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INTRODUCTION

This report represents the final report of the University of Utah Research Institute under U.S. Department of Energy Contract No. DE-AC07-85ID12489. It consists of the abstracts and references of all technical reports generated by UURI under this contract. This report lists the abstracts in DOE report number sequence. The author index of this report will be useful in locating specific references.

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APPLICATION OF GEOPHYSICS TO EXPLORATION FOR CONCEALED HYDROTHERMAL SYSTEMS IN VOLCANIC TERRAINS

DOE/ID/12489-1
ESL-85027-JP*

by

Phillip M. Wright and Stanley H. Ward

ABSTRACT

Exploration for concealed geothermal systems in volcanic terrains will require well planned and executed programs to succeed and be cost-effective. The geologic record indicates that large hydrothermal convection systems occur only sporadically around plutons, and so a great deal more than identifying heat sources will be needed. Geophysical surveys can contribute to integrated exploration programs if used properly. This paper discusses some potential applications of geophysics and how it might be integrated into an exploration program.

* Also published in the Geothermal Resources Council, 1985 Transactions, 9, 423-428.

DERIVATIZED HYDROCARBONS AS GEOTHERMAL TRACERS

DOE/ID/12489-2
ESL-86014-JP*

by

Michael C. Adams, J. H. Ahn, H. Bentley, Joseph N. Moore, and S. Veggeberg

ABSTRACT

Thirty-nine potential geothermal tracers have been tested for thermal stability at temperatures up to 250°C. The tracers were aromatic hydro carbons with moieties of trifluoromethyls, onates, methyls, fluorides, or carboxyls. Significant decay of these tracers, except for the per fluorinated compounds, was noted only between 200°C and 250°C. At 200°C, 32 of the 39 tracers survived for one week; at 250°C, 15 survived. The perfluorinated tracers decayed completely at all temperatures tested. These results show that certain derivatized hydrocarbons are potentially suitable as geothermal tracers. Future research will include testing these tracers in the presence of solid, liquid and gas phases that are common in geothermal reservoirs.

* Also published in the Geothermal Resources Council, 1986 Transactions, 10, 415,420.

ELECTRICAL RESISTIVITY ANOMALIES AT NEWBERRY VOLCANO, OREGON— COMPARISON WITH ALTERATION MINERALOGY IN GEO COREHOLE N-1

DOE/ID/12489-3
ESL-86015-JP*

by

Phillip M. Wright and Dennis L. Nielson

ABSTRACT

Corehole N-1, drilled on the south flank of Newberry volcano in Oregon by GEO Operator Corp. under a cooperative agreement with DOE, encountered about 15 separate horizons between 2800 ft. and 4000 ft. that are good electrical conductors as shown by an induction log. These conductors correlate with horizons of altered basaltic, andesitic and lactitic ash and tuff in a lithologic section composed predominately of basaltic andesite flows. X-ray diffraction and scanning electron microscope analyses show the dominant alteration type to be a calcium smectite and we believe that the alteration is low temperature in origin. Surface electrical geophysical surveys have detected a widespread resistivity low in the Newberry area. A portion of this resistivity low is believed to be associated with the high-temperature hydrothermal system in Newberry caldera, whereas other portions of the low appear to be caused by the altered horizons on the flanks of the volcano. Delineation of the high-temperature system by electrical surveys may be difficult or impossible because of effects from the altered rocks.

* Also published in the Geothermal Resources Council, 1986 Transactions, 10, 247-252.

SIZE, DEPTH AND RELATED STRUCTURES OF INTRUSIONS UNDER STRATOVOLCANOES AND ASSOCIATED GEOTHERMAL SYSTEMS

DOE/ID/12489-4
ESL-86023-TR*

by

Bruce S. Sibbett

ABSTRACT

The subvolcanic structural configuration of faults, stress field, permeability controls and intrusion(s) shape, size and depth are primary factors controlling the location and quality of a geothermal system. Subvolcanic stocks under stratovolcanoes are typically 1 to 3 km in diameter and emplaced at depths of 1 to 2 km. Shallow magma chambers in general are typically 4 to 9 km deep, and several times larger than the subvolcanic stocks.

Likely subvolcanic structure are radial compression fractures around the magma chamber, and above the chamber extension faulting, stockwork fractures and breccia pipes. Pre-existing or regional structures and stress field will influence the location and shape of magma bodies and associated thermal systems.

This study combines data from areas of active stratovolcanoes and older eroded volcanic areas to formulate a detailed structural mode of the plumbing system under a stratovolcano. The model is correlated with factors controlling associated geothermal systems. A geothermal system may occur at depths of 1-2 km under a stratocone's base. Deeper systems associated with shallow magma chambers are likely to be present.

* Also published in the 1988 Earth-Science Reviews, 25, 291-309.

ARSENIC GEOCHEMISTRY IN GEOTHERMAL SYSTEMS

DOE/ID/12489-5
ESL-86025-TR*

by

Judith M. Ballantyne and Joseph N. Moore

ABSTRACT

Arsenic concentrations in geothermal fluids range from less than 0.1 to nearly 50 ppm, but individual reservoirs have relatively narrow concentration ranges. Arsenic is derived from the host rocks by leaching, but does not behave conservatively, and unlike other trace metals As concentrations bear no relationship to salinity. A positive correlation with temperature and a negative correlation with PH_2S indicate an equilibrium control on As solubility. Both As(III) and As(V), the former predominating, are reported from well discharges. Both oxidation states are present in hot springs. H_3AsO_3 is inferred to be the dominant species in reservoirs, with the possible exception of $HAsS_2$ in one unusually As-rich example. H_3AsO_4 and deprotonated forms are the likely As(V) species in hot springs.

Arsenic solubility in the reservoir fluids is controlled primarily by reactions involving pyrite, which may contain as much as 3.8 weight percent patchily distributed As. Thermodynamic calculations suggest that arsenopyrite solid solution is the most likely explanation for the As content of pyrite, with the maximum measured As content corresponding to 12 mole percent arsenopyrite. The deposition of As in pyrite may be induced by local fluctuations in redox conditions.

Orpiment, realgar, and As-rich stibnite and marcasite are associated with hot springs, but not reservoirs. Orpiment solubility increases with pH and temperature. The higher As content of some hot springs than their associated reservoirs may be due to changes in the solid phase controlling As solubility, and additional As being leached from the host rocks as the waters rise. At or near surface, oxidation of the As(III) to As(V) following complete oxidation of H_2S to SO_4 promotes As precipitation with, or adsorption on, iron oxides and silica.

* Also published in Geological Society of America, Abstracts with programs 1986, 17, 7, 518.

THE NATURE AND GEOLOGIC CHARACTERISTICS OF GEOTHERMAL RESOURCES

DOE/ID/12489-6
ESL-87009-JP

by

Phillip M. Wright

ABSTRACT

Geothermal resources occur where heat is concentrated in the upper levels of the earth's crust, ranging between the surface and about 5 km in depth. Such resources can be broadly divided into those with naturally occurring water, the so-called "hydrothermal" resources, and those without naturally occurring water, the so-called "hot rock" resources. At the present stage of geothermal resource development, we know by far the most about the hydrothermal resource type because this is the only type which can be economically developed today. Little deep drilling has been done in areas which would give us access to the hot rock resources.

Hydrothermal systems are found in many different geologic environments, and to a considerable extent, the characteristics of the environment determine those of the resource. In igneous and volcanic terrains, the hydrologic relationships are complex, and several reservoirs with different fluid compositions may be present. Fluid compositions depend on many factors, including temperature, rock type, origin of the fluids, residence time in the reservoir, boiling, mixing, cooling, fluid/rock interaction and mineral deposition. Heating of the fluids may be the result of nearby intrusive rock containing residual heat or may simply be the result of deep circulation and heating due to the earth's normal geothermal gradient. Permeability is usually controlled by faults, fractures and contacts between different rock types. These hydrothermal systems are usually volumetrically small and confined to a local area of heating and/or enhanced permeability. Typical areal sizes range from 0.1 sq km to 100 sq km.

Geothermal resources in basins are the result of the complex interaction of thermal, chemical and hydrodynamic regimes. Thermal input is usually from the normal heat flux of the earth, but local changes in sedimentary units can affect temperatures and thermal gradients. Fluids may be young meteoric waters, older connate waters, which may be briny, or mixtures. Positive thermal anomalies are often found in areas with complex geologic structures, such as anticlines or faults, which provide permeability for rising waters. Long regional flowpaths are favorable for the development of geothermal systems. Hydrodynamic relationships in immature basins are complicated by the development of overpressured zones and the dewatering of sediments during compaction.

The U.S. Geological Survey has assessed the geothermal resource base in the United States, and finds that the amount is large. Evaluation of volume and temperature data available in 1978 indicated that 1650 E18 joules of energy are present in 215 identified hydrothermal systems having temperatures greater than 90°C to depths of 3 km, excluding energy in National Parks. This is believed to be a minimum figure, but a more accurate estimate is not possible without more information. Electrical energy estimated to be producible from these resources is 23,000 megawatts for 30 years. The energy in the hot rock resources is very poorly known at the present time, but is probably at least two orders of magnitude more than the hydrothermal resource base. It is apparent that geothermal energy development can help replace the use of petroleum as that resource becomes more scarce and costly.

A NEW ILLITE GEOTHERMOMETER

DOE/ID/12489-7
ESL-88004-JP*

by

Judith M. Ballantyne and Joseph N. Moore

ABSTRACT

Sericite, either as illite or illite/smectite, is ubiquitous in geothermal systems. Theoretical Ca- and Na-smectite contents of non-expanding geothermal sericites have been calculated from published electron microprobe analyses. Geothermal sericites can be modeled as solid solutions of muscovite and smectite. For those sericites that fit the model, the amount of smectite in solid solution is related to temperature by expression:

$$T°C = 1.145*10^3/\{[0.35LogNa+0.175LogCa-0.75LogK] + 1.51\} - 273$$

where the concentration units are molalities. This supports the hypothesis that illite and illite/smectite are important controls on the concentrations of Na, K and Ca in geothermal fluids.

* Also published in the Thirteenth Workshop on Geothermal Reservoir Engineering, Stanford University, p. 145-150.

THE RESISTIVITY AND INDUCED POLARIZATION METHODS

DOE/ID/12489-8
ESL-88005-JP

by

Stanley H. Ward

ABSTRACT

This article presents a tutorial of the bases for, and problems encountered with, the resistivity and induced polarization methods in geotechnical and environmental applications. It commences with a discussion of aqueous electrolytic conduction in rocks including consideration of the effects of temperature, rock texture, rock type, geological processes, and of the presence of clay minerals. Both electrode and membrane polarization in soils and rocks are described.

The elementary theory for the resistivity and induced polarization methods is introduced via formulas for electrodes on homogeneous and layered half-spaces. The notion of apparent resistivity is presented. Vertical electric sounding is described in relation to curve types, inversion, equivalence, anisotropy, and correlation. Profiling with resistivity is briefly treated while combined sounding-profiling is treated in more detail for both the resistivity and induced polarization methods. The parameters used to describe the induced polarization phenomena are introduced. A brief discourse follows on data acquisition and processing, including design considerations for transmitters and receivers, electrodes, and wire logistics.

A section on arrays and the factors involved in selecting an array provokes the disclosure that while their application in geotechnical and environmental studies usually is straightforward much remains to be learned about the resistivity and induced polarization methods in general. Specific topics requiring study are comparative studies of various arrays in a) depth of exploration in sounding and in profiling, b) resolution of horizontal structures c) sensitivity to depth, d) sensitivity to lateral effects, e) sensitivity to buried and surface topography, and f) the effectiveness of focused arrays.

References to recent significant publications on 1-D, 2-D, and 3-D forward and inverse interpretation procedures follows. Problems encountered with these methods are initially treated under the section on arrays and are expanded with specific reference to geologic noise and negative induced polarization effects. The advantages of focused arrays are illustrated.

The paper concludes with nine representative examples of applications.

FORECAST AND OUTLOOK FOR GEOTHERMAL ENERGY, 1988-1998

DOE/ID/12489-9
ESL-88006-JP*

by

Phillip M. Wright

ABSTRACT

Hydrothermal resources, one of the several types of geothermal resources, are being actively developed on a worldwide basis. Other types of geothermal energy — geopressured, hot dry rock, and magma — remain uneconomic but show considerable promise for the future. Technical problems inhibit the development of each of the four geothermal types. Geothermal energy is used both for generation of electricity and for direct-heat applications. Use of geothermal energy is desirable because it is an environmentally clean, utility-compatible source of energy that directly displaces the need for more nuclear plants and frees petroleum for other important uses.

Current worldwide hydrothermal generating capacity is about 5,004 electrical megawatts (MWe) in 17 countries, with the United State accounting for 2,212 MWe of the total. Current worldwide direct use of hydrothermal energy amount to about 10,000 thermal megawatts (MWt), with the U. S. Contributing about 400 MWt. Hydrothermal resources worldwide produce enough electrical energy to free about 90 million barrels of petroleum for other uses annually, and hydrothermal electrical production in the Unites States is equivalent to the use of 40 million barrels annually. Worldwide, geothermal use for both electrical and direct-heat applications is equivalent to the burning of about 160 million barrels of petroleum annually.

Geothermal development in the United States is depressed due to the comparatively low energy costs of today and a temporary excess in electrical generating capacity. Because of these factors as well as lack of adequate technology, only a small portion of the known hydrothermal resource base can be used economically today. Growth in geothermal generating capacity in the U. S. is forecast at a rate of about 6 percent per year from the present to the year 2005, with nearly all of this development being in the hydrothermal convective resource type. The Electric Power Research Institute estimates that by 1995 the U. S. will have between 3,400 and 3,800 megawatts of geothermal electricity on line, and by 2005 there will be between 4,900 and 6,800 MWe on line. Such a growth rate is based on the premise that research and development will solve some of the technical problems currently impeding geothermal development.

* Also published in The American] of Petroleum Geologists Bulletin, v.73, no. 10B, 366-374, October 1989.

MAGNETOTELLURIC PROFILING ACROSS LONG VALLEY CALDERA

DOE/ID/12489-10
ESL-88007-PR*

by

Philip E. Wannamaker

ABSTRACT

From November 17 to December 16, 1986, UURI collected thirteen tensor magnetotelluric soundings across the eastern half of Long Valley caldera. The period range of measurement was from less than 0.01 to 300 s and the data quality overall is very good to excellent. The purpose of the survey is to gain control of upper crustal conductivity structure and to ascertain the presence of a deep hydrothermal or magmatic system. This work is supported by the DOE/Magma program.

Reconnaissance electrical geophysics together with gravity and refraction seismics suggest substantial upper crustal conductance especially in the east but also in the west and south moats. Bipole-bipole apparent resistivities, telluric ellipse orientations, faulting, and gravity all indicate a NNW structural trend on average beneath our MT profile. Thus, our soundings are presented and interpreted using a fixed N20° x-axis.

* Also published in Lawrence Berkeley Laboratory Report, LBL-23940, 150-158.

EFFECT OF A METAL CASING ON 3D INTERPRETATION OF RESISTIVITY

DOE/ID/12489-11
ESL-88009-JP

by

Douglas J. LaBrecque

INTRODUCTION

The University of Utah Research Institute has had an ongoing effort to develope a suite of borehole methods to locate conductive fracture zones in a geothermal environment. Previous papers have addressed the use of borehole to surface (Newkirk, 1982) (Beasley and Ward, 1986) and borehole to borehole (Yang and Ward, 1985) electrical geophysical methods to detect three-dimensional bodies. However a major concern not addressed in previous work, is the ability to conduct surveys in the presence of metal cased holes. Although it is not possible to conduct surveys from completely metal cased wells, many times wells may have a surface casing but are open at depth or metal cased well may lie close to uncased wells from which surveys will be performed.

Although some work has addressed the effects of a borehole in half-space (Wait and Williams, 1985) (Holladay and West, 1984) on surface geophysical surveys, the authors are unaware of any published work discussing the effects of casing on the types of borehole and borehole to surface methods which are under development for this project or on the influence of coupling between a conductive body and casing.

The purpose of this paper is to discuss the use of the integral equations in modeling the coupled direct current resistivity responses of metal well casings and three dimensional conductive bodies. Further the technique is applied to a number of test cases to determine when borehole to borehole and borehole to surface methods could be used to determine the presence of a conductive body in a geothermal environment.

SEISMIC MONITORING OF ASCENSION ISLAND, SOUTH ATLANTIC

DOE/ID/12489-12
ESL-88011-TR

by

M. Lee Allison

EXECUTIVE SUMMARY

A network of 6 to 8 portable earthquake seismometers recorded seismic activity on Ascension Island from September 12 to December 19, 1987. The goal was to detect and locate earthquakes that define active faults. These would be used in siting geothermal test wells.

During 92 days of active operation, 168 seismic events were recorded, averaging over 1.8 events per day. Forty-four events have been located, or which 7 occurred on the island and 37 offshore but still on the island pedestal. No events have been detected from off the island complex.

In addition to the normal tectonic earthquake numerous harmonic tremors were recognized throughout the survey. Harmonic tremors can indicate magma movement in the subsurface and may precede volcanic eruptions by only hours or days.

Using magnitude formulas developed for Hawaii, the largest event during the survey is magnitude 4.26. The smallest events are about magnitude -2. These are approximately equal to Richter magnitudes.

There were too few events to accurately locate active faults on the island, however, the number and distribution of all the earthquakes argues that the entire island is seismically active and numerous faults should be open providing conduits and reservoirs for geothermal fluids.

Potential dangers exist from earthquakes (ground-shaking and tsunamis) and volcanic eruptions. Continued seismic monitoring is strongly urged to understand the seismic environment and to better predict the timing and location of future activity.

More analysis of the earthquake records gathered can and should be undertaken to understand the dangers to the island.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM — ANNUAL REPORT

DOE/ID/12489-13
ESL-87001-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

APPLICATION OF BOREHOLE BREAKOUT STUDIES TO EXPLORATION AND DEVELOPMENT—AN EXAMPLE FROM COVE FORT/SULPHURDALE, UTAH

DOE/ID/12489-14
ESL-88012-JP*

by

M. Lee Allison and Dennis L. Nielson

ABSTRACT

Borehole breakouts form in response to in-situ stresses and define the principal stress orientations. Horizontal stresses imposed on the rock are concentrated at the borehole margin, perpendicular to the direction applied. Breakouts result from tensile and shear failure at the stress concentration points.

At the Cove Fort-Sulphurdale field breakouts define fault-bounded blocks of rock with independent stress fields related to a particular fault system. Stress directions change between wells and change abruptly across faults within wells. The following is concluded: different stresses on either side of a fault may tend to keep permeability high; stress orientation will determine whether injected fluids return to production fractures; knowledge of stress orientation is required for planning hydrofracture stimulation and directional drilling.

* Also published in Geothermal Resources Council, 1988 Transactions, 12, 213-219.

INDUCED POLARIZATION SPECTRA OF CASCADES CORE SAMPLES

DOE/ID/12489-15
ESL-88013-JP*

by

Alan C. Tripp, Michele M. Lemieux, Phillip M. Wright, and Joseph N. Moore

ABSTRACT

We have measured the induced polarization (IP) phase response of core from the Medicine Lake Burnt Lava hole 62-21 and from the Clackamas Thermal Gradient Hole #1. The core samples were weakly to moderately clay altered, with the alteration of low-temperature origin. The phase values at 1/64 Hz ranged in magnitude from 2 mrad to 16 mrad. Cation exchange capacities (CEC's) ranged from 3 meq/100gms to 40 meq/100gms. There was linearity between the phase and log (CEC) for hematite-poor rocks from flow interiors. We also observed linearity between log(CEC) and phase for all but one flow breccia sample. The remaining flow breccia sample was unique in possessing a large number of zeolite filled interconnected vesicles. Its phase response was the highest measured.

Our work demonstrates that Cascades rocks, when subjected to low temperature alteration can have significant IP responses.

* Also published in Geothermal Resources Council, 1988 Transactions, 12, 265-271.

FLUID CHEMISTRY AND HYDROLOGY OF THE HEBER GEOTHERMAL SYSTEM, CA

DOE/ID/12489-16
ESL-88015-JP*

by

Michael C. Adams, Michele M. Lemieux, Joseph N. Moore, and Steven D. Johnson

ABSTRACT

This paper presents the results of chemical and isotopic analyses of geothermal fluids and microthermometric measurements on fluid inclusions from the Heber geothermal system. The chemical analyses indicate that the reservoir fluids have salinities near 15000 ppm total dissolved solids and low gas contents. Small but consistent differences in the concentrations of total CO_2, B, Li, O-18, and deuterium are found between the fluids that feed the two power plants. These differences may be due to divergent paths of the thermal fluids as they flow from the south.

Fluid inclusion homogenization temperatures are similar to the present temperatures in a gradient well near the zone of upflow but are generally lower in the other two wells studied. Salinities determined from the freezing measurements suggest that the fluids contained within the inclusions are mixtures of the production fluids and other lower-salinity waters.

* Also published in the 14th Annual Stanford Geothermal Reservoir Engineering 1989 Workshop.

THE EFFECT OF A METAL WELL CASING ON 3D INTERPRETATION OF BOREHOLE RESISTIVITY DATA

DOE/ID/12489-17
ESL-88016-JP*

by

Douglas J. LaBrecque and Stanley H. Ward

ABSTRACT

A method of computing the resistivity coupled responses of three-dimensional bodies of arbitrary conductivity and metal well casings in a half-space is discussed. The method is based on integral equations and uses subsectional basis functions for the body and continuous linear basis functions inside the well casing.

A model study was completed to determine the effect of a conductive casing on the use of borehole, cross-borehole, borehole-to-surface, and surface resistivity measurements to determine fracture locations in a geothermal environment. A suite of model calculations was made for both methods for an elongate conductive platelike body with and without a casing present.

This study did not address induced polarization measurements, but for resistivity alone the response of the casing was smaller than expected. For very long lateral array measurements effects of the casing were negligible when all of the electrodes were one interelectrode spacing below the casing. For the borehole-to-surface method, the effects of the casing were small once the transmitter, down the borehole, was completely below the casing and the receiving dipole at the surface was one casing length away from the casing. For the cross-borehole method effects of casing at the top of the receiving hole could be ignored when the dipole receiver was completely below the bottom of the casing regardless of the transmitter depth. The cross-borehole method was slightly more sensitive to having a surface casing in the transmitting hole but acceptable results were obtained when the transmitter (a single electrode) was completely below the casing and the receiving dipole .5 casing lengths below the bottom of the casing.

* Also Published in the 59th Annual International Society of Exploration Geophysicists 1989 Meeting, 1, 211-214.

TWO-DIMENSIONAL INVERSION OF CROSS-BOREHOLE RESISTIVITY DATA USING MOVEABLE BOUNDARIES

DOE/ID/12489-18
ESL-88017-JP*

by

Douglas J. LaBrecque and Stanley H. Ward

ABSTRACT

A two-dimensional inverse modeling program for direct current resistivity data was developed using the line-integral method to compute forward solutions and a sensitivity matrix. This forward solution is then inverted iteratively using a modified Marquadt-type inversion. An important innovation in this algorithm is that it directly determines locations of boundaries of arbitrarily shaped regions as well as the conductivities within them.

Results are shown for the application of the inversion of synthetic data for the borehole to-borehole and the borehole-to-surface configurations. For all models horizontal boundaries are relatively well resolved but vertical boundaries are poorly resolved. For two-dimensional models the conductivities are accurately determined by the inversion program. When three-dimensional models, and models which were not perpendicular to strike, were interpreted assuming two-dimensional, structures perpendicular to strike, resistivity estimates for confined bodies where significantly in error.

* Also published in the 58th Annual International Society of Exploration Geophysicists 1989 Meeting, 1, 194-197

CROSS-BOREHOLE RESISTIVITY INVERSION

DOE/ID/12489-19
ESL-88018-JP*

by

Craig W. Beasley and Stanley H. Ward

SUMMARY

We have developed a computer algorithm based on the method of finite elements which is capable of both forward and inverse modeling of the cross-borehole resistivity response of a two-dimensional (2-D) earth excited by a three-dimensional (3-D) point source of current. The algorithm, which is formulated in terms of secondary potentials, simultaneously handles multiple transmitter-receiver configurations using pole-pole and pole-dipole arrays (Figure 1). The inversion algorithm solves for block resistivities via a Marquardt-Levenberg damped least-squares technique. Analysis of the accuracy of both forward and inverse modeling indicates that the cross-borehole resistivity method is a viable exploration tool.

* Also published in the 58th Annual International Society of Exploration Geophysicists 1989 Meeting 1, 198-200.

DESIGN OF A BOREHOLE-TO-SURFACE RESISTIVITY SURVEY FOR THE MAGMA ENERGY DEEP EXPLORATION WELL

DOE/ID/12489-20
ESL-88019-JP*

by

Douglas J. LaBrecque

ABSTRACT

Design of a borehole-to-surface survey using the proposed the DOE Magma Energy Program's deep exploration well in Long Valley Caldera is discussed. High and low resolution surveys were considered. The ability to locate structural boundaries was determined by generating data sets for a 3-D conductor in a half-space containing a conductive well casing, adding random noise and inverting the data using 2-D inversion.

The high resolution survey was able to resolve the locations of most of the boundaries of the conductor within 200 m. even with 15% random noise added. However use of 2-D interpretation for 3-D wells caused errors in locating the bottom the conductor away from the well. Interpretation techniques to correct for this distortion must be developed. The low resolution survey was able to determine very gross structures with a resolution of the order of 1000 m.

* Also published in Geothermal Resources Council, 1988 Transactions, 12, 257-261.

RESEARCH CORING IN THE CASCADES—A STATUS REPORT

DOE/ID/12489-21
ESL-88020-JP*

by

Michele M. Lemieux, Phillip M. Wright, and Joseph N. Moore

ABSTRACT

The High Cascades volcanic province has long been suspected to contain considerable geothermal potential. However, few deep wells have been drilled, and much of the data that have been accumulated are proprietary. In response to the need to obtain a better understanding of the Cascades region, the U.S. Department of Energy, Geothermal Technology Division, sponsored a cooperative research program with industry based around obtaining data from research coreholes. This paper is a progress report on the three coreholes completed to date, including a summary of drilling histories and a description of the scientific studies underway and of the open file data available.

* Also published in Geothermal Resources Council, 1988 Transactions, 12, 41-47.

ARSENIC GEOCHEMISTRY IN GEOTHERMAL SYSTEMS

DOE/ID/12489-22
ESL-88022-JP*

by

Judith M. Ballantyne and Joseph N. Moore

ABSTRACT

Arsenic is both boon and bane in the geothermal and gold industries. The presence of arsenic in rocks is used as an exploration guide for geothermal systems and for the epithermal gold deposits which are their fossil analogs. Arsenic is present in trace concentrations in geothermal fluids, and the ratio of its concentration to chloride has been used to identify different aquifers and the extent of evaporation within individual fields. However, arsenic contamination of water supplies is a serious environmental problem in areas where fluids are discharged and not reinjected, such as at Wairakei-Broadlands in New Zealand and Tongonan in the Philippines. In some U.S. geothermal fields its abundance is sufficiently high to require disposal of production line precipitates in hazardous waste sites. Arsenic in epithermal gold ores poses additional problems which require costly handling and in certain cases preclude mine operation.

Despite the importance of arsenic as an exploration pathfinder element and as an environmental contaminant, the behavior of arsenic in high temperature environments is poorly known. Geothermal systems offer an ideal opportunity to investigate its behavior because of the large amount of information available on fluid chemistry, temperature and alteration patterns.

* Also published in 1988, Geochimica et Cosmochimica Acta, 52, 475-483.

A SHEET ZIPPER THEORY OF SMECTITE ILLITIZATION—IMPLICATIONS AND EVIDENCE

DOE/ID/12489-23
ESL-88023-JP*

by

Judith M. Ballantyne

ABSTRACT

A new theory of smectite illitization and illite/smectite formation is proposed, and the predictions of the theory are rested against published information. Chlorite is formed as a byproduct or the illitization reaction.

The formation of illite/smectite is hypothesized to occur by four different and progressive mechanisms. I. Dissolution of smectite layers at layer terminations, initiated by the breaking of R^{+2}-o bonds, followed by the formation of "paired illite" layers by dehydration of K^+ ions, driven by P. H. Nadeau and colleagues. II. Precipitation of lath-like or filamentous illite at the margins of illite/smectite platelets, by deposition of products from the dissolution of internal smectite layers. The location of lath growth is controlled largely by the position of channelways provided by edge dislocations within the crystal, along which dissolution products are transported. III. Sealing together of paired illite layers into a massive illite structure, by replacement of exchangeable cations on the outer faces of the illite pairs by K^+. IV. Solid phase rearrangements of ions into a muscovite-like structure.

Predictions of the theory are supported by published studies in the areas of scanning and transmission electron microscopy, X-ray diffraction, mineral chemistry, hydrothermal fluid chemistry, and kinetics.

* Also published in the 1988 Geological Society of America, Abstracts with Program, 20, 7, A357.

HYDROTHERMAL PROCESSES

DOE/ID/12489-24
ESL-88026-TR*

by

Dennis L. Nielson, Judith M. Ballantyne, and Jeffrey B. Hulen

ABSTRACT

The study of the Valles caldera hydrothermal system has used an integrated approach to 1. establish models for the volcanic-hydrothermal system, and 2. demonstrate the application of methodologies including lithologic logging, structural synthesis, hydrothermal alteration, and fluid inclusion geothermometry. This approach has largely been based on data developed by Union Oil Co. in the Baca project, and it has recently been supplemented by two core holes drilled under the Continental Scientific Drilling Program.

The Valles is representative of a caldera-hosted geothermal system which is the most complex type of volcanic-related geothermal systems. Understanding the hydrothermal processes requires a knowledge of eruptive history and associated structural development that determine location of permeable areas within the caldera. Tracking of fluid flow has utilized alteration mineralogy and fluid inclusions. The principal cause of the destruction of permeability in the Valles and many other geothermal systems is flooding of fractures by illite. The formation of this mineral is being studied in detail at UURI.

The composition of illite is partly dependent on the temperature at which it forms. Modeling of geothermal illites as smectite-muscovite solid solutions has resulted in the development of a new chemical geothermometer that is potentially useful in the temperature range 200° to 300°C. However, because temperature is not the only factor affecting illite formation, it is necessary to quantify the effects of other factors. Chemical environment, and whether or not the illite fills fractures or replaces a precursor mineral, also affect the composition of the illite formed. Understanding of the mechanism of illite formation is necessary before the geothermometer can be used quantitatively to determine temperatures of formation.

A new theory for the mechanism of illite formation has been developed. This theory provides a framework for understanding the geological occurrence of both illite/smectite and illite, and for developing new exploration and industrial uses of these minerals. New studies to refine the use of the illite geothermometer are underway at UURI.

* Also published in the 1988 Lawrence Berkeley Laboratory Report, LBL-25635.

THE EFFECT OF DISPLACEMENT CURRENT ON THE RESPONSE OF A HIGH-FREQUENCY ELECTROMAGNETIC SYSTEM

DOE/ID/12489-25
ESL-88028-JP

by

D. C. Fraser, John A. Stodt, and Stanley H. Ward

ABSTRACT

The new multicoil DIGHEM^{IV} system employs three frequencies, the highest of which is 56000 Hz. This frequency induces appreciable displacement currents in some geologic environments. An analysis of the current flow induced by the high frequency is presented to assess the limitations of the system. Forward model computations for half-space models for a suite of resistivities and relative dielectric permitivities show that the effects of displacement currents must be considered once they exceed approximately 5% of the conduction currents. An analysis of the effect of neglecting displacement currents during parametric inversion for resistivity alone shows that significant bias error due to model inadequacy is introduced as displacement currents exceed 5% of the conduction currents. When displacement currents are significant, the weighting of the residuals determines the value of resistivity obtained from a joint inversion of the in-phase and quadrature responses. Weighting which overemphasizes the in-phase residual results in an overestimate of the true resistivity, while weighting which overemphasizes the quadrature component results in an underestimate of the true resistivity. Weighting based on the standard deviation of random errors in the in-phase and quadrature measurements does not, in general, remove the systematic errors introduced due to model inadequacy. Errors in the estimated resistivity can exceed 10% as displacement currents exceed 5% of the conduction currents.

REGIONAL EXPLORATION FOR HYDROTHERMAL RESOURCES

DOE/ID/12489-26
ESL-88030-JP*

by

Phillip M. Wright, Dennis L. Nielson, Howard P. Ross, Joseph N. Moore, Stanley H. Ward,

and Michael C. Adams

ABSTRACT

Intrusion of magmas into the crust is controlled on a regional scale by global tectonic and magmatic processes. Magmas generated in the mantle are mafic in composition and are relatively mobile because of their low viscosity. Felsic magmas, which have much higher viscosity, are generated by progressive differentiation from mafic magmas or by fusion of crustal material. They are less mobile than mafic magmas, and tend to accumulate in magma chambers at depths of a few to a few tens of kilometers. With continued magmatic input, felsic magma bodies of large enough size have significant thermal impact on the crust, and are believed to be responsible for most of the known high-temperature hydrothermal convection systems.

The purpose of regional exploration is to locate and prioritize geothermal prospects within large reconnaissance areas of 10,000 to 1,000,000 km^2. Regional exploration for high-temperature hydrothermal systems should concentrate in areas where there are one or more of the following indicators: (1) active or fossil surface manifestations such as hot springs, fumaroles, spring deposits, or hydrothermally altered ground; (2) volcanic rocks less than about 1 million years old, with relatively higher priority assigned if there is evidence for silicic volcanism; (3) high regional heat flow and high thermal gradients; and, (4) active tectonism and seismicity. Indicators (2) and (3) relate to the possible presence of heat sources whereas indicator (4) gives evidence that permeability may be periodically rejuvenated.

Most regional exploration techniques are also used for subregional and detailed exploration of hydrothermal systems. Regional exploration programs should be guided by strategies specifically designed for the area of interest. Such strategies allow systematic application of techniques and promote decision-making at specific stages. A systematic approach helps reduce both the risk of failure and the cost of exploration.

* Also published in Geothermal Science and Technology, in press.

ILLITE/SMECTITE USES IN GEOTHERMAL SYSTEMS

DOE/ID/12489-27
ESL-88031-JP*

by

Judith M. Ballantyne

ABSTRACT

The composition of illite is partly dependent on the temperature at which it forms. Modeling of geothermal illites as smectite-muscovite solid solutions has resulted in the development of a new chemical geothermometer that is potentially useful in the temperature range 200° to 300°C (Ballantyne and Moore, 1988). The calculated smectite content of illite appears to be a reasonable predictor of temperature, at least for the published data available. Because of the exchangeability of interlayer cations in smectite and the general non-reversibility of the smectite to illite reaction, use of the illite geothermometer may be restricted to systems in which the associated aqueous chemistry conforms to the Na-K-Ca geothermometer. Thus illites in sedimentary basin systems, and in waning or fossil hydrothermal systems subjected to subsequent, non-illitizing fluids, may not fit the model.

Because temperature is not the only factor affecting illite formation, it is necessary to quantify the effects of other factors. Chemical environment, and whether or not the illite fills fractures or replaces a precursor mineral, also affect the composition of the illite formed. New studies to refine the use of the illite geothermometer are underway at UURI.

Understanding of the mechanism of illite formation is necessary before the geothermometer can be used quantitatively to determine temperatures of formation. A new theory for the mechanism of illite/smectite and illite formation has been developed at UURI.

Predictions of a four-part mechanism for smectite illitization are born out by published data from diverse sources. The four parts of the mechanism are: Ia. Dissolution of smectite layers at layer terminations, initiated by the breaking of Mg-O bonds. Ib. Formation of paired illite layers by dehydration of K^+ ions, driven by conservation of Al^{3+} from the dissolved smectite layers. II. Precipitation of lath-like or filamentous illite at the margins of illite/smectite platelets, by deposition of products from the dissolution of internal smectite layers. The location of lath growth is controlled in part by the position of channelways provided by edge dislocations within the crystal, along which dissolution products are transported. III. Sealing together of paired illite layers into a massive illite structure, by replacement of exchangeable cations on the outer faces of the pairs by K^+.IV. Solid phase rearrangements of ions into a muscovite-like structure.

Illite and I/S can also be formed by other mechanisms, not requiring a smectite precursor. These include replacement of other minerals, and precipitation from solution.

Predictions of the theory are validated by published information in the areas of electron imaging (SEM and TEM), XRD, chemical composition, ^{29}Si NMR analysis, geothermal fluid composition, hydrothermal experiments and kinetics. New thermodynamic models for illite/smectite are indicated. This theory provides a framework for understanding the geological occurrence of both illite/smectite and illite, and for developing new exploration and industrial uses of these minerals.

* Also Published 1988, in Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology, Lawrence Berkeley Laboratory Report, LBL-25635, 18.

USE OF FLUID INCLUSION STUDIES

IN GEOTHERMAL EXPLORATION AND RESERVOIR CHARACTERIZATION

DOE/ID/12489-28
ESL-88032-JP*

by

Joseph N. Moore and Michael C. Adams

ABSTRACT

A hydrologic model of a geothermal system must include data on the location and characteristics of the reservoir fluids, how these fluids interact, where boiling and mixing occur, and the velocity and direction of fluid movement through the reservoir. These data are vital as input to models that predict the behavior of a geothermal system, and to the placement of production and injection wells.

Chemical analysis of the wellbore discharges and the production characteristics measured during flow tests provide the basis for the hydrologic models currently in use. Unfortunately, most drilling and completion programs are not designed to obtain the samples required for the development of detailed hydrologic models. Geothermal production wells are frequently completed over intervals of hundreds to thousands of feet, and thus the samples obtained from them are averages of different fluids. Exploration wells, in contrast, are often unproductive or produce fluids contaminated with drilling mud.

Additional data on the fluids can be obtained from fluid inclusions contained within minerals deposited by the geothermal fluids. Fluid inclusions are small liquid- or gas-filled cavities up to several tens of microns in diameter, formed during mineral growth or subsequent fracturing. Because the temperature and apparent salinity during their formation can be determined, fluid inclusion data can be interpreted with respect to boiling, mixing, conductive cooling and steam heating by applying methods analogous to those used in the interpretation of fluid analyses. The applications of fluid inclusion data to understanding the fluid flow patterns and distribution of fluid types in geothermal systems of the Imperial Valley has recently been demonstrated by Moore and Adams (1988) and Adams et al. (1988).

We are currently studying the fluid inclusions at Coso, East Mesa, Heber, and Los Azufres under cooperative research agreements with California Energy Inc., GEO, Chevron Resources, and the Comision Federal de Electricidad, respectively. These data are being combined with the results of reservoir engineering studies, analyses of the produced fluids, and the geologic relationships to develop detailed hydrologic models of these systems. This work has allowed us to better define the compositions and distributions of the fluids within these systems.

The data obtained to date indicate that fluid inclusion studies combined with chemical analyses of the fluids can be a powerful tool for obtaining the information needed to develop detailed hydrologic models.

* Also published in Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology Research in Progress, 1988, Lawrence Berkeley Laboratory Report, LBL-25635, 19-22.

PHYSICAL AND CHEMICAL ROCK PROPERTY MEASUREMENTS IN GEOTHERMAL EXPLORATION RESERVOIR STUDIES

DOE/ID/12489-29
ESL-88033-JP*

by

Alan C. Tripp, Michele M. Lemieux, Phillip M. Wright, and Joseph N. Moore

ABSTRACT

Electrical geophysics has been used extensively in geothermal exploration to detect fracture systems and high-temperature brines which give rise to low resistivity zones. However, low temperature clay alteration can also cause a low resistivity zone. We suggest that the IP method can be used to distinguish a low resistivity zone caused by clay alteration from low resistivity zones arising from different causes. We have measured the induced polarization (IP) phase response of core from the Medicine Lake Burnt Lava hole 62-21 and from the Clackamas Thermal Gradient Hole #1. The core samples were weakly to moderately clay altered, with the alteration of low-temperature origin. We noted a direct relationship between the IP response of the samples and their degree of low-temperature alteration.

* Also published in Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology Research in Progress, 1988, Lawrence Berkeley Laboratory Report, LBL-25635, 65
69.

MAGNETOTELLURICS IN DEEP GEOTHERMAL EXPLORATION APPLICATIONS TO THE LONG VALLEY MAGMATIC SYSTEM

DOE/ID/12489-30
ESL-88034-JP*

by

Philip E. Wannamaker

ABSTRACT

The application of magnetotellurics (MT) in geothermal exploration often has been disappointing due to a lack both of high-quality data and of reliable interpretations. Primarily under DOE support, we have developed a research MT system incorporating a remote reference and sophisticated real-time statistical processing which yields the very high quality data needed to resolve subtle features in complex geologic environments. Also, we have produced uniquely versatile two- and three-dimensional interpretation algorithms appropriate to geothermal systems, and have made the algorithms available to others. A key theoretical contribution from our MT computer simulations is an understanding of the utility of 2D interpretation approaches for data taken over 3D prospects. Specifically, the transverse magnetic (TM) mode must be emphasized since it is relatively robust to departures from the 2D assumption.

In Long Valley caldera, we have collected twenty-four high-quality MT soundings with support from the DOE/GTD/Magma program. Our data set reveals a rich variety of conductivity structures which relate to the evolution and present state of the Long Valley system. These include conductive layers on the order of 1 km deep from Clay Pit to the east wall of the caldera, beneath the axial graben of Smokey Bear Flat, and under the west moat. Resistive, probably crystalline basement at high levels is apparent in a central block from the center of resurgence to Clay Pit well. Most intriguing is a subtle anomaly in the transverse electric mode impedance phase which is suggestive of a deep conductive axis centered beneath the axial graben and resurgent dome. A finite element conductivity cross section has been derived for the upper three kilometers of the caldera and modeling is in progress for the deeper portions of the system.

* Also published in Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology Research in Progress, 1988, Lawrence Berkeley Laboratory Report, LBL-25635, 59
64.

STRESS IN ACTIVE GEOTHERMAL SYSTEMS

DOE/ID/12489-31
ESL-88035-JP*

by

M. Lee Allison and Dennis L. Nielson

ABSTRACT

Borehole breakouts form in response to *in-situ* stresses and define the principal stress orientations. Horizontal stresses imposed on the rock are concentrated at the borehole margin, perpendicular to the direction applied. Breakouts result from tensile and shear failure at the stress concentration points.

Multiple stress fields separated by faults are present in wells in Roosevelt Hot Springs, Cove Fort/Sulphurdale, and Baca geothermal fields. The stresses are independent of regional forces and appear to be directly related to local or adjacent faults.

Determination of individual stress blocks allows prediction of hydrofrac direction, and discrimination of intervals favorable for pressure maintenance or waste injection.

* Also published in Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology Research in Progress, 1988, Lawrence Berkeley Laboratory Report, LBL-25635, 11
17.

DEVELOPMENT OF CHEMICAL TRACERS FOR RESERVOIR STUDIES

DOE/ID/12489-32
ESL-88036-JP

by

Michael C. Adams and Joseph N. Moore

ABSTRACT

Fluid tracers are necessary in order to define the movement of injected spent brine through a geothermal system. Because of high detection limits, the commonly used halide tracers are expensive or inaccurate to use with injection tests. At UURI we have tested 40 compounds for their use as geothermal tracers. Of these, 15 have been shown to be stable at temperatures of up to 250°C, and at least 4 are stable to 300°C. These tracers have detection limits of approximately 50 ppb, and we are currently working on lowering them to 60 ppt. We will be testing several of these tracers under actual geothermal conditions in a large-scale injection test at Dixie Valley this year.

FRACTURE SYSTEMATICS IN HIGH-TEMPERATURE GEOTHERMAL FIELDS—

ROLES OF INHERITED STRUCTURES AND STRESS FIELD REORIENTATION

DOE/ID/12489-33
ESL-88039-JP*

by

Dennis L. Nielson, Jeffrey B. Hulen, and M. Lee Allison

ABSTRACT

Geologic mapping in high-temperature geothermal fields inevitably demonstrates very complex fault patterns. In the U. S., it has been a common exploration axiom that permeability is greatest at the intersection of fault systems; however, little thought has been given to the mechanism of formation of intersecting faults. Analysis of fault systematics indicates that faults within high-temperature geothermal systems are commonly formed under the influence of two or more stress orientations. Inherited structures are classified as older faults that are superimposed on younger rocks. Changes in stress orientation and magnitude with time may maintain, enhance or destroy permeability depending on the orientation of the stress fields with respect to pre-existing faults. This includes the process of reactivation of older faults and the use of these faults as geothermal reservoirs. Hydrothermal alteration generally destroys permeability, and the formation of clays and other alteration products at temperatures below the epidote isograd inhibit the structural regeneration of fluid flow channels.

* Also published in the International Symposium of Geothermal Energy, Kumamoto and Beppu, Japan, 28-30.

DIPOLE-DIPOLE ELECTRICAL RESISTIVITY SURVEYS

AT WASTE DISPOSAL STUDY STIES IN NORTHERN UTAH

DOE/ID/12489-34
ESL-88040-JP*

by

Howard P. Ross, Claron E. Mackelprang, and Phillip M. Wright

ABSTRACT

A large number of old landfills, and chemical- and industrial-waste disposal sites have been located in alluvial and Bonneville lakebed deposits of northern Utah. Fine-grained silts and clay layers within these deposits are important as aquitards to the vertical migration of waste fluids and as low-permeability zones which channel the subsurface movement of groundwater and fluid contaminants. Dipole-dipole resistivity surveys are a cost-effective technique for mapping the configuration of underlying clay layers as well as the near-surface discontinuities of landfills and buried disposal trenches.

Dipole-dipole profiles were completed over two large landfills and three waste-disposal pits at Hill Air Force Base, Utah, in 1982 as part of a Phase II hydrogeologic survey within the U. S. Air Force Installation Restoration Program. Apparent resistivities observed with 9-meter dipoles varied from more than 700 ohm-m to less than 10 ohm-m on several profiles. This range of apparent resistivities indicates the heterogeneous nature of the alluvial material, variation in the degree of saturation, and the presence of, or depth to, clay layers.

Numerical modeling of selected profiles aided in mapping the top of clay layers at depths of 3 to 20 meters, the prefill surface of a large landfill, and the morphology of a slump block at one chemical-waste disposal pit. The resistivity data, supplemented by ground magnetic and self-potential profiles, provided guidance for a drilling and sampling program and continuity for understanding the sampling results.

* Also published in Utah Geological Association Pub. 17, 1989, *in* Geology and Hydrology of Hazardous Waste, Mining-Waste, Waste-Water and Repository Sites in Utah, 69-79.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

JANUARY 1 -- MARCH 31, 1988
APRIL 1 — JUNE 30, 1988

DOE/ID/12489-35
ESL-88041-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

SHORT NOTE—APPLICATION OF ELECTROMAGNETIC RECIPROCITY

DOE/ID/12489-36
ESL-88042-JP

by

Alan C. Tripp and Gerald W. Hohmann

INTRODUCTION

Electromagnetic reciprocity enables the geophysicist to gain insight into the behavior of electromagnetic fields and to save time and money by avoiding redundant measurements or computations. Although the electrical engineering literature has many discussions on electrical and electromagnetic reciprocity (e.g., Harrington, 1967; Monteath, 1973; Kong, 1986), applying the reciprocity relations in specific situations can be confusing. In this not we attempt to clarify the application of electromagnetic reciprocity in practical geophysical cases.

GAMMA-RAY SPECTROMETRY AND RADON EMANOMETRY IN ENVIRONMENTAL GEOPHYSICS

DOE/ID/12489-37
ESL-88043-JP

by

Dennis L. Nielson, Linpei Cui, and Stanley H. Ward

ABSTRACT

Gamma-ray spectrometry, airborne or ground, may be useful in a wide variety of geologic mapping applications because the concentrations of uranium, thorium, and/or potassium may be diagnostic of rock type. However, in areas of little outcrop, the surface material must be either residual or locally derived before gamma-ray spectrometry can be applied successfully for geologic mapping. Mapping of rocks high in thorium and uranium will, under appropriate conditions, delineate lithologies that may be a source of radon.

To be of maximum use data from gamma-ray spectrometry surveys must be acquired with utmost care. Accordingly, attention must be directed to the evaluation of such problems as disequilibrium in the uranium decay series, removal of atmospheric background radiation, the effect of rainfall and other meteorological phenomena, calibration of spectrometers, statistical errors in count rates, fields of view of gamma-ray detectors, and the effect of overburden. Modern instrumentation, calibration, and analysis are such that data can be evaluated with such care that as little as 1 ppm U, 1 ppm Th, or 0.1 percent K can be detected reliably with an airborne or ground gamma-ray spectrometry survey.

Radon is a gas whose short half-life (3.8 days for ^{222}Rn) enables it to travel only a limited distance in the geologic environment. It is a daughter product of the uranium and thorium decay series and has been used in the exploration for uranium ore deposits. Radon is liberated into pore fluid or gas by the recoil of the nucleus on formation from radium. To some extent, diffusion processes are also active. Once liberated from the crystalline rock, transport takes place either by diffusion or coupling with the flow of soil gas or groundwater. The flux of radon from the soil to the atmosphere generally follows a diffusion model. However, atmospheric variables may deplete or enhance the concentration of radon, particularly at shallow depths.

Gamma-ray spectrometry and radon emanometry are being applied to the definition of radioactive waste sites as shown in an example from Salt Lake City, Utah. In addition, both techniques are being used to assess geologic cause s of indoor radon pollution. Examples are also given to demonstrate that radon can be used to locate faults and fractures.

THE REGIONAL EVALUATION OF RADON HAZARD

DOE/ID/12489-38
ESL-88044-TR

by

Linpei Cui

ABSTRACT

Gamma-ray spectrometry, airborne or ground, may be useful in a wide variety of geologic mapping applications. However, in areas of little outcrop, the surface material must be either residual or locally derived before gamma-ray spectrometry can be applied successfully. Mapping of rocks high in thorium and uranium will, under appropriate conditions, delineate lithologies that may be a source of radon.

To be of maximum use data from gamma-ray spectrometry surveys must be acquired with utmost care. Accordingly, attention must be directed to the evaluation of such problems as disequilibrium in the uranium decay series, removal of atmospheric background radiation, the effect of rainfall and other meteorological phenomena, calibration of spectrometers, statistical errors in count rates, fields of view of gamma-ray detectors, and the effect of overburden. Modern instrumentation, calibration, and analysis are such that data can be evaluated with such care that as little as 1 ppm U, 1 ppm Th, or 0.1 percent K can be detected reliably with an airborne or ground gamma-ray spectrometry survey.

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Gamma-ray spectrometry and radon emanometry are being applied to the definition of radioactive waste sites as shown in an example from Salt Lake City, Utah. In addition, both techniques are being used to assess geologic causes of indoor radon pollution. Examples are also given to demonstrate that radon can be used to locate faults and fractures, evaluate slope stability, map caves in karst terrain, and locate groundwater associated with a fault zone.

The Soviet satellite COSMOS-954 upon entering the earth's atmosphere disintegrated into radioactive debris spread over a large area in Northern Canada. Thirty-five hundred pieces of debris were eventually found aided by airborne gamma-ray spectrometry.

The Soviet nuclear accident at Chernobyl caused radioactive debris to be carried by winds west-northwest imposing a serious risk to health downwind. Airborne and ground gamma-ray spectrometry permitted Swedish agencies to map the parts of their country with the highest levels of contamination.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

JULY 1 — SEPTEMBER 30, 1988

DOE/ID/12489-38a
ESL-88046b-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

FINAL REPORT—ASCENSION ISLAND GEOTHERMAL PROJECT

DOE/ID/12489-39
ESL-88047-TR

by

Dennis L. Nielson, M. Lee Allison, Michael C. Adams
University of Utah Research Institute

and

Susan G. Stiger, Martin M. Plum, G. R. Berglund
Idaho National Engineering Laboratory

ABSTRACT

This report summarizes the results of geothermal exploration and drilling and testing of a deep test well on Ascension Island in the South Atlantic Ocean. The U.S. Air Force is interested in reliable, economic methods to produce power and potable water on Ascension and geothermal energy would satisfy that objective. Geothermal development would be invulnerable to disruption due to external economic or political factors, a distinct advantage for critical U.S. Air Force operations on this remote island.

The siting and drilling of the Ascension #1 well was the culmination of an exploration program that began in 1982. The well was started on August 3, 1986 and terminated on January 23, 1988. Ascension #1 intersected geothermal fluids at several levels below a depth of 8000 feet. The temperatures of these fluids are in the upper range of commercial geothermal reservoirs at similar depths. However, the volume of fluid flow was limited. While attempting to improve production by drilling a second leg, a mechanical failure resulted in loss of the well.

Economic analyses indicate that replacement of the existing diesel power generating equipment with a geothermal power plant could result in savings of as much as $112 million over the primary replacement alternative, a gas turbine. A geothermal power plant offers the additional advantage of producing about three times the current U. S. potable water demand on Ascension. On the basis of the discovery of a geothermal resource and excellent economic factors, continued drilling is recommended. An independent of panel of industry experts verified the high resource potential and recommended continued drilling.

A FLUID FLOW MODEL OF THE COSO GEOTHERMAL SYSTEM—

DATA FROM PRODUCTION FLUID AND FLUID INCLUSIONS

DOE/ID/12489-40
ESL-89001-JP*

by

Joseph N. Moore, Michael C. Adams, Barbara P. Bishop, and Paul Hirtz

ABSTRACT

Coso is one of several high-temperature geothermal systems associated with recent volcanic activity in the Basin and Range province. Within this fracture-dominated system, temperatures as high as 340°C have been measured at depths of less than 2.5 km. Chemical analyses of the production fluids show that steep gradients in the salinities, gas concentrations, and temperatures occur within the reservoir. Salinities and CO_2 contents range from 1.05 wt.% TDS and 0.95 wt.% CO_2 in the southern part of the field to 0.37 wt.% TDS and 0.06 wt.% CO_2 in the north and east.

Fluid inclusion data have been used to characterize the compositions and temperatures of the reservoir outside the production zones. Homogenization temperatures of the fluid inclusions ranged from 328° to less than 100°C. Ice- and clathrate-melting temperatures indicate that the fluids have salinities up to 1.4 equivalent wt.% NaCl and variable but significant CO_2 contents.

The chemical and fluid inclusion data define a plume of thermal fluid that rises from depth in the south, and travels outward toward the north and east.

* Also published in the Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, in press.

FLUID CHEMISTRY AND HYDROLOGY OF THE HEBER GEOTHERMAL SYSTEM, CA

DOE/ID/12489-41
ESL-89002-JP*

by

Michael C. Adams, Michele M. Lemieux, Joseph N. Moore, and Steven D. Johnson

ABSTRACT

Heber is one of several moderate-temperature geothermal resources occurring in the Salton Trough. Chemical and isotopic analyses of the geothermal fluids and microthermometric measurements on fluid inclusions have been conducted to refine the existing geologic and reservoir engineering models of this system. Chemical analyses indicate that the reservoir fluids have salinities near 15,000 ppm total dissolved solids and low gas contents. Small but consistent differences in the concentrations of ΣCO_2, B, Li, O18, and deuterium are found between the fluids that feed the two power plants. These differences may be due to divergent paths of the thermal fluids as they flow from the south to the north.

Heating and freezing measurements have been made on fluid inclusions from three thermal gradient wells. Homogenization temperatures are similar to the present temperatures in the gradient well closest to the center of upwelling but are generally lower in the other wells, indicating some cooling has occurred or flowpaths have changed. Salinities determined from the freezing measurements suggest that the fluids contained within the inclusions are mixtures of the production fluids and other lower-salinity fluids. Local variations in the CO_2 contents of the fluids are indicated by the presence of CO_2 clathrate in some inclusions found in one of the gradient wells.

* Also published in the 14th Annual Stanford Geothermal Reservoir Engineering 1989 Workshop.

CROSS-BOREHOLE RESISTIVITY INVERSION—

THEORY AND APPLICATIONS TO MONITORING ENHANCED OIL RECOVERY

DOE/ID/12489-42
ESL-89003-TR*

by

Craig W. Beasley

ABSTRACT

An algorithm capable of both forward and inverse modeling of cross-borehole resistivity data has been developed. The method of finite elements (FEM) forms the basis of the forward algorithm which computes the secondary electric potential response of a two-dimensional (2-D) earth excited by a three-dimensional (3-D) point source of direct current (commonly referred to as the 2-D/3-D problem). Total potentials are obtained by adding analytic primary potentials to the computed secondary potentials. The inverse algorithm which is applied to the forward algorithm is an iterative, smoothed least-squares minimization applied to an objective function. The objective function is a weighted sum of the squared residuals between observed and computed data sets and the inversion parameters are the resistivities of constant-resistivity blocks.

As is typical with any 2-D/3-D problem, the governing differential equation for the forward problem is formulated in wavenumber domain via a Fourier transform which removes the effects of the source in the strike direction. The FEM is applied to the transformed equation and potentials in wavenumber domain are computed for a discrete number of transform variables. These potentials are then numerically inverse transformed to obtain potentials in 3-D Cartesian domain. An analysis of the effects of using different transform variables is presented. The inverse transform method presented here allows for a cosine transform so that transmitters and receivers are not required to be contained within the plane perpendicular to strike.

The inverse algorithm is then applied to synthetic pole-pole and pole-dipole data contaminated with random noise in an attempt to ascertain what can realistically be resolved from cross-borehole resistivity inversions. Modeling indicates that the ability of the technique to recover correct electrical structure is highly dependent upon model parameterization, indicating the need to utilize all available well log and geologic information when designing a starting model for an inversion.

Finally, inverse program is then used to evaluate the applicability of cross-borehole resistivity inversion to monitoring enhanced oil recovery (EOR) processes. The synthetic model study, which is generic rather than site specific, is directed towards tracking hot water and steam floods. Also included is a discussion of EOR induced rock resistivity variations. The analysis shows that for typical resistivity contrasts associated with EOR processes, repeatedly performing cross-borehole resistivity surveys can be a successful method of tracking EOR fronts.

* Also published as a Ph.D., Thesis, University of Utah, Department of Geology and Geophysics, January 1989, 133p.

THEORETICAL STUDIES OF THE CROSS-BOREHOLE AND BOREHOLE-TO-SURFACE RESISTIVITY METHODS

DOE/ID/12489-43
ESL89004-TR*

by

Douglas J. LaBrecque

ABSTRACT

A two-dimensional (2-D) direct-current resistivity forward-modeling algorithm based on the line-integral equation solved using the Nystrom method is discussed. The accuracy of the Nystrom method solution is equal or superior to the finite-difference and finite-element algorithms to which it was compared.

A modified Marquardt numerical inverse algorithm was developed based on the Nystrom method solution. The inverse algorithm, which determines location of boundaries of arbitrarily shaped regions as well as the conductivities within them, was investigated using synthetic data. It was found that a priori information could be used to allow the inverse algorithm to avoid extraneous minima. Two-dimensional inverse modeling located the boundaries of a three-dimensional (3-D) conductor for synthetic data taken perpendicular to strike. However, the 2-D inverse modeling produced poor results for synthetic data taken at an obtuse angle to strike.

A robust inversion algorithm that iteratively removes the effects of large, random errors in a few data points was able to reduce but not eliminate the effects of geologic noise. In some cases it was difficult to determine the existence of multiple conductors in a half-space or that a conductor contained multiple regions. In one case inversion assuming a conductor in a half-space properly located the boundaries a 2-D conductor on an interface between two different quarter-spaces.

An algorithm was developed that uses the method of integral-equations to calculate the scattered potential due to a finite length well casing in the presence of arbitrary 3-D bodies. The algorithm was used to compare the responses of a conductive 100 m by 1000 m by 1000 m vertical dike with and without the casing present for a variety of arrays. These include borehole, cross-borehole, borehole-to-surface arrays. Results showed that the effects of the conductive casing were usually smaller than anticipated.

* Also published as a Ph.D. Thesis, University of Utah, Department of Geology and Geophysics, March 1989, 212p.

ANNUAL REPORT FOR FY88—GEOTHERMAL RESEARCH

DOE/ID/12489-44
ESL-89005-TR

edited by

Phillip M. Wright

INTRODUCTION

The University of Utah Research Institute (UURI) is a self-supporting non-profit corporation wholly owned by the University of Utah. The Institute receives no direct financial support from either the University of Utah or the State of Utah. We conduct both public and proprietary scientific and educational work for governmental agencies, academic institutions, private industry, and individuals.

UURI is a highly flexible organization of about 20 professionals, 8 support personnel and 5 to 25 students. Most of the professionals are full-time scientists and engineers. We comprise four divisions: the Earth Science Laboratory (ESL), the Environmental Studies Laboratory (EVSL), the Center for Remote Sensing and Cartography (CRSC) and the Engineering Technology Laboratory (ETL).

UURI and the University of Utah maintain a close relationship. Dr. James J. Brophy, President of UURI, is the Vice President for Research at the University and Dr. Milton E. Wadsworth, Secretary of UURI, is Dean of the College of Mines and Earth Sciences. Our Broad of Trustees consists of five University vice presidents and four people from the private sector.

For the past eleven years, the Earth Science Laboratory of UURI has been involved in geothermal energy research on behalf of the U. S. Department of Energy. Our work predominately concerns the development of new exploration, reservoir definition, mapping and monitoring techniques for hydrothermal systems. This report gives a brief overview of the objectives and FY88 results of our current research projects. References to past work are documented in our report entitled *Publications and Geothermal Sample Library Facilities of the Earth Science Laboratory, University of Utah Research Institute*, which will be sent to you on request.

We maintain a commitment to be of assistance in our research work to the geothermal industry. Inquiries or comments regarding our research are always welcome.

SHORT NOTE ON THIN-LAYER TELLURIC MODELLING OF MAGNETOTELLURIC RESPONSES

DOE/ID/12489-45
ESL-89006-JP*

by

Philip E. Wannamaker

INTRODUCTION

Modeling of three-dimensional thin-sheet telluric anomalies has been a popular means of estimating the distortions of magnetotelluric (MT) response functions in the vicinity of upper crustal resistivity inhomogeneity (e.g., Hermance, 1982; Kaikkonen, 1986). This is because structures with an arbitrary three-dimensional (3-D) shape in plan view can be simulated with modest computational effort; under the assumption of no vertical current flow across the thin sheet into an infinitely resistive basement, the 3-D problem reduces to a 2-D solution across the sheet. Since only a single frequency is considered, however, i.e., the zero-frequency limit, one is limited in the conclusions that can be drawn about the effects of 3-D structures. The purpose of this note is to clarify restrictions on the ability to perform 2-D MT interpretations in 3-D areas based on just thin-sheet telluric modeling.

The simulations presented herein were obtained from a finite element algorithm modified from the dipole-dipole resistivity program of Rijo (1977) and Fox et al. (1980). The original point current sources were omitted and plane-wave telluric variations modeled by applying boundary conditions corresponding to uniform incident voltage gradients first in the -y and then in the -x directions. The x- and y-components of electric field are calculated from three-point differences of nodal voltages at and adjacent to each receiver site. Magnetic fields result from integration of the free-space Green's tensor over the entire domain of current flow (the thin sheet). Further details of the methods plus calculations verifying the solution are given in Wannamaker (1985).

* Also published in Geophysics, Vol. 55 (March 19900, No. 3, 372-375.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

SEPTEMBER 30, 1988 — DECEMBER 31, 1988

DOE/ID/12489-46
ESL-89007-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

FLUID INCLUSION SYSTEMATICS OF THE COSO GEOTHERMAL SYSTEM

DOE/ID/12489-47
ESL-89012-ABS*

by

Joseph N. Moore

ABSTRACT

Studies of active geothermal fields afford a unique opportunity to correlate fluid processes in shallow crustal environments with the evidence provided by fluid inclusions. As a result of recent geothermal development, rock and fluid samples have now become available from many high-temperature geothermal systems. In this paper we present fluid inclusion data from ten wells drilled at the Coso geothermal system, located on the eastern side of the Sierra Nevada Range 60 km west of Death Valley. The geothermal system occurs in Mesozoic granitic and metamorphic rocks that have been intruded and overlain by Quaternary rhyolite and basalt.

Chemical analyses of production fluids from 27 wells define steep gradients in salinities, gas concentrations, and temperatures across the reservoir. Salinities and CO_2 contents range from 1.05 wt% TDS and 0.95 wt% CO_2 in the deep upflow zone located in the southern part of the field to 0.37 wt% TDS and 0.06 wt% CO_2 in shallow production zones located in the northern and eastern parts of the field. Corresponding geothermometer temperatures range from 200°C in the shallow production zones to 362°C in the deeper zones to the south.

Fluid inclusion data are in close agreement with the chemical data. Two-phase liquid-rich inclusions were studied in vein calcite, quartz, and anhydrite. Homogenization temperatures (Th) of these inclusions correspond closely to the downhole measurements, indicating that the inclusions are contemporaneous with geothermal activity. Ice-melting temperatures (Tm-ice) ranged from 0.0° to -2.8°C but individual samples typically display large variations. These variations and positive melting temperatures of CO_2 clathrate in some samples indicate that the inclusion fluids have significant but variable CO_2 contents.

Plots of Th vs. Tm-ice define a fluid mixing trend that includes the compositions of the production fluids. These relationships suggest that the deep upwelling fluid has a temperature of 325°C, an equivalent NaCl salinity of 1.4 wt%, and up to 2.3 wt% CO_2. Deviations of Tm-ice from the mixing trend reflect boiling and gas transfer between fluids. Chloride-enthalpy-gas relationships also demonstrate that boiling, mixing, and gas transfer can explain the variations in the fluid chemistry.

* Also published *in* Proceedings of the 2nd Annual meeting of the Pan American Conference on Research in Fluid Inclusions, (PACROF II), 1989.

COMPARATIVE STUDY OF HIGH PERFORMANCE LIQUID CHROMATOGRAPHIC PARAMETERS USED FOR THE ANALYSIS OF CARBOXYLIC AND SULFONIC ACID

DOE/ID/12489-48
ESL-89013-TR

by

Michael C. Adams, Laslo Fabry, and Joseph N. Moore

ABSTRACT

An isocratic method suitable for the simultaneous quantification of 2 to 4 geothermal tracers has been developed. The tracers were selected from 16 fluorinated and methylated benzoic acid, 3 phenylacetic acid and 4 benzene sulfonic acid compound in geothermal water samples is described. The procedure requires only filtering for the preparation of the samples and provides accurate measurements over two orders of magnitude and down to the lower ppb levels, even in a matrix of high salinity. The performances of silica based C_{18} and polymer reversed phases are compared and optimized for the analysis of tracers combinations in geothermal waters.

DOE/ID 12489-49

WAS NOT ASSIGNED TO ANY PUBLICATION

STABILITY AND USE OF ORGANIC COMPOUNDS AS GEOTHERMAL TRACERS

DOE/ID/12489-50
ESL-89015-TR

by

Michael C. Adams, Joseph N. Moore, and Lazlo Fabry

ABSTRACT

A broad range of decay rates was found for the thermal degradation of aromatic acids tested as potential geothermal tracers. The most stable class of compounds tested were the benzenesulfonates, followed by the methylated benzoic acids. The least stable compounds were the fluorinates, especially the perfluorinated acids. Decarboxylation, desulfonation and possibly defluorination were the dominant mechanisms of decay. The most influential factors in the rate of decay were the identity and location of the substituents on the aromatic ring, with the highest rates of decay occurring where the substituent was located adjacent to the group undergoing reaction.

Simultaneous injection of tracer pairs can produce information on the effective temperature of the injection-production flowpath if one or both of the tracers decay at the temperature of the reservoir. Use of reactive tracers coupled with kinetic data on their rates of decay also allows the calculation of a conservative tracer breakthrough curve.

STRATIGRAPHY OF THE LOS AZUFRES GEOTHERMAL RESERVOIR

DOE/ID/12489-51
ESL-89016-JP*

by

Antonio Razo M., Rogelio Huitron E., Joseph N. Moore, Alan C. Tripp, and Michele M. Lemieux

ABSTRACT

The reservoir at Los Azufres is developed primarily in lava flows, breccias, and tuffaceous deposits of the Mil Cumbres andesites. Chemical analyses of samples from five wells drilled in the northern part of the field has led to the recognition of four distinct volcanic sequences within the upper 2500 m of the reservoir. These sequences can be correlated across the field.

The upper three sequences consist dominantly of andesite with minor interbedded basaltic andesite and dacite. These sequences can be differentiated on the basis of their rare-earth element, MgO, TiO_2, and P_2O_5 contents. The deepest volcanic sequence encountered in the wells is composed mainly of basaltic andesite interbedded with minor andesite.

* Also published *in* Proceedings of the Symposium in the Field of Geothermal Energy, 1989, San Diego, CA, 63-72.

RECENT DEVELOPMENTS IN GEOLOGY, GEOCHEMISTRY, AND GEOPHYSICS APPLIED

TO HYDROTHERMAL RESERVOIR MAPPING AND MONITORING

DOE/ID/12489-52
ESL-89017-TR*

by

Joseph N. Moore, Dennis L. Nielson, and Phillip M. Wright

ABSTRACT

Progress in research and development of four of UURI's projects are reviewed in this paper. First, the development of chemical tracers has evolved to a field test in the Dixie Valley geothermal system in Nevada. Second, the measurement of *in situ* stress continues to demonstrate changes with location in the orientation of stress within active geothermal systems. Third, we continue to develop hydrologic models of geothermal systems based upon fluid inclusion measurements. Fourth, we are developing equipment that will allow testing of borehole-to-borehole and borehole-to-surface electrical resistivity techniques for locating fluid-filled fractures.

* Also published in the Geothermal Program Review VII, DOE/San Francisco, CA, 21-23, March 1989, 31-34.

CHEMISTRY OF LOS AZUFRES RESERVOIR FLUIDS

—DATA FROM FLUID INCLUSIONS

DOE/ID/12489-53
ESL-89018-TR*

by

Michele M. Lemieux, Joseph N. Moore, E. Gonzales P., G. Izqiuerdo, and R. Huitron E.

ABSTRACT

Fluid inclusions from the northern portion of the Los Azufres geothermal system were studied to better characterize the chemistry of the reservoir and the processes occurring in it. Freezing measurements indicate that the fluids in the upper 2500 m of the thermal system have low salinities and contain variable but significant CO_2 contents. Fluids with CO_2 contents greater that 3.7 weight percent form a cap over the geothermal system that thickens outward from the high-temperature discharge zone. Boiling point to depth relationships suggests that pressures within the CO_2-enriched cap were locally higher than hydrostatic.

* Also published in the Symposium in the Field of Geothermal Energy, San Diego, CA Program, 29-36.

AEROMAGNETIC STUDIES LOS AZUFRES GEOTHERMAL AREA, MICHOACAN MEXICO

DOE/ID/12489-54
ESL-89019-TR*

by

Howard P. Ross, Phillip M. Wright, Antonio Razo M., G. H. Garcia E., Jesus F. Arellano G., J. J. Arredondo F., and J. L. Guerrero G.

ABSTRACT

Detailed and regional aeromagnetic surveys were completed over the Los Azufres geothermal area in central Mexico. Many mapped faults are clearly expressed in the detailed magnetic data because these faults penetrate to the surface and many are reflected in the topography. East-trending faults are often cut by younger north- to -northwest trending structures which can be interpreted from the magnetic data. A large zone of mapped hydrothermal alteration is apparent in the magnetic data as an area of unusually low (0-50 nT) magnetic relief. Interpreted structures trend NW into this area and are weakly expressed within the alteration zone. The regional survey records several major volcanic - intrusive complexes as large, positive magnetic anomalies, including the Los Azufres area. The source of the Los Azufres magnetic high appears to be bounded by northwest- and north-trending regional structures.

* Also published in the Symposium in the Field of Geothermal Energy, 1989, San Diego, CA Program, 55-61.

PUBLICATIONS AND GEOTHERMAL SAMPLE LIBRARY FACILITIES OF ESL/UURI

DOE/ID/12489-55
ESL-89020-TR

by

Phillip M. Wright, Kathryn A. Ruth, David R. Langton, and Michael J. Bullett

STATEMENT

This is a listing of ESL/UURI publications from 1976 to the present, complete with an index by Dr. Wright, and a record of rock samples which are held at our geothermal sample library. This list is updated yearly and reissued every January.

INTERPRETATION OF LANDSAT THEMATIC MAPPER SATELLITE IMAGERY

AT

LOS AZUFRES GEOTHERMAL FIELD, MICHOACAN, MEXICO

DOE/ID/12489-56
ESL-89021-TR*

by

Phillip M. Wright, Hector Lira H., and Douglas R. Ramsey

ABSTRACT

This report documents part of a cooperative study by CFE and UURI of a Landsat 5 image of the Los Azufres geothermal area and its surroundings. The objective was to determine if processing and interpretation of satellite imagery are useful in volcanic environments for mapping structures, hydrothermal alteration, rock types and/or soil geochemical anomalies manifest in vegetation. Several processing steps were carried out using the ERDAS image-processing system installed on an AT-equivalent PC at UURI in an attempt to detect characteristic signatures from hydrothermally altered areas and to enhance linear and other structurally related geologic features.

A great deal of structural information is recorded in the Landsat image. Most of the interpreted linear features are believed to be due to faulting and fracturing, and there are more interpreted linears than there are mapped faults. The additional information contributed from the image interpretation may prove useful in planning for further development of the Los Azufres area.

Signatures reasonably characteristic of hydrothermally altered areas were developed after considerable experimentation with various false-color images of the direct digital data and of derived band ratios. This is a significant result because it implies that the method may be useful in helping to assess other areas of known geothermal occurrence which are less thoroughly mapped than is Los Azufres.

We believe that satellite imagery interpretation may contribute cost effectively to an exploration program by (1) outlining areas of strong and/or young faulting, (2) outlining areas where faulting and fracturing are more intense, (3) detecting hydrothermal alteration with a reasonable degree of reliability after calibration over known alteration, (4) outlining areas of young volcanic deposits, and (5) helping to guide geologic field work and prioritize areas. The cost per unit area of coverage is relatively small compared to some other techniques such as geologic mapping.

* Also published in the Symposium in the field of Geothermal Energy, San Diego, CA Program, 73-76.

HYDROGEOCHEMISTRY OF THE HEBER GEOTHERMAL SYSTEM, CA

DOE/ID/12489-57
ESL-89023-JP*

by

Michael C. Adams, Michele M. Lemieux, Joseph N. Moore, and Steven D. Johnson

ABSTRACT

This paper presents the results of chemical and isotopic analyses of geothermal fluids and microthermometric measurements on fluid inclusions from the Heber geothermal system. The chemical analyses indicate that the reservoir fluids have salinities near 13000 ppm total dissolved solids and low gas contents. Small but consistent differences in the concentrations of total CO_2, B, Li, O-18, and deuterium are found between the fluids that feed the two power plants. These differences may be due to divergent paths of the thermal fluids as they flow from the south. Fluid inclusion homogenization temperatures are similar to the present temperatures in gradient wells near the zone of upflow but are lower in two wells studied outside this zone. Freezing measurements indicate that the fluids contained within the inclusions are mixtures of the production fluids and meteoric waters that have migrated through permeable sandstones within the reservoir.

* Also published in the American Association of Petroleum Geologist Guidebook, in press.

EFFECTS OF ANISOTROPY ON CROSS-BOREHOLE RESISTIVITY MEASUREMENTS WITH APPLICATIONS IN A COAL ENVIRONMENT

DOE/ID/12489-58
ESL-89028-JP*

by

Douglas J. LaBrecque and Stanley H. Ward

SUMMARY

The effects of anisotropy on cross-borehole resistivity measurements were investigated using a three-dimensional finite-difference modeling program developed by the authors. A model study was conducted to determine the effect of background anisotropy on the ability of cross-borehole resistivity to detect a collapse feature penetrating a coal seam. Results showed that moderate levels of anisotropy strongly affected the cross-borehole resistivity measurements. In one-dimensional environments the anisotropic regions were characterized by large smoothly varying responses which could be misconstrued as two-dimensional or three-dimensional structures. These responses were comparable in magnitude with that of the coal seam. The response of a three-dimensional conductor in half-space was significantly different from the response of the same conductor in a half-space containing one or more anisotropic layers. It appears that in layered sedimentary environments anisotropy must be considered to interpret the cross-borehole resistivity data.

* Also published in the 59th Annual Internation Society of Exploration Geophysicists Meeting, Oct 29 - Nov 21, 1989, 1,375-378.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

JANUARY 1 — MARCH 31, 1989

DOE/ID/12489-59
ESL-89030-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

AN ESTIMATION OF SINGLE INJECTOR TRACER TEST IMPULSE RESPONSES

DOE/ID/12489-60
ESL-89031-JP*

by

Alan C. Tripp, Michael C. Adams, Joseph N. Moore, and Phillip M. Wright

ABSTRACT

Interpretation of tracer tests presupposes a single tracer injection mass history – ideally a single slug of tracer. Unfortunately, tracer injection functions can be very erratic, leading to variations in the recovered tracer concentrations. Under these circumstances it is essential to correct the data for the erratic tracer injection, thereby recovering the impulse or slug response of the injector-producer system.

We discuss a method for estimating the impulse response using the Wiener-Hopf equation. The estimation technique involves forming and solving a Toeplitz matrix approximation of the Wiener-Hopf equation for the impulse response. The elements of the matrix are autocorrrelations of the injection tracer mass with respect to time, while the known vector is the cross-correlation of the injected tracer mass and the produced tracer concentrations. The matrix solution is easy to formulate and computationally rapid.

The Wiener-Hopf method has several advantages over other published techniques for correction for tracer reinjection. First, the method can estimate the impulse response in principle no matter how complicated the initial injection tracer mass history. It is also the least-squares estimator of the impulse response.

We illustrate the impulse estimation technique using reactive and non-reactive tracer data gathered at Dixie Valley.

* Also published in the Fifteenth Workshop on Geothermal Reservoir Engineering, Stanford University, in press.

DIPOLE-DIPOLE ELECTRICAL RESISTIVITY SURVEYS

AT

WASTE DISPOSAL STUDY SITES IN NORTHERN UTAH

DOE/ID/12489-61
ESL-89033-JP*

by

Howard P. Ross, Phillip M. Wright, and Claron E. Mackelprang

ABSTRACT

A large number of old landfills, and chemical- and industrial-waste disposal sites have been located in alluvial and Bonneville lakebed deposits of northern Utah. Fine-grained silts and clay layers within these deposits are important as aquitards to the vertical migration of waste fluids and as low-permeability zones which channel the subsurface movement of ground water and fluid contaminants. Dipole-dipole resistivity surveys are a cost-effective technique for mapping the configuration of underlying clay layers as well as the near-surface discontinuities of landfills and buried disposal trenches.

Dipole-dipole profiles were completed over two large landfills and three waste-disposal pits at Hill Air Force Base, Utah, in 1982 as part of a Phase II hydrogeologic survey within the U. S. Air Force Installation Restoration Program. Apparent resistivities observed with 9-meter dipoles varied from more than 700 ohm-meters to less than 10 ohm-meters on several profiles. This range of apparent resistivities indicates the heterogeneous nature of the alluvial material, variation in the degree of saturation, and the presence of, or depth to, clay layers.

Numerical modeling of selected profiles aided in mapping the top of clay layers at depths of 3 to 20 meters, the prefill surface of a large landfill, and the morphology of a slump block at one chemical-waste disposal pit. The resistivity data, supplemented by ground magnetic and self-potential profiles, provided guidance for a drilling and sampling program and continuity for understanding the sampling results.

* Also published in the Utah Geological Association Pub. 17 in Geology and Hydrology of Hazardous Waste, Mining-Waste, Waste-water and Repository Sites in Utah, 69-79.

APPLICATION OF THE CROSS-BOREHOLE DIRECT CURRENT RESISTIVITY TECHNIQUE FOR EOR PROCESS MONITORING — A FEASIBILITY STUDY

DOE/ID/12489-62
ESL-89034-JP*

by

Craig W. Beasley, Alan C. Tripp, Douglas J. LaBrecque, John A. Stodt, Stanley H. Ward,

and Phillip M. Wright

ABSTRACT

The cross-borehole resistivity method measures the electrical potential in one well due to direct-current flowing between electrodes situated in another well. This arrangement permits the sensing of regions remote from either well. The paper examines the use of the cross-borehole method in sensing electrical resistivity perturbations caused by steam-floods, water-floods, and fire-floods.

Our examination consists of three parts. We first estimate the magnitude of resistivity perturbations caused by EOR processes. We then calculate the theoretical voltage responses, for several theoretical sweep geometries, for a 2.5 acre well-spacing and a hypothetical shallow, heavy-oil field. For ease of computation, we assume that the swept zone is two-dimensional. Finally, we contaminate the calculated voltages with Gaussian noise with a 5% standard deviation and invert them in a least-squares sense to sweep geometry estimates. The starting models for these inversions are dissimilar to the theoretical sweep geometries. After ten or so iterations the estimated sweep geometries agree well with the theoretical geometries when the models are sufficiently well discretized. This shows that interpretation of cross-borehole data can give information about sweep geometries. We conclude that the cross-borehole resistivity technique has promise in monitoring enhanced oil recovery (EOR) processes, particularly when combined with effective two- or three-dimensional inversion schemes.

* Also published in Borehole Geophysics: Petroleum, Hydrogeology, Mining and Engineering Applications, International Symposium at The University of Arizona Laboratory for Advanced Subsurface Imaging (LASI), February 1 - 3, 1990, Tucson, Arizona. Also rewritten as ESL 89058-JP, DOE/ID/12489-83.

MODELING THREE-DIMENSIONAL MAGNETOTELLURIC RESPONSES USING INTEGRAL EQUATIONS

DOE/ID/12489-63
ESL-89035-JP

by

Philip E. Wannamaker

ABSTRACT

Documentation for PW3D: algorithm for modeling magnetotelluric responses of three-dimensional bodies in layered earths using integral equations

Recent progress in integral equation modeling of three-dimensional magnetotelluric responses includes the ability to simulate 3-D structures which outcrop, which transect layer interfaces, and which extend indefinitely in one or more directions. The most important factor in achieving this capability is an accurate treatment of the electric surface charge. In particular, a previous integro-difference formulation for evaluating charges has been abandoned in favor of true surface integrations over the source cells with potential differencing across the field cells in the 3-D body. The new procedure constitutes a good approximation to Galerkin's method while preserving internal consistency in terms of pulse basis functions. Also, the secondary Green's functions due to the layering are separated into current and charge components with the latter treated using midpoint surface integrations over the rectangular cells of the body. For cells in the layer just below the air-earth interface, a DC dipole term representing an image current in the air is removed from the secondary Green's functions and integrated analytically over the image cell surfaces. Matrix element and receiver field calculations are greatly speeded by obtaining the secondary Green's functions through 1-D cubic interpolation from tables rather than through the 3-D or 2-D interpolation carried out previously.

GEOTHERMAL EXPLORATION OF ASCENSION ISLAND

SOUTH ATLANTIC OCEAN

DOE/ID/12489-64
ESL-89036-JP*

by

Dennis L. Nielson and Susan G. Stiger

ABSTRACT

This report summarizes the results of geothermal exploration and drilling and testing of a deep test well on Ascension Island in the South Atlantic Ocean. The U.S. Air Force is interested in reliable, economic methods to produce power and potable water on Ascension and geothermal energy would satisfy that objective. Geothermal development would be invulnerable to disruption due to external economic or political factors, a distinct advantage for critical U.S. Air Force operations on this remote island.

The siting and drilling of the Ascension #1 well was the culmination of an exploration program that began in 1982. The well was started on August 3, 1986 and terminated on January 23, 1988. Ascension #1 intersected geothermal fluids at several levels below a depth of 8000 feet. The temperatures of these fluids are in the upper range of commercial geothermal reservoirs at similar depths. However, the volume of fluid flow was limited. While attempting to improve production by drilling a second leg, a mechanical failure resulted in loss of the well.

Economic analyses indicate that replacement of the existing diesel power generating equipment with a geothermal power plant could result in savings of as much as $112 million over the primary replacement alternative, a gas turbine. A geothermal power plant offers the additional advantage of producing about three times the current U. S. potable water demand on Ascension. On the basis of the discovery of a geothermal resource and excellent economic factors, continued drilling is recommended. An independent of panel of industry experts verified the high resource potential and recommended continued drilling.

* Also published in Geothermal Resources Council, 1989 Transactions, 13,187-191.

STRESS IN GEOTHERMAL SYSTEMS

DOE/ID/12489-65
ESL-89037-JP*

by

Dennis L. Nielson

ABSTRACT

This paper analyzes the components of stress in geothermal systems. Previous work has shown that geothermal systems often have a stress orientation different from the regional direction and that the orientation of the stress components may change within an individual well. Decoupling of the stress within a geothermal system from the regional stress appears to take place along faults that are inherently weak due to the presence of geothermal fluids. Variations in stress within a system could result from local stress due to fluid pressure, temperature or volcanic processes or to bend of stress lines around active faults. Analysis of data from the Baca geothermal system demonstrates that temperature variations are the principal cause of stress variations.

* Also published in Geothermal Resources Council, 1989 Transactions, 13, 271-276.

TRACER STUDIES I: THERMAL DECAY KINETICS OF FLUORESCEIN

DOE/ID/12489-66
ESL-89038-TR

by

Michael C. Adams and Jon Davis

ABSTRACT

Fluorescein is a dye used to trace the path of injected fluids through geothermal reservoirs. We have measured its thermal stability at temperatures up to 300°C in hydrothermal autoclaves at various fluid compositions, pHs, and oxygen concentrations. The results of these experiments indicate that fluorescein will decay less than 10% during a one month tracer test in geothermal reservoirs with temperatures below 210°C. For tracer tests involving longer times and/or higher temperatures, the activation parameters presented in this study can be used to correct for thermal decay. These parameters were applied to a tracer test conducted at the Dixie Valley, Nevada geothermal system to correct for the thermal decay of fluorescein and to deduce the effective temperature of the injection-production flow path.

PETROGRAPHIC AND FLUID INCLUSION EVIDENCE FOR PAST BOILING \ BRECCIATION AND ASSOCIATED HYDROTHERMAL ALTERATION ABOVE THE NW GEYSERS STEAM FIELD, CALIFORNIA

DOE/ID/12489-67
ESL-89039-JP*

by

Joseph N. Moore, Jeffrey B. Hulen, Michele M. Lemieux,

Jeffrey N. Sternfeld and Mark A. Walters

ABSTRACT

Many of the wells drilled in the Northwest Geysers have encountered thin, scattered zones of hydrothermally brecciated graywacke above the steam reservoir. The breccias are characterized by open-space fillings of quartz, calcite, adularia, albite, pyrite, and pyrrhotite. Secondary sericite occurs within the clasts. Fluid inclusion measurements indicate that the quartz and calcite formed from boiling fluids with temperatures between 313° and 223°C. These fluids had estimated salinities ranging from .35 to 1.7 equivalent weight percent NaCl and variable but significant gas contents. Variations in the homogenization temperatures of these inclusions suggest that they record the downward movement of the water table with time. As the water table declined, slightly acidic condensate reacted with the breccias to produce sericite.

* Also published in Geothermal Resources Council, 1989 Transactions, 13, 467-472.

DOE/ID 12489-68

WAS NOT ASSIGNED TO ANY PUBLICATION

SURFACE-TO-BOREHOLE ELECTROMAGNETIC EXPERIMENT AT ROOSEVELT HOT SPRINGS — A FEASIBILITY STUDY

DOE/ID/12489-69
ESL-89041-JP*

by

Alan C. Tripp, Howard P. Ross, John A. Stodt, and Phillip M. Wright

ABSTRACT

The electrical resistivity structure of a geothermal reservoir is a function of many reservoir properties, such as temperature, water salinity, the presence of steam, hydrothermal alteration mineralogy, porosity, and fracture density and orientation. Thus, determining the resistivity structure of a particular reservoir can be of great use in planning optimal exploitation of the resource.

There are many conceivable ways of estimating the resistivity structure of a reservoir from geophysical measurements. In this paper, we describe one method in which a coil receiver is situated in a borehole and the transmitter is a current line grounded on the earth's surface. This particular method is easy to use in the field and can give good resolution of conductive features at depth. We illustrate the applicability of the technique to detect fracture zones at depth in the vicinity of Well 9-1 at Roosevelt Hot Springs.

* Also published in Geothermal Resources Council, 1989 Transactions, 13, 289-293.

THE DIXIE VALLEY, NEVADA TRACER TEST

DOE/ID/12489-70
ESL-89042-JP*

by

Michael C. Adams, William R. Benoit, C. Doughty, Gudmundar S. Bodvarsson,

and Joseph N. Moore

ABSTRACT

Three injection wells in the Dixie Valley, Nevada geothermal field were tagged with organic tracers. The tracers used were benzoic acid, benzenesulfonic acid, 4-ethylbenzenesulfonic acid, and fluorescein. Six production wells were intensively sampled for 2.5 months. During this period one well, 76-7, showed breakthrough. The presence of benzoic acid and fluorescein in the 76-7 production fluid demonstrated that breakthrough was from well 32-18. Concentration ratios of these compounds varied during the test period, as predicted from laboratory experiments. These ratios predict an average flowpath temperature of 230°C for the early-time data and a range from 218° to 232°C for the later data. These temperatures are consistent with the observed temperatures in the reservoir.

A numerical reservoir model of the Dixie Valley field was employed to predict the results of the tracer tests. The model was used to estimate needed tracer quantities and sampling frequencies. The results of the model are in qualitative agreement with the observed tracer breakthrough. Differences between calculated and observed arrival times may be due to the large mesh size used in the model and a possible underestimate of the average fracture porosity.

* Also published in Geothermal Resources Council, 1989 Transactions, 13, 215-220.

THE USE OF TRACERS TO ANALYZE THE EFFECTS OF REINJECTION INTO FRACTURED GEOTHERMAL RESERVOIRS

DOE/ID/12489-71
ESL-89043-JP

by

Michael C. Adams, Joseph N. Moore, and Phillip M. Wright

ABSTRACT

Forty aromatic acids have been tested in hydrothermal autoclaves for use as high-temperature geothermal tracers. These compounds included fluorinated aromatic acids which are the most stable groundwater tracers. The laboratory experiments show that the most stable compounds are benzenesulfonates and methylated or carboxylated benzoic acids. Fifteen of these compounds are stable at 250°C. Fluorinated compounds were unstable at high temperatures, with their stability being proportional to the degree of fluorination.

Three of the new tracers were used in an injection tracer test at Dixie Valley, Nevada. This field experiment demonstrated that organic tracers can be used to establish fluid connections between injection and production wells in a geothermal field. The tracer return curves derived from these injection tests were adequately characterized in the parts per billion range. We have also demonstrated that by injecting two tracers with different stabilities, the average temperature of the injection-production flowpath can be defined.

FINAL REPORT TO DOE ON THE GEOTHERMAL TECHNICAL SESSION AT THE CONFERENCE ENTITLED *RENEWABLE ENERGY IN THE AMERICAS* SPONSORED BY US/ECRE, MIAMI FL, MAY 30-JUNE 3, 1989

DOE/ID/12489-72
ESL-89044-TR

by

Phillip M. Wright

INTRODUCTION

Between May 30 - June 2, 1989, a conference was held in Miami, Florida entitled "Renewable Energy in the Americas -- Special Emphasis on the Caribbean". The sponsor of the conference was the U. S. Export Council for Renewable Energy (US/ECRE). This conference was the culmination of a multi-year effort to enhance the economic well-being of the area while increasing exports of U. S. technology and goods to the area. This program supports former-President Reagan's announced Caribbean Basin Initiative.

UURI formed a technical session on geothermal resource development for presentation at the conference. The objective of the geothermal session was to present the technical, service and equipment manufacturing capabilities of the U. S. geothermal industry to delegates visiting from other countries, who are potential customers of our industry.

Latin America and the Caribbean areas have substantial geothermal potential. Volcanic and hydrothermal activity are known to occur throughout the region. Mexico, El Salvador and Nicaragua all have geothermal electrical power generation on line and Costa Rica and Guatemala have plants under construction. Countries in Central America and the Caribbean believed to have the long-term potential for hundreds to thousands of megawatts of geothermal energy are Mexico, El Salvador, Guatemala, Costa Rica and Nicaragua. Dominica, Honduras, Panama, St. Lucia, St. Vincent, Grenada, Haiti, The Dominican Republic and Montserrat-Nevis-St. Kitts all have potentials that range from a few to a few hundred megawatts. In South America, Colombia, Ecuador, Peru, Chile, Brazil and Argentina all have resources that could be developed. It is apparent that a large potential market for U. S. technology and equipment exists in the region. A great deal of effort will be required for the U. S. to capture its share of this market because of intense international competition and because of depressed economic conditions in these countries.

REVIEW OF GEOTHERMAL DEVELOPMENT AND FUTURE OUTLOOK

DOE/ID/12489-73
ESL-89045-JP

by

Phillip M. Wright

Hydrothermal resources, one of the several types of geothermal resources, are being actively developed on a worldwide basis. Other types of geothermal energy -- geopressured, hot dry rock, and magma -- remain uneconomic but show considerable promise for the future. Technical problems and low energy prices inhibit the development of each of the 4 geothermal types. Geothermal energy is used both for generation of electricity and for direct-heat applications. Use of geothermal energy is desirable because it is an environmentally clean, utility -- compatible source of energy that directly displaces the need for more nuclear plants and frees petroleum for other important uses.

Current worldwide hydrothermal generating capacity is about 5,457 electrical megawatts (MWe) in 18 countries, with the United States accounting for 2,609 MWe of the total. current worldwide direct uses of hydrothermal energy amount to about 10,000 thermal megawatts (MWt).

Geothermal development in the United States currently is depressed due to comparatively low energy costs and a temporary excess in electrical generating capacity. Because of these factors as well as lack of adequate technology, only a small portion of the known hydrothermal resource base can be used economically today.

Also published in The American Assoication of Petroleum Geologists Bulletin, 73, 10B, 366-374.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

APRIL 1 — JUNE 30, 1989

DOE/ID/12489-74
ESL-89046-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

VARIATIONS OF *IN-SITU* STRESS IN GEOTHERMAL SYSTEMS OF THE BASIN AND RANGE PROVINCE

DOE/ID/12489-75
ESL-89047-JP

by

M. Lee Allison and Dennis L. Nielson

INTRODUCTION

Borehole Breakouts

Systematic wellbore elongations were first recognized by Cox (1970) from the oriented caliper information on 4-arm dipmeter logs in the Alberta Basin of Canada. Orientation of the asymmetries was remarkably uniform over a large region. Babcock (1978) argued a geologic origin for breakouts and suggested they resulted from spalling in fracture zones intercepted by the well. He proposed the term borehole "breakouts" to describe discrete intervals of elongate oversize holes. Bell and Gough (1979) found both empirically and theoretically that the breakouts formed in the direction of the least principal horizontal stress due to stress concentrations on the borehole walls. Subsequent workers (Blanton, 1985; Fordjor et al., 1983, Gough and Bell, 1981 and Haimson and Herrick, 1983; Hickman et al., 1985; Podrouzek and Bell, 1985; Stock et al., 1985; Teufel, 1985; and Zoback et al. 1985) have demonstrated the clear relationship between breakouts and in-situ stress, verified from other stress indicators.

Bell and Gough (1979) proposed that the breakout-producing stresses were lithospheric-scale, operating over broad regions of North America. Following papers on breakouts related them to regional stress orientations either implicitly or explicitly (Gough and Bell, 1982; Gough et al., 1983; Fordjor et al., 1983). Deviations from the mean or average were largely attributed to reading errors, unnamed anomalies, misinterpretation of non-stress-induced borehole elongations (such as washouts, keyseats, or drilling-induced fractures), or were ignored. There are a couple of exceptions. Podrouzek and Bell (1985) reported two breakout sets in wells on the Scotian Shelf which they attributed to a regional stress and a local reorientation of it, and Bell and Babcock (1986) listed "minor populations" of breakouts in addition to the major orientation for individual wells. Overall, however, stresses reported from breakout data have been characterized as regional.

PW2DI-v1.00: FINITE ELEMENT PROGRAM FOR MAGNETOTELLURIC FORWARD MODELING AND PARAMETERIZED INVERSION OF TWO DIMENSIONAL EARTH RESISTIVITY STRUCTURE

(USER DOCUMENTATION)

DOE/ID/12489-76
ESL-89049-TR

by

Philip E. Wannamaker

ABSTRACT

Algorithm PW2DIS is a finite element program for simulation of magnetotelluric responses of two-dimensional earth resistivity structure, including topography and bathymetry, as well as the response-parameter sensitivities (Jacobian or derivative matrix). Linear interpolation of the unknown field parallel to strike over triangular sub domains is utilized in conjunction with the Galerkin method of basis weighting to derive a system of linear equations which approximates the governing Helmholtz equations. From the field parallel to strike, the auxiliary vertical and transverse fields obtain from a numerical approximation to Maxwell's equations. Both transverse electric (TE) and transverse magnetic (TM) modes of plane-wave excitation can be modeled. Parallel methodology is utilized for computing the response-parameter sensitivities. Specifically, sensitivities are computed at all nodes in the mesh due to changes in individual polygon resistivity.

The forward problem described herein solves directly for secondary variations in the field parallel to strike, plus the subsequent auxiliary fields. This approach has circumvented a difficulty with numerical precision at low frequencies observed in total field solutions for the TM mode especially, but also for the TE mode. To simulate topographic or bathymetric variations, the nodal values of the field parallel to strike used in computing the auxiliary fields are kept entirely within the earth (or the seawater for bathymetry) to avoid discontinuities in resistivity associated with the air-earth interface. Example input and output files showing forward problem and sensitivity results are included at the end for user verification.

MODEL STUDIES ON THE RESOLUTION OF ELECTROMAGNETIC CROSS-BOREHOLE AND SURFACE-TO-BOREHOLE DELINEATION AND MONITORING OF GEOTHERMAL AND PETROLEUM RESERVOIRS

DOE/ID/12489-77
ESL-89051-JP*

by

Alan C. Tripp, Gerald W. Hohmann, Phillip M. Wright, John A. Stodt, and Howard P. Ross

SUMMARY

Electrical resistivity variations in geothermal and petroleum reservoirs reflect variations in reservoir characteristics which are of interest in reservoir exploration. Indeed, these resistivity variations give information which complements information contained in acoustic rock properties. However, some practicing geophysicists have felt that electrical resistivity variations on the reservoir scale cannot be resolved in practice. On the contrary, preliminary modelling suggests that in many cases fluctuations of practical interest can be detected using surface-to-borehole or cross-borehole electromagnetic techniques.

* Also published in the 14th Annual Stanford Geothermal Reservoir Engineering Workshop.

MAGNETOTELLURIC TRANSECT OF LONG VALLEY CALDERA: RESISTIVITY CROSS SECTION, STRUCTURAL IMPLICATIONS, AND THE LIMITS OF A TWO-DIMENSIONAL ANALYSIS

DOE/ID/12489-78
ESL-89047-JP*

by

Philip E. Wannamaker , Phillip M. Wright, Zhou Zi-xing, Li Xing-bin, and Zhao Jing-xiang

ABSTRACT

Twenty-four magnetotelluric (MT) soundings have been collected in an E-W profile across the center of Long Valley caldera. The average station spacing is approximately 1 km and appears adequate to sample the important features of the upper crustal and deeper resistivity structures. Additional control on the shallowest resistivity is provided by a continuous profile of time domain electromagnetic soundings coincident with the western portion of the MT line. Our MT data set reveals numerous resistivity structures which illuminate the evolution and present state of the Long Valley system. Many of these have been quantified through two-dimensional (2-D) finite element modeling emphasizing the transverse magnetic (TM) mode. Important structural components include low-resistivity layers 0.5-1.5 km is the eastern half of the caldera, beneath the axial graben of the resurgent dome, and under the west caldera moat. Most of this layering appears to lie in post-caldera Early Rhyolite tuffs, and the uppermost unwelded Bishop Tuff. These rhyolite units have been observed to be porous and highly altered and to commonly contain Pleistocene intercalated lacustrine clays. The remainder and majority of the Bishop Tuff appears highly resistive. A low resistivity layer also occurs below the axial graben near the base of the Bishop Tuff (1.5 km). Hydrothermal fluids or alteration in pre-caldera volcanic strata or, less likely, carbonaceous metasediments may be the cause of this. Resistive, probably crystalline basement at high levels is apparent beneath the center of resurgence. Low resistivities are modeled at a depth around 5 km below the entire west moat and central graben and may represent a zone of hydrothermal fluids released from magma crystallization, with potential magmatic contributions at greater depths. The correspondence between this low resistivity and teleseismic delay and low density zones found in other studies is quite striking. A subtle anomaly in the transverse electric (TE) mode impedance is weakly suggestive of a mid-crustal conductive axis centered beneath the central graben and resurgent dome. However, it cannot be simulated by two-dimensional transverse electric calculations and requires a full three-dimensional evaluation to ensure that the anomaly does not represent resistivity complexity in just the upper few kilometers. A fundamental, caldera-wide 3-D effect is documented by comparison of observed and computed TE impedance and vertical magnetic field data. The abrupt termination of conductive caldera sediments less than 10 km north and south of our profile greatly depresses the observed TE apparent resistivity and vertical magnetic field relative to the model calculations for periods greater than 0.3 s for the central and eastern caldera. Analysis of the TE mode data also suggests that a similar finite-strike effect lies in the response at periods greater than 3 s due to the mid-crustal west moat conductor. The TM mode measurements are judged to also contain some large-scale departure from the 2-D assumption related to horizontal current gathering from the north and south. This inflates the apparent resistivity and decreases the phase somewhat around 10 s over the central portion of the caldera relative to the 2-D model response. The regional profile of resistivity for the data at hand can be modeled with a 40 ohm-m basal half-space beneath 30 km of crust of 1000 ohm-m or more.

Although stations outside the caldera are very desirable to constrain this deep profile better, there is no evidence for a discrete low-resistivity layer deep below Long Valley in contrast to our interpretation in the northeastern Basin and Range.

* Also Publsihed in Geophysics, Vol. 56 (July 1991), in press.

MAPPING HYDRAULIC FRACTURES USING A BOREHOLE-TO-SURFACE RESISTIVITY METHOD

DOE/ID/12489-79
ESL-89054-JP*

by

Ti Wang, John A. Stodt and D. J. Sternmen

SUMMARY

A 3D inversion algorithm for DC resistivity data based on the α-center approach has been developed. It is aimed at providing a tool for on-site interpretation of hydraulically created fractures or existing fault zones which are more conductive than their host rocks, or at providing initial guesses of locations of fractures or fault zones for more sophisticated interpretation algorithms. The algorithm incorporates line sources of current to allow modeling of data obtained by using a conductive well casing as a current electrode. Electrode configurations commonly used in borehole-to-surface, surface-to-borehole, cross-borehole, and surface-to-surface surveys are incorporated easily.

The algorithm has been applied to field data which were collected during hydraulic fracturing experiments in a set of four shallow, closely spaced boreholes located on the southeast edge of ELDA Landfill in Cincinnati, Ohio (Murdock, 1989). Our numerical results show that the α-center approach can locate fractures which are more conductive than their host rocks. A limitation of the method is that it is unable to determine the sizes of the fractures. At present, only conductive inhomogeneities are considered in the α-center formulation.

* Also published in Borehole Geophysics: Petroleum, Hydrogeology, Mining and Engineering Applications, International Symposium at The University of Arizona Laboratory for Advanced Subsurface Imaging (LASI), February 1 - 3, 1990, Tucson, Arizona.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

JULY 1—SEPTEMBER 30, 1989

DOE/ID/12489-80
ESL-89055-JP

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

BOREHOLE ELECTRICAL GEOPHYSICS APPLIED TO GEOTHERMAL DEVELOPMENT

DOE/ID/12489-81
ESL-89056-JP*

by

Phillip M. Wright

SUMMARY

Borehole electrical geophysical methods have considerable potential for helping to define hot and permeable zones in geothermal systems, for tracing the flow of cooler injected fluids and for determining the degree of water saturation in vapor-dominated systems. On the basis of these and other potential applications, both the Geothermal Technology Division and the Office of Basic Energy Sciences of the U. S. Department of Energy are sponsoring research in borehole geophysics.

At UURI, we are developing methods to perform field surveys and to model and interpret various borehole-to-borehole, borehole-to-surface and surface-to-borehole arrays. The status of our research may be summarized as follows: (1) forward modeling algorithms have been developed and published to examine resistivity, mise-à-la-masse, VLF, CSAMT, and time-domain EM and to examine the effects of casing in wells and of geological and electrical noise; (2) two inverse two-dimensional resistivity algorithms have been devised and successfully applied to simulated field data; (3) a multi-array resistivity system has been designed and we are beginning construction of the prototype; and (4) we are seeking appropriate wells in geothermal and other areas in which to test the methods.

* Also published in Borehole Geophysics: Petroleum, Hydrogeology, Mining and Engineering Applications, International Symposium at The University of Arizona Laboratory for Advanced Subsurface Imaging (LASI), February 1 - 3, 1990, Tucson, Arizona.

COMPETITIVE ECONOMICS OF GEOTHERMAL ENERGY—

THE EXPLORATION AND DEVELOPMENT PERSPECTIVE

DOE/ID/12489-82
ESL-89057-JP*

by

Dennis L. Nielson

INTRODUCTION

Geothermal energy is competitive with other sources of electrical power. However, geothermal projects present some unique challenges compared with other resources, principally from the standpoint of timing of high risk investment early in the project life. At this stage, the geothermal resource must be discovered and its potential assessed.

In reviewing past projects, it is found that return on investment can be improved through proper project management. Unnecessary surveys are often run, efforts are duplicated, and wells are often drilled that will not sustain subsequent production. Exploration and development has often been drawn out over years resulting in much higher costs than necessary. The scientific and management infrastructure required to bring projects on line quickly and within budget is often not present, particularly in developing countries.

The chance of exploration success and overall project economics can be greatly improved using properly designed exploration strategies, new technology and experienced scientists and exploration managers.

* Presentation at the World Bank.

APPLICATION OF THE CROSS-BOREHOLE DIRECT CURRENT RESISTIVITY TECHNIQUE FOR EOR MONITORING—A FEASIBILITY STUDY

DOE/ID/12489-83
ESL-89058-JP*

by

Craig W. Beasley, Alan C. Tripp, Douglas J. LaBrecque, John A. Stodt, Stanley H. Ward,

and Phillip M. Wright

SUMMARY

The cross-borehole resistivity method measures the electrical potential in one well due to direct-current flowing between electrodes situated in another well. This arrangement permits the sensing of regions remote from either well. The paper examines the use of the cross-borehole method in sensing electrical resistivity perturbations caused by steam-floods and water-floods.

* Also published in Borehole Geophysics: Petroleum, University of Arizona Laboratory for Advanced Subsurface Imaging (LASI), February 1 - 3, 1990, Tucson, Arizona. Paper rewritten as ESL-89058-JP, DOE/ID/12489-83).

THE OCCURRENCE OF CO_2-ENRICHED FLUIDS IN ACTIVE GEOTHERMAL SYSTEMS—DATA FROM FLUID INCLUSIONS

DOE/ID/12489-84
ESL-89059-JP*

by

Joseph N. Moore, Michele M. Lemieux, and Michael C. Adams

ABSTRACT

The condensation of CO_2 and steam in groundwaters above zones of boiling is thought to produce the CO_2-enriched fluids that are commonly found on the margins of high-temperature geothermal systems. Evidence for significant CO_2 flux has been found in fluid inclusions from the geothermal systems at Los Azufres, Mexico, and Zunil, Guatemala. These geothermal fields have measured temperatures close to 300°C.

CO_2-enriched fluid inclusions are widely distributed in both geothermal systems. These inclusions define a cap over each system that thickens outward from the main upwelling zones. Fluid inclusions from the upper portions of the caps frequently produce CO_2 clathrate upon freezing that melts at temperatures above 0°C. These inclusions have calculated CO_2 contents that range up to 5 weight percent. Ice-melting temperatures indicate that inclusions from the lower portions of the caps are also enriched in gas but contain less than 4 weight percent CO_2. The concentrations of CO_2 in the clathrate-bearing inclusions require trapping at pressures above hydrostatic. These pressures may have developed intermittently as fracture permeabilities were reduced by mineral deposition.

* Also published in the Fifteenth Annual Stanford Geothermal reservoir Engineering 1990 Workshop, in press.

NUMERICAL EVALUATION OF THE ATTENUATION OF TIME VARYING MAGNETIC FIELDS BY A CONDUCTING MAGNETICALLY PERMEABLE WELL CASING

DOE/ID/12489-85
ESL-90001-JP

by

Andrew Cook, Alan C. Tripp, Phillip M. Wright, and John A. Stodt

ABSTRACT

The paper presents numerical algorithms for calculating the attenuation of time-varying magnetic fields through electrically conducting, magnetically permeable casing. The algorithms can calculate the step-function response of the casing or the transfer function for time-harmonic field extension. The magnetic field can be either parallel or perpendicular to the casing. FORTRAN code suitable for use on a PC-AT or a compatible, is included.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

OCTOBER 1—DECEMBER 31, 1989

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Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

GEOLOGY AND GEOPHYSICS OF THE ZUNIL GEOTHERMAL SYSTEM

DOE/ID/12489-87
ESL-90007-JP*

by

Duncan Foley, Joseph N. Moore, Susan J. Lutz, Julio C. Palma A.,

Howard P. Ross, Edgar Tobias G., and Alan C. Tripp

ABSTRACT

The Zunil geothermal system in western Guatemala is located adjacent to the active volcanic centers of Santa Maria and Cerro Quemado, where the northeast-trending Zunil fault system transects the proposed Quetzaltenango caldera. The volcanic and intrusive host rocks of the geothermal system are highly altered, with the degree of alteration and veining increasing with depth. The effects of hydrothermal alteration are reflected in both the resistivity and gravity data. The electrical soundings define the presence of a resistive basement at depths of 200-400 m that correlates with a change in the clay mineralogy of the volcanic rocks. Trends in conductivity--thickness products also may reflect an increase in the development of electrically conductive clays away from the upwelling center. Hydrothermal alteration may be reflected in the gravity data as low amplitude gravity highs. Both the field mapping and gravity studies define a series of northwest- and northeast-trending faults.

* Also published in the 14th Geothermal Resources Transactions, 1990 Transactions, p. 1405-1412.

THE OCCURRENCE OF CO_2-ENRICHED FLUIDS IN AN ACTIVE GEOTHERMAL SYSTEM—DATA FROM FLUID INCLUSIONS

DOE/ID/12489-88
ESL-90008-ABS*

by

Joseph N. Moore, Michele M. Lemieux, and Michael C. Adams

Boiling is an important process in the upper 1 to 2 kilometers of many active geothermal systems and is now generally thought to be the primary cause of ore deposition in many fossil epithermal deposits. In active systems, the condensation of steam and CO_2 released by boiling may lead to the development of acidic $NaHCO_3$ fluids and the formation of clay-rich caps above the deeper NaCl reservoirs. Analogous steam-heated reservoirs have been proposed to explain the origin of the argillic alteration above epithermal deposits.

Evidence of high CO_2 and steam flux has been found in liquid-rich fluid inclusions from the upper and marginal portions of several active geothermal systems. These inclusions define caps over the deeper NaCl fluids that thicken outward from the main upwelling zones. Fluid inclusions from the uppermost portions of the caps represent steam-heated groundwaters that have temperatures up to approximately 200°C and low salinities and gas contents. Beneath this zone is a region enriched in CO_2. Inclusions from the upper part of this region commonly form CO_2 clathrate upon freezing that melts at temperatures above 0°C. These inclusions have calculated CO_2 contents that range up to 5 weight percent. Ice-melting temperatures indicate that inclusions from the lower portions of the caps are also enriched in gas but contain less than 4 weight percent CO_2.

Inclusions that have CO_2 contents greater than 4 weight percent are frequently associated with planes of vapor-rich inclusions, hydrothermal breccias, and argillic alteration. These features, and the consistent homogenization temperatures of inclusions within individual secondary planes suggest that they trapped a single phase CO_2-rich liquid which was near its boiling point.

Pressures in geothermal systems are normally close to hydrostatic. While our calculations indicate that most of the inclusions studied could have formed under hydrostatic conditions, this does not appear to have been the case for inclusions with positive clathrate melting temperatures. The high CO_2 contents of these inclusions requires trapping at pressures that were several tens of bars above hydrostatic. Higher pressures could have resulted from the combined effects of decreased fracture permeabilities due to mineral deposition and tectonic activity.

* Also published in the Pan American Conference on research in Fluid Inclusions (PACROFI III).

GEOCHEMICAL STRUCTURE OF THE COSO GEOTHERMAL SYSTEM, CA

DOE/ID/12489-89
ESL-90009-JP*

by

Joseph N. Moore, Michael C. Adams, Barbara Bishop-Gollan,

John F. Copp, and Paul Hirtz

ABSTRACT

Coso is one of several high-temperature geothermal systems associated with recent volcanic activity in the Basin and Range province. Within this fracture-dominated system, temperatures as high as 342°C have been measured at depths of less than 2.5 km. Chemical analyses of the production fluids show that steep gradients in the salinities, gas concentrations, and temperatures occur within the reservoir. Salinities range from 0.80 wt% TDS in the southwestern portion of the field to 0.48 wt% TDS in the north.

Fluid inclusions have been used to characterize the compositions and temperatures of the reservoir fluids outside the production zones. Homogenization temperatures of the fluid inclusions range from 328° to less than 100°C. Ice and clathrate melting temperatures indicate that the fluids have salinities up to 1.4 equivalent weight percent NaCl and variable but locally significant CO_2 contents.

The chemical and fluid inclusion data demonstrate that the northern and southeastern fluids are fed by upwelling and lateral flow from a deep two-phase reservoir in the southwest.

* Also published in the American Association of Petroleum Geologists, Guidebook, Coso Field Trip, AAPG EMD #1, p. 25-39.

DELINEATION OF THERMAL UPFLOW AND OUTFLOW PLUME WITH ELECTRICAL RESISTIVITY AND SELF-POTENTIAL DATA— NEWCASTLE GEOTHERMAL AREA, UT

DOE/ID/12489-90
ESL-90010-JP*

by

Howard P. Ross, Robert E. Blackett, Michael A. Shubat, and Claron E. Mackelprang

ABSTRACT

An integrated geological, geophysical and geochemical study has been underway in the Newcastle geothermal area of southwest Utah. Electrical resistivity and self-potential studies were undertaken late in the study in an attempt to provide additional delineation and characterization of this blind geothermal system. The electrical resistivity data detect the outflow plume and, with numerical modeling, indicate the probable upflow zone of the thermal fluids. Self-potential data map a well-defined minimum between the higher temperature shallow gradient holes and this is interpreted to be the principal conduit of fluids which feeds the outflow plume.

* Also published in Geothermal Resources Council, 1990 Transactions, 14, 1531-1536.

GEOCHEMISTRY AND HYDROLOGY OF THE ZUNIL GEOTHERMAL SYSTEM, GUATEMALA

DOE/ID/12489-91
ESL-90011-JP*

by

Michael C. Adams, Leland L. Mink, Joseph N. Moore, Lloyd D. White, and A. Caicedo, A.

ABSTRACT

The chemical and isotopic relationships of fluids from wells and springs in the region of the Zunil geothermal field follow a clear and consistent pattern with respect to their location. The chemical data define a plume of high-temperature water that originates in the western part of the existing well field. As this high-temperature fluid travels south and east, it boils and mixes with shallow steam-heated waters. The shallow fluids, which overlie and extend beyond the deeper sodium chloride reservoir, discharge as sulfate- and bicarbonate-rich thermal springs. Cl-enthalpy relationships suggest that the deep fluid may have a temperature as high as 335°C and a chlorinity up to 1550 ppm.

* Also published in Geothermal Resources Council, 1990 Transactions, 14, 837-844.

THOUGHTS ON STRESS AROUND STRUCTURE OF THE GEYSERS GEOTHERMAL FIELD

DOE/ID/12489-92
ESL-90012-JP*

by

Dennis L. Nielson and Donald Brown

ABSTRACT

This paper approaches the structural geology of The Geysers geothermal field from the perspective of stress relationships. The least principal stress is horizontal and oriented approximately N80W while $\sigma_1 \approx \sigma_2$. A number of published reports on production trends are reviewed and show that pressure sinks are developing along the conjugate shear directions while injected fluids preferentially utilize structures perpendicular to σ_3. Stress in the vicinity of the reservoir is approximated by a simple two-dimensional model for stress in the vicinity of a subsurface excavation. This model demonstrates areas of high and low stress surrounding the reservoir. It also demonstrates our concept that a structural arch has resulted in the decoupling of the reservoir from the vertical stress. These relationships may be important in planning and managing successful re-injection into the reservoir.

* Also published in Geothermal Resources Council, 1990 Transactions, 14, 1685-1690.

REMOTE DETECTION OF ACTIVE FAULTS USING BOREHOLE BREAKOUTS IN THE HEBER GEOTHERMAL FIELD, IMPERIAL VALLEY, CA

DOE/ID/12489-93
ESL-90014-JP*

by

M. Lee Allison

ABSTRACT

Analysis of borehole breakouts from wells in the Heber geothermal field in the southern Imperial Valley of California reveals three broadly defined breakout orientations: north-south (azimuth range 350-10 degrees), NE-SW (35-70 degrees), and WNW-ESE (70-130 degrees). Wells closest to faults are dominated by breakout orientations expected for extensional faults of those directions. Thermal gradient maps confirm an east-west trending thermal anomaly apparently truncated to the east against the Imperial Fault. The breakout data suggests that this anomaly is a manifestation of a hydrothermally active fracture system not presently being produced. Mapping the relative density of local breakout trends offers the potential of identifying the location and orientation of hydrothermal and other active faults and fractures.

* Also published in Geothermal Resources Council, 1990 Transactions, 14,1359-1364.

POSSIBLE VOLCANOTECTONIC CONTROLS OF HIGH-TEMPERATURE THERMAL FLUID UPFLOW IN THE VALLES CALDERA, NM

DOE/ID/12489-94
ESL-90015-JP*

by

Jeffrey B. Hulen and Dennis L. Nielson

ABSTRACT

Although normal faults and discrete stratigraphic aquifers are important thermal-fluid channels in the Valles hydrothermal system, higher-order permeability controls may be critical for development of commercial quality geothermal reservoirs in the Valles caldera. All six (of a total 24) commercially producible geothermal wells in the caldera are clustered within a 2 km^2 area coinciding with a prominent subsurface temperature and pressure anomaly defining a major upflow plume. These anomalies occur at the western edge of an inferred central vent zone for initial Plinian eruptions of the Tshirege Member (1.13 Ma) of the Bandelier Tuff; crystal-rich tuffs possibly ejected from this vent zone thicken dramatically as the zone is approached. We suggest that fractures and faults induced during development of this vent zone could control the current upflow of high-temperature thermal fluids, and that future wells targeted closer to the vent zone have an excellent chance of being commercially productive. Other probable major permeability controls in the Valles caldera include intersecting fault sets as well as ring-fracture zones around small, concealed, pre-Bandelier-age calderas.

* Also published in Geothermal Resources Council, 1990 Transactions, 14, 1457-1464.

INTERPRETATION OF LANDSAT THEMATIC MAPPER SATELLITE IMAGERY

AT

LOS AZUFRES GEOTHERMAL FIELD, MICHOACAN, MEXICO

DOE/ID/12489-95
ESL-90016-JP*

by

Phillip M. Wright, Hector Lira H., and Douglas R. Ramsey

ABSTRACT

This report documents part of a cooperative study by CFE and UURI of a Landsat 5 image of the Los Azufres geothermal area and its surroundings. The objective was to determine if processing and interpretation of satellite imagery are useful in volcanic environments for mapping structures, hydrothermal alteration, rock types and/or soil geochemical anomalies manifest in vegetation. Several processing steps were carried out using the ERDAS image-processing system installed on an AT-equivalent PC at UURI in an attempt to detect characteristic signatures from hydrothermally altered areas and to enhance linear and other structurally related geologic features.

A great deal of structural information is recorded in the Landsat image. Most of the interpreted linear features are believed to be due to faulting and fracturing, and there are more interpreted linears than there are mapped faults. The additional information contributed from the image interpretation may prove useful in planning for further development of the Los Azufres area.

Signatures reasonably characteristic of hydrothermally altered areas were developed after considerable experimentation with various false-color images of the direct digital data and of derived band ratios. This is a significant result because it implies that the method may be useful in helping to assess other areas of known geothermal occurrence which are less thoroughly mapped than is Los Azufres.

We believe that satellite imagery interpretation may contribute cost effectively to an exploration program by (1) outlining areas of strong and/or young faulting, (2) outlining areas where faulting and fracturing are more intense, (3) detecting hydrothermal alteration with a reasonable degree of reliability after calibration over known alteration, (4) outlining areas of young volcanic deposits, and (5) helping to guide geologic field work and prioritize areas. The cost per unit area of coverage is relatively small compared to some other techniques such as geologic mapping.

* Also published in Geothermal Resources Council, 1990 Transactions, 14, 1553-1559.

TIMING AND TEMPERATURE OF PETROLEUM ENTRAPMENT IN THE GRANT CANYON OIL FIELD, NEVADA

DOE/12/12489-96
ESL-90023-ABS*

by

Jeffrey B. Hulen, S. Robert Bereskin, and Michele M. Lemieux

ABSTRACT

Vein minerals in dolomite breccia record the temperature, relative timing, and geochemical environment of petroleum entrapment in the prolific Grant Canyon oilfield. Early "saddle" dolomite and late-stage quartz host two- and three-phase (liquid water and/or oil plus vapor) fluid inclusions. Primary oil-bearing inclusions, however, are confined to the quartz, suggesting that initial petroleum entrapment followed saddle dolomite deposition but accompanied subsequent quartz veining. Primary inclusions with a wide range of oil/water ratios are commonly found in individual growth zones of single quartz crystals, indicating entrapment from a dispersion of oil droplets in aqueous solution.

All the Grant Canyon fluid inclusions observed to date homogenize to the liquid phase at relatively low temperatures: aqueous inclusions in saddle dolomite at 112.7-132.7°C; primary oil, water, and oil/water inclusions in quartz at 103.8-120.9°C; and secondary inclusions with oil and water in various proportions at 90.4-123.9°C. Ice-melting temperatures reveal that aqueous fluids associated with petroleum in both primary and secondary inclusions are relatively dilute (<2.2 wt. % equiv. NaCl).

Current reservoir conditions at Grant Canyon are similar to those implied by the fluid-inclusion systematics summarized above: dilute thermal waters from reservoir depths reach temperatures of 121°C (up to 171°C in the nearby—1.4 km—Bacon Flat field). We suggest that at both fields, oil migration, entrapment, and perhaps maturation may be intimately related to development of a dilute, moderate- to high-temperature, meteoric-hydrothermal system.

* Also published in the American Association of Petroleum Geologists, 1990 Annual Meeting Bulletin, 74, 1328.

HIGH-TEMPERATURE ORIGIN FOR FRACTURED CARBONATE RESERVOIRS IN THE BLACKBURN OIL FIELD, NV

DOE/ID/12489-97
ESL-89052-JP*

by

Jeffrey B. Hulen, S. Robert Bereskin, and Louis C. Bortz

ABSTRACT

Preliminary petrographic and fluid-inclusion studies of drill cuttings and core from the Blackburn oil field reveal that many of the oil-saturated fractures, veinlets, and breccias in the dolomite reservoir rock may be of high-temperature hydrothermal origin. Textures of the earliest-formed fracture/veinlet networks and breccias suggest development by explosive hydrothermal fracturing; the veinlets themselves preserve evidence that high-temperature fluids favorable for such natural hydrothermal rock rupture once circulated in these rocks. Primary fluid-inclusion homogenization temperatures indicate that early vein dolomite precipitated from hydrothermal brines at temperatures exceeding 350°C (662°F). Younger (?) quartz-sphalerite-galena veinlets developed from dilute aqueous solutions at >225°C (437°F).

The high paleotemperatures recorded by early vein dolomite in the now much cooler (about 120°C(248°F)) Blackburn reservoir rock imply an ancient magmatic heat source, in this case almost certainly a small granodiorite stock (Tertiary?) adjoining and possibly underlying the field. Other carbonate-hosted petroleum reservoirs in eastern Nevada are also intimately associated with felsic intrusives. We propose that igneous-related, high-temperature hydrothermal fracturing could have created reservoir porosity and permeability at some or all of these fields, and that future petroleum exploration in the Basin and Range might profitably incorporate the search for concealed plutons.

* Also published in the American Association of Petroleum Geologists, 1990 Bulletin, 74, 679.

ANNUAL REPORT FOR FY89—GEOTHERMAL RESEARCH

DOE/ID/12489-98
ESL-90018-TR

edited by

Phillip M. Wright

INTRODUCTION

This report gives a summary of geothermal research projects and accomplishments at the University of Utah Research Institute for Fiscal Year 1989. The work reported here was sponsored mainly by the Geothermal Technology Division of the U. S. Department of Energy (DOE) under the Hydrothermal Reservoir Research program. Technical monitor and administration of this work comes from the Idaho Operations Office of DOE through contract DE-AC07-85ID12489. Some of the work in the Valles Caldera of New Mexico was sponsored by the Office of Basic Energy Sciences of DOE through contract DE-FG02-88ER13936. Readers interested in obtaining more information are invited to contact UURI directly. Reports listed herein under the individual project can be obtained from UURI for the cost of reproduction.

MANAGEMENT OF GEOTHERMAL RESOURCES

DOE/ID/12489-99
ESL-90017-PR*

by

Dennis L. Nielson, Phillip M. Wright, Michael C. Adams, Joseph N. Moore, Alan C. Tripp

ABSTRACT

Research at UURI concentrates on quantifying the processes taking place in geothermal systems and in developing methods to detect and monitor those systems. The past year's research has placed a greater emphasis on problems identified at The Geysers. As more geothermal systems reach a mature stage of production, production declines will become more common unless effective resource management techniques are developed.

Work is progressing on the development of vapor-phase tracers, and we are planning a tracer test with several of the operators. Mineralogical and geochemical studies to determine the origin and distribution of corrosive steam are continuing in cooperation with GEO Operator and UNOCAL.

Hydrogeochemical studies using fluid-inclusion and chemical data are continuing at Coso, Steamboat, Heber and the Valles caldera. This work is documenting fluid flow in fractured geothermal systems and in changes in fluid chemistry caused by production.

Our investigation of the application of borehole geophysics has continued with the development of two different 2-dimensional inversion algorithms for interpretation of cross borehole and borehole-to-surface data. Instrumentation is being assembled to field test the method. We believe that these techniques can be effective in mapping permeable zones and reservoir boundaries. In addition, this method can potentially be used to monitor drying out of vapor-dominated reservoirs and cold-water influx into liquid-dominated reservoirs.

Investigations of the state of stress in the Heber geothermal field suggest that borehole breakouts may be related to the proximity of major fracture zones. Concepts of stress have been used to develop a model for The Geysers system in which a structural arch effectively decouples the reservoir from the vertical stress. This model will be important in planning injection to control pressure declines.

* Also published in and prepared for Annual DOE Technical Review in San Francisco, April 16-20.

HIGH-TEMPERATURE NATURAL HYDRAULIC FRACTURING AS A RESERVOIR CONTROL IN THE BLACKBURN OIL FIELD, NEVADA — IMPLICATIONS FOR PETROLEUM EXPLORATION IN THE BASIN AND RANGE PROVINCE

DOE/ID/12489-100
ESL-90020-ABS*

by

Jeffrey B. Hulen, S. Robert Bereskin, and Louis C. Bortz

ABSTRACT

Petrographic and fluid-inclusion studies of the Blackburn oil field reveal that fractures and breccias now hosting oil in the Devonian dolomite reservoir rock were induced in part by natural, high-temperature hydraulic fracturing. Homogenization temperatures and ice-melting temperatures of fluid inclusions in vein dolomite suggest that this fracturing was effected by high-temperature (341 - >400°C) hydrothermal brines circulating above (and heated by) a small granodiorite intrusion. Oil entrapment followed cooling of this hydrothermal system after an unknown length of time; the system simply helped create the field's critical secondary porosity and permeability.

Four other (of a total six) commercial, carbonate-hosted eastern Nevada oil reservoirs (Eagle Springs, Kate Springs, Bacon Flat, and Grant Canyon) are intimately associated with small felsic plutons. Since such intrusives account for less than 10% of outcropping rocks in this region, the oil/pluton association seems more than coincidental. Our findings at Blackburn suggest that igneous-related hydraulic fractures and breccias could be key controls at some or all of these fields, and that buried plutons could become important exploration targets in the Basin and Range.

Although hydraulic fractures and breccias around plutons are previously unknown as petroleum reservoirs, they commonly host hydrothermal ore deposits. The geometries of such ore-bearing fracture/breccia bodies (e.g. pipes, dikes, and inverted bowls) are well-documented. We suggest that incorporating these features into Nevada petroleum exploration models could help both with development of existing fields and discovery of new ones.

* Also published in the American Association of Petroleum Geologists, 1990 Bulletin, 74, 679.

ESTIMATION OF EFFECTIVE RESERVOIR TEMPERATURE WITH REACTIVE TRACERS

DOE/ID/12489-101
ESL-90021-JP

by

Alan C. Tripp, Michael C. Adams, and Phillip M. Wright

INTRODUCTION

Chemical tracers have been successfully used to assess the degree of hydrologic communication between geothermal wells (Robinson and Tester, 1984; Robinson, 1985; Adams et al., 1989). Several authors (Birdsell and Robinson, 1988; Adams et al., 1989; Adams and Davis, 1990) have also suggested using reactive tracers to estimate reservoir temperatures. In these studies, a reactive tracer, whose kinetic decay properties with respect to temperature are known, is injected into one well and recovered in another. One simple way of interpreting the experimental data is to normalize the recovered amount of reactive tracer by the recovered amount of a conservative tracer, injected at the same time as the reactive tracer. The subsequent ratio is compared to the reactive tracer kinetic model to calculate a temperature which would account for the proportion of tracer decay observed. Another possible interpretation technique is to calculate the decay ratio for various temperature distributions and flow distributions and compare these computed ratios with the measured ratios.

The purpose of this paper is to build a simple model for the decay of a reactive tracer under a non-isothermal flow regime. We will then discuss ways in which such a model can be used to estimate reservoir temperatures. We will also discuss the accuracy of temperature estimates based on this model.

FAULT-CONTROLLED THERMAL STRESS AS A FRACTURING MECHANISM IN HYDROTHERMAL SYSTEMS

DOE/ID/12489-102
ESL-88045-JP*

by

M. Lee Allison

ABSTRACT

Hydrothermal fluids circulating along open faults or fractures in thigh temperature geothermal systems will produce thermal stresses large enough to fracture the adjacent rock. Assuming a uniform elastic semi-infinite half-space a thermal stress will develop proportional to the temperature difference between the hydrothermal fluid and the normal rock/fluid beyond the system. In accord with thermal stress studies on oceanic ridges the vertical stress esl_{22} is assumed to be based on the thermal gradient. In contrast to those studies however, the maximum stress esl_{xx} is normal to the fluid-hosting fault and the strain is zero. Stress along the fracture, esl_{yy}, is assumed to be zero because the convecting fluid will equalize temperatures quickly after entering the system. The model is a steady-state system in which hydrothermal fluids continue to replace those that cool and pass out of the system. Thus, adjacent rocks do not cool as in the cases of oceanic lithosphere or dike injection. For typical rock values the thermal stress is from 1 to 2 kbars for each ΔT of 100°C across the field. Typical continental deviatoric stresses are 0.1 to 1 kbar.

In an extensional environment (esl_1 vertical) faults develop ideally in the direction of esl_2 and perpendicular to esl_3. When later hydrothermal fluids are injected along the faults the new thermal stress results in a reorientation of the total stress field. Stress normal to the fault changes from esl_3 to esl_1. Stress along the fault changes from esl_2 to σ_3. Thus in the reoriented system new fractures and faults will form at a high angle to the pre-existing ones. This may help account for complex fracture patterns in hydrothermal systems.

* Also published in the EOS, 1988 Transactions, AGU, 69, 1451.

MULTIPLE FAULT-BOUNDED STRESS FIELDS IDENTIFIED BY BOREHOLE BREAKOUTS

DOE/ID/12489-103
ESL-88046-JP*

by

M. Lee Allison and Dennis L. Nielson

ABSTRACT

Multiple stress fields have been identified from borehole breakouts in geothermal wells in Nevada, Utah, and New Mexico. Stress fields change orientation abruptly at faults in individual wells. Significant changes in stress directions also exist between wells, separated by faults, in the geothermal fields,. At the Roosevelt and Cove Ft.-Sulphurdale fields in Utah, each stress fields can be related to a particular fault or fault set. In the Valles caldera in New Mexico., the stress systems are related to resurgent doming. Stress systems in Dixie Valley, Nevada, also show close correspondence to local fault orientation.

The origin of very distinct multiple fault-bounded stress fields may be explained by large thermal stresses associated with geothermal activity.. In these fields geothermal production is largely controlled by fractures and faults. Hot fluids circulating along a fault will produce a uniaxial thermal stress perpendicular to the fault surface. Using typical rock values the thermal stress is roughly 1 to 2 kbars for a temperature difference across the field of 100 °C. This compares to typical continental deviatoric (tectonic) stresses on the order of 0.1 to 1 kbar. Thus, hydrothermally active faults can produce thermal stress as large or larger than the ambient regional stresses. Within a geothermal system a fault-bounded mass of rock would have a stress field resolved from the regional stress and the thermal stresses of the bounding faults. Large faults with a high fluid-carrying capacity or those that are particularly hot would control the resultant stress orientation. This work had applications for exploration and development of fracture-controlled hydrothermal systems.

* Also published in the Geological Society of America, Abstracts with programs 1988, 20, 7, A182.

FRACTURE PERMEABILITY IN THE COSO GEOTHERMAL SYSTEM, CA

DOE/ID/12489-104
ESL-88048-JP*

by

Jeffrey B. Hulen, John F. Copp, M. Lee Allison, and Dennis L. Nielson

ABSTRACT

The high temperature Coso hydrothermal system is hosted entirely by highly fractured Cretaceous igneous and metamorphic rocks intruded and overlain by Plio-Pleistocene volcanics. All permeability is fracture-controlled. Geologic mapping demonstrates NW-oriented dikes of different ages and lithologies are offset by NNE-trending normal faults with strike-slip components. Fracture orientations from dipmeter logs in the south end of the field define both NNE- and NW-trends. The deep NW-trending, steeply dipping fracture zones are an important source of permeability.

In-situ stress determinations from borehole breakouts in the wells show multiple stress orientations, a phenomena seen in other geothermal fields. Breakouts in some borehole segments deviated more than 14° from vertical, trend consistently 15-20° counterclockwise of the drift azimuths providing possible estimate of the S_H/S_h magnitude. The ratio changes in different fault blocks. Change in orientation and magnitude of the stresses in different fault blocks will determine which fracture systems are open and productive. Integrated analysis of the relationship of surface and subsurface fractures and faults with localized stress fields is allowing better determination of productive intervals in the field.

* Also published in the EOS, 1988 Transactions, AGU, 69, 1172.

DOE/ID/12489-105

WAS NOT ASSIGNED TO ANY PUBLICATION

EVOLUTION OF THE WESTERN VALLES CALDERA COMPLEX, NEW MEXICO:

EVIDENCE FROM INTRACALDERA SANDSTONES, BRECCIAS AND SURGE DEPOSITS

DOE/ID/12489-106
ESL-88050-JP*

by

Jeffrey B. Hulen, Dennis L. Nielson, Thomas Little

ABSTRACT

Scientific core drilling in the Pleistocene Valles caldera complex (encompassing the Valles (1.13 Ma) and coaxial Toledo (1.50 Ma) calderas) of north-central New Mexico has provided new insight into the origins of sandstones, breccias, and pyroclastic surge deposits interbedded with the thick intracaldera ignimbrite sequence. These rocks were previously interpreted from geothermal drill cuttings as dominantly fluvial in origin. As such, representing significant erosional intervals, they formed much of the basis for subdividing the intracaldera ignimbrite sequence (up to 2000 m in apparent thickness where drilled) into four major units: the lower tuffs (>1.50 Ma); the Otowi (1.50 Ma) and Tshirege (1.13 Ma) Members of the Bandelier Tuff; and a new unit, the upper tuffs, believed to be post-Bandelier in age (<1.13 Ma). All but the upper tuffs correspond to mapped outflow-facies ignimbrite sheets. However, Continental Scientific Drilling Program (CSDP) coreholes VC-2A (compl. 1986) and VC-2B (compl. 1988), in the Sulphur Springs area of the Valles caldera, have provided continuous core revealing for the first time that some intracaldera rocks previously thought to be exclusively clastic actually have multiple origins. Some of these rocks are probably pyroclastic surge deposits; others could be lithic-rich breccias of various origins incorporated near-instantaneously in ignimbrites during ash-flow eruption and concomitant caldera collapse.

These new findings demonstrate the value of continuous core for subsurface characterization and correlation of complex intracaldera lithologies; they also necessitate revision of Nielson and Hulen's (1984) cuttings-based intracaldera stratigraphic framework. For example, the hematinic S_2 "sandstone" was initially interpreted as marking an erosional interval between the Tshirege Member of the Bandelier Tuff and the overlying, petrographically similar upper tuffs. Core from VC-2A and VC-2B, however, shows that the S_2 cuttings could also represent disaggregated, Permian redbed-rich, lithic-lag breccias or caldera-collapse mesobreccias. If this is the case, then most or all of the upper tuffs are actually uppermost Tshirege Member ignimbrites. In similar fashion, and upon review of previously applied correlation criteria, the "lower tuffs" of the western Valles caldera complex could represent both genuine pre-Bandelier ignimbrites and those of the lowermost Otowi Member. The core, however, shows that in the Sulphur Springs subsurface the lower tuffs are separated from overlying ignimbrite sheets by prominent erosional and eruptive breaks; they appear to be slightly more mafic than the overlying tuffs, and host distinctive pumice lapilli. At this site, the lower tuffs almost certainly pre-date the Otowi Member and are probably correlative with the outflow-facies San Diego Canyon ignimbrites (1.78 Ma).

Core from VC-2A and VC-2B supports earlier interpretation of the S_3 "sandstone" as a major marker horizon separating the intracaldera Otowi and Tshirege Members of the Bandelier Tuff, but clearly shows that this important unit is not, as previously thought, entirely a simple intracaldera epiclastic apron. In VC-2A, the S_3 has the superficial appearance of a sandstone but contains abundant blocky shards as well as accretionary and armored lapilli; it is also soft-sediment-

deformed and invades overlying non-welded tuff as small clastic dikes. We believe that here, the S_3 was emplaced by a wet pyroclastic surge. In nearby corehole VC-2B, the S_3 consists of a basal, massive, sediment-gravity-flow (?) sandstone overlain by sandstone and dacite breccias with accretionary and armored lapilli-bearing tuffaceous matrices. These deposits are probably caldera-collapse mesobreccias, formed simultaneously with early Tshirege Member ash-flow eruptions through or into a Toledo caldera lake.

* Also published in Journal of Geophysical Research, 96, June 1991 (in press).

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WAS NOT ASSIGNED TO ANY PUBLICATION

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STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

JANUARY 1 — MARCH 31, 1990

DOE/ID/12489-109
ESL-90023-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

ENERGY DEVELOPMENT PROCESS —

EXPLORATION, DEVELOPMENT AND CONVERSION TECHNOLOGY

DOE/ID/12489-110
ESL-90026-TR*

by

Phillip M. Wright

SUMMARY

The U.S. geothermal industry is a world leader in technology and can supply equipment, goods and services for all phases of geothermal development. Development begins with exploration to locate resources, proceeds with resource mapping and evaluation through drilling and culminates with the construction and operation of fluid-gathering and disposal systems and a plant for electrical generation or direct-heat uses. The exploration and resource evaluation stages are usually time consuming and the most risky. Having an experienced team, using modern technology, and using a staged exploration strategy help mitigate risks. Drilling for reservoir testing and for production and injection of fluids is a major cost item in any development. U.S. drilling technology is demonstrably equal or superior to that of any in the world.

Electrical generation plants are available in essentially any size from a few hundred kilowatts to more than 100 megawatts, and the U.S. industry has made considerable innovation in plants in recent years. Both flash-steam and binary-cycle plants are being successfully used. Modern, U.S. plants have an on-line record of 95% or more -- a record that betters that of fossil and nuclear plants considerably. Projects in the range 0.5 to 10 MWe can usually be completed, including discovery of the resource, in 2 years time or less, while projects in the range 10 to 100 MWe may take a year or more longer. The risk of the plant not operating as designed is very low.

The risk that the production characteristics of the reservoir will deteriorate to unpredicted and unacceptable levels can be mitigated through well testing, appropriately designed production/injection strategies and monitoring of temperature, pressure and chemistry of produced fluids. Installation and operation of one or more small, well-head plants at a reservoir ultimately slated for major development has the advantage of generating some revenue from electricity sales while testing production from the reservoir. The data generated can be used in computer-based reservoir models to enhance the ability of the reservoir engineer to predict performance.

* EXIM Bank Presentation.

GEOTHERMAL RESOURCE DEVELOPMENT IN UTAH

DOE/ID/12489-111
ESL-90027-JP*

by

Phillip M. Wright, Robert E. Blackett and Howard P. Ross

Geothermal resources are being actively developed on a worldwide basis. Current worldwide geothermal electrical generating capacity is about 5,700 megawatts, with the United States accounting for 2,940 megawatts of the total. Current direct uses of geothermal energy probably amount to more than 15,000 thermal megawatts, with the U.S. contributing about 18.8×10^{12} BTU/yr or 630 thermal megawatts. Geothermal resources worldwide produce enough energy to displace the use of about 160 million barrels (bbl) of petroleum annually. Utah has two areas, Roosevelt Hot Springs and Cove Fort/Sulphurdale, with a present combined installed electrical generating capacity of more than 30 MWe. In addition, there are a number of commercial applications of the direct use of lower-temperature geothermal resources in Utah, utilizing about 7×10^{11} BTU/year or 24 thermal megawatts. Most of Utah's known geothermal resources and its potential for future development lie within the Basin and Range geologic province, and within the Basin and Range-Colorado Plateaus transition zone.

Geothermal development in Utah is presently rather depressed due to the comparatively low energy costs of today and the excess electrical generating capacity that has existed in the West. Growth in geothermal generating capacity in the U.S. is forecast at a rate between 6 and 9 percent per year from the present to the year 2005, with essentially all of this development being in the hydrothermal convective type of resources.

* Also published in the Utah Geological Association Guidebook, "Energy and Mineral Resources of Utah," 1991, in press

A PRACTICAL GUIDE TO THE IDENTIFICATION AND SIGNIFICANCE OF COMMON LAYER SILICATES IN ACTIVE GEOTHERMAL SYSTEMS

DOE/ID/12489-112
ESL-90028-TR*

by

Dennis L. Nielson and Jeffrey B. Hulen

INTRODUCTION

The common layer silicates, such as kaolin and illite, are abundant and widespread in the majority of active, high-temperature geothermal systems. Perhaps the most temperature-sensitive secondary minerals, they tend to be systematically zoned with respect to these systems' high-grade heat centers and permeable thermal fluid channels. Their distribution therefore provides valuable clues for the efficient and cost-effective location of these features. Moreover, layer silicates can be readily and inexpensively concentrated from their host rocks and characterized by X-ray diffraction (XRD) techniques. In this briefing document, we present an overview of the common layer silicate mineral groups, discuss their identification, and address their significance to geothermal exploration and development. For more detailed and technical accounts, the reader is referred to Brindley and Brown (1980) and Moore and Reynolds (1989).

* Also published as part of the Geothermal Resources Council, Short Course, 1990.

ELECTROMAGNETIC INDUCTION STUDIES

DOE/ID/12489-113
ESL-90029-JP*

by

Philip E. Wannamaker and Gerald W. Hohmann

INTRODUCTION

In the last four years, we have witnessed a revolution in electromagnetic induction studies. Although its roots may be traced back for decades, events of the past few years demonstrate most clearly just how much has been achieved [Booker et al., 1988; Booker and Chave, 1989]. The principal foundations of the new state of the field include instrumentation and data processing advances, proper survey design, innovative modeling and inversion/modeling approaches, and knowledge of what electrical resistivity structure can contribute to earth science generally. Advances in many of these areas have been lead by researchers in the United States and Canada, though many also result from work and cooperation of a genuinely international nature. The approximately 500 references contained in the bibliography attest to the diversity of efforts in this field. For background and research efforts prior to 1986, the reviews of Chave and Booker [1987] and Hermance [1983] are recommended.

In this review, we address EM induction work in the United States applied to solid earth investigations, oceanographic studies, environmental studies, and exploration for minerals, petroleum, and geothermal resources. References to work in other countries are included where necessary to set the U. S. work in context. The paper commences with the topic of data collection and instrumentation methodology, followed by a discussion of EM response function estimation. Subsequently, the substantial progress in forward modeling and inversion, particularly for two- and three-dimensional geometries, is presented. The relationship of electrical resistivity to physicochemical state in the earth has been clarified substantially, but important new controls are coming to light also. Finally, the last four years have seen vigorous programs of field measurements and their interpretation, most notably the EMSLAB project in the U. S. and the LITHOPROBE program in Canada. Applied induction work now contains a large component focused on environmental problems and reservoir assessment using both surface and borehole geophysics.

* Also published as a Report to the International Union of Geodesy and Geophysics. Also published in the Reviews of Geophysics, v.29, in press (Summer 1991).

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

APRIL 1 — JUNE 30, 1990

DOE/ID/12489-114
ESL-90030-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document.

STATE COOPERATIVE RESERVOIR ANALYSIS PROGRAM QUARTERLY REPORT—

JULY 1 — SEPTEMBER 30, 1990

DOE/ID/12489-115
ESL-90031-PR

by

Howard P. Ross

STATEMENT

University of Utah Research Institute provides technical project management services to the Department of Energy for the State Cooperative Analysis Program, formerly the State Coupled Program (SCP), and issues quarterly and annual progress reports to DOE/GTD and DOE/ID manager responsible for this program. These reports are short summaries of project status for the participating state teams and do not have technical abstracts. Prior to January 1, 1988 quarterly reporting was by means of informal memoranda and these are not included in this document..

HYDROTHERMAL ENERGY - AN IMPORTANT PART OF AMERICA'S ENERGY STRATEGY

Proceedings for United States Department of Energy
Geothermal Program Review VIII, San Francisco
April 18-20, 1990, p. 19-26

by

Kenneth J. Taylor, Marshall Reed and Howard P. Ross

ABSTRACT

The U.S. Dept. of Energy (DOE) established a Geothermal Energy Program in the mid-1970's as one response to America's need to develop alternative energy sources. One element within the Geothermal Industrialization, Reservoir Technology, and Conversion Technology as separate tasks. The successes which have resulted from this program, combined with anticipated future progress, will increase the role of geothermal energy as a contributor to our nation's future energy needs. Geothermal energy has become an important component of the U.S. National Energy Strategy.