above, we find the equations:

$$H_z' = (\cos\alpha_T)\ H_z^h + (\sin\alpha_T)\ H_z^v \qquad (1)$$

$$H_x' = (\cos\alpha_T)\ H_x^h + (\sin\alpha_T)\ H_x^v \qquad (2)$$

Since the receiver axis is inclined to the datum by an angle α_R, the z and x field components referred to the coordinate system of the receiver, H_z'' and H_x'', are related to the components H_z' and H_x' by the equations

$$H_z'' = (\cos\alpha_R)\ H_z' + (\sin\alpha_R)\ H_x' \qquad (3)$$

$$H_x'' = (\cos\alpha_R)\ H_x' - (\sin\alpha_R)\ H_z' \qquad (4)$$

The magnetic field produced by an inclined transmitter of unit moment and measured by a receiver whose axis is tilted with respect to the datum may be calculated by means of equations (1) through (4). Since the ellipticity and tilt angle of the scattered field are independent of the oscillating dipole moment, the theoretical ellipticity ε and tilt angle α may be determined by substituting the values of H_z'' and H_x'' in polar form, $H_z'' = H_z e^{i\phi_z}$ $H_x'' = H_x e^{i\phi_x}$, into the equations (Smith and Ward, 1974):

$$\tan 2\alpha = \frac{2(H_z/H_x)\cos\Delta\phi}{1-(H_z/H_x)^2} \qquad (5)$$

and

$$\varepsilon = \frac{H_z H_x \sin\Delta\phi}{[H_z e^{i\Delta\phi}\sin\alpha + H_x\cos\alpha]^2} \qquad (6)$$

where $\Delta\phi = \phi_z - \phi_x$. The values of ellipticity and tilt angle calculated from equations (5) and (6) are the theoretical values used in the inversion algorithm.

FINAL REPORT

VOLUME 77-5

EY-76-S-07-1601

I. Introduction

The final report under contract EY-76-S-07-1601 is being submitted as a series of volumes as follows:

Volume 77-0	*October, 1977
Volume 77-1	*September, 1977
Volume 77-2	December, 1977
Volume 77-3	December, 1977
Volume 77-4	December, 1977
Volume 77-5	December, 1977
Volume 77-6	December, 1977
Volume 77-7	January, 1978
Volume 77-8	January, 1978

*Submitted

Other volumes will be submitted in accordance with the contractual reporting schedule.

II. Reports Delivered

Task 76.1.21 Color photos

Stereo color aerial photographs were made available to industry for copying at industry's expense on November 28, 1977 at 11:00 a.m. This final report on this task merely records that fact.

Task 77.1.14 Proposal Review (MOD A002)

All activities under this task have been completed. No tangible deliverables were required.

Task 76.1.14 Simultaneous modeling of multiple data sets

A technique for simultaneous inversion of MT and Schlumberger data was developed and tested on some available deep crustal data from

South Africa. The publication resulting and included herewith is:

> Petrick, W. R., W. H. Pelton, and S. H. Ward, 1977, Ridge Regression Inversion Applied to Crustal Resistivity Sounding Data from South Africa, Geophysics, vol. 42, no. 5, p. 995-1005.

Joint inversion of Schlumberger and electromagnetic sounding data was developed and applied to geothermal data from Roosevelt Hot Springs KGRA. The publication resulting and included herewith is:

> Tripp, A. C., S. H. Ward, W. R. Sill, C. M. Swift, Jr., W. R. Petrick, 1978, Electromagnetic and Schlumberger Resistivity Sounding in the Roosevelt Hot Springs KGRA, Geophysics, in press.

To utilize multiple inversion schemes at a convective hydrothermal system in the Eastern Great Basin will require applications of three-dimensional forward algorithms now available for gravity, magnetics, and AMT/MT. Unfortunately the pertinent data sets available for Roosevelt Hot Springs KGRA (or Monroe Hot Springs KGRA, for that matter) are not compatible since the physical property distributions giving rise to the gravity field is not coincident with that giving rise to the magnetic field, and so on.

Thus, we have turned to interpreting each data set independently and then drawing a schematic model of the subsurface which accepts all data sets. An example of this procedure is contained in "Ward, S. H., J. M. Bodell, W. D. Brumbaugh, J. A. Carter, K. L. Cook, T. J. Crebs, T. L. Olsen, W. T. Parry, W. R. Sill, R. B. Smith, I. Thangsuphanich, and A. C. Tripp, 1978, Geophysics of the Roosevelt Hot Springs Thermal Area, Utah", submitted to Geology and included in Final Report Volume 77-2.

Task 76.1.11 Drill and Log 10 Heat Flow Holes

All thermal gradients and heat flows appear in Technical Report 77-3. The summary of drilling progress, costs, and lithologs is enclosed.

Cost Analysis and Drilling Data
Thermal Gradient and Heat Flow Holes, 1976

by

J. A. Whelan

Cost Analysis and Drilling Data

Thermal Gradient and Heat Flow Holes, 1976

1.0 Introduction and Summary

1.1 This report summarizes the summer 1976 drilling program in the Roosevelt KGRA near Milford. Results of geologic, hydrothermal alteration, thermal gradient, heat flow, and rock properties made with cores or cuttings from these holes will be published in other reports.

Ten holes were drilled, totaling 2732 feet. Total funds expended, not including University of Utah supervision, or supplies, chiefly black-iron pipe, were $29,320. Cost per foot for NX-core drilling, on holes was $15.08. Cost per foot for rotary drilling in alluvium was $4.98 per foot.

Locations of the holes are shown in Figures 1 through 5.

Summary data on individual holes is given in Appendix (A). Detailed logs are available at the University of Utah to interested parties. Cores and cuttings may be examined there.

2.0 Administration

2.1 Permission to Drill. On Federal Lands permission to drill was requested on Notice of Intent to Conduct Geothermal Resource Exploration Operations (Form 3200-9, December, 1973). On state lands, permission to drill was obtained from the Division of State Lands, Department of Natural Resources. If state lands were leased, permission was also obtained from the leasees. On private land, permission was obtained from the owners.

2.2 Two drilling contracts were utilized. General features are described below:

2.2.1 Jensen Construction and Drilling Company. The basic features of this contract were as follows:

(a) Mobilization and moving were at $1.50 per mile per unit (drill, water truck, pickup truck).

(b) Rig time, including the drill, a 1966 Hyarth, driller and helper, water truck and pickup truck was $45.00 per hour.

(c) Water truck driver, when needed was furnished at $70.00 per day.

(d) Bits were furnished at cost. Credit was given for diamond salvage.

(e) Core boxes and casing lost in the hole were paid for at cost.

(f) Other supplies -- cement, drilling mud, casting plaster were charged for at cost plus 10 percent delivery charge.

2.2.2 The Wortley Engineering contract had the following features:

(a) No mobilization charge.

(b) Moves were at hourly "rig time" rate.

(c) Rig time was charged at $24 per hour which included a driller and helper, pickup truck, a Joy 12 drill, an air compressor, and a water pump tank combination.

(d) Supplies were furnished at cost.

3.0 Procedure

3.1 Site Preparation. No holes required site preparation.

3.2 Surveying. All holes were tape and compass surveyed to the nearest land survey monument. Surveys are provided in hole data, Appendix (A).

3.3 Geologist. A geologist was present on the drill coring.

3.4 Hole completion. Thermal gradient holes and the alteration hole were completed by setting bottom capped one-inch black iron pipe in the hole, back filling with cuttings or sand to within 10 feet of the surface and from 10 feet to the surface with concrete. The heat flow holes were completed by setting one-inch black iron pipe with a check valve on the bottom. Water was circulated until good returns were obtained, followed by grout until it returned. Then a swabber, consisting of three tight fitting rubber stoppers on a threaded rod was forced into the check valve. After the grout or cement set, the black iron pipe was filled with water. All sites were raked or tilled and were seeded with 83 percent by weight crested wheat grass and 17 percent bitter brush between 15 September and December 1.

4.0 Costs

4.1 Costs for individual holes for Wortley Engineering are given in Appendix A. Costs for individual holes are not available for Jensen Drilling and Construction. Average costs for Jensen Drilling and Construction are given in Table 1 and for Wortley Engineering in Table 2.

TABLE 1 Average Costs, NX Core Drilling

Year	1975	1976	1976
Contract Agency	NSF	ERDA	USGS
Company	Boyles Brothers	Jensen	Jensen
Company Location	Salt Lake City, UT	Springville UT	Springville UT
Number of Holes	7	4	6
Total Footage	1727	1255	1589
Cost Per Foot			
Mobilization Move in, move out	2.81	0.57	1.04
Rig Time	11.68	11.05	9.58
Bits (Net)	1.59	3.16	3.07
Supplies & Materials	1.50	0.30	0.51
Casing and Shoes lost in hole	0.07	--	0.42
	17.65	15.08	14.62

TABLE 2 Average Costs, Rotary Drilling, Wortley Company, Summer, 1976

	Cost Per Foot
Rig Time	$3.67
Diamond Bits	0.08
Rotary Bits	0.78
Surface Pipe	0.14
Supplies & Materials	0.31
Average Cost Per Foot	$4.98

APPENDIX A - Descriptions of Holes

Thermal Gradient Hole 1

LOCATION: NW 1/4, SW 1/4, Sec. 15,T26S,R9W. (SLB & M)
994.8 Ft. S85°E from quarter corner 16/15.

LAND STATUS: Public Domain (BLM).

DATES OF DRILLING: July 12, 1976 - July 15, 1976

DEPTH: 185 Feet

COST ANALYSIS

	Total Cost $	Cost Per Foot $
Rig Time	614.00	3.32
Rotary Bits (2)	152.00	0.82
Supplies and Materials	68.40	0.37
Totals	834.40	4.51

SUMMARY OF DRILLERS LOG: 0-20 drilled and cemented surface, pipe. 0-205 feet. Drilled ahead of coring hole. Final effective depth 185 feet.

SUMMARY OF LITHOLOGIC LOG: Alluvium. Poorly sorted subangular granite wash, sand to gravel size. Contains streaks of magnetite.

WATER: None encountered

COMPLETION DATA: Set black iron pipe to 185 feet. Backfilled with cuttings to 10 feet from the surface. Cemented top 10 feet. Site tilled and reseeded with crested wheat grass and bitter brush, 10:2 by weight.

Thermal Gradient Hole 2

LOCATION: SW 1/4 Sec. 5, T6S, R9W (SLB & M)
2469 Ft. East and 1108 Ft. North of $\frac{6|5}{7|8}$

LAND STATUS: Public Domain (BLM).

DEPTH: 232 Feet

COST ANALYSIS

	Total Cost $	Cost Per Foot $
Rig Time	870.00	3.75
Rotary Bits (2)	152.00	0.66
30-ft. of 2.5-inch casing @ $1.50/foot	45.00	0.19
Supplies and Materials	68.00	0.29
Totals	1135.00	4.89

DRILLERS LOG:
0-15 feet. Drilled and cemented.
0-50 feet. Set casing to 30 feet. Hole coring.
50-125 feet. Drilling.
125-220 feet. Soft with small boulders.
220-232 feet. Set black iron pipe to 212 feet because of coring.

SUMMARY OF LITHOLOGIC LOG: Granite wash (cuttings from boulders), coarse sand with magnetite streaks.

WATER: None encountered.

COMPLETION DATA: Set capped black iron pipe to 212 feet. Backfilled with sand and cuttings to 10 feet from the surface. Cemented to surface. Site tilled and reseeded with crested wheat grass and bitter brush, 10:2 by weight.

Thermal Gradient Hole 3

LOCATION: SE 1/4 Sec. 19, T26S, R9W (SLB & M).
2670 feet N54°W from Sec. Corner
19 | 20
30 | 29

LAND STATUS: Private

DATES OF DRILLING: 24 June 1976 to 11 July 1976

COST ANALYSIS

	Total Cost $	Cost per Foot $
Rig Time	1194.00	3.67
Rotary Bits (3)	228.00	0.70
Surface Pipe 10'-3" iron	36.61	0.11
Supplies and Materials	77.00	0.24
Totals	1535.61	4.72

SUMMARY OF DRILLERS LOG:
0-10 feet. Set Casing. Cemented.
10-45 feet. Drill and cement each day.
45-132 feet. Drilled ahead with casing.

SUMMARY OF LITHOLOGIC LOG:
0-20 feet. Granite wash, gravely sand.
20-45 feet. Silt
45-85 feet. Granite wash. Gravely sand
85-95 feet. Gravel
95-325 feet. Granite wash sand.
Magnetite present through entire hole.

WATER: None encountered

COMPLETION DATA: Set capped black iron pipe to 305 feet. Backfilled with cuttings and sand to within 10 feet of the surface. Cemented top 10 feet. Cleaned and reseeded site with crested wheat grass and bitter brush (10:2 by weight).

Thermal Gradient Hole 5

LOCATION: SE 1/4, Sec. 14, T26S, R9W (SLB & M).
3047.4 feet N53E° of $\frac{S14}{S22}$ 1/4

LAND STATUS: Public Domain (BLM)

DATES DRILLED: 2 September 1976 - 7 September 1976

DEPTH: 170 Feet

COST ANALYSIS

	Total Cost $	Cost Per Foot $ (overall)
Rig Time	1158.00	6.81
Rotary Bits (3)	228.00	1.34*
Diamond Bits (1) 20' - 3 inch	100.00	0.53**
Casing	30.00	0.18
Supplies and Materials	129.10	0.76
Totals	1645.10	9.68

*150 feet drilled. $1.52 per foot
**20 feet drilled. $5.00 per foot.

SUMMARY OF DRILLERS LOG: 0-20 feet. Drilled. Set 20-feet casing.
20-150 feet. Rotary drilling. Lost circulation.
150-170 feet. Changed to Diamond Bit. Lost circulation.

SUMMARY OF LITHOLOGIC LOG: 0-150 feet. Granite wash with magnetite streaks.
150-170 feet. Fractured granite. Biotite altered to chlorite. Abundant iron and manganese staining.

WATER: None encountered

COMPLETION DATA: Ran capped PVC pipe to 162 feet. Backfilled to 10 feet from the surface. Cemented 10 feet to surface. Cleaned and reseeded site.

Thermal Gradient Hole 6

LOCATION: SE 1/4, Sec. 7 T26S, R9W (SLB & M)
3710 feet N 54° W of 7 | 8
18 | 17

LAND STATUS: Private.

DATES DRILLED: 20 August 1976 to 24 August 1976

DEPTH: 315 feet

COST ANALYSIS: Details not available. Total cost $1065.45, or $3.38 per foot.

SUMMARY OF DRILLERS LOG: Not available.

SUMMARY OF LITHOLOGIC LOG: Granite wash with streaks of magnetite.

WATER: None encountered

COMPLETION DATA: Set 305 feet of capped, one-inch PVC pipe in the hole. Back filled to 10 feet of surface. Cemented top 10 feet. Raked and reseeded drill site.

Thermal Gradient Sec. 16

LOCATION: NW 1/4, Sec. 16, T26S, R9W (SLB & M)
4483 ft. S41W from 9 | 10
16 | 15

LAND STATUS: State

DATES DRILLED: 2 September 1976 through 7 September 1976

DEPTH: 250 feet

COST ANALYSIS:

	Total Cost $	Cost Per Foot $
Rig Time	816.00	3.26
Rotary Bits (3)	228.00	0.91
Surface pipe 15'-3-inch	37.00	0.15
Supplies and Materials	52.60	0.21
Totals	1133.60	4.53

SUMMARY OF DRILLERS LOG:
0-15 feet. Drilled, set 3-inch steel casing, cemented.
15-55 feet. Drilling, hole coring.
55-250 feet. Drilling.

SUMMARY OF LITHOLOGIC LOG:
0-25 feet. Gravel of granitic composition.
25-185 feet. Granite wash with magnetite streaks.
185-215 feet. Quartz sand.
215-250 feet. Granite wash with magnetite streaks.

WATER: None encountered.

COMPLETION DATA: Ran 235 feet of capped one-inch black iron pipe. Backfilled to ten feet from surface, cemented ten feet to surface. Cleaned and reseeded site with 10:2 by weight crested wheat grass and bitter brush.

Alteration Hole 1-76

LOCATION: NE 1/4, SW 1/4, Sec. 34, T26S, R9W (SLB & M).
East 1926 feet and south 2756 feet from
28 | 27
33 | 34

LAND STATUS: Private

DATES DRILLED: 21 June 1976 - 25 June 1976

DEPTH: 201.8 feet.

COST ANALYSIS: Not available.

DRILLERS LOG: 0-10.8 feet. Rotary drilling.
10.8-201.8 feet. Core drilling.
Lost circulation at 150.8 feet, added cement.
Lost circulation at 188.0 feet, changed from water to bentonite drilling mud.

CORE RECOVERY: 74 percent

SUMMARY OF LITHOLOGIC LOG: 0-10.8 feet. Granite wash
10.8-61.4 feet. Silica cemented granite wash alluvium.
61.4-201.8 feet. Altered and fractured granite containing some pyrite, chlorite, and sphene.

WATER: None encountered

COMPLETION DATA: Set capped one-inch black iron pipe to 200 feet. Backfilled with cuttings to 10 feet from the surface. Site cleaned and reseeded with 10:2 by weight crested wheat grass and bitter brush.

Heat Flow Hole No. 1

LOCATION: NW 1/4, Sec. 8, T27S, R8W (SLB & M)
1620 feet East and 162 feet south of $\frac{6\mid 5}{8}$

LAND STATUS: Public domain (BLM).

DATES DRILLED: 28 June 1976 - 15 July 1976; 2 August 1976 - 9 August 1976

DEPTH: 508.4 feet.

COST ANALYSIS: Not available

DRILLERS LOG: 0-101.7 feet. Rotary drilling.
101.7-508.4 feet. Coring.
Continuous sanding in hole. Lost circulation at 432.0 feet. Wide crevice at 450 feet. Tried regaining circulation from top and bottom. Failed. Cemented. Cased hole to 467.0 feet with NX drill rods. Commenced drilling with BX rods. Extreme difficulty in recovering NX rods.

LITHOLOGIC LOG: 0-101.7 feet. Muddy top soil.
101.7-316.5 feet. Altered granite, chlorite prominent.
316.5-318.0 feet. Basic dike.
316.5-508.4 feet. Intermittent aplite dikes in granite containing biotite and chlorite. Iron, manganese, and chlorite staining on fractures.

PERCENT CORE RECOVERY: 65 percent.

COMPLETION DATA: Set one-inch black iron pipe to 504 feet. Pumped cement into pipe until surface returns were obtained and pushed it out with a swabber. Cleaned site and reseeded site with crested wheat grass and bitter bush (10:2 by weight).

Hole Number 3 Heat Flow

LOCATION: SE 1/4, Sec. 25, T26S, R9W
3432 ft. N79E from 26 | 25
35 | 36

LAND STATUS: Public Domain (BLM).

DATES DRILLED: 9 August 1976 - 27 August 1976

DEPTH: 489.3 feet.

COST ANALYSIS: Not available

DRILLERS LOG: 0-29.0 feet. Rotary drilling.
29.0-489.3 feet. Core drilling.

LITHOLOGIC LOG: 0-29.0 feet. Granite wash.
29.0-106.6 feet. Fractured granite with biotite and chlorite.
74.0-81.0 feet. Basic dike.
81.2-82.7 feet. Basic dike.
106.6-489.3 feet. Intermittent aphite dike in granite containing biotite and chlorite. Some sphene, hemitic, manganuferous, and chloritic staining in fractures.

PERCENT CORE RECOVERY: 96

COMPLETION DATA: Set one-inch black iron pipe to 487 feet. Pumped cement into pipe until surface returns were obtained and pushed cement out of pipe with a swafter. Cleaned site and reseeded it with crested wheat grass and bitter bush (10:2 by weight).

Opal Dome Hole

LOCATION: NE 1/4 Sec. 16, R9W, T26S (SLB & M)
2548 feet S77W of
9 | 10
16 | 15

LAND STATUS: State opal lease to A. &.L. McDonald

DATES DRILLED: 9 August 1976

DEPTH: 55.2 feet

COST ANALYSIS: Not available

DRILLERS LOG: 0-4.7 feet. Rotary drilling.
4.7-55.2 feet. Core drilling.

LITHOLOGIC LOG: Coring began just below 5 feet. The first 23 feet consists dominantly of massive or banded opal with some clay interbeds, which become more abundant near the bottom of this section of the core. From 23 to 33 feet the core consists mainly of silicified sediment with minor opal layers. Below this to the bottom the core is made of cemented alluvium, either brown or light green, and varying considerably in its coherence.

COMPLETION: Abandoned.

FOR DETAILS SEE: Brown, F. H. (1977). Attempt at Paleomagnetic Dating of Opal, Roosevelt Hot Springs KGRA. Technical Report, vol. 77-1, Contract EY-76-S-07-1601, ERDA, 13 p.

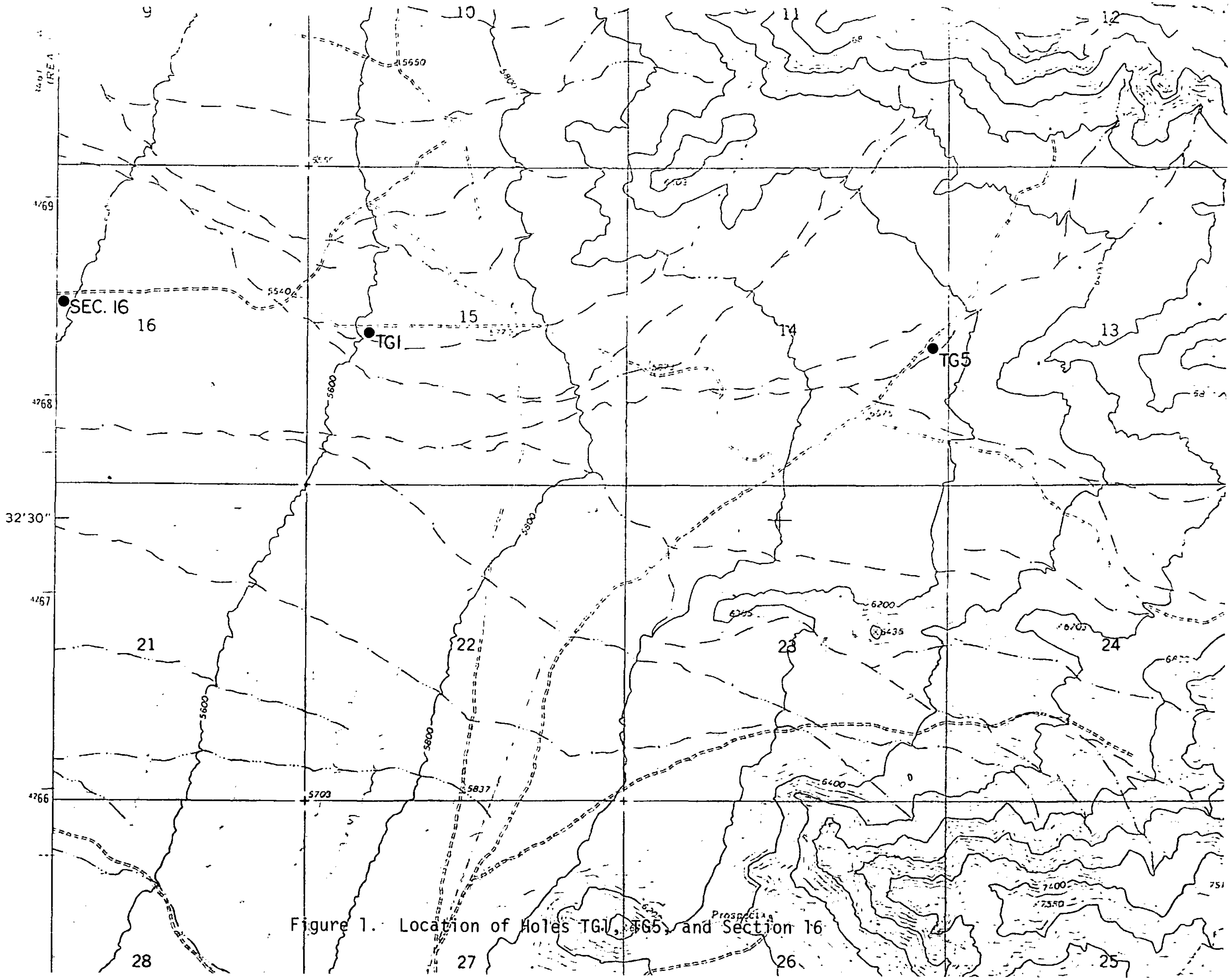


Figure 1. Location of Holes TG1, TG5, and Section 16

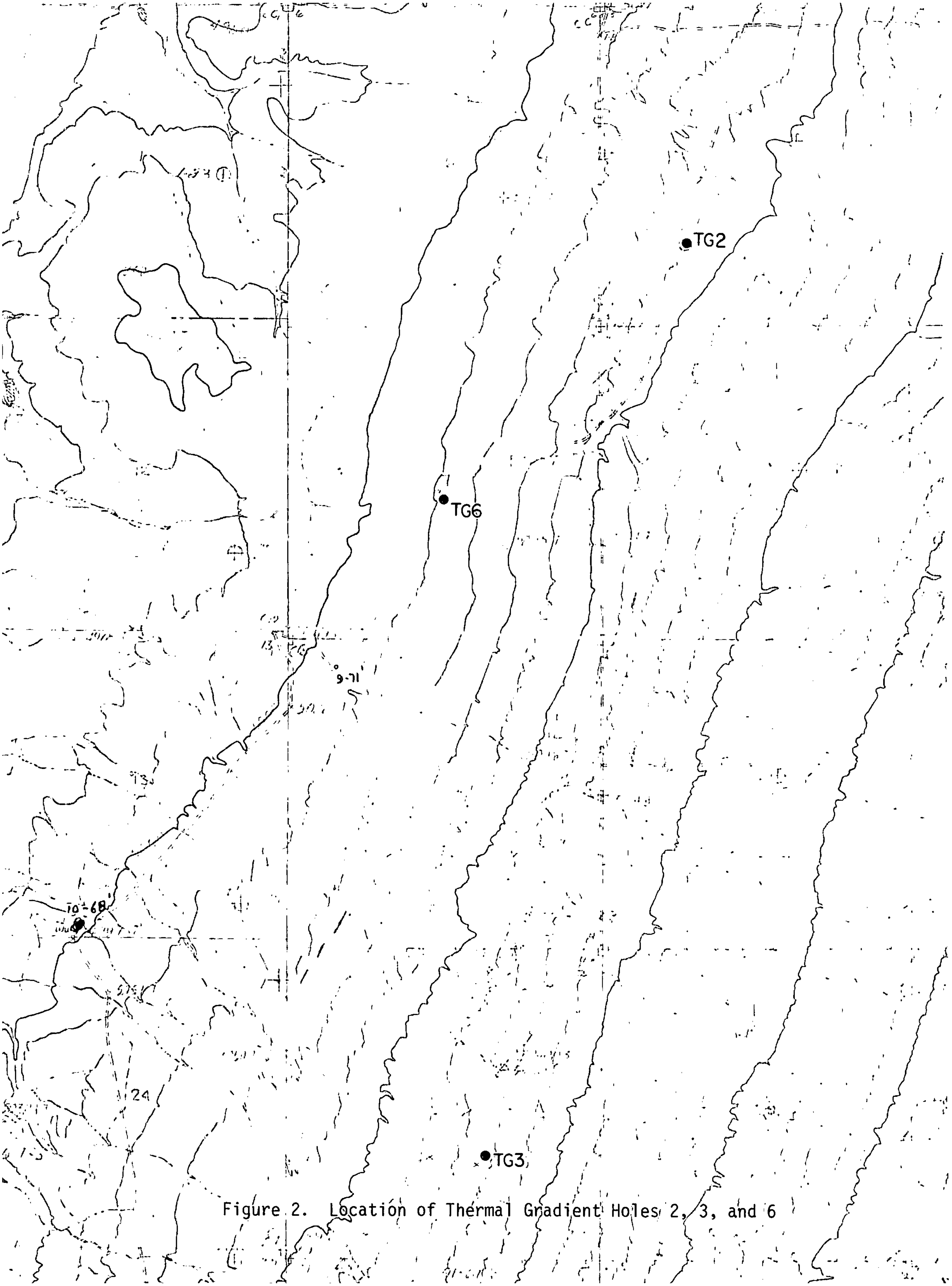


Figure 2. Location of Thermal Gradient Holes 2, 3, and 6

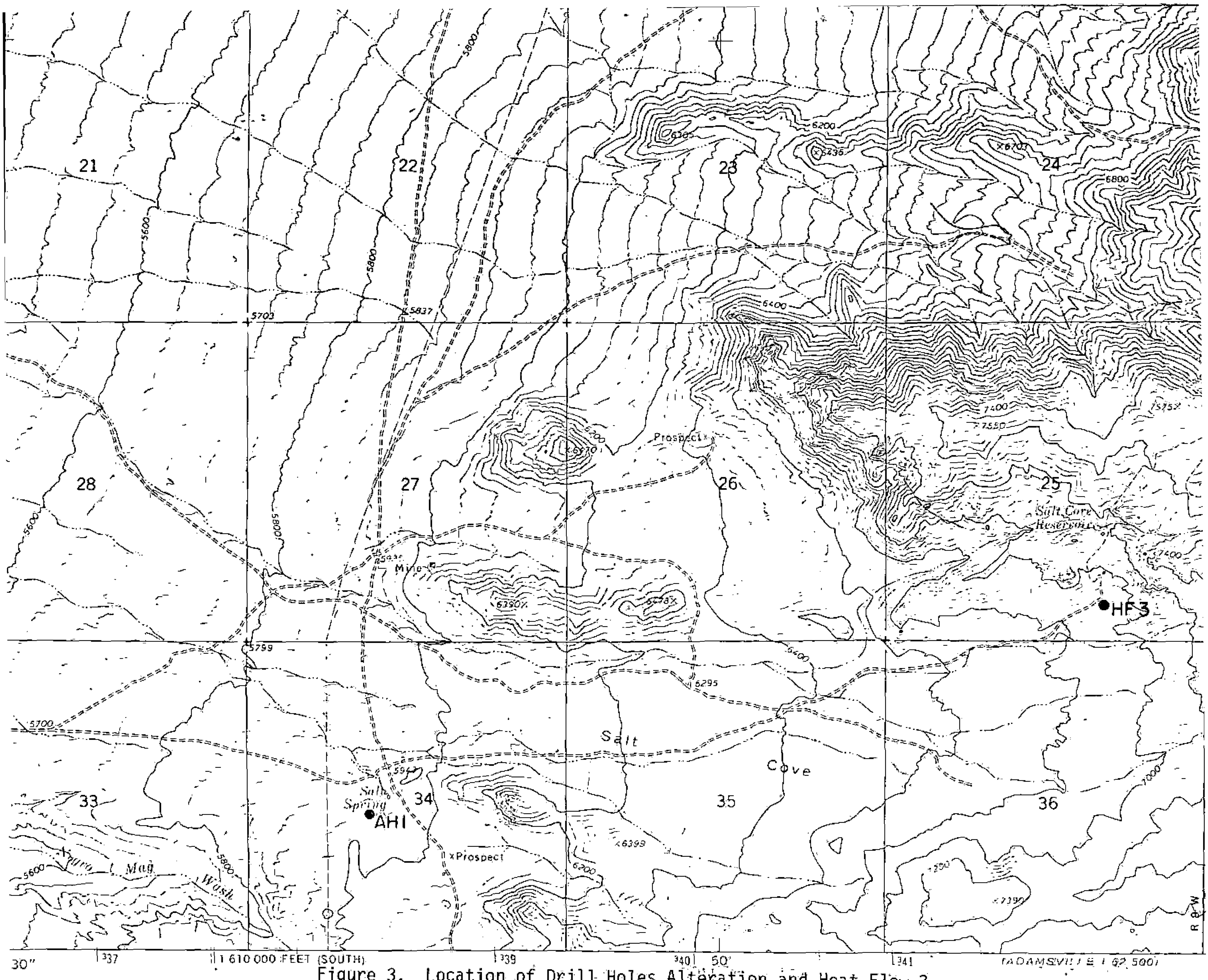


Figure 3. Location of Drill Holes Alteration and Heat Flow 3

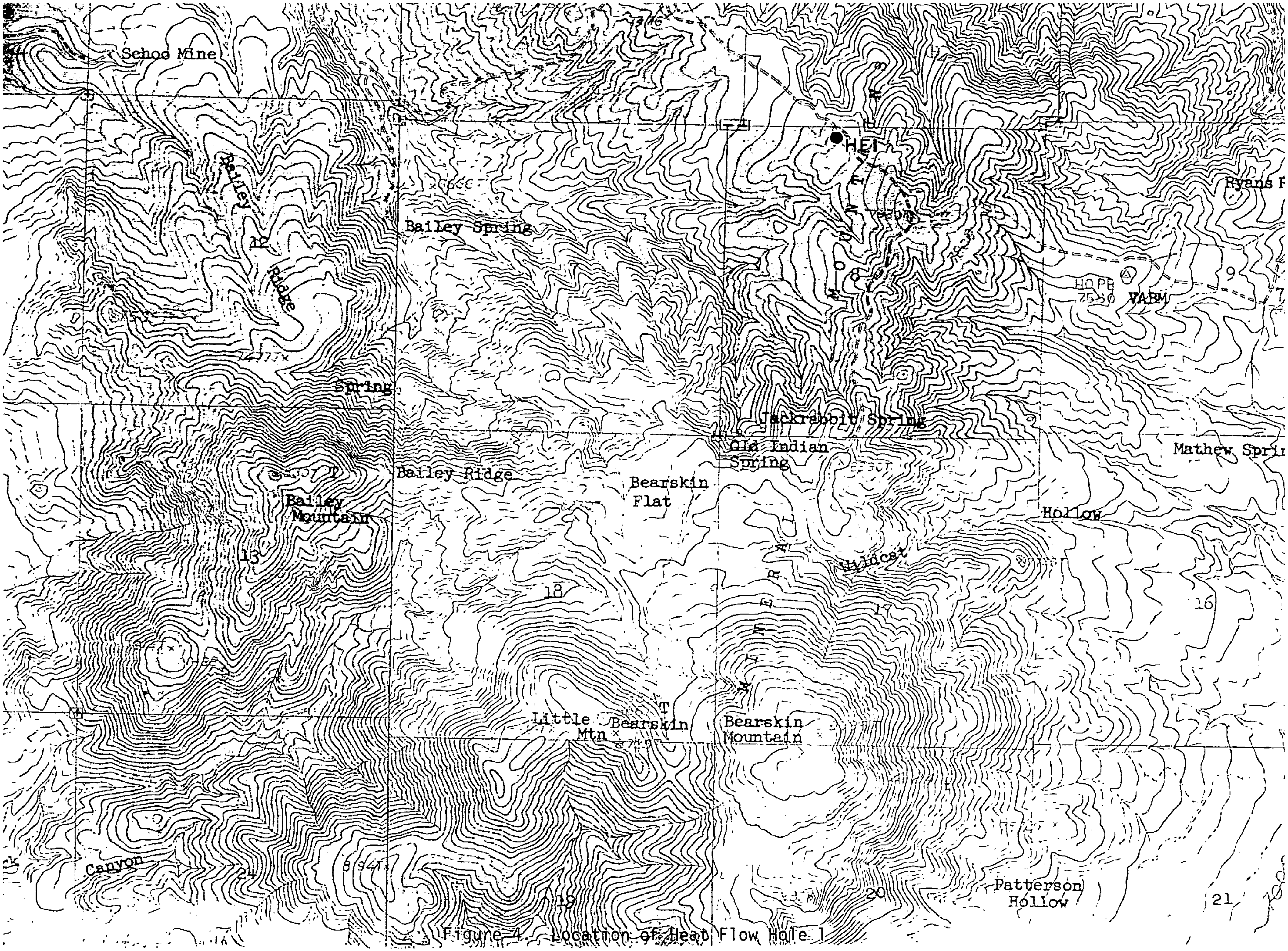


Figure 4. Location of Heat Flow Hole 1

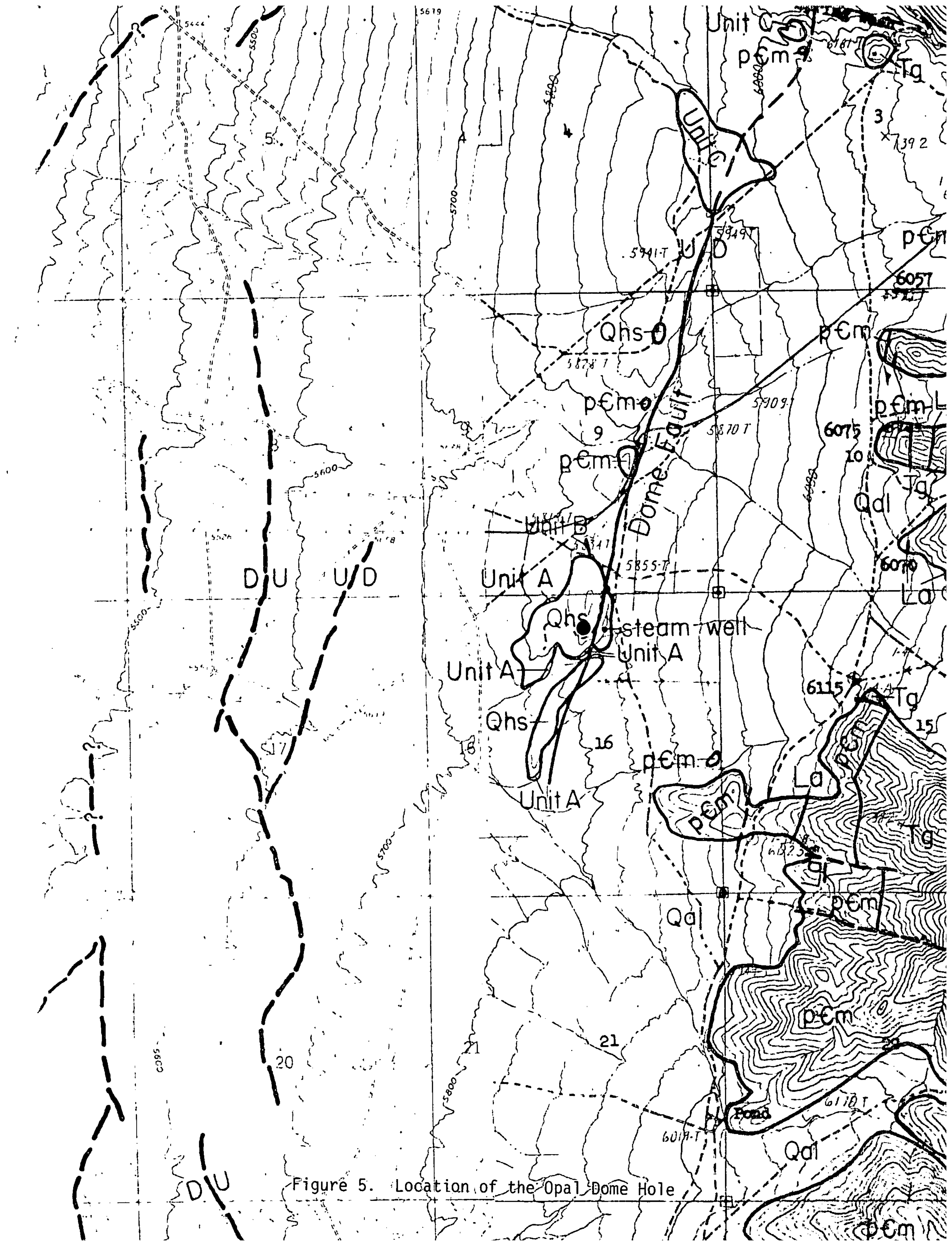


Figure 5. Location of the Opal Dome Hole