GL01121

EARTH SCIENCE LABORATORY

REPORT INFORMATION AND CONTROL SHEET

TO BE COMPLETED BY PROJECT MANAGER

Library Use Only
CONTRACT REPORT NO. ________
UURI/ESL NO. ________
OPEN FILE NO. ________

REPORT TITLE: Quarterly Progress Report 1 Mar-31 May, 1984

AUTHOR(S): Staff

PUBLIC INFO X PROPRIETARY ____

PROJECT MANAGER: Wright

CONTRACT NUMBER: DE-AC03-84SF12196

REPORT SATISFIES: X Required Deliverable ____ Extra Deliverable

COMMENTS: ________

FINAL TECHNICAL REVIEW: Phillip M. Wright — Project Manager Signature — 25 June 84 — Date

____ Section Manager Initial ____ Date

DNW — Technical Vice President Initial ____ Date

DISCLAIMER INCLUDED: Yes ____ Not Applicable ____

PLANNED DISTRIBUTION: (* see below) 1 Wash DC; 1 SAN; 1 LBL, 1 Stanford; 2 ID; Internal: SHW; DNW; DLN; JNM; DEW + FLGS; WF, SD

PRINTING: Number of Copies 15 Deadline for Delivery ASAP

Binding Instructions Tan report cover, stapled ok

Binding Completed ____ Initial ____ Date

FINAL DISTRIBUTION:
Attach Letter of Transmittal ____ Initial ____ Date

* See with Forsberg for addresses for distribution -

QUARTERLY PROGRESS REPORT
March 1, 1984 to May 31, 1984

RESEARCH AND TECHNOLOGY DEVELOPMENT

for

DOE'S GEOTHERMAL RESERVOIR DEFINITION PROGRAM

This is a report of work sponsored by the Department of Energy
under Contract No. DE-AC03-84SF12196

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way
Salt Lake City, Utah 84108
801-524-3422

June 15, 1984

TABLE OF CONTENTS

SUMMARY

Three projects are currently active in developing methods for fracture detection, i.e. detection of permeable zones. At the Salton Sea geothermal system in California, we are quantifying the trace element chemistry of chip samples and performing analyses on gases from fluid inclusions for organic compounds for two wells belonging to Union Oil Company. We find zoning in both trace elements and organic gases. We hope that these studies will lead to zoning pictures useful in identifying permeable horizons. At the Baca geothermal system in the Valles Caldera of New Mexico, recent studies in the zoning of hydrothermal alteration have shown that the permeability relationships observed during drilling at Baca by Union Oil Company can be explained by a combination of stratigraphy, structure (faulting) and hydrothermal alteration. Comparison of spinner data with our results shows that fluid production commonly occurs in a deep interval of largely non-welded tuffs. In wells where this same interval neither produces or accepts fluid, the unit is shown to be sealed by alteration minerals.

We are examining various geophysical methods for fracture detection. Our approach is to model numerically the geologic framework for a number of different electrical geophysical techniques in order to predict fracture detectability. We have recently written a computer code to model the resistivity signature of fractures located between two boreholes. This code has been used to demonstrate that some field distributions of electrodes would not permit detection of the fracture whereas others would. We are continuing development of several other computer codes to model this difficult problem for other electrical geophysical technques.

We have been continuing our studies of the Meager Creek geothermal system in British Columbia. B. C. Hydro has given us custody of core and chips from

this system, which we believe to perhaps be illustrative of what may be found at the roots of some of the Cascades province volcanic systems. We are working to quantify the mineralogy of hydrothermal alteration in order to study the evolution of the system through time. Our work to date has yielded the important result that fluid flow presently appears to be strongly influenced by diabase dikes that cut the intrusion. If the same is true in other Cascades systems, deep permeability might be very difficult to find.

OVERVIEW OF CURRENT RESEARCH

Our current program supports research in DOE's Reservoir Definition Program. A number of general problem areas are being addressed under this line item. Three projects are directed toward finding better methods for fracture detection and mapping. We are continuing development work on fracture mapping techniques using mineralogy and geochemistry at The Geysers and the Imperial Valley (Project 1) and at Baca (Project 2). The basic idea behind both of these projects is to develop better means to map stratigraphy from borehole samples, and then to correlate the stratigraphy from borehole to borehole. Offsets in stratigraphy among boreholes can then be interpreted in terms of the occurrence, location, and orientation of faults, folds and other permeability-controlling structures. These methods, unexploited so far in geothermal reservoir definition and development, show great promise to be powerful tools for industry. A third project (Project 5) is a comprehensive evaluation of the use of electrical geophysical techniques in a borehole, between two boreholes and between borehole and surface for fracture detection, using numerical modeling to determine fracture detectability There has been no such evaluation in geothermal environments, and a great deal of money could be spent on dead-end research without one because there are so many quite separate electrical techniques.

A second major topic area is that of reservoir definition in andesitic volcanic environments. Such environments are quite important worldwide, but remain undeveloped in the U. S. We are continuing work at Meager Creek, B. C., which is a major hydrothermal system in the Cascades andesitic environment. Although this area is outside the U. S., it has several advantages: it has important subsurface information in the form of 3 deep

(10,000 foot) wells, one of which produces hydrothermal fluids at 230°C; it is controlled by B. C. Hydro, who will allow all data, including data collected by private contractors to them, to be used and published (unlike U. S. companies); and, B. C. Hydro has given UURI custodial privileges over the core and cuttings from the 3 deep wells and other shallower holes. We are continuing development of geochemical techniques to characterize this area (Project 3).

UURI has continued to be a leader in the world in development of interpretation techniques and computer modeling for electrical geophysical methods. We have a comprehensive library of computer techniques and codes, and have made most of our programs available for industry. We are upgrading magnetotelluric (MT) and controlled source audiomagnetotelluric (CSAMT) interpretive techniques by developing means to apply topographic corrections to these surveys (Project 4). Topography causes significant changes to MT and CSAMT data that must be removed before interpretation in terms of subsurface geology can be performed, but no good means exists today to make these corrections.

PROJECT 1. Fracture Mapping Using Mobile and Immobile Trace Elements and Clays--Imperial Valley and The Geysers, CA.

Background

Since 1977, the Earth Science Laboratory has been involved in the application of trace- and major-element geochemistry to fracture mapping of geothermal reservoirs in Basin and Range Province and in volcanic environments. As a result of these studies, there is now abundant evidence to indicate that many elements are redistributed along the fluid channelways in the reservoir rocks as the fluids move through them, and that these geochemical signatures can be used to locate and predict the locations of permeable zones.

Our current studies reflect the need to develop better models of the geometry and fluid-flow paths of the geothermal systems of the Imperial Valley type. Toward this goal, Union Geothermal has provided ESL with samples from two recently drilled wells in their Salton Sea geothermal field. During FY 83 work was initiated on these samples using funds provided by DOE/ID under Contract No. DE-AC07-80ID12079. The work described below is a continuation of this investigation and represents a cooperative effort with Union. This investigation has been designed to answer the following questions:

> Does chemical zoning in trace and major elements exist within geothermal systems of the Imperial Valley type, and if so, can these data be used to a) locate zones of high permeability, b) predict thermal conditions within the reservoirs, c) characterize the distribution of fluid types, and d) locate and characterize reservoir field boundaries?

Current Progress

Work on our investigations of cuttings from the Salton Sea geothermal

system continued with significant progress. The cuttings are from two wells drilled by Union Oil Co.; one is productive and located in the center of the field, the other is cold and located on the margin of the field.

Detailed lithologic logs of the cuttings from both wells have been prepared. The logging indicates that the wells penetrated thick segments of mudstone and arkosic sands above 1200 feet and thinly interbedded arkose, siltstone, and shale at greater depths. Hydrothermal silicates and sulphides are present in both wells, indicating that the geothermal system was more extensive in the past.

Chemical analyses of twenty samples from the productive well also indicate that the rocks in the upper and lower portions of the well differ in their composition. When the chemistry of the samples is compared on a constant volume basis, the data show that sandstones from the upper parts of the wells are lower in both aluminum and titanium than sands from deeper depths. Silica, sodium, potassium, calcium, strontium, cobalt, nickel, copper, lead, zinc, cadmium, silver and arsenic have been redistributed by the geothermal system. Work is under way to relate these chemical changes to the mineralogy of the samples.

In order to examine other potential zoning patterns, the organic gas compositions of fluid inclusions contained in the altered rocks from the production well have been determined. The data suggest that the hydrocarbons methane, ethane and propane are zoned with depth. Methane and propane are enriched in zones of hydrothermal alteration in the upper portions of the well, whereas ethane and propane appear to be enriched in the lower portions of the well.

The significance of these changes and their relationship to the broad minerlaogic and geochemical changes which have affected the reservoir rocks are being currently investigated.

PROJECT 2. Fracture Mapping Using Mineralogic Analyses and Stratigraphic Correlation--Baca, NM.

Background

The Baca Geothermal Demonstration Project was cancelled in 1982 due to the inability of Union Oil Company to deliver the required amount of geothermal steam to power a 50 MWe plant. In fact, sufficient steam resources had been proven to provide only 15 MWe. Low reservoir permeability (6000 md-ft) was cited as one of the principal problems. Compilation of subsurface data from UOC well logs by Hulen and Nielson of UURI has suggested that stratigraphic units within the Bandelier Tuff, as well as fractures, provide important reservoir controls and should have been considered in the siting of geothermal wells. Subsequent to this work, UURI received proprietary cuttings from the Baca Project area under a cooperative research arrangement with Union, and initiated study of these cuttings using funds provided by Contract No. DE-AC07-80ID12079.

During our studies of the past year, we have developed a working relationship with the Geothermal Division of Union Oil Co. which has allowed us increasingly greater access to data pertaining to the subsurface geology of the Baca geothermal reservoir. Our accomplishments to date include definition of the host rock stratigraphy of the reservoir, definition of its structural setting, a model of the structural evolution of the reservoir which explains the low permeabilities encountered by Union, an evaluation of the preliminary work on the geochemistry of the reservoir rocks and their alteration mineralogy. Union has indicated that they are willing to provide additional cuttings samples for our study, and they have even invited us to map surface geology with them at the Baca site. These are data and access which have previously been unavailable to other scientists outside of Union.

Current Progress

Our current work largely involves the study of subsurface cuttings samples from the Baca geothermal area, New Mexico. The purpose of the study is to compare hydrothermal alteration zonation with our structural and stratigraphic models to locate major fractures and faults and evaluate fracture controls, fluid volume, and temperatures of the system. As a result of last FY's effort, a paper entitled "Internal Geology and Evolution of the Redondo Dome, Valles Caldera, New Mexico," by D. L. Nielson and J. B. Hulen, was written and is in press in the Journal of Geophysical Research. As a result of work this FY, a paper entitled "Results of Deep Drilling in the Valles Caldera, New Mexico," by D. L. Nielson and J. B. Hulen, was presented at the International Symposium on Observation of the Crust Through Drilling at Tarrytown, New York on May 23 and 24, 1984. The presentation of this paper satisfies one of the deliverables for contract No. DE-AC03-84SF12196, namely, the presentation of results at a professional meeting. The scientific results of our studies to date this year are summarized in the following paragraphs.

Deep drilling and reservoir engineering studies in the Baca geothermal field, Valles caldera, New Mexico, have enabled us to examine closely the relationships of structure, stratigraphy and hydrothermal alteration to reservoir temperature, pressure, permeability and thermal fluid flow. The Baca system is hot-water dominated with measured temperatures up to 341°C. Host rocks for the Baca system are principally densely welded felsic ash-flow tuffs and intermediate-composition flows which have no primary permeability. Fluid flow has been confined to major throughgoing, steeply-dipping normal faults and subsidiary fractures as well as to vertically restricted stratigraphic aquifers. The hottest and most productive portion of the Baca field coincides with the thickest section of a deep stratigraphic aquifer

where it is disrupted by numerous major northeast- and east-west-trending normal fault zones. Throughout the field, however, structural and stratigraphic permeability have been extensively modified by hydrothermal alteration.

Alteration in the Baca field is of three distinctive types: argillic, propylitic and phyllic. Strong argillic alteration forms a blanket mostly above the water table and is developed in formerly permeable non-welded tuffs. It is characterized by the assemblage smectite, mixed-layer illite-smectite, kaolinite, quartz and pyrite. Pervasive propylitic alteration, weakly developed in felsic host rocks but intense in deep intermediate composition volcanics, comprises chlorite, calcite, epidote/allanite, illite, pyrite and hematite. Illite, pyrite and quartz are the principal constituents of phyllic zones, which are commonly, but not invariably, associated with major thermal fluid entries. Other identical phyllic zones, obviously once permeable, now are hydrothermally sealed. The presence in the Baca field of normally high-temperature mineral phases at shallow depths and correspondingly low temperatures indicates that cool rocks at high levels have been hotter in the past. These relationships indicate either that isotherms have collapsed due to cooling of the system, or that they have retreated without overall heat loss due to structural uplift.

Permeability relationships revealed in Baca boreholes during drilling or subsequent reservoir tests are readily explained by stratigraphy, structure and hydrothermal alteration in various combinations. For example, spinner surveys run during injection tests show that massive fluid loss commonly occurs in a deep interval of largely non-welded tuffs (the Lower Tuffs of Nielson and Hulen, 1984). In wells where this interval neither produces fluid naturally nor accepts it during injection, it is shown to be hydrothermally sealed.

The active Baca geothermal system shows many similarities to volcanic-hosted epithermal precious metal vein deposits. These ore systems are similar to Baca in tectonic setting, host rocks, hydrothermal alteration mineralogy and zoning, temperature range, fluid origin, and possibly trace element zoning. Fluid salinities at Baca are, however, low for such deposits. Although epithermal veins have not been penetrated in the Baca wells, chemical analyses of selected pyrite phyllic zones show silver concentrations approaching ore grade.

PROJECT 3. Reservoir Definition in Andesitic Volcanic Terrains.

Background

The majority of the world's high-temperature geothermal resource is closely associated with active volcanism. There is little doubt that potent heat sources, capable of driving large geothermal convection cells, must exist widely in the volcanic belts of the Cascades, central Alaska and the Aleutian Islands in the western U. S. as well as elsewhere in the world. These heat sources and associated geothermal systems are here interpreted to be a generic classification including all systems associated with andesitic volcanism overlying convergent plate margins. In this category, a relatively small amount of data are already in the public domain from Japan, Momotombo (Nicaragua), Newberry Caldera (Oregon), Lassen (California), Meager Creek (British Columbia), Los Azufres (Mexico), Adak Island in the Aleutians, and other areas which have been or are the sites of active exploration. The key aspects of exploration in this environment are knowledge of the location of heat sources (high-level plutons) and the locations and nature of fracture systems which would allow meteoric fluids to communicate with the hot rock and ascend to within reasonable drilling depths.

The western andesitic volcanic province of the U. S. remains one of the areas of very high geothermal potential which has seen relatively little systematic exploration by the U. S. geothermal industry. One of the reasons for this has undoubtedly been the reluctance of Federal agencies (mainly the U. S. Forest Service) to lease lands for exploration. Another reason has been that there are relatively few surface manifestations of geothermal activity which attract explorationists. The lack of thermal features at the surface has often been attributed to high rainfall, which may effectively eliminate surface thermal phenomena and require deep temperature-gradient measurements

to see through the near-surface, cold-water aquifers. Therefore, with the exception of several specific locations such as Lassen, Meager Creek, and Newberry, exploration is concerned with the discovery of "blind" systems. It is thus very risky and, to the present time, many companies have chosen not to take these risks. What is necessary for successful exploration in such an environment is a system model based on heat source and permeability relationships. From this, effective exploration strategies can be developed both for exploration for and within (reservoir definition) geothermal systems in andesitic volcanic environments, as has been done by our group at UURI for the Basin and Range Province.

During FY 82, work was initiated on a cooperative geochemistry investigation of the Meager Creek geothermal system with the B. C. Hydro and Power Authority under funding provided by Contract No. DE-AC07-80ID12079. The Meager Creek system is currently one of the best documented of the geothermal systems associated with active magmatism in North America. The objectives of this work were to 1) characterize the chemistries of thermal fluids in an active magmatic invironment through the analysis of field data and through mathamatical modeling of fluid-mineral equilibria, 2) evaluate the effects of the various factors that can affect the fluid chemistries, 3) determine the effects of fluids of different chemistries on rocks typical of volcanic terrains, and 4) utilize this information to help locate "blind" geothermal systems associated with recent high level magma chambers.

Because the composition of many minerals formed in geothermal environments is senstive to both the chemistry of the circulating fluids and their temperature, our initial efforts have been directed toward determining the alteration minerals present in core and cuttings from wells within the field. From this information and partial chemical analyses of hot spring and

reservoir fluids, the chemistry of the geothermal fluids at various places in the reservoir can be deduced. This allows us to determine the structure of the reservoir and to make predictions about the location of the highest-temperature, highest-permeablility portions of the reservoir.

Current Progress

Progress was made in several areas on our study of the Meager Creek geothermal system. Our mineralogic work has included an analysis of the clay mineralogy and thin-section studies of approximately two hundred samples from wells M-7, 10, 12 and MC-1. MC-1 is a deep (3000 m) production well which produces fluids near 200°C and has a bottom-hole temperature of about 250°C. M-7 is a 360 m thermal gradient well with a bottom-hole temperature of 200°C; M-70 is 100 m deep and had a bottom-hole temperature of 160°C; and M-12 is a cold (60°C) 600 m well on the margin of the field. The four wells provide an illustrative three-dimensional cross-section of the thermal system.

Through our petrographic studies, we have recognized and documented several distinct mineral assemblages related to three different hydrothermal events. The oldest consists of plagioclase + hornblende + epidote and was formed during regional metamorphism of Coast Range sedimentary and igneous rocks in Mesozoic time. Subsequent alteration related to intrusion of quartz-diorite produced the illite + chlorite + epidote and was associated with the deposition of veins containing quartz, sulfides and potassium feldspar. This alteration occurred prior to the present geothermal activity.

Hydrothermal alteration related to the active geothermal system has affected the Pliocene to Recent dikes which intrude the Coast Range complex. Geothermally altered rocks contain clays, illite, chlorite and epidote and potassium feldspar and are associated with carbonate-cemented veins and breccias. The distribution of carbonate minerals suggest that the formation

of the veins and breccias may have been related to a tectonic event which induced widespread fracturing and boiling of the thermal fluids.

The X-ray diffraction studies indicate that the sheet silicates include illite, chlorite, illite/smectite and smectite. The smectite and mixed layer illite/smectite are strongly zoned with depth in the four wells. The data indicate that these clay minerals are present only in rocks whose temperatures are less than 165°C.

New chemical analyses of well-bore and spring precipitates indicate that many of the trace elements being remobilized by the geothermal system are also strongly zoned. Fluids from the deepest portions of the field precipitate Ag, Cu, Ni and high levels of Zn. Fluids from intermediate levels are depositing high levels of Sr, As, and Bi, whereas the precipitates deposited by fluids from shallow levels are enriched only in Bi.

The results of these mineralogic and geochemical studies will be used to select samples for electron microprobe and isotopic analyses. These data will be coupled with appropriate thermochemical models to determine the distribution and composition of the various fluids present in the thermal system.

PROJECT 4. Improvements in 2D and 3D Interpretation for MT - Line Source and IP-Resistivity Surveys.

<u>Background</u>

We have developed 2D finite element algorithms for both resistivity and MT-line source solutions under a previous NSF grant. These programs approximate the unknown voltage or field using linear basis functions over triangular subdomains. In particular, this allows precise simulation of sloping interfaces. Moreover, Galerkin's method of defining basis weighting functions minimizes the norm of the approximating error over the domain of the operator (the earth section). For the EM problem, the program initially computes the unknown field parallel to strike, from which auxiliary fields are calculated by a difference approximation to Maxwell's equations.

The ability to model sloping interfaces with these algorithms is an advantage over finite difference programs. Wannamaker has used this 2D code for the MT source to allow for the effects of high-contrast lateral heterogeneity at the surface and obtain a model of deep resistivity structure in S. W. Utah. These 2D programs have been very popular with industry and research organizations since their release. They have been useful interpretation aids requiring only modest computer resources.

Recently, UURI documented dipole-dipole resistivity responses over topography using our 2D finite-element program. These responses easily can differ by a factor of two from the flat earth signature. On the other hand, the effects of topography on plane wave and line source responses are not well known, but we expect them to be serious. Very few results using the surface integral equation approach are available. Moreover, the remaining citations have implemented finite difference solutions which approximate topography using jagged steps. We believe this is a poor approximation to nature,

especially when the electric field is normal to topographic trends, and wish to remedy this deficiency using our finite element code.

While these 2D programs have proved valuable, limitations to purely 2D analysis are being recognized increasingly. Rather arbitrary 3D structures can be treated for MT by the volume integral equation method of UURI but substantial computing facilities must be available. However, an important component to three-dimensionality in MT responses is a nearly frequency-independent telluric distortion due to current-gathering. These distortions have been simulated in the past using elliptical inclusions of finite difference approximations to thin-layer inhomogeneity. Once again, finite difference approximations are less satisfactory, compared to simulations using finite elements, due to the step-like nature of the model resistivity structure. We are undertaking a straightforward development of a 3D thin-layer MT algorithm from our 2D program which would allow boundaries in plan view to have arbitrary orientation. In the course of this work, an analagous 3D program for IP-resistivity also is being created.

Current Progress

Toward improvement of our finite element program for modeling magnetotelluric responses of 2D structures of arbitrary cross-section, we have successfully implemented the ability to simulate topography. Verification of the solution for the TM mode stems from comparison with an analytic solution for a resistive hemi-cylinder in a uniform half-space. To avoid discontinuities in electric field, we must ensure that nodal values in the difference approximations to Maxwell's equations are selected entirely within the earth for all possible topographic configurations. Verification for the TE mode awaits computations from the Rayleigh scattering approach of G. R. Jiracek of San Diego State University. The finite-element program is

advantageous in that topography and subsurface structure can be modeled simultaneously.

PROJECT 5. Fracture Detection using Downhole Electrical Geophysical Techniques.

Background

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

Methods which we are studying include mise-a-la-masse, induced polarization, magnetometric resistivity, and time-domain electromagnetic.

Current Progress

A brief review of all pertinent eastern-and western-bloc literature concerning electrical borehole geophysics has been completed and an annotated bibligraphy has been prepared.

A surface-integral algorithm has been designed to compute the resistivity anomalies observed down a borehole with the positions of the electrodes on surface varied. The model used is two-dimensional. In one configuration, one current electrode is placed on surface at infinity while the second current electrode is sequentially placed on either side and on top of the borehole. The two potential electrodes are run down the borehole as in a "long normal" resistivity array. The position of a fault zone, near a borehole, and its dip

can be determined. The method can be implemented as a slight modification of a long normal array conventionally used in well logging. A variant on this method involving potential electrodes on surface and a current electrode down the borehole does not look promising. A report on this research is in preparation.

An existing three-dimensional integral equation algorithm has been modified to handle elongate bodies which simulate fault zones. The mise-a-la-masse and magnetometric resistivity methods will be analyzed in borehole applications via this algorithm. While this algorithm is extremely long, complex, and interactive, we have managed to modify it to use elongate parallelopiped cells rather than the equidimensional cells used earlier. The modified algorithm has been tested and found to be satisfactory. We will now commence the modeling studies.

A two-dimensional finite element algorithm is under development for borehole resistivity detection of very thin fault zones cutting through a layered earth with topography superimposed. It will take another month or more to complete this algorithm.

We have just started an analysis of time-domain electromagnetic methods in borehole geophysical detection of fault zones. Existing algorithms are being used.

QUARTERLY PROGRESS REPORT
March 1, 1984 to May 31, 1984

RESEARCH AND TECHNOLOGY DEVELOPMENT
for
DOE'S GEOTHERMAL RESERVOIR DEFINITION PROGRAM

This is a report of work sponsored
by the Department of Energy under
Contract No. DE-AC03-84SF12196

Earth Science Laboratory

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

QUARTERLY PROGRESS REPORT
March 1, 1984 to May 31, 1984

RESEARCH AND TECHNOLOGY DEVELOPMENT

for

DOE'S GEOTHERMAL RESERVOIR DEFINITION PROGRAM

This is a report of work sponsored by the Department of Energy
under Contract No. DE-AC03-84SF12196

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way
Salt Lake City, Utah 84108
801-524-3422

June 15, 1984

TABLE OF CONTENTS

SUMMARY

Three projects are currently active in developing methods for fracture detection, i.e. detection of permeable zones. At the Salton Sea geothermal system in California, we are quantifying the trace element chemistry of chip samples and performing analyses on gases from fluid inclusions for organic compounds for two wells belonging to Union Oil Company. We find zoning in both trace elements and organic gases. We hope that these studies will lead to zoning pictures useful in identifying permeable horizons. At the Baca geothermal system in the Valles Caldera of New Mexico, recent studies in the zoning of hydrothermal alteration have shown that the permeability relationships observed during drilling at Baca by Union Oil Company can be explained by a combination of stratigraphy, structure (faulting) and hydrothermal alteration. Comparison of spinner data with our results shows that fluid production commonly occurs in a deep interval of largely non-welded tuffs. In wells where this same interval neither produces or accepts fluid, the unit is shown to be sealed by alteration minerals.

We are examining various geophysical methods for fracture detection. Our approach is to model numerically the geologic framework for a number of different electrical geophysical techniques in order to predict fracture detectability. We have recently written a computer code to model the resistivity signature of fractures located between two boreholes. This code has been used to demonstrate that some field distributions of electrodes would not permit detection of the fracture whereas others would. We are continuing development of several other computer codes to model this difficult problem for other electrical geophysical technques.

We have been continuing our studies of the Meager Creek geothermal system in British Columbia. B. C. Hydro has given us custody of core and chips from

this system, which we believe to perhaps be illustrative of what may be found at the roots of some of the Cascades province volcanic systems. We are working to quantify the mineralogy of hydrothermal alteration in order to study the evolution of the system through time. Our work to date has yielded the important result that fluid flow presently appears to be strongly influenced by diabase dikes that cut the intrusion. If the same is true in other Cascades systems, deep permeability might be very difficult to find.

OVERVIEW OF CURRENT RESEARCH

Our current program supports research in DOE's Reservoir Definition Program. A number of general problem areas are being addressed under this line item. Three projects are directed toward finding better methods for fracture detection and mapping. We are continuing development work on fracture mapping techniques using mineralogy and geochemistry at The Geysers and the Imperial Valley (Project 1) and at Baca (Project 2). The basic idea behind both of these projects is to develop better means to map stratigraphy from borehole samples, and then to correlate the stratigraphy from borehole to borehole. Offsets in stratigraphy among boreholes can then be interpreted in terms of the occurrence, location, and orientation of faults, folds and other permeability-controlling structures. These methods, unexploited so far in geothermal reservoir definition and development, show great promise to be powerful tools for industry. A third project (Project 5) is a comprehensive evaluation of the use of electrical geophysical techniques in a borehole, between two boreholes and between borehole and surface for fracture detection, using numerical modeling to determine fracture detectability There has been no such evaluation in geothermal environments, and a great deal of money could be spent on dead-end research without one because there are so many quite separate electrical techniques.

A second major topic area is that of reservoir definition in andesitic volcanic environments. Such environments are quite important worldwide, but remain undeveloped in the U. S. We are continuing work at Meager Creek, B. C., which is a major hydrothermal system in the Cascades andesitic environment. Although this area is outside the U. S., it has several advantages: it has important subsurface information in the form of 3 deep

(10,000 foot) wells, one of which produces hydrothermal fluids at 230°C; it is controlled by B. C. Hydro, who will allow all data, including data collected by private contractors to them, to be used and published (unlike U. S. companies); and, B. C. Hydro has given UURI custodial privileges over the core and cuttings from the 3 deep wells and other shallower holes. We are continuing development of geochemical techniques to characterize this area (Project 3).

UURI has continued to be a leader in the world in development of interpretation techniques and computer modeling for electrical geophysical methods. We have a comprehensive library of computer techniques and codes, and have made most of our programs available for industry. We are upgrading magnetotelluric (MT) and controlled source audiomagnetotelluric (CSAMT) interpretive techniques by developing means to apply topographic corrections to these surveys (Project 4). Topography causes significant changes to MT and CSAMT data that must be removed before interpretation in terms of subsurface geology can be performed, but no good means exists today to make these corrections.

PROJECT 1. Fracture Mapping Using Mobile and Immobile Trace Elements and Clays--Imperial Valley and The Geysers, CA.

Background

Since 1977, the Earth Science Laboratory has been involved in the application of trace- and major-element geochemistry to fracture mapping of geothermal reservoirs in Basin and Range Province and in volcanic environments. As a result of these studies, there is now abundant evidence to indicate that many elements are redistributed along the fluid channelways in the reservoir rocks as the fluids move through them, and that these geochemical signatures can be used to locate and predict the locations of permeable zones.

Our current studies reflect the need to develop better models of the geometry and fluid-flow paths of the geothermal systems of the Imperial Valley type. Toward this goal, Union Geothermal has provided ESL with samples from two recently drilled wells in their Salton Sea geothermal field. During FY 83 work was initiated on these samples using funds provided by DOE/ID under Contract No. DE-AC07-80ID12079. The work described below is a continuation of this investigation and represents a cooperative effort with Union. This investigation has been designed to answer the following questions:

> Does chemical zoning in trace and major elements exist within geothermal systems of the Imperial Valley type, and if so, can these data be used to a) locate zones of high permeability, b) predict thermal conditions within the reservoirs, c) characterize the distribution of fluid types, and d) locate and characterize reservoir field boundaries?

Current Progress

Work on our investigations of cuttings from the Salton Sea geothermal

system continued with significant progress. The cuttings are from two wells drilled by Union Oil Co.; one is productive and located in the center of the field, the other is cold and located on the margin of the field.

Detailed lithologic logs of the cuttings from both wells have been prepared. The logging indicates that the wells penetrated thick segments of mudstone and arkosic sands above 1200 feet and thinly interbedded arkose, siltstone, and shale at greater depths. Hydrothermal silicates and sulphides are present in both wells, indicating that the geothermal system was more extensive in the past.

Chemical analyses of twenty samples from the productive well also indicate that the rocks in the upper and lower portions of the well differ in their composition. When the chemistry of the samples is compared on a constant volume basis, the data show that sandstones from the upper parts of the wells are lower in both aluminum and titanium than sands from deeper depths. Silica, sodium, potassium, calcium, strontium, cobalt, nickel, copper, lead, zinc, cadmium, silver and arsenic have been redistributed by the geothermal system. Work is under way to relate these chemical changes to the mineralogy of the samples.

In order to examine other potential zoning patterns, the organic gas compositions of fluid inclusions contained in the altered rocks from the production well have been determined. The data suggest that the hydrocarbons methane, ethane and propane are zoned with depth. Methane and propane are enriched in zones of hydrothermal alteration in the upper portions of the well, whereas ethane and propane appear to be enriched in the lower portions of the well.

The significance of these changes and their relationship to the broad minerlaogic and geochemical changes which have affected the reservoir rocks are being currently investigated.

PROJECT 2. Fracture Mapping Using Mineralogic Analyses and Stratigraphic Correlation--Baca, NM.

Background

The Baca Geothermal Demonstration Project was cancelled in 1982 due to the inability of Union Oil Company to deliver the required amount of geothermal steam to power a 50 MWe plant. In fact, sufficient steam resources had been proven to provide only 15 MWe. Low reservoir permeability (6000 md-ft) was cited as one of the principal problems. Compilation of subsurface data from UOC well logs by Hulen and Nielson of UURI has suggested that stratigraphic units within the Bandelier Tuff, as well as fractures, provide important reservoir controls and should have been considered in the siting of geothermal wells. Subsequent to this work, UURI received proprietary cuttings from the Baca Project area under a cooperative research arrangement with Union, and initiated study of these cuttings using funds provided by Contract No. DE-AC07-80ID12079.

During our studies of the past year, we have developed a working relationship with the Geothermal Division of Union Oil Co. which has allowed us increasingly greater access to data pertaining to the subsurface geology of the Baca geothermal reservoir. Our accomplishments to date include definition of the host rock stratigraphy of the reservoir, definition of its structural setting, a model of the structural evolution of the reservoir which explains the low permeabilities encountered by Union, an evaluation of the preliminary work on the geochemistry of the reservoir rocks and their alteration mineralogy. Union has indicated that they are willing to provide additional cuttings samples for our study, and they have even invited us to map surface geology with them at the Baca site. These are data and access which have previously been unavailable to other scientists outside of Union.

Current Progress

Our current work largely involves the study of subsurface cuttings samples from the Baca geothermal area, New Mexico. The purpose of the study is to compare hydrothermal alteration zonation with our structural and stratigraphic models to locate major fractures and faults and evaluate fracture controls, fluid volume, and temperatures of the system. As a result of last FY's effort, a paper entitled "Internal Geology and Evolution of the Redondo Dome, Valles Caldera, New Mexico," by D. L. Nielson and J. B. Hulen, was written and is in press in the Journal of Geophysical Research. As a result of work this FY, a paper entitled "Results of Deep Drilling in the Valles Caldera, New Mexico," by D. L. Nielson and J. B. Hulen, was presented at the International Symposium on Observation of the Crust Through Drilling at Tarrytown, New York on May 23 and 24, 1984. The presentation of this paper satisfies one of the deliverables for contract No. DE-AC03-84SF12196, namely, the presentation of results at a professional meeting. The scientific results of our studies to date this year are summarized in the following paragraphs.

Deep drilling and reservoir engineering studies in the Baca geothermal field, Valles caldera, New Mexico, have enabled us to examine closely the relationships of structure, stratigraphy and hydrothermal alteration to reservoir temperature, pressure, permeability and thermal fluid flow. The Baca system is hot-water dominated with measured temperatures up to 341°C. Host rocks for the Baca system are principally densely welded felsic ash-flow tuffs and intermediate-composition flows which have no primary permeability. Fluid flow has been confined to major throughgoing, steeply-dipping normal faults and subsidiary fractures as well as to vertically restricted stratigraphic aquifers. The hottest and most productive portion of the Baca field coincides with the thickest section of a deep stratigraphic aquifer

where it is disrupted by numerous major northeast- and east-west-trending normal fault zones. Throughout the field, however, structural and stratigraphic permeability have been extensively modified by hydrothermal alteration.

Alteration in the Baca field is of three distinctive types: argillic, propylitic and phyllic. Strong argillic alteration forms a blanket mostly above the water table and is developed in formerly permeable non-welded tuffs. It is characterized by the assemblage smectite, mixed-layer illite-smectite, kaolinite, quartz and pyrite. Pervasive propylitic alteration, weakly developed in felsic host rocks but intense in deep intermediate composition volcanics, comprises chlorite, calcite, epidote/allanite, illite, pyrite and hematite. Illite, pyrite and quartz are the principal constituents of phyllic zones, which are commonly, but not invariably, associated with major thermal fluid entries. Other identical phyllic zones, obviously once permeable, now are hydrothermally sealed. The presence in the Baca field of normally high-temperature mineral phases at shallow depths and correspondingly low temperatures indicates that cool rocks at high levels have been hotter in the past. These relationships indicate either that isotherms have collapsed due to cooling of the system, or that they have retreated without overall heat loss due to structural uplift.

Permeability relationships revealed in Baca boreholes during drilling or subsequent reservoir tests are readily explained by stratigraphy, structure and hydrothermal alteration in various combinations. For example, spinner surveys run during injection tests show that massive fluid loss commonly occurs in a deep interval of largely non-welded tuffs (the Lower Tuffs of Nielson and Hulen, 1984). In wells where this interval neither produces fluid naturally nor accepts it during injection, it is shown to be hydrothermally sealed.

The active Baca geothermal system shows many similarities to volcanic-hosted epithermal precious metal vein deposits. These ore systems are similar to Baca in tectonic setting, host rocks, hydrothermal alteration mineralogy and zoning, temperature range, fluid origin, and possibly trace element zoning. Fluid salinities at Baca are, however, low for such deposits. Although epithermal veins have not been penetrated in the Baca wells, chemical analyses of selected pyrite phyllic zones show silver concentrations approaching ore grade.

PROJECT 3. Reservoir Definition in Andesitic Volcanic Terrains.

Background

The majority of the world's high-temperature geothermal resource is closely associated with active volcanism. There is little doubt that potent heat sources, capable of driving large geothermal convection cells, must exist widely in the volcanic belts of the Cascades, central Alaska and the Aleutian Islands in the western U. S. as well as elsewhere in the world. These heat sources and associated geothermal systems are here interpreted to be a generic classification including all systems associated with andesitic volcanism overlying convergent plate margins. In this category, a relatively small amount of data are already in the public domain from Japan, Momotombo (Nicaragua), Newberry Caldera (Oregon), Lassen (California), Meager Creek (British Columbia), Los Azufres (Mexico), Adak Island in the Aleutians, and other areas which have been or are the sites of active exploration. The key aspects of exploration in this environment are knowledge of the location of heat sources (high-level plutons) and the locations and nature of fracture systems which would allow meteoric fluids to communicate with the hot rock and ascend to within reasonable drilling depths.

The western andesitic volcanic province of the U. S. remains one of the areas of very high geothermal potential which has seen relatively little systematic exploration by the U. S. geothermal industry. One of the reasons for this has undoubtedly been the reluctance of Federal agencies (mainly the U. S. Forest Service) to lease lands for exploration. Another reason has been that there are relatively few surface manifestations of geothermal activity which attract explorationists. The lack of thermal features at the surface has often been attributed to high rainfall, which may effectively eliminate surface thermal phenomena and require deep temperature-gradient measurements

to see through the near-surface, cold-water aquifers. Therefore, with the exception of several specific locations such as Lassen, Meager Creek, and Newberry, exploration is concerned with the discovery of "blind" systems. It is thus very risky and, to the present time, many companies have chosen not to take these risks. What is necessary for successful exploration in such an environment is a system model based on heat source and permeability relationships. From this, effective exploration strategies can be developed both for exploration for and within (reservoir definition) geothermal systems in andesitic volcanic environments, as has been done by our group at UURI for the Basin and Range Province.

During FY 82, work was initiated on a cooperative geochemistry investigation of the Meager Creek geothermal system with the B. C. Hydro and Power Authority under funding provided by Contract No. DE-AC07-80ID12079. The Meager Creek system is currently one of the best documented of the geothermal systems associated with active magmatism in North America. The objectives of this work were to 1) characterize the chemistries of thermal fluids in an active magmatic invironment through the analysis of field data and through mathamatical modeling of fluid-mineral equilibria, 2) evaluate the effects of the various factors that can affect the fluid chemistries, 3) determine the effects of fluids of different chemistries on rocks typical of volcanic terrains, and 4) utilize this information to help locate "blind" geothermal systems associated with recent high level magma chambers.

Because the composition of many minerals formed in geothermal environments is senstive to both the chemistry of the circulating fluids and their temperature, our initial efforts have been directed toward determining the alteration minerals present in core and cuttings from wells within the field. From this information and partial chemical analyses of hot spring and

reservoir fluids, the chemistry of the geothermal fluids at various places in the reservoir can be deduced. This allows us to determine the structure of the reservoir and to make predictions about the location of the highest-temperature, highest-permeablility portions of the reservoir.

Current Progress

Progress was made in several areas on our study of the Meager Creek geothermal system. Our mineralogic work has included an analysis of the clay mineralogy and thin-section studies of approximately two hundred samples from wells M-7, 10, 12 and MC-1. MC-1 is a deep (3000 m) production well which produces fluids near 200°C and has a bottom-hole temperature of about 250°C. M-7 is a 360 m thermal gradient well with a bottom-hole temperature of 200°C; M-70 is 100 m deep and had a bottom-hole temperature of 160°C; and M-12 is a cold (60°C) 600 m well on the margin of the field. The four wells provide an illustrative three-dimensional cross-section of the thermal system.

Through our petrographic studies, we have recognized and documented several distinct mineral assemblages related to three different hydrothermal events. The oldest consists of plagioclase + hornblende + epidote and was formed during regional metamorphism of Coast Range sedimentary and igneous rocks in Mesozoic time. Subsequent alteration related to intrusion of quartz-diorite produced the illite + chlorite + epidote and was associated with the deposition of veins containing quartz, sulfides and potassium feldspar. This alteration occurred prior to the present geothermal activity.

Hydrothermal alteration related to the active geothermal system has affected the Pliocene to Recent dikes which intrude the Coast Range complex. Geothermally altered rocks contain clays, illite, chlorite and epidote and potassium feldspar and are associated with carbonate-cemented veins and breccias. The distribution of carbonate minerals suggest that the formation

of the veins and breccias may have been related to a tectonic event which induced widespread fracturing and boiling of the thermal fluids.

The X-ray diffraction studies indicate that the sheet silicates include illite, chlorite, illite/smectite and smectite. The smectite and mixed layer illite/smectite are strongly zoned with depth in the four wells. The data indicate that these clay minerals are present only in rocks whose temperatures are less than 165°C.

New chemical analyses of well-bore and spring precipitates indicate that many of the trace elements being remobilized by the geothermal system are also strongly zoned. Fluids from the deepest portions of the field precipitate Ag, Cu, Ni and high levels of Zn. Fluids from intermediate levels are depositing high levels of Sr, As, and Bi, whereas the precipitates deposited by fluids from shallow levels are enriched only in Bi.

The results of these mineralogic and geochemical studies will be used to select samples for electron microprobe and isotopic analyses. These data will be coupled with appropriate thermochemical models to determine the distribution and composition of the various fluids present in the thermal system.

PROJECT 4. Improvements in 2D and 3D Interpretation for MT - Line Source and IP-Resistivity Surveys.

Background

We have developed 2D finite element algorithms for both resistivity and MT-line source solutions under a previous NSF grant. These programs approximate the unknown voltage or field using linear basis functions over triangular subdomains. In particular, this allows precise simulation of sloping interfaces. Moreover, Galerkin's method of defining basis weighting functions minimizes the norm of the approximating error over the domain of the operator (the earth section). For the EM problem, the program initially computes the unknown field parallel to strike, from which auxiliary fields are calculated by a difference approximation to Maxwell's equations.

The ability to model sloping interfaces with these algorithms is an advantage over finite difference programs. Wannamaker has used this 2D code for the MT source to allow for the effects of high-contrast lateral heterogeneity at the surface and obtain a model of deep resistivity structure in S. W. Utah. These 2D programs have been very popular with industry and research organizations since their release. They have been useful interpretation aids requiring only modest computer resources.

Recently, UURI documented dipole-dipole resistivity responses over topography using our 2D finite-element program. These responses easily can differ by a factor of two from the flat earth signature. On the other hand, the effects of topography on plane wave and line source responses are not well known, but we expect them to be serious. Very few results using the surface integral equation approach are available. Moreover, the remaining citations have implemented finite difference solutions which approximate topography using jagged steps. We believe this is a poor approximation to nature,

especially when the electric field is normal to topographic trends, and wish to remedy this deficiency using our finite element code.

While these 2D programs have proved valuable, limitations to purely 2D analysis are being recognized increasingly. Rather arbitrary 3D structures can be treated for MT by the volume integral equation method of UURI but substantial computing facilities must be available. However, an important component to three-dimensionality in MT responses is a nearly frequency-independent telluric distortion due to current-gathering. These distortions have been simulated in the past using elliptical inclusions of finite difference approximations to thin-layer inhomogeneity. Once again, finite difference approximations are less satisfactory, compared to simulations using finite elements, due to the step-like nature of the model resistivity structure. We are undertaking a straightforward development of a 3D thin-layer MT algorithm from our 2D program which would allow boundaries in plan view to have arbitrary orientation. In the course of this work, an analagous 3D program for IP-resistivity also is being created.

Current Progress

Toward improvement of our finite element program for modeling magnetotelluric responses of 2D structures of arbitrary cross-section, we have successfully implemented the ability to simulate topography. Verification of the solution for the TM mode stems from comparison with an analytic solution for a resistive hemi-cylinder in a uniform half-space. To avoid discontinuities in electric field, we must ensure that nodal values in the difference approximations to Maxwell's equations are selected entirely within the earth for all possible topographic configurations. Verification for the TE mode awaits computations from the Rayleigh scattering approach of G. R. Jiracek of San Diego State University. The finite-element program is

advantageous in that topography and subsurface structure can be modeled simultaneously.

PROJECT 5. Fracture Detection using Downhole Electrical Geophysical Techniques.

Background

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

Methods which we are studying include mise-a-la-masse, induced polarization, magnetometric resistivity, and time-domain electromagnetic.

Current Progress

A brief review of all pertinent eastern-and western-bloc literature concerning electrical borehole geophysics has been completed and an annotated bibligraphy has been prepared.

A surface-integral algorithm has been designed to compute the resistivity anomalies observed down a borehole with the positions of the electrodes on surface varied. The model used is two-dimensional. In one configuration, one current electrode is placed on surface at infinity while the second current electrode is sequentially placed on either side and on top of the borehole. The two potential electrodes are run down the borehole as in a "long normal" resistivity array. The position of a fault zone, near a borehole, and its dip

can be determined. The method can be implemented as a slight modification of a long normal array conventionally used in well logging. A variant on this method involving potential electrodes on surface and a current electrode down the borehole does not look promising. A report on this research is in preparation.

An existing three-dimensional integral equation algorithm has been modified to handle elongate bodies which simulate fault zones. The mise-a-la-masse and magnetometric resistivity methods will be analyzed in borehole applications via this algorithm. While this algorithm is extremely long, complex, and interactive, we have managed to modify it to use elongate parallelopiped cells rather than the equidimensional cells used earlier. The modified algorithm has been tested and found to be satisfactory. We will now commence the modeling studies.

A two-dimensional finite element algorithm is under development for borehole resistivity detection of very thin fault zones cutting through a layered earth with topography superimposed. It will take another month or more to complete this algorithm.

We have just started an analysis of time-domain electromagnetic methods in borehole geophysical detection of fault zones. Existing algorithms are being used.

EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108
(801) 524-3422

QUARTERLY PROGRESS REPORT
March 1, 1984 to May 31, 1984

RESEARCH AND TECHNOLOGY DEVELOPMENT
for
DOE'S GEOTHERMAL RESERVOIR DEFINITION PROGRAM

This is a report of work sponsored
by the Department of Energy under
Contract No. DE-AC03-84SF12196

Earth Science Laboratory

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

ESL

QUARTERLY PROGRESS REPORT
March 1, 1984 to May 31, 1984

RESEARCH AND TECHNOLOGY DEVELOPMENT

for

DOE'S GEOTHERMAL RESERVOIR DEFINITION PROGRAM

This is a report of work sponsored by the Department of Energy
under Contract No. DE-AC03-84SF12196

by

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way
Salt Lake City, Utah 84108
801-524-3422

June 15, 1984

TABLE OF CONTENTS

SUMMARY

Three projects are currently active in developing methods for fracture detection, i.e. detection of permeable zones. At the Salton Sea geothermal system in California, we are quantifying the trace element chemistry of chip samples and performing analyses on gases from fluid inclusions for organic compounds for two wells belonging to Union Oil Company. We find zoning in both trace elements and organic gases. We hope that these studies will lead to zoning pictures useful in identifying permeable horizons. At the Baca geothermal system in the Valles Caldera of New Mexico, recent studies in the zoning of hydrothermal alteration have shown that the permeability relationships observed during drilling at Baca by Union Oil Company can be explained by a combination of stratigraphy, structure (faulting) and hydrothermal alteration. Comparison of spinner data with our results shows that fluid production commonly occurs in a deep interval of largely non-welded tuffs. In wells where this same interval neither produces or accepts fluid, the unit is shown to be sealed by alteration minerals.

We are examining various geophysical methods for fracture detection. Our approach is to model numerically the geologic framework for a number of different electrical geophysical techniques in order to predict fracture detectability. We have recently written a computer code to model the resistivity signature of fractures located between two boreholes. This code has been used to demonstrate that some field distributions of electrodes would not permit detection of the fracture whereas others would. We are continuing development of several other computer codes to model this difficult problem for other electrical geophysical technques.

We have been continuing our studies of the Meager Creek geothermal system in British Columbia. B. C. Hydro has given us custody of core and chips from

this system, which we believe to perhaps be illustrative of what may be found at the roots of some of the Cascades province volcanic systems. We are working to quantify the mineralogy of hydrothermal alteration in order to study the evolution of the system through time. Our work to date has yielded the important result that fluid flow presently appears to be strongly influenced by diabase dikes that cut the intrusion. If the same is true in other Cascades systems, deep permeability might be very difficult to find.

OVERVIEW OF CURRENT RESEARCH

Our current program supports research in DOE's Reservoir Definition Program. A number of general problem areas are being addressed under this line item. Three projects are directed toward finding better methods for fracture detection and mapping. We are continuing development work on fracture mapping techniques using mineralogy and geochemistry at The Geysers and the Imperial Valley (Project 1) and at Baca (Project 2). The basic idea behind both of these projects is to develop better means to map stratigraphy from borehole samples, and then to correlate the stratigraphy from borehole to borehole. Offsets in stratigraphy among boreholes can then be interpreted in terms of the occurrence, location, and orientation of faults, folds and other permeability-controlling structures. These methods, unexploited so far in geothermal reservoir definition and development, show great promise to be powerful tools for industry. A third project (Project 5) is a comprehensive evaluation of the use of electrical geophysical techniques in a borehole, between two boreholes and between borehole and surface for fracture detection, using numerical modeling to determine fracture detectability There has been no such evaluation in geothermal environments, and a great deal of money could be spent on dead-end research without one because there are so many quite separate electrical techniques.

A second major topic area is that of reservoir definition in andesitic volcanic environments. Such environments are quite important worldwide, but remain undeveloped in the U. S. We are continuing work at Meager Creek, B. C., which is a major hydrothermal system in the Cascades andesitic environment. Although this area is outside the U. S., it has several advantages: it has important subsurface information in the form of 3 deep

(10,000 foot) wells, one of which produces hydrothermal fluids at 230°C; it is controlled by B. C. Hydro, who will allow all data, including data collected by private contractors to them, to be used and published (unlike U. S. companies); and, B. C. Hydro has given UURI custodial privileges over the core and cuttings from the 3 deep wells and other shallower holes. We are continuing development of geochemical techniques to characterize this area (Project 3).

UURI has continued to be a leader in the world in development of interpretation techniques and computer modeling for electrical geophysical methods. We have a comprehensive library of computer techniques and codes, and have made most of our programs available for industry. We are upgrading magnetotelluric (MT) and controlled source audiomagnetotelluric (CSAMT) interpretive techniques by developing means to apply topographic corrections to these surveys (Project 4). Topography causes significant changes to MT and CSAMT data that must be removed before interpretation in terms of subsurface geology can be performed, but no good means exists today to make these corrections.

PROJECT 1. Fracture Mapping Using Mobile and Immobile Trace Elements and Clays--Imperial Valley and The Geysers, CA.

Background

Since 1977, the Earth Science Laboratory has been involved in the application of trace- and major-element geochemistry to fracture mapping of geothermal reservoirs in Basin and Range Province and in volcanic environments. As a result of these studies, there is now abundant evidence to indicate that many elements are redistributed along the fluid channelways in the reservoir rocks as the fluids move through them, and that these geochemical signatures can be used to locate and predict the locations of permeable zones.

Our current studies reflect the need to develop better models of the geometry and fluid-flow paths of the geothermal systems of the Imperial Valley type. Toward this goal, Union Geothermal has provided ESL with samples from two recently drilled wells in their Salton Sea geothermal field. During FY 83 work was initiated on these samples using funds provided by DOE/ID under Contract No. DE-AC07-80ID12079. The work described below is a continuation of this investigation and represents a cooperative effort with Union. This investigation has been designed to answer the following questions:

> Does chemical zoning in trace and major elements exist within geothermal systems of the Imperial Valley type, and if so, can these data be used to a) locate zones of high permeability, b) predict thermal conditions within the reservoirs, c) characterize the distribution of fluid types, and d) locate and characterize reservoir field boundaries?

Current Progress

Work on our investigations of cuttings from the Salton Sea geothermal

system continued with significant progress. The cuttings are from two wells drilled by Union Oil Co.; one is productive and located in the center of the field, the other is cold and located on the margin of the field.

Detailed lithologic logs of the cuttings from both wells have been prepared. The logging indicates that the wells penetrated thick segments of mudstone and arkosic sands above 1200 feet and thinly interbedded arkose, siltstone, and shale at greater depths. Hydrothermal silicates and sulphides are present in both wells, indicating that the geothermal system was more extensive in the past.

Chemical analyses of twenty samples from the productive well also indicate that the rocks in the upper and lower portions of the well differ in their composition. When the chemistry of the samples is compared on a constant volume basis, the data show that sandstones from the upper parts of the wells are lower in both aluminum and titanium than sands from deeper depths. Silica, sodium, potassium, calcium, strontium, cobalt, nickel, copper, lead, zinc, cadmium, silver and arsenic have been redistributed by the geothermal system. Work is under way to relate these chemical changes to the mineralogy of the samples.

In order to examine other potential zoning patterns, the organic gas compositions of fluid inclusions contained in the altered rocks from the production well have been determined. The data suggest that the hydrocarbons methane, ethane and propane are zoned with depth. Methane and propane are enriched in zones of hydrothermal alteration in the upper portions of the well, whereas ethane and propane appear to be enriched in the lower portions of the well.

The significance of these changes and their relationship to the broad minerlaogic and geochemical changes which have affected the reservoir rocks are being currently investigated.

PROJECT 2. Fracture Mapping Using Mineralogic Analyses and Stratigraphic Correlation--Baca, NM.

Background

The Baca Geothermal Demonstration Project was cancelled in 1982 due to the inability of Union Oil Company to deliver the required amount of geothermal steam to power a 50 MWe plant. In fact, sufficient steam resources had been proven to provide only 15 MWe. Low reservoir permeability (6000 md-ft) was cited as one of the principal problems. Compilation of subsurface data from UOC well logs by Hulen and Nielson of UURI has suggested that stratigraphic units within the Bandelier Tuff, as well as fractures, provide important reservoir controls and should have been considered in the siting of geothermal wells. Subsequent to this work, UURI received proprietary cuttings from the Baca Project area under a cooperative research arrangement with Union, and initiated study of these cuttings using funds provided by Contract No. DE-AC07-80ID12079.

During our studies of the past year, we have developed a working relationship with the Geothermal Division of Union Oil Co. which has allowed us increasingly greater access to data pertaining to the subsurface geology of the Baca geothermal reservoir. Our accomplishments to date include definition of the host rock stratigraphy of the reservoir, definition of its structural setting, a model of the structural evolution of the reservoir which explains the low permeabilities encountered by Union, an evaluation of the preliminary work on the geochemistry of the reservoir rocks and their alteration mineralogy. Union has indicated that they are willing to provide additional cuttings samples for our study, and they have even invited us to map surface geology with them at the Baca site. These are data and access which have previously been unavailable to other scientists outside of Union.

Current Progress

Our current work largely involves the study of subsurface cuttings samples from the Baca geothermal area, New Mexico. The purpose of the study is to compare hydrothermal alteration zonation with our structural and stratigraphic models to locate major fractures and faults and evaluate fracture controls, fluid volume, and temperatures of the system. As a result of last FY's effort, a paper entitled "Internal Geology and Evolution of the Redondo Dome, Valles Caldera, New Mexico," by D. L. Nielson and J. B. Hulen, was written and is in press in the Journal of Geophysical Research. As a result of work this FY, a paper entitled "Results of Deep Drilling in the Valles Caldera, New Mexico," by D. L. Nielson and J. B. Hulen, was presented at the International Symposium on Observation of the Crust Through Drilling at Tarrytown, New York on May 23 and 24, 1984. The presentation of this paper satisfies one of the deliverables for contract No. DE-AC03-84SF12196, namely, the presentation of results at a professional meeting. The scientific results of our studies to date this year are summarized in the following paragraphs.

Deep drilling and reservoir engineering studies in the Baca geothermal field, Valles caldera, New Mexico, have enabled us to examine closely the relationships of structure, stratigraphy and hydrothermal alteration to reservoir temperature, pressure, permeability and thermal fluid flow. The Baca system is hot-water dominated with measured temperatures up to 341°C. Host rocks for the Baca system are principally densely welded felsic ash-flow tuffs and intermediate-composition flows which have no primary permeability. Fluid flow has been confined to major throughgoing, steeply-dipping normal faults and subsidiary fractures as well as to vertically restricted stratigraphic aquifers. The hottest and most productive portion of the Baca field coincides with the thickest section of a deep stratigraphic aquifer

where it is disrupted by numerous major northeast- and east-west-trending normal fault zones. Throughout the field, however, structural and stratigraphic permeability have been extensively modified by hydrothermal alteration.

Alteration in the Baca field is of three distinctive types: argillic, propylitic and phyllic. Strong argillic alteration forms a blanket mostly above the water table and is developed in formerly permeable non-welded tuffs. It is characterized by the assemblage smectite, mixed-layer illite-smectite, kaolinite, quartz and pyrite. Pervasive propylitic alteration, weakly developed in felsic host rocks but intense in deep intermediate composition volcanics, comprises chlorite, calcite, epidote/allanite, illite, pyrite and hematite. Illite, pyrite and quartz are the principal constituents of phyllic zones, which are commonly, but not invariably, associated with major thermal fluid entries. Other identical phyllic zones, obviously once permeable, now are hydrothermally sealed. The presence in the Baca field of normally high-temperature mineral phases at shallow depths and correspondingly low temperatures indicates that cool rocks at high levels have been hotter in the past. These relationships indicate either that isotherms have collapsed due to cooling of the system, or that they have retreated without overall heat loss due to structural uplift.

Permeability relationships revealed in Baca boreholes during drilling or subsequent reservoir tests are readily explained by stratigraphy, structure and hydrothermal alteration in various combinations. For example, spinner surveys run during injection tests show that massive fluid loss commonly occurs in a deep interval of largely non-welded tuffs (the Lower Tuffs of Nielson and Hulen, 1984). In wells where this interval neither produces fluid naturally nor accepts it during injection, it is shown to be hydrothermally sealed.

The active Baca geothermal system shows many similarities to volcanic-hosted epithermal precious metal vein deposits. These ore systems are similar to Baca in tectonic setting, host rocks, hydrothermal alteration mineralogy and zoning, temperature range, fluid origin, and possibly trace element zoning. Fluid salinities at Baca are, however, low for such deposits. Although epithermal veins have not been penetrated in the Baca wells, chemical analyses of selected pyrite phyllic zones show silver concentrations approaching ore grade.

PROJECT 3. Reservoir Definition in Andesitic Volcanic Terrains.

Background

The majority of the world's high-temperature geothermal resource is closely associated with active volcanism. There is little doubt that potent heat sources, capable of driving large geothermal convection cells, must exist widely in the volcanic belts of the Cascades, central Alaska and the Aleutian Islands in the western U. S. as well as elsewhere in the world. These heat sources and associated geothermal systems are here interpreted to be a generic classification including all systems associated with andesitic volcanism overlying convergent plate margins. In this category, a relatively small amount of data are already in the public domain from Japan, Momotombo (Nicaragua), Newberry Caldera (Oregon), Lassen (California), Meager Creek (British Columbia), Los Azufres (Mexico), Adak Island in the Aleutians, and other areas which have been or are the sites of active exploration. The key aspects of exploration in this environment are knowledge of the location of heat sources (high-level plutons) and the locations and nature of fracture systems which would allow meteoric fluids to communicate with the hot rock and ascend to within reasonable drilling depths.

The western andesitic volcanic province of the U. S. remains one of the areas of very high geothermal potential which has seen relatively little systematic exploration by the U. S. geothermal industry. One of the reasons for this has undoubtedly been the reluctance of Federal agencies (mainly the U. S. Forest Service) to lease lands for exploration. Another reason has been that there are relatively few surface manifestations of geothermal activity which attract explorationists. The lack of thermal features at the surface has often been attributed to high rainfall, which may effectively eliminate surface thermal phenomena and require deep temperature-gradient measurements

to see through the near-surface, cold-water aquifers. Therefore, with the exception of several specific locations such as Lassen, Meager Creek, and Newberry, exploration is concerned with the discovery of "blind" systems. It is thus very risky and, to the present time, many companies have chosen not to take these risks. What is necessary for successful exploration in such an environment is a system model based on heat source and permeability relationships. From this, effective exploration strategies can be developed both for exploration _for_ and _within_ (reservoir definition) geothermal systems in andesitic volcanic environments, as has been done by our group at UURI for the Basin and Range Province.

During FY 82, work was initiated on a cooperative geochemistry investigation of the Meager Creek geothermal system with the B. C. Hydro and Power Authority under funding provided by Contract No. DE-AC07-80ID12079. The Meager Creek system is currently one of the best documented of the geothermal systems associated with active magmatism in North America. The objectives of this work were to 1) characterize the chemistries of thermal fluids in an active magmatic invironment through the analysis of field data and through mathamatical modeling of fluid-mineral equilibria, 2) evaluate the effects of the various factors that can affect the fluid chemistries, 3) determine the effects of fluids of different chemistries on rocks typical of volcanic terrains, and 4) utilize this information to help locate "blind" geothermal systems associated with recent high level magma chambers.

Because the composition of many minerals formed in geothermal environments is senstive to both the chemistry of the circulating fluids and their temperature, our initial efforts have been directed toward determining the alteration minerals present in core and cuttings from wells within the field. From this information and partial chemical analyses of hot spring and

reservoir fluids, the chemistry of the geothermal fluids at various places in the reservoir can be deduced. This allows us to determine the structure of the reservoir and to make predictions about the location of the highest-temperature, highest-permeablility portions of the reservoir.

Current Progress

Progress was made in several areas on our study of the Meager Creek geothermal system. Our mineralogic work has included an analysis of the clay mineralogy and thin-section studies of approximately two hundred samples from wells M-7, 10, 12 and MC-1. MC-1 is a deep (3000 m) production well which produces fluids near 200°C and has a bottom-hole temperature of about 250°C. M-7 is a 360 m thermal gradient well with a bottom-hole temperature of 200°C; M-70 is 100 m deep and had a bottom-hole temperature of 160°C; and M-12 is a cold (60°C) 600 m well on the margin of the field. The four wells provide an illustrative three-dimensional cross-section of the thermal system.

Through our petrographic studies, we have recognized and documented several distinct mineral assemblages related to three different hydrothermal events. The oldest consists of plagioclase + hornblende + epidote and was formed during regional metamorphism of Coast Range sedimentary and igneous rocks in Mesozoic time. Subsequent alteration related to intrusion of quartz-diorite produced the illite + chlorite + epidote and was associated with the deposition of veins containing quartz, sulfides and potassium feldspar. This alteration occurred prior to the present geothermal activity.

Hydrothermal alteration related to the active geothermal system has affected the Pliocene to Recent dikes which intrude the Coast Range complex. Geothermally altered rocks contain clays, illite, chlorite and epidote and potassium feldspar and are associated with carbonate-cemented veins and breccias. The distribution of carbonate minerals suggest that the formation

of the veins and breccias may have been related to a tectonic event which induced widespread fracturing and boiling of the thermal fluids.

The X-ray diffraction studies indicate that the sheet silicates include illite, chlorite, illite/smectite and smectite. The smectite and mixed layer illite/smectite are strongly zoned with depth in the four wells. The data indicate that these clay minerals are present only in rocks whose temperatures are less than 165°C.

New chemical analyses of well-bore and spring precipitates indicate that many of the trace elements being remobilized by the geothermal system are also strongly zoned. Fluids from the deepest portions of the field precipitate Ag, Cu, Ni and high levels of Zn. Fluids from intermediate levels are depositing high levels of Sr, As, and Bi, whereas the precipitates deposited by fluids from shallow levels are enriched only in Bi.

The results of these mineralogic and geochemical studies will be used to select samples for electron microprobe and isotopic analyses. These data will be coupled with appropriate thermochemical models to determine the distribution and composition of the various fluids present in the thermal system.

PROJECT 4. Improvements in 2D and 3D Interpretation for MT - Line Source and IP-Resistivity Surveys.

Background

We have developed 2D finite element algorithms for both resistivity and MT-line source solutions under a previous NSF grant. These programs approximate the unknown voltage or field using linear basis functions over triangular subdomains. In particular, this allows precise simulation of sloping interfaces. Moreover, Galerkin's method of defining basis weighting functions minimizes the norm of the approximating error over the domain of the operator (the earth section). For the EM problem, the program initially computes the unknown field parallel to strike, from which auxiliary fields are calculated by a difference approximation to Maxwell's equations.

The ability to model sloping interfaces with these algorithms is an advantage over finite difference programs. Wannamaker has used this 2D code for the MT source to allow for the effects of high-contrast lateral heterogeneity at the surface and obtain a model of deep resistivity structure in S. W. Utah. These 2D programs have been very popular with industry and research organizations since their release. They have been useful interpretation aids requiring only modest computer resources.

Recently, UURI documented dipole-dipole resistivity responses over topography using our 2D finite-element program. These responses easily can differ by a factor of two from the flat earth signature. On the other hand, the effects of topography on plane wave and line source responses are not well known, but we expect them to be serious. Very few results using the surface integral equation approach are available. Moreover, the remaining citations have implemented finite difference solutions which approximate topography using jagged steps. We believe this is a poor approximation to nature,

especially when the electric field is normal to topographic trends, and wish to remedy this deficiency using our finite element code.

While these 2D programs have proved valuable, limitations to purely 2D analysis are being recognized increasingly. Rather arbitrary 3D structures can be treated for MT by the volume integral equation method of UURI but substantial computing facilities must be available. However, an important component to three-dimensionality in MT responses is a nearly frequency-independent telluric distortion due to current-gathering. These distortions have been simulated in the past using elliptical inclusions of finite difference approximations to thin-layer inhomogeneity. Once again, finite difference approximations are less satisfactory, compared to simulations using finite elements, due to the step-like nature of the model resistivity structure. We are undertaking a straightforward development of a 3D thin-layer MT algorithm from our 2D program which would allow boundaries in plan view to have arbitrary orientation. In the course of this work, an analagous 3D program for IP-resistivity also is being created.

Current Progress

Toward improvement of our finite element program for modeling magneto-telluric responses of 2D structures of arbitrary cross-section, we have successfully implemented the ability to simulate topography. Verification of the solution for the TM mode stems from comparison with an analytic solution for a resistive hemi-cylinder in a uniform half-space. To avoid discontinuities in electric field, we must ensure that nodal values in the difference approximations to Maxwell's equations are selected entirely within the earth for all possible topographic configurations. Verification for the TE mode awaits computations from the Rayleigh scattering approach of G. R. Jiracek of San Diego State University. The finite-element program is

advantageous in that topography and subsurface structure can be modeled simultaneously.

PROJECT 5. Fracture Detection using Downhole Electrical Geophysical Techniques.

Background

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

Methods which we are studying include mise-a-la-masse, induced polarization, magnetometric resistivity, and time-domain electromagnetic.

Current Progress

A brief review of all pertinent eastern-and western-bloc literature concerning electrical borehole geophysics has been completed and an annotated bibligraphy has been prepared.

A surface-integral algorithm has been designed to compute the resistivity anomalies observed down a borehole with the positions of the electrodes on surface varied. The model used is two-dimensional. In one configuration, one current electrode is placed on surface at infinity while the second current electrode is sequentially placed on either side and on top of the borehole. The two potential electrodes are run down the borehole as in a "long normal" resistivity array. The position of a fault zone, near a borehole, and its dip

can be determined. The method can be implemented as a slight modification of a long normal array conventionally used in well logging. A variant on this method involving potential electrodes on surface and a current electrode down the borehole does not look promising. A report on this research is in preparation.

An existing three-dimensional integral equation algorithm has been modified to handle elongate bodies which simulate fault zones. The mise-a-la-masse and magnetometric resistivity methods will be analyzed in borehole applications via this algorithm. While this algorithm is extremely long, complex, and interactive, we have managed to modify it to use elongate parallelopiped cells rather than the equidimensional cells used earlier. The modified algorithm has been tested and found to be satisfactory. We will now commence the modeling studies.

A two-dimensional finite element algorithm is under development for borehole resistivity detection of very thin fault zones cutting through a layered earth with topography superimposed. It will take another month or more to complete this algorithm.

We have just started an analysis of time-domain electromagnetic methods in borehole geophysical detection of fault zones. Existing algorithms are being used.

EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108
(801) 524-3422