MASTER

MANAGEMENT ASSISTANCE AND
TECHNICAL SUPPORT FOR THE PROGRAMS
IN EXPLORATION TECHNOLOGY

FINAL REPORT

For the Period
December 1, 1978 - February 28, 1980

Work performed under Contract No.

DE-AC07-79ET27002

**Department of Geology and Geophysics
University of Utah
Salt Lake City, Utah (USA)**

UNIVERSITY OF UTAH AUTHORS

JOHN R. BOWMAN, STANLEY H. EVANS, JR., GERALD W. HOHMANN, WILLIAM P. NASH
GARY R. REYNOLDS, WILLIAM R. SILL, STANLEY H. WARD

SUBCONTRACT - ESL/UURI AUTHORS

ODIN D. CHRISTENSEN, WILFORD L. FORSBERG, WILLIAM E. GLENN, TERRY J. KILLPACK
JOSEPH N. MOORE, DENNIS L. NIELSON, STANLEY H. WARD, PHILLIP M. WRIGHT

**Prepared for
DEPARTMENT OF ENERGY
Division of Geothermal Energy**

SEPTEMBER, 1980

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DEPARTMENT OF GEOLOGY AND GEOPHYSICS
UNIVERSITY OF UTAH
SALT LAKE CITY, UTAH 84112 (USA)

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1.0 INTRODUCTION

A substantial amount of the technology development initiated under this contract will be continued in FY80 under the U.S. Department of Energy Contract No. DE-AC07-80ID12079 "Management Assistance and Technical Support for Geothermal Programs Administered by the Idaho Operations Office of DOE." This is within the spirit of the continued technique development effort under the Geothermal Exploration and Assessment Technology Program Plan.

During the course of the contract (No. DE-AC07-79ET27002), there were ten technical reports processed for public distribution. These reports are listed in Section 2.0 Comprehensive List of Reports. Also, our reports issued under the other U.S. Department of Energy Contract Nos. DE-AC07-78ET28392 and EY-76-S-7-1601 are shown in Attachments 1 and 2 respectively. These lists are included to provide a perpetual list of technical reports produced under our geothermal investigation sponsored by the U.S. Department of Energy.

2.0 COMPREHENSIVE LIST OF REPORTS

Contract No. DE-AC07-79ET/27002

- DOE/ET/27002-1 An Interactive Modeling System for 2-D Magnetotelluric and Line Source Resistivity Data (MT2D Users Guide and Documentation), by C. Nutter, September, 1979.
- DOE/ET/27002-2 Documentation and Analysis of the Schlumberger Interactive 1-D Inversion Program SLUMB, by S. Sandberg, September, 1979.
- DOE/ET/27002-3 Three-Dimensional Resistivity Inversion Using Alpha Centers, by W. R. Petrick, Jr., W. R. Sill and S. H. Ward, December, 1979.
- DOE/ET/27002-4 Integral Equation Modeling of Three-Dimensional Magnetotelluric Response, by S. C. Ting and G. W. Hohmann, December, 1979.
- DOE/ET/27002-5 A Strategy of Exploration for High Temperature Hydrothermal Systems in the Basin and Range Provinces, by S. H. Ward, H. P. Ross and D. L. Nielson, December, 1979.
- DOE/ET/27002-6 Program Review, Geothermal Exploration and Assessment Technology Program (Including a Report of the Reservoir Engineering Group), by D. L. Nielson, December, 1979.
- DOE/ET/27002-7 Multielement Geochemistry of Solid Materials in Geothermal Systems and Its Application Part 1: The Hot-Water System at the Roosevelt Hot Springs KGRA Utah, by R. W. Bamford, O. D. Christensen and R. M. Capuano, February, 1980.
- DOE/ET/27002-8 Magnetotelluric Models of the Roosevelt Hot Springs Thermal Area, Utah, by P. E. Wannamaker, S. H. Ward, G. W. Hohmann and W. R. Sill, September, 1980.
- DOE/ET/27002-9 Induced Polarization Data at Roosevelt Hot Springs Geothermal Area, Utah, by J. J. Chu, August, 1980.
- DOE/ET/27002-10 Final Report for Contract DE-AC07-79ET27002 by J. R. Bowman et al., September, 1980.

3.0 RESEARCH TASKS ACTIVITIES

Task 5.1 Management Assistance

The objectives of the Management Assistance task in the Geothermal Exploration and Assessment Technology Program have been to assist DOE in program planning, coordination, review, and documentation. In addition, the task includes aid in procurement preparation, proposal review, and contract progress review.

The baseline document for the Exploration and Assessment Technology Program is "Program Review: Resource Evaluation, Reservoir Confirmation, and Exploration Technology" by S. H. Ward, 1978. This document contains the recommendations of seven Technical Review Committees made up of approximately 50 recognized experts in geothermal exploration. The recommendations of these experts were used to direct the programs at ESL/UURI and UU/GG. In addition they were used to assist DOE/ID in formulation of RFPs and PRDAs. These documents were released by DOE/ID as Program Research and Development Announcement DE-RA07-79ET27077 and Request For Proposals DE-RP07-79ID12038, DE-RP07-79ID12039, DE-RP07-79ID12040, and DE-RP07-79ID12041. In addition to these procurements, pass-through monies were used to enlarge the data bases at selected Industry Coupled Case Study areas; this portion of the program was coordinated between DOE/NV and ESL/UURI. ESL/UURI provided technical advice on the proposal review of the RFPs and PRDAs and subsequent contract negotiations.

The Technical Review Committees which provide input to the Geothermal Exploration and Assessment Technology Program were reconvened during May, 1979

in Marina Del Rey, California. These committees recommended programs requiring technology development. These recommendations are published in Nielson, 1979 (abstract at the end of this section) and have been incorporated into the statements of work for the FY80 Exploration and Assessment Technology Programs of ESL/UURI and UU/GG. In addition, these recommendations were used by DOE/ID to generate procurements on 1) microearthquake survey and analysis (DE-SC07- 80ID12144), 2) characteristics of water-rock interaction (DE-SC07-80ID12145), 3) relationships between thermal conductivity and physical parameters from well logs (DE-SC07-80ID12146), and 4) improvements in geothermometry (DE-SC07- 80ID12147).

During FY79 and FY80, two formal program reviews of the Exploration and Assessment Technology Program were held for DOE. The first of these was held in Washington, D.C. on January 31, 1979 and the second was held in Salt Lake City on February 29, 1979.

The Exploration and Assessment Technology Program also sponsored a workshop on Seismic Exploration in the Geysers-Clear Lake Area of California. The workshop was coordinated by Ron Ward of University of Texas, Dallas.

Abstract

"Program Review, Geothermal Exploration and Assessment Technology Program (Including a Report of the Reservoir Engineering Group)", by D. L. Nielson, December, 1979 (DOE/ET/27002-6).

The Department of Energy's Geothermal Exploration and Assessment Technology Program was established to aid geothermal exploration and thus the

development of geothermal resources in the United States. In the near-term this involves the adaptation of exploration and assessment techniques from the minerals and petroleum industry to geothermal applications. In the near- to far-term it involves the development of new technology which will improve the cost-effectiveness of geothermal exploration.

In order to coordinate this DOE program with the needs of the geothermal exploration industry, seven consortia of geothermal experts were convened to define technical problems facing the industry. The reports of these consortia were reviewed by managers from industry, and the resultant recommendations were used to formulate procurements and define a technology development program at the Earth Science Laboratory/University of Utah Research Institute and the Department of Geology and Geophysics/University of Utah. The reports of the seven consortia along with the review by industry managers are documented in:

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

Task 5.2 Geological Technique Development

A report on this topic has been in preparation for some time. It represents an integration of all of our data at Roosevelt Hot Springs KGRA into a model of this convective hydrothermal system. Our intent under this contract was to produce a report that adequately described our notions of the system model at the time of the report - an interim report in that sense. Preliminary reports were presented at the IUGG meeting in Canberra, Australia (see abstracts at the conclusion of this section). However, because of recent exciting developments of single and multiple data set modeling of available geological, geochemical, geophysical, and hydrological data, our efforts have necessarily increased in integrating these data sets. It seems unwise, therefore, to turn out an interim report. Therefore we have expanded the scope of this task and deferred its deliverable into the time frame of the successor to the original contract. The deliverable is therefore deferred until January, 1981.

Abstracts

Paper Presented No. 1

"ROOSEVELT HOT SPRINGS GEOTHERMAL SYSTEM: GEOLOGICAL AND GEOPHYSICAL MODELS", by S. H. Ward, D. S. Chapman, S. H. Evans Jr., D. L. Nielson, P. E. Wannamaker and W. R. Wilson, December, 1979.

The Roosevelt Hot Springs geothermal system is located on the western flank of the Mineral Mountains in the Basin and Range province of the U.S.A. Reservoir temperatures of 265°C have been measured as shallow as 500 m and the system has an estimated production potential of 300 MWe. Geological and

geophysical models of the geothermal system have the following characteristics: (1) Felsic igneous activity began 22 m.y. ago with the intrusion of the main phases of the Mineral Mountains pluton. Additional igneous pulses occurred at about 9 m.y. and 0.5 m.y. B.P. with the extrusion of rhyolite domes and flows and pyroclastic eruptions. (2) Three principal fault trends cut the Mineral Mountains and control the geometry of the geothermal reservoir. The earliest faults were formed during the period of denudation faulting which presumably developed as a result of tectonic instability during the uplift of the Mineral Mountains. These faults have been cut by EW and NNE-trending fault zones. The NNE-trending zones have in recent past controlled the deposition of opaline sinters and presently control active fumaroles. (3) The subsurface electrical resistivity pattern, as revealed by one-dimensional modeling of Schlumberger and two-dimensional modeling of dipole-dipole soundings, consists of steeply dipping low resistivity (5-20 Ωm) structures that correspond spatially to hydrothermally altered fracture zones. Modeling of MT data with a 2-D transverse magnetic algorithm has enabled resolution of crustal structure in this complex 3-D environment that consists of a hydrothermally altered region in a fractured pluton juxtaposed by normal faulting against a clay-rich sediment-filled valley. The generalized crustal profile under the Mineral Mountains consists of 35 km of 3000 Ωm crust below which resistivities drop to 100 Ωm . The main difference between this profile and other Basin and Range profiles is the occurrence at Roosevelt of a highly resistive body (several thousand ohm-meters) 2 km below the thermal anomaly. (4) A heat flow map has been constructed from detailed thermal gradient and conductivity measurements in 53 drill holes. Heat flow contours are strongly

controlled by fault patterns. The 400 and 1000 mWm^{-2} contours enclose areas of 56 and 16 km^2 respectively; total conductive heat loss at the surface within the 400 mWm^{-2} contour is 60 MW above background. The heat loss budget cannot be satisfied by the cooling of identified igneous units; it necessitates resupply of heat, possibly from a long sought-after but still elusive magma chamber.

X
Paper Presented No. 2

"HEAT FLOW OBSERVATIONS IN THE EASTERN BASIN AND RANGE PROVINCE, U.S.A.,
WITH EMPHASIS ON MIOCENE AND YOUNGER IGNEOUS SYSTEMS", by
David S. Chapman, December, 1979.

Fifty-seven new regional heat flow determinations have been made in the eastern Basin and Range physiographic province of the western U.S.A, an area known for extensional tectonics and recurrent volcanism over the last 17 m.y. Excluding geothermal areas, the mean of these regional measurements is 90 ± 10 (s.d.) mW m^{-2} , lending support to the hypothesis of near-melting conditions at the base of the crust for much of the Basin and Range province. Several areas having localized heat flow in excess of 200 mW m^{-2} have been identified but not in detail: (1) the Monroe hydrothermal system, set in an extensive and faulted volcanic pile of Miocene age, has an integrated heat loss of 8 MW which is best explained by forced convection of meteoric water; (2) the Twin Peaks volcanic system where an estimated 400 km^3 of rhyolite and granite were emplaced between 2.7 and 2.1 m.y. ago, but for which there is no present thermal anomaly; and (3) the Mineral Mountains - Roosevelt Hot Springs system where silicic magma emplacements at 20-10 m.y. (pluton), 0.8 m.y. (obsidian

flows), and 0.5 m.y. (rhyolite domes) have been recorded, and where anomalous conductive heat loss exceeds 60 MW. Heat loss budgets for all these systems provide useful constraints on magmatic heat sources.

5.3 Exploration Architecture

A topical report on this subject was released on December 3, 1979 under the title, "A Strategy of Exploration for High Temperature Hydrothermal Systems in the Basin and Range Province". This report was presented at the national meeting of the American Association of Petroleum Geologists in Denver. In addition, the manuscript has been accepted for publication in the American Association of Petroleum Geologists Bulletin. The abstract of that report, reproduced below, completes our reporting under this task.

Abstract

"A Strategy of Exploration for High Temperature Hydrothermal Systems in the Basin and Range Provinces", by S. H. Ward, H. P. Ross and D. L. Nielson, December, 1979, (DOE/ET/27002-5).

A fifteen phase strategy of exploration for high-temperature convective hydrothermal resources in the Basin and Range province, recommended herein, features a balanced mix of geological, geochemical, geophysical, hydrological, and drilling activities. The strategy is based on a study of data submitted under the Department of Energy's Industry Coupled Case Study Program. Justification for inclusion in or exclusion from the strategy of all pertinent geoscientific methods is given. With continuing research on methods of exploration for and modeling of convective hydrothermal systems, this strategy is expected to change and become more cost-effective with time. Variations on the basic strategy are to be expected where the geology or hydrology requires it. Personal preferences, budgetary constraints, time and land position constraints, and varied experience may cause industrial geothermal exploration

managers to differ with our strategy. For those just entering geothermal exploration, the strategy is expected to be particularly useful.

Task 5.4 Case Studies Support - Isotopes RHS KGRA

This project was designed to obtain oxygen isotopic information on the 0.7 to 0.5 m.y. old silicic volcanics associated with the Roosevelt Hot Springs thermal area. Information on isotopic geothermometry and water-rock interaction parameters is expected to be gained from this study. To date eighteen high-quality mineral separates have been produced and are awaiting analysis. Early this summer preliminary oxygen data was obtained on some glass samples, yielding $\delta^{18}O$ numbers that were lighter than expected. Unfortunately shortly after these analyses were completed a water recirculator failure caused damage to seals and other components of the silicate extraction line. This damage was repaired and steps taken to protect the silicate line from any future cooling failures. Analyses continued immediately after repairs were made. The project is scheduled to be completed and a topical report submitted by December 1, 1980.

Task 5.5 Case Studies Support - Geophysics RHS KGRA

A report on bipole-dipole work at Roosevelt Hot Springs KGRA has been deferred for delivery under Contract No. DE-AC07-80ID12079, Task 5.41.

The telluric ratio survey and data processing have been completed. Data interpretation is underway and should be completed in an intensive effort planned for September, 1980. However, report writing, illustration preparation, and editing will need to be carried over to FY81.

A report on IP work at Roosevelt Hot Springs KGRA has been completed and an abstract of that report is included below.

Abstract

"Induced Polarization Data at Roosevelt Hot Springs Geothermal Area, Utah", by Jean J. Chu, August, 1980 (DOE/ET/27002-9).

Both field and laboratory broadband multispectral data have been gathered in a study of IP phenomena at the Roosevelt Hot Springs geothermal area. The field survey involved two traverses across the main part of the present hydrothermal system. The laboratory research gathered data at 25°C, 50°C, and 75°C, on hydrothermally altered rocks from the hot springs area.

Laboratory data indicate a small IP effect of 3 to 23 milliradians (mrad) at low frequencies (~ 0.004 Hz). High frequency ($\sim 10^3$ Hz) IP data ranged from 20 to 100 mrad. The IP effect is frequency dependent, and does not seem to be affected markedly by moderate changes in temperature; it is also dependent upon the quantities of pyrite and clay minerals. Pyrite affects the phase spectrum well above 1 Hz, and its effect is different from that of polarizable

clays.

The field data show that one can obtain both positive and negative phase values due to electromagnetic coupling. An accurate estimate of the uncoupled IP response, using the double Cole-Cole model, depends upon the proper weighting of the observed data. Extrapolated phase data reveal a small anomalous region of 20 to 34 mrad along one of the profiles; the majority of the data ranged from 7 to 15 mrad.

The laboratory and field data indicate only a small IP effect over the hydrothermal system; it could be considered as background and hence of no consequence. Thus, there seems to be no large-scale delineation of the geothermal field.

Task 5.6 Application of EM Techniques

Theoretical Modeling

A three-dimensional integral equation magnetotelluric modeling program was adapted to active source applications. The original program modeled electromagnetic scattering of incident plane waves by a prismatic conductive anomaly in a conductive half space host. Subroutines were written to generate incident fields in the scattering body and at surface receiver locations for an arbitrary finite source wire layout over a conductive half space.

Implementation of an algebraic transformation that greatly reduces computation costs for symmetric bodies and arbitrary source fields, and generalization from cubic to prismatic discretization cells are complete. The program has been applied to controlled source audio-magnetotelluric modeling, and to experimental design model studies for the low-frequency, active-source geothermal exploration experiment conducted at the Roosevelt Hot Springs KGRA.

Data Acquisition and Processing

Sophisticated digital recording and in-field processing instrumentation has been designed and built. A portable microprocessor-controlled four channel receiver has been employed in the low-frequency, active-source EM experiment at Roosevelt Hot Springs KGRA in which a cryogenic magnetometer was used to measure three-component magnetic field amplitudes and phase. The primary target was a conductive anomaly associated with the hydrothermal reservoir. A computer simulation of the digital receiver recording a vertical magnetic field from a vertical magnetic dipole source at the surface of a conductive half-space has been developed in order to ascertain such effects as analogue to digital conversion with finite precision and dynamic range,

sampling rates with associated anti-aliasing filter response, and cosine correlation processing. Telluric noise digital simulation having a power spectrum matched to spectra obtained from field measurements was developed in order to simulate in-field processing techniques for noise removal. Techniques simulated and applied in the field include real time digital high pass filtering and stacking. Remote reference noise removal in which relative gain and offset are determined by a least squares fit of data samples several cycles in length, then differenced to extract a weak signal buried in low frequency noise has also been simulated. Field application is anticipated when the MT computer-controlled system having telemetric remote reference capabilities is ready.

The project will be carried over into the next FY.

Task 5.7 Electrical Modeling

Five topical reports have been released under this task and the abstracts of these reports are presented below.

Abstract No. 1

"An Interactive Modeling System for 2-D Magneto-telluric and Line Source Resistivity Data" (MT2D Users Guide and Documentation), by Carleen Nutter, September, 1979 (DOE/ET/27002-1).

A two-dimensional finite element program developed at the University of Utah has been described in a 1978 report by John Stodt, titled "Documentation of a Finite Element Program for Solution of Geophysical Problems Governed by the Inhomogeneous 2-D Scalar Helmholtz Equation." This program handles the two-dimensional magnetotelluric TE and TM mode problems, as well as the infinite line source problem. The program uses linear interpolation of the unknown field over triangular sub-domains of the region where a solution is sought in conjunction with the Galerkin technique to derive a system of linear equations which approximate the governing partial differential equation. The solution of this linear system of equations gives the approximate field values at the nodes of the discretized domain.

The interactive modeling system is a set of programs and subprograms, with a single logical entry and a single logical exit, which allows the user to manipulate model parameters, execute the finite element program, and display output. Five distinct logical functions are available to the user.

This system was written for the UNIVAC 1108, under the EXEC-8 (level 33).

operating system, at the University of Utah Computer Center (UU/CC). It contains approximately 5,000 lines of FORTRAN and card image code. There are five main programs, 58 FORTRAN subroutines, and 16 card image utility elements. The largest program uses 57 K words of memory; the smallest uses 10 K words.

Entry into the interactive system is through a program called TERMS, which is the terminal selection program. TERMS automatically executes program MASTER after it stores the flag variable for the terminal type in a random access file. Each of the functions (including TERMS and MASTER) has access to this data file. Information is written to or from this data file as it is needed by the various functions.

Once in MASTER, the interactive system executive, all activity is controlled through an options selection mechanism. The user selects an appropriate action from a list of possible actions to proceed through the modeling session. The interactive system prompts the user when input is required.

The five logical functions controlled from MASTER allow the user to 1) INPUT the model parameters which are used by the finite element program and, optionally, a set of field data which can be used to compare with the theoretical data generated by the finite element program MT-LS, 2) EDIT the model parameters and field data to update the model or correct input.

X

Abstract No. 2

"Documentation and Analysis of the Schlumberger Interactive 1-D Inversion Program SLUMB", by Stewart Sandberg, September, 1979 (DOE/ET/27002-2).

This computer program is designed to accept field data from a Schlumberger resistivity array and invert it in terms of a one-dimensional layered geoelectrical model. Because the inverse problem is non-linear, an initial-guess model is required. This input model can be obtained by traditional curve matching, or by repeated use of a forward algorithm.

This program was written in FORTRAN V in 1976 by Luiz Rijo. It was developed on a UNIVAC 1108 computer, operating under EXEC. 8 (level 31). The program size is approximately 16 K decimal words. (The UNIVAC has a word size of 36 bits.) The program is designed for interactive use using a Tektronix 4014 Graphics Display terminal.

Dup

Abstract No. 3

"Three-Dimensional Resistivity Inversion Using Alpha Centers", by W. R. Petrick, Jr., W. R. Sill and S. H. Ward, December, 1979 (DOE/ET/27002-3).

The alpha center formulation leads to a forward routine that is fast enough to make three-dimensional (3-D) resistivity inversion practical.

The method of alpha centers represents a class of solutions to the D.C. conduction equation based on certain nonlinear substitutions for electric potential and earth conductivity. The inversion routine results in a conductivity distribution defined by alpha centers which simultaneously fits the data from several parallel or perpendicular dipole-dipole profiles.

To illustrate the characteristics of this modeling approach, we applied the inversion algorithm to three theoretical and four field data sets. The four field data sets represent samples from massive sulfide and geothermal environments. The technique gives fairly good estimates of the positions of conductive inhomogeneities but poor estimates of their actual conductivities.

The entire inversion algorithm requires less than 15,000 words of computer memory, thus making it tractable for small computers. We envision two major applications. The first is for in-field data interpretation to site drilling locations or guide further exploration. The second is for obtaining a good initial guess for more sophisticated and costly multi-dimensional inversion schemes.

out

Abstract No. 4

"Integral Equation Modeling of Three-Dimensional Magnetotelluric Response", by S. C. Ting and G. W. Hohmann, December, 1979 (DOE/ET/27002-4).

We have adapted a three-dimensional (3-D) volume integral equation to magnetotelluric (MT) modeling. Incorporating an integro-difference scheme increases the accuracy somewhat. Utilizing the two symmetry planes of a buried prismatic body and a normally incident plane wave source greatly reduces the required computation time and storage. Convergence checks and comparisons with one-dimensional (1-D) and two-dimensional (2-D) models indicate that our results are valid.

In this paper, we show theoretical surface anomalies due to a 3-D

prismatic conductive body buried in a half-space earth. Instead of studying the electric and magnetic fields, we have obtained impedance tensor and magnetic transfer functions by imposing two different source polarizations. Manipulation of the impedance tensor and magnetic transfer functions yields the following MT quantities: apparent resistivity and phase, impedance polar diagrams, tipper direction and magnitude, principal directions, skew and ellipticity. With our preliminary analyses of these MT quantities, we have found that three-dimensionality is usually revealed by all of them. Furthermore, we have recognized two pairs of complementary parameters; apparent resistivity and phase, and skew and ellipticity. Because of surface charges at conductivity boundaries, low-frequency 3-D responses are much different from 1-D and 2-D responses. Thus, in many cases 3-D models are required for interpreting MT data.

Although an overall 3-D MT interpretation is still not practical, combined 2-D and 3-D modeling could be applied to yield a gross 3-D structure, which is composed of a cross section and its strike extent. In doing so, we suggest that the cross section be obtained from higher frequency 2-D $E_{\perp}$ modeling, and that the strike extent be derived by matching with lower frequency $E_{\parallel}$ mode results due to corresponding 3-D models. In addition, we have indicated that some simple 3-D features, e.g., location above conductive zone, corners, and symmetry lines, can be easily recognized.

Sup

Abstract No. 5

"Magnetotelluric Models of the Roosevelt Hot Springs Thermal Area, Utah",
by Philip E. Wannamaker, Stanley H. Ward, Gerald W. Hohmann and William
R. Sill, August, 1980 (DOE/ET/27002-8).

The Roosevelt Hot Springs (RHS) thermal area, which includes a hot-water-dominated, fracture zone reservoir near the eastern margin of the Basin-Range tectonic province, conceivably possesses a whole family of resistivity structures that includes the following: deep hot brine reservoirs, deep-seated partially molten heat sources in the crust or upper mantle that drive the convective system, near-surface hydrothermal alteration zones, wet sedimentary fill in valleys, and a regional, apparently one-dimensional resistivity profile of the crust and upper mantle. This complex resistivity makeup, peculiar to RHS but probably similar to that at other geothermal areas in the Great Basin, must be treated as being fully three-dimensional (3-D). In an attempt to understand these structures, we have obtained broadband (10^{-3} to 10^2 Hz) tensor magnetotelluric (MT) data including apparent resistivities (ρ_a), impedance phases (ϕ) and vertical magnetic field transfer functions for 93 sites in the vicinity of this resource area.

The preservation of normal current density combined with the finite lateral extent of 3-D bodies results in discontinuities in electric field regardless of polarization or frequency of incident field. Such effects are referred to as polarization charge or current-gathering phenomena. Distortions in any apparent resistivity or vertical admittance element

magnitudes around a 3-D body will approach a non-zero, essentially frequency-independent function below some low-frequency limit. This is not so for tipper element magnitudes as well, generally, as anomalies in phases of all MT functions which diminish below this limit. Furthermore, small-scale geologic noise may cause anomalies in apparent resistivity, tipper element magnitudes and the phases of all functions as pronounced as those of large bodies, though the spatial extent of the former will be relatively confined. We emphasize that ρ_a soundings near such noise may be distorted sufficiently so that 1-D and 2-D transverse electric (TE) interpretations aimed at describing a deeper feature of interest may be subject to serious errors. However when comparing the responses of large and small structures, the frequency ranges over which their respective anomalies in any MT quantity occur are separated roughly according to the square of the scale change between the structures. This may hence encourage use of tipper element magnitudes and the phases of all MT quantities in order to observe more directly the presence of larger structure buried beneath small-scale geologic noise.

An integral equation numerical simulation of variable hydrothermal alternation and valley sedimentary fill by conduction prisms in a conducting half-space shows that, at relatively high frequencies, rather complicated signatures result relating to an outwardly propagating secondary wavefront. Below our defined low frequency limit, the MT quantities are to first order those of a static electric dipole in the earth. For variable hydrothermal alteration and other geologic noise, this limit is met below about 1 Hz. The distortion in low frequency apparent resistivities over representative 3-D geological noise may approach two orders of magnitude and as such would have a

very deleterious effect upon the results of 1-D or 2-D TE interpretation.

Current-gathering in the valley is reflected in a regional distortion of the electric field affecting all stations at RHS to arbitrarily low frequencies. MT quantities around valley sedimentary fill reach their low frequency limit at about 0.01 Hz. The valley induces a large ρ_a anisotropy near its edge where the bulk of the soundings at RHS are located. The anisotropy does not vanish as frequency diminishes; both principal apparent resistivities are nearly equidistant from the background apparent resistivity of the 1-D host. This strong anisotropy, along with the distorting effects of small-scale geologic noise, invalidates 1-D interpretation at RHS. In terms of active convective hydrothermal systems, polarization charges in and around the near-surface conductivity structure within a thermal area created by the upward convection of hot brines with attendant hydrothermal alteration of rocks and alluvium may themselves be the cause of an apparent but false deep conductor beneath the system, suggestive of a partially molten heat source, if ρ_a soundings within this shallow structure are interpreted with a 1-D inverse algorithm.

Model studies have also pointed out severe limitations to the application of 2-D TE algorithms even for evaluating valley sediments. Corresponding 3-D and 2-D TE apparent resistivity and impedance phase signatures depart significantly below about 0.3 Hz. However, for centrally located profiles across geometrically regular 3-D prisms, the principal quantities ρ_{yx} and ϕ_{yx} , where x is the direction normal to the profiles, may be interpreted successfully using a 2-D transverse magnetic (TM) algorithm. A variety of MT

strike estimators may be used to select which data may be treated as the transverse magnetic mode. For interpreting deeper, larger structure in the face of geologic noise, we favor an estimator based upon maximizing the magnitude of tipper element K_{zy} . If reliable tipper element estimates are not available, rotation of co-ordinate axes to a uniform direction compatible with regional geologic trends should give roughly equivalent results.

Based upon the insight derived from the 3-D model studies, we have modeled two, east-west profiles of soundings across the eastern edge of the Milford Valley with a 2-D TM finite element algorithm. The first profile, some 6 km north of the hot springs, provides mainly information on the valley sediments and the regional resistivity profile. The stations of the second profile directly over the hot springs concentrate on structure beneath the thermal anomaly such as the brine reservoir or deep heat source. Generally excellent fits of computed results to observed data along with detailed but overall well-resolved geoelectric cross sections have been obtained. Very conductive sediments ($\rho = 1.1 \Omega\text{-m}$), probably mostly Quaternary Lake Bonneville clays, appear in the Milford Valley to a depth approaching 700 m. Below this, great thicknesses (>1 km) of modest resistivity material ($\rho = 25 \Omega\text{-m}$), possibly Tertiary semiconsolidated sediments, are believed to exist, although resolution of this feature is not good.

In the upper 300 m of the finite element cross-section beneath the hot springs, the resistivity sequence progresses downward from 50 $\Omega\text{-m}$ material of 100 m maximum thickness through more conductive units (2 to 6 $\Omega\text{-m}$) into a resistive medium of 450 $\Omega\text{-m}$, a sequence comparing favorably to that determined

by DC resistivity and controlled-source audiomagnetotelluric surveys. Below this at a depth of 400 m, a deeply extending (2 km), highly resistive (50,000 Ω -m) prism was included in the section in an attempt to fit the data below 10 Hz directly over the thermal anomaly. A significant lack of fit to the measurements remains so that we are not convinced that such a highly resistive structure exists. Sensitivity tests of the data suggest that a geometrically regular reservoir of conductive brine beneath the thermal anomaly is quite unlikely so that our search for any economic thermal reservoir at RHS must be considered unsuccessful at this point. No lateral resistivity anomalies below 3 km affect that mode of data identified as TM at RHS. Hence, our search for any deep heat source must also be considered unsuccessful to this time. If a structure of high resistivity contrast representing such a source exists beneath the hot springs, its east-west extent is too narrow to be resolved by the TM algorithm. A future, fully 3-D evaluation utilizing all measured ρ_a 's and ϕ 's along with vertical magnetic field functions will be attempted to assess both any deep heat source and any economic thermal reservoir.

We have, however, succeeded in estimating the apparently 1-D regional resistivity profile to depths in excess of 100 km. Considering the total profile, we observe a rise in resistivity from a few hundred Ω -m to about 3,000 Ω -m as we leave the surface to a depth of 11 km. Subsequently, the resistivity falls, probably in a smooth manner, to some 200 Ω -m at 35 km. Encountered next is an abrupt drop to 20 Ω -m material, which remains seemingly uniform to a depth of 65 km, where an equally abrupt rise to 200 Ω -m introduces an apparently basal half-space. Sensitivity computations indicate

that this deep conductive layer exists and its estimated depth to top is accurate to <10 km. We presently endorse the following physical model. The conduction mechanism of the upper 15 km of crust in the region is dominantly electrolytic conduction in aqueous pore and fracture fluids. Increasing pressure and temperature with depth causes solid-state crustal mineral semiconduction to be henceforth most important, leading to rather uniform decrease in resistivity to 35 km. The 20 Ω -m layer isolated from 35 to 65 km in the upper mantle is of particular interest. Presuming a mantle of uniform composition and downward increasing temperature, an order-of-magnitude rise to 200 Ω -m at 65 km cannot be explained by considering only solid state semiconduction. We thus propose electrolytic conduction in an interconnected partial melt layer of low melt fraction ($\sim 2\%$) to represent the medium from 35 to 65 km. This layer may be a manifestation of a N-S trending reservoir of basaltic liquid in the upper mantle of the eastern Great Basin supplying the repeated volcanism here for the past 10 m.y. Semiconduction is favored though as the most important mechanism for the lowermost medium of 200 Ω -m. Possible high lateral resistivity contrasts, such as may be associated with the Basin-Range to Colorado Plateau lithosphere transition about 100 km to the east, do not appear to have a measureable effect on our observations at RHS. However, this transition as well as other characteristics of the tectonics and physical state of the Great Basin interior, its eastern margin and the Colorado Plateau itself should be accurately determined by a series of MT measurements along an ESE trend from central Nevada to the Four Corners area.

Task 5.8 Geochemical Technique Development

Geochemical technique development work has been primarily directed toward confirming the presence of the geochemical dispersion patterns about geothermal systems documented in earlier work, toward expanding the suite of elements for which this zonation can be documented, and toward improving geochemical techniques applicable to geothermal exploration. To accomplish these objectives, detailed multielement geochemical studies were continued at Roosevelt Hot Springs, Utah (RHS), and at the Geysers, California, and an application of techniques developed to date completed at Cove Fort/Sulphurdale, Utah. In support of these activities, geochemical instrumentation and procedures have been significantly improved and software systems developed for data management and presentation.

Geochemical analyses necessary for development of a three-dimensional geochemical zoning model has primarily been concentrated on the hot-water geothermal system at RHS. The existing data base was augmented by analysis of 100-foot composite whole rock samples and specific gravity concentrates from Getty Oil Company's well Utah State 52-12, detailed geochemical logging of Utah State 72-16 and 14-2, and, detailed soil surveys (Capuano and Bamford, 1978, Bamford et al., 1980).

The results of these analyses have been integrated to produce an empirical three-dimensional geochemical model for the RHS, Bamford et al., 1980, (abstract at the end of this section).

In order to evaluate the general applicability of the geochemical model developed at RHS to other systems, similar work continues at The Geysers,

California. Complete sample suites from 9 additional wells have been obtained from Shell Oil Co., Union Oil Co., and Aminoil USA Inc. These companies are cooperating with the Earth Science Laboratory (ESL) geochemical technique development program by providing lithologic, drilling and geophysical logging data as well. Laboratory analysis of samples has nearly been completed. Preliminary evaluation of the data indicates that prominent chemical patterns are present, that they correlate directly with lithologic and geothermal features, and that the potential of geochemical logging as a tool for well evaluation is great.

One application of the proposed geochemical exploration technique was completed at Cove Fort/Sulphurdale, Utah, a field containing features of both liquid-and vapor-dominated systems. Multielement analysis of a suite of samples from 19 temperature gradient holes indicated the presence of near-surface geochemical distributions apparently related to the geothermal system. The report of this work (Bamford and Christensen, 1978) documents the element distributions, makes recommendations for further geologic and geochemical work, and presents general exploration models for this geothermal system based on the available information.

Preliminary mercury soil surveys were also conducted in two other areas to determine the association of Hg in soils over structures with nearby low-temperature geothermal associations and without any nearby geothermal associations. These include, respectively, tranverses across a fault in the vicinity of Ogden Hot Spring east of Ogden, Utah (sec. 23 and 26, T6N, R1W), and a traverse across the Wasatch Fault south of Salt Lake City, Utah (sec. 11

and 12, T3S, R1E). Soil sampled at the warm spring site outside Ogden, Utah was highly anomalous in Hg suggesting, that with further study, Hg soil geochemistry might prove useful in the evaluation of low-temperature systems.

In addition to the geochemical technique development program, the ESL geochemical laboratory has provided analytical services in support of other geothermal programs. These include major and trace element analysis of rocks in support of geologic studies at the Nevada Industry-Coupled Case Study areas and at RHS as well as analysis of geothermal fluids in support of User Assistance programs. Laboratory equipment and procedures have been significantly improved to more effectively handle analysis of these materials.

As a consequence of this work, five major results may be identified:

- (1) The geochemical laboratory facility has developed into a highly functional and flexible lab capable of either custom research analysis or production-level rapid multielement analysis of a variety of samples. Effective software for management, statistical evaluation, and graphical presentation of data have been implemented on the ESL PRIME 400 computer system.
- (2) An empirical geochemical zoning model has been developed for the hot-water geothermal system at RHS, documenting chemical distribution patterns characteristically developed adjacent to hot-water entries and within the volume of rock peripheral to the main thermal reservoir. The chemical distributions can be related to the time-integrated distribution of the water-rock interaction associated with structural aquifers.

- (3) Establishment of this model confirms the applicability of solids geochemistry to geothermal exploration, to well completion decisions, and to evaluation of the configuration of partly explored geothermal systems. Geochemical techniques applicable during early and intermediate stages of the exploration and confirmation of a geothermal resource have been developed. These include geochemical logging of well cuttings and detection of surface and near-surface geochemical zoning by analysis of soils or temperature gradient hole drill cuttings.
- (4) An exceptional multielement geochemical data collection has been acquired for 10 wells in The Geysers vapor-dominated field. Development of a three-dimensional geochemical model for this system will contribute significantly to our understanding of chemical processes operative in hydrothermal systems and enable refinement of exploration techniques.
- (5) The geochemical support provided to other ESL activities has contributed to the quality and scope of geologic studies at ESL and has provided a valuable service to potential geothermal users through the User Assistance program.

DUB

Abstract

"Multielement Geochemistry of Solid Materials in Geothermal Systems and Its Application Part 1: The Hot-Water System at the Roosevelt Hot Springs KGRA Utah", by R. W. Bamford, O. D. Christensen and R. M. Capuano, February, 1980 (DOE/ET/27002-7).

Geochemical studies of the geothermal system at Roosevelt Hot Springs, Utah (RHS), have led to development of chemical criteria for recognition of major features of the system and to a three-dimensional model for chemical zoning in the system. Based on this improved level of understanding, several new or modified geochemical exploration and assessment techniques have been defined and are probably broadly applicable to evaluation of hot-water geothermal systems.

The main purpose of this work was the development or adaptation of solids geochemical exploration techniques for use in the geothermal environment. The approach used was multielement geochemical analysis of solid samples including soils, whole rock materials, and +3.3 specific gravity fractions derived by heavy liquid separation from the whole rock materials. Whole rock materials were predominantly suites of contiguous 10-foot cuttings samples from geothermal wells, but also included suites of cuttings samples from temperature gradient drill holes, diamond drill core, and surface rock samples. A broad spectrum of major, minor, and trace elements was determined for these samples and used to establish spatial associations of hydrothermal element enrichments and depletions relative to critical geothermal features.

Principal zones distinguished in the geothermal system are a reservoir

zone which encompasses all rock with high-temperature (>400°F) reservoir potential, a self-sealed zone developed at and beyond the reservoir zone margin and which is gradually encroaching on the reservoir, and a peripheral zone developed within and beyond outer parts of the self-sealed zone. Hydrothermal element enrichments which characterize these zones are As, Li, Be, and Zn (and probably Fe, Mg Cr, P, Co, Ni, Cu, Zr, La, and Ce) in the reservoir zone, especially at hot-water entries; Hg plus the reservoir zone assemblage (less Zn?) in inner parts of the self-sealed zone; Hg, Mn, and Zn plus the reservoir zone assemblage in outer parts of the self-sealed zone; and Mn and Zn (and possibly W and Mo) in the peripheral zone. Na, Sr, and possibly Ba are variably depleted from rock in the immediate vicinity of hot-water entries within the reservoir zone and inner self-sealed zone. Minor Hg enrichments are developed locally in the reservoir but are generally several orders of magnitude smaller than those which characterize the self-sealed zone.

The RHS zoning model appears to be broadly applicable to other hot-water geothermal systems based on partially documented similarities in hydrothermal element distributions for a few of these systems, general similarities in thermal water chemistry for many systems, and tentatively inferred causes of key element deposition. The model thus provides a basis for establishing solids geochemical techniques applicable to the exploration and assessment of hot-water geothermal systems in general. Three multielement techniques, detailed soil surveys (or surface rock sampling), large-scale "surface" surveys utilizing shallow drill hole cuttings samples (commonly temperature gradient hole cuttings), and geochemical logging of deep drill holes, are

indicated to be useful. These techniques, especially the geochemical logging, are shown to offer potentially high cost-effectiveness, and consequently, can be recommended for initial routine use.

The zoning model can possibly be utilized to provide insights into the nature and geometry of vapor-dominated systems evolved from hot-water systems, but otherwise is expected to have only limited applicability to these systems.

ATTACHMENT 1

COMPREHENSIVE LIST OF REPORTS
Contract DE-AC07-78ET28392
(Formerly Contract No. EG-78-C-07-1701)

<u>Report No.</u>	<u>Report Title</u>
DOE/ET/28392-1	Hydrothermal Alteration at the Roosevelt Hot Springs Thermal Area, Utah: Petrographic Characterization of the Alteration to 2 Kilometers Depth: Ballantyne, J. M. and Parry, W. T.; April, 1978 (ID0/78-1701.a.1.1).
DOE/ET/28392-2	Magnetotelluric Investigations at the Roosevelt Hot Springs KGRA and Mineral Mountains, Utah: Wannamaker, Philip; May, 1978 (ID0/78-1701.a.6.1).
DOE/ET/28392-3	Program Review: Resource Evaluation, Reservoir Confirmation, and Exploration Technology: Ward, S. H.; May, 1978 (ID0/78-1701.b.5.1).
DOE/ET/28392-4	Geology and Alteration of the Coso Geothermal Area, Inyo, Co., CA: Hulen, J. B.; 1978 (ID0/78-1701.b.4.1; ESL-3).
DOE/ET/28392-5	Geological and Geophysical Analysis of Coso Geothermal Exploration Hole No. 1 (CGEH-1), Coso Hot Springs KGRA, California: Galbraith, R. M., 1978, (ID0/7801701.b.4.2, ESL-5).
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DOE/ET/28392-7	Hydrothermal Alteration at the Roosevelt Hot Springs Thermal Area, Utah: Thermal Power Co. Well Utah State 72-16: Rohrs, D., Parry, W. T.; July, 1978 (ID0/78-1701.a.1.1.3).
DOE/ET/28392-8	Aspects of Forced Convective Heat Transfer in Geothermal Systems: Kilty, K., Chapman, D. S., Mase, C.; July, 1978 (ID0/78-1701.a.6.4.1).
DOE/ET/28392-9	Stratigraphy and Alteration, 15 Shallow Thermal Gradient Holes, Roosevelt Hot Springs KGRA and Vicinity, Millard and Beaver Counties, Utah: Hulen, J. B., 1978 (ID0/78-1701.b.1.1, ESL-9).

- DOE/ET/28392-10 Annotated Bibliography of the Geology of the Roosevelt Hot Springs Known Geothermal Resource Area and the Adjacent Mineral Mountains, March, 1978: McKinney, D. B.; 1978 (IDO/78-1701.b.1.1.4, ESL-10).
- DOE/ET/28392-11 Topographic Effects in Resistivity Surveys: Fox, R. C., Hohmann, G. W., and Rijo, L.; 1978 (IDO/78-1701.b.3.2.1, ESL-11).
- DOE/ET/28392-12 Hydrothermal Alteration at the Roosevelt Hot Springs Thermal Area, Utah: Characterization of Rock Types and Alteration in Getty Oil Co. Well Utah State 52-21: Ballantyne, G. H.; November, 1978 (IDO/78-1701.a.1.1.4).
- DOE/ET/28392-13 Three Dimensional Magnetotelluric Modeling: Ting, S. C., Hohmann, G. W.; October, 1978 (IDO/78-1701.a.6.2).
- DOE/ET/28392-14 Monroe, Utah, Hydrothermal System: Results from Drilling of Test Wells MC1 and MC2: Chapman, D. S., Harrison, R.; October, 1978 (IDO/78-1701.a.6.4.2, IDO/76-1601 vol. 77-16).
- DOE/ET/28392-15 Geothermal Exploration and Assessment Technology Program Plan, Final Report: Ward, S. H., and Wright, P. M.; October 30, 1978 (IDO/78-1701.b.5A).
- DOE/ET/28392-16 Hydrothermal Alteration at the Roosevelt Hot Springs Thermal Area, Utah: Modal Mineralogy, and Geochemistry of Sericite, Chlorite, and Feldspar From Altered Rocks, Thermal Power Co. Well Utah State 14-2: Ballantyne, J. M.; November, 1978 (IDO/78-1701.a.1.1.5).
- DOE/ET/28392-17 Hydrothermal Alteration at the Roosevelt Hot Springs Thermal Area, Utah: W. T. Parry, N. L. Bryant, R. E. Dedolph, Ballantyne, J. M., Ballantyne, G. H., Rohrs, D. T., and Mason, J. L.; November, 1978 (IDO/78-1701.1.1).
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- DOE/ET/28392-21 Self Potential Survey, Roosevelt Hot Springs, Utah: Sill, W. E., and Johng, D. S.; January, 1979 (IDO/78-1701.a.2.3).
- DOE/ET/28392-22 Interactive Dipole-Dipole Resistivity and IP Modeling of Arbitrary Two-Dimensional Structures (IP2D Users Guide and Documentation); Killpack, T. J., and Hohmann, G. W.; 1979 (IDO/78-1701.b.3.2.3, ESL-15).
- DOE/ET/28392-23 Induced Polarization Measurements at Roosevelt Hot Springs Thermal Area, Utah: Chu, J. J., Sill, W. R., and Ward, S. H.; June, 1979 (IDO/78-1701.a.2.4.1).
- DOE/ET/28392-24 Interpretation of a Seismic Refraction Profile Across the Roosevelt Hot Springs, Utah and Vicinity: Gertson, R. C., and Smith, R. B.; March, 1979 (IDO/78-1701.a.3).
- DOE/ET/28392-25 The Telluric-Magnetotelluric Method in Two- and Three-Dimensional Environments: Stodt, J. A., Hohmann, G. W., and Ting, S. C.; August, 1979.
- DOE/ET/28392-26 Cancelled as a report; information was given in 1979 SPE paper.
- DOE/ET/28392-27 Geology of the Cove Fort-Sulphurdale KGRA with Bibliographic Annotations and Petrographic Descriptions by B. Sibbett: Moore, J. N., and Samberg, S. M.; 1979 (ESL-18).
- DOE/ET/28392-28 Multielement Geochemical Exploration Data for the Cove Fort-Sulphurdale Known Geothermal Resource Area, Beaver and Millard Counties, Utah: Bamford, R. W., and Christensen, O. D.; 1979 (ESL-19).
- DOE/ET/28392-29 Bipole-Dipole Interpretation with Three-Dimensional Models (including a field study of Las Alturas, New Mexico): Hohmann, G. W., and Jiracek, G. R.; 1979 (ESL-20).
- DOE/ET/28392-30 Detailed Gravity and Aeromagnetic Surveys of the Cove Fort-Sulphurdale Known Geothermal Resource Area (KGRA) and Vicinity, Millard and Beaver Counties, Utah; Cook, K. L., Serpa, L. F., and Pe, Win; 1980.
- DOE/ET/28392-31 Structural Fabric and In-situ Stress Analyses of the Roosevelt Hot Springs KGRA: Yusas, M. R., and Bruhn, R. L.; November, 1979.
- DOE/ET/28392-32 An Evaluation of Hypocenter Location Techniques With Applications to Southern Utah: Regional Earthquake Distributions and Seismicity of Geothermal Areas: Wechsler, D. J., and Smith, R. B.; December, 1979.

- DOE/ET/28392-33 Geologic Map of San Emidio Geothermal Area: Moore, J. N.; December, 1979 (ESL-23).
- DOE/ET/28392-34 Geology of the Soda Lake Geothermal Area: Sibbett, B. S.; 1979 (ESL-24).
- DOE/ET/28392-35 Interpretation of Electrical Resistivity and Shallow Seismic Reflection Profiles, Whirlwind Valley and Horse Heaven Areas, Beowawe KGRA, Nevada: Smith, C.; 1980 (ESL-25).
- DOE/ET/28392-36 Geology and Alteration of the Baltazor Hot Springs and Painted Hills Thermal Areas, Humboldt County, Nevada: Hulen, J. B.; 1979 (ESL-27).
- DOE/ET/28392-37 Numerical Modeling and Interpretation of Dipole-Dipole Resistivity and IP Profiles, Cove Fort-Sulphurdale KGRA, Utah: Ross, H. P.; 1979 (ESL-26).
- DOE/ET/28392-38 Interpretation of Well Log Data from Four Drill Holes at Roosevelt Hot Springs KGRA: Glenn, W. E., and Hulen, J. B.; 1979 (ESL-28).
- DOE/ET/28392-39 Detailed Gravity and Aeromagnetic Surveys in the Black Rock Desert Area, Utah: Serpa, L. F., and Cook, K. L.; 1980.
- DOE/ET/28392-40 Geology of the Central Mineral Mountains, Beaver County, Utah: Sibbett, B. S., and Nielson, D. L.; March, 1980 (ESL-33).
- DOE/ET/28392-41 Summary of Potassium/Argon Age Dating: Evans, S. H., Jr.; March, 1980.
- DOE/ET/28392-42 Geothermal Exploration at Hill Air Force Base, Ogden, Utah: Glenn, W. E., Chapman, D. S., Foley, D., Capuano, R. M., Sibbett, B. S., Cole, D. and Ward, S. H.; March, 1980 (ESL-34).
- DOE/ET/28392-43 Geochemistry of Sericite and Chlorite in Well 14-2, Roosevelt Hot Springs Geothermal System, and in Mineralized Hydrothermal Systems: Ballantyne, J. M.; June, 1980.
- DOE/ET/28392-44 Model Study of the Regional Hydrogeologic Regime, Roosevelt Hot Springs, Utah: Smith, J. L.; May, 1980.
- DOE/ET/28392-45 Compositional Gradient In Natural Silicic Liquids: Evans, S. H., Jr.; 1980.
- DOE/ET/28392-46 A Light Stable Isotope Study of the Roosevelt Hot Springs Thermal Area, Southwestern Utah: Rohrs, D. T.; May, 1980.
- DOE/ET/28392-47 Final Report for Contract DE-AC07-79ET27002 by J. R. Bowman et al; September, 1980.

ATTACHMENT 2

COMPREHENSIVE LIST OF REPORTS
Contract EY-76-S-07-1601
FINAL REPORTS

- 77-0 Final Report, Volume 77-0 by S. H. Ward, October, 1977.
- 77-1 An Evaluation of AIRTRACE in the Geothermal Environment, by Laurence P. James and Robert W. Bamford, September, 1977.
- 77-2 Part I - Geology and Geochemistry of the Roosevelt Hot Springs - A Summary Part II - Geophysics of the Roosevelt Hot Springs Thermal Area, Utah Part III - Roosevelt Hot Springs Area Field Trip, by W. T. Parry, S. H. Ward, W. P. Nash, and others, December, 1977.
- 77-3 Long-Term Seismic Monitoring of the Roosevelt-Cove Fort KGRA's, by Robert B. Smith, December, 1977.
- 77-4 Refraction Shooting Near Roosevelt Hot Springs: Data, by Micro Geophysics, December, 1977.
- 77-5 Final Report, Volume 77-5, by S. H. Ward, J. A. Whelan, and others, December, 1977.
- 77-5.6 Dipole-Dipole Resistivity of a Portion of the Coso Hot Springs KGRA, Inyo County, California, by Richard C. Fox, May, 1978.
- 77-5.7 Low-Altitude Aeromagnetic Survey of a Portion of the Coso Hot Springs KGRA, Inyo County, California, by Richard C. Fox, May, 1978.
- 77-6 Analysis of Sodium and Potassium in Silicate Rocks by a Lithium Metaborate Fusion Method, by W. P. Nash and Harrison Crecraft, December, 1977.
- 77-7 Gravity and Ground Magnetic Surveys in the Monroe and Joseph KGRA's and Surrounding Region, South Central Utah, by M. E. Halliday and K. L. Cook, June, 1978.
- 77-8 Electrical Energizing of Well Casings, by W. R. Sill and S. H. Ward, January, 1978.
- 77-9 Precision Leveling and Gravity Studies at Roosevelt Hot Springs KGRA, Utah by Kenneth L. Cook and James A. Carter, March, 1978.

- 77-10 Quaternary Rhyolite from the Mineral Mountains, Utah, U.S.A.,
by S. H. Evans, Jr. and W. P. Nash, March, 1978.
- 77-11 Regional Gravity and Aeromagnetic Surveys of the Mineral
Mountains and Vicinity, Millard and Beaver Counties, Utah, by
James A. Carter and Kenneth L. Cook, April, 1978.
- 77-12 Seismic Refraction Survey, Roosevelt Hot Springs Thermal
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- 77-13 Fluid Dynamic Properties of Rhyolitic Magmas, Mineral
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Characteristics Part II: Physical Properties, by W. P. Nash
and S. H. Evans, Jr., July, 1978.
- 77-14 Geochemistry of Solid Materials From Two U.S. Geothermal
Systems and Its Application to Exploration, by Robert W.
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- 77-15 Three Dimensional Magnetotelluric Modeling, by G. W. Hohmann
and Sam C. Ting, July, 1978.

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TOPICAL REPORTS

- 76-1 Dipole-Dipole Resistivity Delineation of the Near Surface at
the Roosevelt Hot Springs KGRA, by S. H. Ward and W. R. Sill,
November, 1976.
- 76-2 A Thermodynamic Model of the Hydrolysis of Microcline in Acid
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December, 1976.
- 76-3 Magnetotelluric Survey and Resistivity Maps, Roosevelt Hot
Springs, Utah, by Geotronics Corporation, October, 1976.
- 77-1 Attempt at Paleomagnetic Dating of Opal, Roosevelt Hot
Springs, KGRA, by F. H. Brown, February, 1977.
- 77-2 Geothermal Exploration Architecture, by S. H. Ward,
April, 1977.
- 77-3 Thermal Gradients and Heat Flow at Roosevelt Hot Springs, by
W. R. Sill and J. Bodell, July, 1977.
- 77-4 Gravity Survey of the Cove Fort-Sulphurdale KGRA and the
North Mineral Mountains Area, Millard and Beaver Counties,
Utah, William D. Brumbaugh and Kenneth L. Cook, August, 1977.

- 77-5 Hydrothermal Alteration at Roosevelt Hot Springs KGRA - DDH 1976-1, by Nancy Lee Bryant and W. T. Parry, August, 1977.
- 77-6 Gravity and Ground Magnetic Surveys of the Thermo Hot Springs KGRA Region Beaver County, Utah, by Robert F. Sawyer and K. L. Cook, September, 1977.
- 77-7 Geologic Map of the Central and Northern Mineral Mountains, Utah, compiled by S. H. Evans, Jr., from the work of D. Bowers, F. H. Brown, S. Davies, R. Dedolph, S. H. Evans, Jr., H. C. Liese, W. P. Nash, W. T. Parry and J. A. Whelan, July, 1977.
- 77-8 Geophysical Study of the Monroe-Red Hill Geothermal System, (formerly 77-17) by Charles Mase, David S. Chapman and S. H. Ward, October, 1978.
- 77-9 Mineral Mountains Magmatism: Chemical and Thermal Evolution, by W. P. Nash and S. H. Evans, Jr., February, 1979.
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