Geothermal Reservoir Technology Research Program

Abstracts of Selected Research Projects

March 1993

Edited by:
Marshall J. Reed

U.S. Department of Energy
Assistant Secretary for Energy Efficiency
and Renewable Energy
Geothermal Division
Washington, DC 20585

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FORWARD

This compendium of extended abstracts for the Geothermal Reservoir Technology Program presents a short review of many of the current research projects funded by the U.S. Department of Energy. We hope that this compilation of information will be of interest and of use to members of the United States geothermal industry. The abstracts were written and edited to communicate the research progress with everyone involved in the technical aspects of geothermal energy development. Care has been taken to provide definitions for many special terms used. These abstracts were written to provide accurate explanations of scientific and engineering studies.

The multi-disciplinary nature of the problems in reservoir technology leads to a number of interrelated research projects. The organization of this compendium provides groupings of research projects to show this interrelationship. To provide better access to information concerning any single topic or method, the index provides the beginning page number for each abstract that deals with the key word listed. The key words indicate several other relationships between the research projects. Many of the abstracts describe research applied to The Geysers geothermal field in California. Requests from the geothermal industry to help with the problems of pressure and productivity decline gave the impetus to apply many of the research techniques to The Geysers reservoir. These projects are nearing completion, and the knowledge gained from study of The Geysers will greatly assist future research on injection and reservoir processes in other U.S. geothermal systems.

These extended abstracts are intended to clearly present the objectives, technical approach, and project status of each project. Each also contains discussions of the background, research results, and future plans for the project. References are given for recent technical publications concerning the projects. The names, addresses, and telephone and telefax numbers are given for the DOE program manager and the principal investigators. Please feel free to contact the principal investigators if you desire more information or if you have any questions. All of the contacts listed will be happy to discuss the research projects.

This research program in Geothermal Reservoir Technology is designed to support the needs of utility, industrial, community, and private utilization of geothermal resources through development and verification of new technology for exploration, fluid production and injection, and prediction of reservoir lifetime. The approach used to accomplish these objectives is to: (1) conduct DOE-sponsored research to meet the long-term research needs of the geothermal industry; and (2) fund cost-shared research with industry in areas of greatest current need. The Geothermal Reservoir Technology Program relies on the continuing review and direction of the U.S. geothermal industry. Industry leaders are looked to for the identification of priority research areas and for guidance in the operation of this research program.

Marshall J. Reed
Program Manager
March 1993

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INTRODUCTION

THE GEOTHERMAL RESERVOIR TECHNOLOGY PROGRAM

Marshall J. Reed
Geothermal Division, U. S. Department of Energy

KEY WORDS

Reservoir studies, exploration, field tests

PROGRAM OBJECTIVE

The overall objective of the Geothermal Reservoir Technology Program is to provide the United States geothermal industry with the theoretical and analytical tools needed to locate, characterize, develop, and operate both domestic and foreign geothermal systems for the maximum production of energy. The research funded by the Department of Energy focuses on those generic or broad-based research needs of the industry that can not be addressed by individual companies. This research is important in providing the U.S. geothermal industry with advanced technology to help meet the nation's energy needs and to maintain superiority in geothermal development.

APPROACH

This multi-disciplinary research program uses cost-shared projects with industry as a nucleus for identifying and executing research to solve the major impediments to full use of our geothermal resources. When a technological need is identified by industry, a project is developed to make the best use of available research capabilities in National Laboratories, universities, and commercial research groups. Rather than attack critical problems one at a time, this program uses parallel research projects to investigate several important technological problems simultaneously. Many of the current research projects are interrelated, and technological breakthrough in one project will often aid several others.

PROJECT STATUS

Background

The Geothermal Reservoir Technology Program is the outgrowth of several previously separate research programs in exploration technology, reservoir analysis, brine injection technology, resource assessment, and brine chemistry. As funding declined during the 1980s, the level of activity in each of these programs decreased to the point that separate programs were no longer justified. In recent years, the combined research program has focused the accumulated knowledge and talents of researchers on specific problems of great importance such as The Geysers reservoir decline.

Preceding research programs conducted field tests that were often separate from the industrial development of geothermal resources, but declining budgets have made such activities as well drilling and field testing too costly to conduct without the cooperation and participation of the geothermal industry. Recent experience has shown that research conducted as cost-shared projects with industry has the greatest likelihood of being successfully incorporated into commercial operations and benefiting industry.

In the late 1970s and early 1980s, a program in industry coupled drilling was active in cost-shared (50% DOE : 50% industry) exploration drilling. That program was able to drill exploration wells in 14 geothermal prospect areas in Nevada and Utah; and, today, 8 of those prospects are producing electricity from the geothermal resource. This is an example of successful cooperation with the

geothermal industry.

Research Results

The Geothermal Reservoir Technology Program has been able to spur the development of modeling and simulation of geothermal reservoir processes. Research projects at several cooperating institutions have helped move the development of oil and gas reservoir modeling into the more complex simulation of fractured, multi-phase, multi-temperature geothermal systems. Research projects have advanced the state-of-the-art in microearthquake analysis to the point where we are now able to identify fractured rocks which act as fluid flow paths for production and injection. The development of chemical tracers which are compatible with the environment and can be detected at minute levels has enabled the geothermal industry to predict the cooling effect of injection, and to distribute injection wells in the most favorable locations to maintain reservoir pressure and flow rate.

Some of the current research projects under this program are described in the following abstracts. The future direction of this research depends strongly on the interest and guidance received from the US geothermal industry. Geothermal developers are encouraged to become thoroughly familiar with the research projects, to guide the research in the direction of greatest benefit, and to incorporate the results of the research into their exploration, development, and reservoir management.

Plans

An industry cost-shared (50:50) drilling project will begin in 1994 to provide the United States with the known geothermal reserves that will be needed to support expanded development of electrical generating capacity over the next ten years. This cost-shared drilling project is designed to share the risk of geothermal exploration with the developers in order to identify geothermal resources before they are needed.

A strong effort will continue in the development of geothermal reservoir simulators that will reliably predict the recovery of available energy over the lifetime of a geothermal reservoir. A parallel effort will proceed to refine reservoir simulation so that it will be a useful tool in the day to day management of geothermal reservoirs.

Efforts are underway to integrate the available tools for geothermal exploration into a relational package with the capabilities of evaluation and decision making for the drilling and analysis of a geothermal prospect. The fundamental testing of an integrated exploration system will rely on several geothermal exploration case histories now being developed in cooperation with the geothermal industry. The success of this effort will depend heavily on the participation of industry.

REFERENCES

McLarty, L., and Reed, M. J., 1992, The U.S. geothermal industry: Three decades of growth: Energy Sources, v. 14, p. 443-455.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-8076

EXPLORATION FOR NEW DISCOVERIES

GEOHERMAL RESOURCE EVALUATION BASED ON HEAT FLOW AND THERMAL CONDUCTIVITY DATA FOR THE UNITED STATES

David D. Blackwell

Department of Geological Sciences, Southern Methodist University

KEY WORDS

Geothermal resources, heat flow, thermal conductivity

PROJECT OBJECTIVE

The object of this project is to develop information and techniques to use in conjunction with ongoing DOE geothermal resource evaluation projects to improve the precision of the assessment of the geothermal resource potential of the United States. This project will increase the precision and accuracy of geothermal resource estimates and assessments by making available, in useful formats, the most up to date heat flow, geothermal gradient, and thermal conductivity information for the United States. This research is also an important tool for geothermal developers conducting regional exploration for new geothermal prospect areas.

APPROACH

This project will build on the heat flow data base that was used in the preparation of the Geological Society of America, Decade of North American Geology (DNAG), Geothermal Map of North America, published by the NOAA Geophysical Data Center (The Geophysics of North America CD-ROM [compact disk - read only memory]). This data base will be continually updated with recently released information. The expanded heat flow data base will be combined with thermal conductivity data to calculate the distribution of temperature at depth. Highly accurate heat flow measurements will be stored as digital, map-based data to provide reliable information over large areas of the United States.

PROJECT STATUS

Background

This project extends earlier national heat flow evaluations by Sass and Lachenbruch in 1979 and the preliminary analysis of Blackwell and Steele in 1990. The project, based on the uniquely complete and detailed geothermal data base, a digitized heat flow contour data set from the DNAG Geothermal Map of North America was initiated in 1991-1992.

One important focus is on producing a heat flow data set in contoured and gridded form for the conterminous United States at a resolution finer than 10 km that can serve as a site-specific data set of temperatures for depths from 0 to 4 km. This information in turn can serve as a basic input for more specific geothermal evaluation programs both by this project and in other DOE and non-DOE geothermal resource evaluation projects. Wide distribution of the results in digital form is a major part of the project effort. A particularly important additional part of the project is to improve the accuracy of the prediction of temperatures in the 0 to 4 km depth range in the Central and Eastern conterminous United States by determining the thermal conductivity distribution in the sedimentary section above basement. These results will have special application to the evaluation of the low-temperature geothermal potential. These results will supplant the calculations of Blackwell and Steele in 1990 which were carried out on a broad, 5° x 5°, area average and based on the assumptions that surface temperature was 0°C and that the thermal conductivity was constant with depth.

Research Results

Preliminary results for one aspect of the study are illustrated in Figure 1 where data sets for (1) surface temperature, (2) thickness of sedimentary rock, (3) mean thermal conductivity of the sedimentary section, and (4) areal heat flow have been combined to calculate temperature at a depth of 4 km in parts of the eastern United States. For the purposes of illustration at this small scale the data have been used at a 10-minute interval although the data themselves are aggregated at the 5-minute interval. This type of map can be used to direct exploration and possible exploitation plans to appropriate areas.

This type of information shows that there are major regional variations in the potential for geothermal resources in the eastern US, as there are in the western US. At a depth of 4 km for example, there are regions of relatively high temperature in the northern Midwest, in the Louisiana area, in the eastern Iowa region, and in the western New York/northwestern Pennsylvania areas. Figure 1 also illustrates that there are large gaps in the data base. For example, Kentucky has no heat flow data at all, and there are large gaps in several other areas. The improved data base can be used to rate areas of the country on their suitability for various types of geothermal use based on their regional thermal conditions.

Plans

The most accurate analytical techniques will be used to perform regional resource estimates. The specific tasks for 1993 include the release an updated heat flow data base including data published subsequent to that used for the DNAG Geothermal Map of North America. The updated results will be made available on computer compatible media in open-file form. In addition, a 5-minute digitized version of the revised heat flow contours will be used with the estimates of the thermal conductivity of the rocks in the upper 4 km of the crust to calculate a digital temperature-depth map of the Eastern and Central States. The values of thermal conductivity for the major lithologic units in each section will be evaluated using the published heat flow data for specific sites. Included in this project is a long-term task to develop a hydrothermal data base to be associated with the heat flow data base. We will also study the statistics of thermal distribution and evaluate the potential field of basement heat production in the Eastern United States to estimate heat flow in areas with no direct thermal measurements.

In the western US, past geothermal exploration activity has been basically site specific. The known areas of readily exploitable resources are, however, generally being exploited, or will be soon. The future development of geothermal energy will involve a fresh look at areas for exploration. Also, only part of the exploration information that has been collected in the past is publicly available to be used as a basis for new exploration. A detailed presentation of existing thermal results from hundreds of drill holes will be of great value in this next phase of geothermal exploration. This project aims to put this information into the context of the existing regional and local geothermal data as illustrated on the Geothermal Map of North America.

REFERENCES

- Blackwell, D. D., and Steele, J. L., 1990, Mean temperature in the crust of the United States for hot dry rock resource evaluation: Unpublished Report to Sandia National Laboratories, 28 p.
- Blackwell, D. D., and Steele, J. L., 1992, DNAG geothermal map of North America, 1:5,000,000: Geological Society of America.

Figure 1. Map of the eastern United States showing projected temperature at 4 km depth.

Blackwell, D. D., Steele, J. L., and Carter, L. S., 1989, Heat flow data base for the United States: in Geophysics of North America CD-ROM, eds. A. M. Hittleman, J. O. Kinsfather, and H. Meyers, NOAA, National Geophysical Data Center.

Blackwell, D. D., Steele, J. L., and Carter, L. S., 1991, Heat flow patterns of the North American Continent; A discussion of the Geothermal map of North America: in Neotectonics of North America, eds. D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell, Geological Society of America, Decade of North American Geology, Decade Map Volume 1, p. 423-437.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigator:

David D. Blackwell
Department of Geological Sciences
Southern Methodist University
Dallas, TX 75275
Phone: (214) 768-2745
FAX: (214) 768-4289

ADVANCES IN THE APPLICATION OF THE SELF-POTENTIAL METHOD FOR GEOTHERMAL EXPLORATION

Michael Wilt and Paul W. Kasameyer
Lawrence Livermore National Laboratory

KEY WORDS

Self potential, fluid flow, monitoring, field data acquisition, modeling

PROJECT OBJECTIVE

The objective of this research is to develop techniques to overcome problems in data collection and interpretation for the self-potential (SP) method in geothermal exploration. Although the SP method has shown promise in detecting deep-seated geothermal activity, it is not widely used due to (1) uncertainties in data collection, and (2) inability to interpret the results. This research has importance to geothermal exploration because refinements in the interpretation of SP surveys could make this method a more useful and inexpensive way to locate and characterize geothermal prospects.

APPROACH

The LLNL program is examining methods to reduce external and geological noise in SP surveys and to enhance interpretation of SP data through improved knowledge of SP cross-coupling coefficients and direct SP modeling from a flow simulator.

PROJECT STATUS

Background

Figure 1 (after a paper by Corwin and Hoover in 1979) illustrates two problems of SP data collection: (1) the effect of near-surface geology, and (2) drift and scatter. The two SP profiles were collected along the same survey line over Leach Hot Springs, in north-central Nevada. They show a long-wavelength anomaly, associated with the geothermal system, with many shorter-wavelength features superimposed. In many surveys, these short-wavelength features obscure the deeper signals of interest. In addition, there is a 5 to 10 millivolt difference between the profiles, a repeatability error that is typical of carefully collected SP data.

Modeling SP data sets has been unsatisfying even when there is an obvious association with geothermal activity. Existing codes assume the source is either a large polarizable object, such as a sphere or plate, or a discrete subsurface region generating high temperatures or pressures. Neither of these assumptions provides a satisfying link between the causative fluid- or heat-flow process and the SP voltages.

Research Results

A. Data Collection: Evaluation of Temporal Filtering:

To evaluate several possible causes of SP scatter and drift we devised a system to collect an entire profile of data simultaneously. The system features an 18 channel seismic cable attached to a Hewlett Packard digital voltmeter and scanner, both controlled by a desktop computer (Figure 2). The computer originates a data collection run, collects and stores the data, and does statistical analysis and "smart stacking".

Figure 3 shows results of using the system to measure variations of SP voltages for periods up to two hours after the emplacement of electrodes along an SP profile near Mammoth Lakes, California. Each plotted point represents the average of twenty measured voltages; standard deviations (not shown) were

Figure 1 Repeated SP surveys collected near Leach Hot Springs, Nevada (after Corwin and Hoover, 1979).

Figure 2 Schematic diagram of the SP data collection system

typically 0.1 mV or less. The three profiles show the same basic character but individual points typically differ by 5 to 10 mV, which greatly exceeds the calculated standard deviations for each profile. At this site, the automatically collected data is no quieter than data collected manually. Although our system reduces common-mode thermal drift and external noise, this advantage is offset by voltage variations which occur because electrodes with different thermal and electrochemical characteristics are used at each location.

The observed 5 mV/km telluric noise level was barely detectable for most of the SP data so we did not need the smart-stacking capabilities of our system. In high resistivity areas or in northern latitudes, telluric noise can be more than 100 times higher, and temporal filtering and "smart stacking" could be valuable. Short-term signal averaging did not significantly improve data quality. We postulate that electrochemical effects and local thermal cycles, which probably cause the drift, are much longer than the averaging times.

The automatic system offers no distinct advantage in routine collection of SP data in a quiet area. This complex system is, in fact, slower and more cumbersome to deploy. The 5 to 10 millivolt scatter in most surveys may be a consequence of burying nonpolarizable electrodes in shallow holes. The automatic system does offer significant advantages for continuous monitoring of SP voltages, since up to 1000 stations can be measured from a single system. This suggests that SP could be used as a low-cost method for monitoring changes in a geothermal field during exploitation.

B. Data Collection: Evaluation of Spatial Filtering:

To test methods of separating short- and long-wavelength SP anomalies we collected data on a 20 m by 40 m grid covering a 0.5 square km area in Long Canyon near Mammoth Lakes, California. The site, which lies 3 km east of the Casa Diablo geothermal power plant, was chosen for its proximity to known geothermal activity and the availability of existing subsurface resistivity and heat- and fluid-flow information.

SP data were collected in 17 profiles, 40 m apart, with stations spaced at 20 m along each profile. The profiles cross several hot springs, and the area is known to have high temperatures at depths less than 20 m. Corwin reported in 1990 that than 1000 data points were manually collected by two crews in 6 days using the two-point method. Individual profiles were tied together using three cross lines. A two-person crew could typically survey the line (using compass and tape) and make over 100 measurements in a 10 hour day.

We show unfiltered and filtered contour plots of the collected data in Figures 4a and 4b. The filtered map, which is made by applying a five-point smoothing operator to the data, considerably reduces the noise and jitter and emphasizes longer-wavelength features. A prominent feature of the map is the arcuate-shaped high which looks suspiciously like the existing Mammoth Creek drainage system visible on the topographic map, but is displaced to the northwest. Although the cause of many individual features is not yet understood, several prominent features can be modeled using simple programs. We are at an early stage of analyzing this data set and plan to apply our geothermal flow simulator to model this data.

Plans

Modeling of SP Data: Enhanced Methods:

To use SP data as part of a geothermal flow model it is necessary to have knowledge of the flow field, the subsurface resistivity distribution, and the SP cross-coupling coefficients. These coefficients, which relate the fluid flow to the underground currents, are the least understood of the physical

Mammoth SP Profile A-A'

Figure 3 Repeated SP profiles collected with the automatic system

NW

SE

100 m

Figure 4a) Raw SP voltages collected over a two-dimensional grid 4b) filtered SP data

properties that control SP. In a subcontract from LLNL, Dr. Douglas LaBreque from the University of Arizona has agreed to do a compilation of all SP, fluid, and heat flow cross-coupling coefficients. His task is to compile this data, reduce the measurements to a common set of units, and tabulate the results in an easy-to-use format. His report is due in September, 1993.

A final part of our program involves the inclusion of SP voltage calculations in a geothermal fluid-flow simulator. We calculate the SP voltages from the velocity of fluid and heat-flow processes and the subsurface resistivity and cross-coupling coefficient distribution. Used as a forward modelling program this approach should help us correlate SP anomalies with fluid- and heat-flow processes. Used as part of an inversion, the code can constrain the flow model to fit temperature, pressure, and SP data. This research is a joint effort between LLNL and Lawrence Berkeley Laboratory. The geothermal simulator was developed by Bodvarsson (1982) and the SP calculations are being done by UC Berkeley graduate student K. Yasukawa and M. Wilt of LLNL using codes adapted from those published by Sill in 1982 and by Wilt and Butler in 1990. The modeling codes are currently being checked against analytical solutions, and they will soon be applied to geothermal problems.

With the development of advanced modeling capability we are seeking SP data sets in geothermal areas from public and private sources for interpretation. With good-quality data we can evaluate this simulator and perhaps add to the knowledge of these fields. In addition we are seeking a developed geothermal site to deploy our monitoring network. In this manner we can correlate SP voltage changes with observed temperature and pressure fluctuations due to production and assess the usefulness of this low-cost monitoring technique.

REFERENCES

Corwin, R.F., 1990, "The Self-Potential Method for Environmental and Engineering applications" in Geotechnical and Environmental Geophysics, v. 1, p. 127-147; published by Society of Exploration Geophysicists Investigations in Geophysics.

Wilt, M.J. and Butler, D., 1990, Numerical Modeling of SP Anomalies: Documentation of Program SPPC and Applications: in Geotechnical Applications of the Self Potential (SP) Method, Technical Report REMR-GT-6 Department of the Army, Waterways Experiment Station, Corps of Engineers.

CONTACTS

DOE Program Manager:

Marshall Reed
U. S. Department of Energy, CE-122
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Michael Wilt	Phone: (510) 422-3152
Paul W. Kasameyer	Phone: (510) 422-6487
Mail Code, L-208	
Lawrence Livermore National Laboratory	
Livermore, CA 94551	
FAX: (510) 422-3925	

GEOPHYSICS RESEARCH - SELF-POTENTIAL STUDIES

Howard P. Ross
University of Utah Research Institute

KEY WORDS

Self-potential, field studies, hot springs, exploration

PROJECT OBJECTIVES

The objectives of this project are to continue the evaluation of the Self-Potential (SP) method as a cost-effective technique for the geothermal exploration of covered areas, especially in the Basin and Range Province, and to assist state resource teams in the delineation of fluid upflow zones for resources nearing or in development.

Specific objectives are:

- 1) To complete detailed field surveys over selected resources of interest to state teams and/or potential developers, which have sufficient supporting data to contribute to an understanding of the self-potential response;
- 2) complete qualitative and quantitative interpretations of the SP and supporting data, and present the results; and
- 3) examine geologic and recording noise problems that confuse the SP expression of thermal systems, and reduce confidence in SP surveys as a low-cost exploration tool.

APPROACH

The objectives will be attained by expanding the database of self-potential studies in geothermal areas, particularly covered areas or known low-to moderate-temperature resource areas where more expensive geophysical methods are not typically used.

PROJECT STATUS

Background

The Self-Potential (SP) geophysical method is an established geophysical technique used since the 1800s for mineral exploration. The method, which measures naturally occurring voltage differences at the surface of the earth, has been used increasingly for engineering, hydrologic, environmental and geothermal applications since the early 1970s. Although SP anomalies have been observed at many geothermal systems, the expression may be positive, negative, dipolar or very complex. This mixed expression is confusing, and reduces confidence in and use of the method in geothermal resource exploration and development. Theoretical studies generally support the occurrence of positive anomalies over geothermal upflow zones, but positive and negative anomalies are reported throughout the world over geothermal areas. The method could provide a low-cost exploration technique for low- and moderate-temperature resources if confidence in the method is improved.

Research Results

Recent studies by UURI and state teams have mapped well-defined minima in close association with fluid upflow in Utah and New Mexico. Several systems have been mapped in some detail (Newcastle, Wood's Ranch, Thermo, UT; Rincon and Radium Springs, NM) and survey results presented at the GRC (see references). The dominant expression of these resources, using station spacings of 60 m, 30 m, or smaller, is a SP low. Figure 1 shows the SP expression of the recently discovered Rincon geothermal system, which is located 30 miles northwest of Las Cruces, New Mexico in the southern Rio Grande rift. Four well-defined minima of -60 to -110 mV occur within a broad elliptical low.

Figure 1a. Generalized areal distribution of temperature gradients in the Rincon area. Simplified structural geology, and radon anomalies are also shown. Temperature gradients for each well are measured gradient or range of gradients in °C/km.

Figure 1b. Self-potential survey results, Rincon area, New Mexico. SP contour intervals are 10 and 50 mV.

Figure 2. Self-potential contour map for the Thermo area.

The SP survey indicates a substantial extent to the thermal system indicated by drillhole RAD-8 at anomaly A1.

A detailed SP survey completed at Thermo Hot Springs, Utah recorded only weak (± 20 mV) dipolar anomalies over two large hot spring mounds (Figure 2; from the report of Ross and others in 1991). Extension of the survey, using profiles radiating outward from survey base stations, detected a significant (-116 mV) minima displaced approximately 1.5 km from the southern hot spring mound and almost 3 km from a deep exploration test well. Shallow temperature gradient information near the SP minima are encouraging for the presence of a covered, thermal fluid upflow zone, but additional testing is required to explain this SP anomaly.

More recent surveys show both positive and negative anomalies associated with two major hydrothermal systems with surface expression in Utah, Meadow-Hatton and Baker (Abraham) hot springs. These results are being prepared for presentation at the GRC. Another survey was conducted as a difficult test for the method over a covered resource in Nevada which is being explored by the geothermal industry.

Plans

Plans for the remainder of FY-93 include documentation and presentation of the new Utah and Nevada data, and completion of surveys in progress in Utah and New Mexico. Quantitative interpretation of the survey data is underway and may provide new insight into factors which dictate the polarity and complexity of SP anomalies. A substantial effort in numerical modeling is required before new generalizations should be expected.

REFERENCES

Ross, H. P., Blackett, R. E., Shubat, M. A., and Mackelprang, C. E., 1990, Delineation of fluid upflow and outflow plume with electrical resistivity and self-potential data, Newcastle geothermal area, Utah: Geothermal Resources Council Transactions, v. 14, p. 1531-1536.

Ross, H. P., Blackett, R. E., and Shubat, M. A., 1991, Exploring for concealed hydrothermal resources using the self-potential method, Escalante Desert, Utah: Geothermal Resources Council Transactions, v. 15, p. 279-287.

Ross, H. P., Blackett, R. E., and Shubat, M. A., 1991, Wood Ranch thermal anomaly, Iron County, Utah, self-potential survey and fluid chemistry: Utah Geological Survey Miscellaneous Publication 91-4, 21 p.

Ross, H. P. and Witcher, J. C., 1992, Self-potential expression of hydrothermal resources in the southern Rio Grande Rift, New Mexico: Geothermal Resources Council Transactions, v. 16, p. 247-253.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Howard P. Ross
Earth Science Laboratory Division
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, UT 84108
Phone: (801) 584-4444
FAX: (801) 584-4453

ELECTRICAL GEOPHYSICAL RESEARCH FOR EXPLORATION AND RESERVOIR ASSESSMENT

Philip E. Wannamaker, John A. Stodt, and Phillip M. Wright
University of Utah Research Institute

KEY WORDS

Electromagnetics, magnetotellurics, field instrumentation, resistivity, algorithms, inversion

PROJECT OBJECTIVE

Electrical geophysical methods are widely used by the geothermal industry and by research institutions in the exploration and assessment of geothermal resources in a variety of geological environments. The objectives of this project are to improve the methodology of electrical geophysical techniques by making them more accurate, more efficient, and easier to implement so that they will be available for increased use by the geothermal industry and researchers. Since most of the known geothermal resources are presently being developed or utilized, there is a need to identify and evaluate new geothermal reservoirs. In the past, electrical methods have been hampered by an inadequate interpretation of measured data, and by inadequate quality of the measurements themselves. In particular, the need to carry out at least two-dimensional, and often three-dimensional, data collection and modeling efforts is increasingly recognized.

APPROACH

During the past year, our efforts in numerical simulation and inversion have concentrated on the integral equation (I.E.) method for 3-D geometries and finite electromagnetic (EM) sources, and on the finite element (F.E.) method for 2-D geometries and DC resistivity sources. Substantial new accuracies and efficiencies have been implemented. The I.E. approach is advantageous for finite sources because it exploits the concept of localized structure in an ambient host, since finite sources excite the earth primarily in their immediate vicinity. We believe that feasible 3-D inversion algorithms are possible for finite-source field data using this concept. In the 2-D finite source problem, DC resistivity is developed because it is more tractable numerically than the EM problem and field instrumentation is simpler. Finally, our field instrumentation efforts in magnetotellurics have lead to development of a digital remote-reference system capable of very high quality results. The basic capability has been augmented recently with triple-site capability and E-field profiling which is in the final stages of debugging.

PROJECT STATUS

Background

In 3-D EM interpretation, accurate and efficient differential equation solutions have been elusive. For this reason, and because there is a need for checks on other approaches, we have continued to pursue integral equation solutions (Figure 1). Furthermore, the unfortunate death of one of the leading developers I.E., Dr. Gerald W. Hohmann, in May, 1992, has caused us to increase our effort to preserve the gains in this field of research. The starting point for our development has been the code for 3-D structures in a layered earth by Wannamaker. This algorithm was recently augmented to allow capability for arbitrarily-shaped structures which outcrop, transect layer interfaces of the 1-D host, and which may trend indefinitely in one or more dimensions. In 2-D DC resistivity modeling, serious accuracy and efficiency shortcomings have long existed in the integral transform for the spatial-voltage variations, in IP-effect calculations, and in the response-parameter Jacobians for inversion. These shortcomings were addressed in our own versatile code for DC modeling which can include the effects of topography (Figure 2). Finally, for MT field instrumentation, our own field experience

demonstrated the need for a system incorporating digital remote-reference capability, in-field processing, multi-site capability, and E-field profiling (Figure 3).

Research Results

In 3-D EM simulation, we have attempted to create a robust algorithm which can accommodate diverse EM sources within a unified computational framework. This was deemed worthwhile given the new accuracy and versatility stated above. In addition to plane waves sources, we have implemented and verified the use of this algorithm with dipole-dipole and tensor CSAMT sources. The source-receiver arrays may have arbitrary location and orientation with respect to the structures. Efficiencies in matrix and receiver field calculations for multiple frequencies are achieved by separating and saving the laborious zero-frequency components and by separating and saving the cell Green's functions in disk arrays. The latter are independent of body cell conductivity, but require the majority of computational effort, and thus will cut inversion times by factors of several to an order of magnitude. Originally independent program modules for matrix generation, factorization, receiver field calculation, and Hankel transform table generation have been combined into a single code capable of producing efficient, multi-frequency results in a single run through the use of careful, structured programming. Incorporation of additional finite sources within this framework will be straightforward. This is considered to be the most accurate and versatile code for 3-D simulations using the I.E. method. A documentation report of about 50 pages is available describing the method and operation.

Our work in DC resistivity modeling has produced a finite-element algorithm for simulating dipole-dipole resistivity/IP responses of 2-D earth resistivity structure, including topography, as well as least-squares inversion for the resistivities and IP effect of discrete polygonal regions in the model. New accuracy in the forward results (total voltage in Cartesian space) is achieved using a discrete inverse Fourier transform which treats the log singularity at small spatial wavenumbers and the exponential decay at large wavenumbers. Accuracy in this transform now appears to be about 0.1%, instead of the typically 3-4% we had to live with in the past. The Jacobian element equations are evaluated using electrical reciprocity, allowing sensitivities for an arbitrary number of parameters with minimal computing effort. This efficiency is essential for incorporating modern concepts of regularized (minimum structure) inversion, which is a high priority for us in the near future. Efficient Jacobian computation underlies subsequent IP inversion, which is obtained following the resistivity inversion with negligible computational effort.

With completion of the current upgrade, our MT field system possesses the following attributes, all considered essential or highly desirable in a modern magnetotelluric system. First, digital radio telemetry will ensure smooth and unbiased MT data under almost all conditions. Second, data profiles will be adequately sampled given abundant E_y data. Third, the electric field apparatus will be back-packable. Fourth, the rate of productivity will be high even with a two-person crew (three or four deemed better for E-profiling). This stems from telemetry, real-time processing and multi-tasking at the truck allowing complete soundings on-site and greatly reducing setup time. Also, productivity in E_y profiling is much enhanced by obtaining most of this data only at relatively high frequencies. Furthermore, the development of this system has been intended as insurance against the often fragile stability of MT contractors in the unsteady petroleum and geothermal exploration markets.

An 80486 PC at the recording truck is the source of hardware setup and synchronization information for the sensor sites and is responsible for time series reception over radios, spectra and coherency calculation and sorting, MT function processing, and time series and MT function archiving. Operation at the recording truck is carried out using an IBM compatible PC-80486 and a multi-tasking control program (Quarterdeck's DeskView (R)) to prioritize individual jobs each running under MS-

DOS. Digital data communications between the truck control computer and those at the sensor sites are performed using a relatively new transceiver/modem product, the ESTeem wireless modem. The radio-modem provides error-checked, packetized radio communications and networking over ranges up to 30 miles under favorable conditions (manufacturer's claim). Modem firmware allows for radio repeaters when topography makes line of site transmission difficult. Precise timing control for repeaters and for the E-field profiling capability will be provided by timing signals of GPS receivers which are being integrated under DOE support.

Using cascade decimation for spectral estimation, data quality of individual subsets of spectra can be assessed in the field using multiple coherency between base E and H fields, or between reference and base fields. For the real-time processing, the operator can specify an E- or an H-field remote reference, the length of the time series sub-sequences to define the spectral bandwidth, set a low-power cutoff for spectra to keep components with relatively high signal-to-noise, set a high-power cutoff for the time series to reject sub-sequences containing spike noise or possible non-plane wave contributions, and specify the number of periodograms to average at each level of decimation before coherence sorting takes place. The multi-tasking environment can accommodate additional robust processing of time series files or perhaps response-function inversion while new data are being collected. The high-level language environment with multi-tasking can allow straightforward loading of new or modified processing or interpretation software from other researchers. Raw and processed data are archived on PC diskettes and can be distributed to other researchers with a simple Fortran read program to unload our data packet format. Example soundings using the mode of a five-channel base site and a two-channel magnetic reference site have been published by Wannamaker and Johnston in 1991.

Plans

Progress in 3-D I.E. interpretation should proceed in three main areas. One should be the incorporation of additional source configurations, for instance downhole source arrays for reservoir assessment purposes, or surface and airborne loop-loop arrays for exploration for new geothermal resources. Second, extension to high frequencies ($>10\text{kHz}$) for small-scale investigations, including environmental, necessitates improved Green's function evaluation. Finally, advancing toward inversion capability, initiated with efficient Jacobian calculations, is merited by the accuracy, versatility and efficiency achieved to date. Regularized (minimum-structure) imaging or inversion of DC resistivity responses over 2-D structures, for both surface and downhole arrays is the next logical step in our 2-D DC efforts. Finally, in-field verification and collection of new data with our latest MT system upgrade is imminent. The collection of an incremental amount of new soundings in the eastern Great Basin environment we have long been studying will strongly leverage new research findings on the structural and magmatic development of this province.

REFERENCES

- Wannamaker, P. E., and Johnston, J. M., 1991, Uncovering Sevier overthrust structure and potential hydrocarbon source rock using magnetotellurics: Utah Geological Survey, Open-File Report, 13 p.
- Wannamaker, P. E., 1992, EMIE3D - v1.00: Integral equations algorithm for modeling magnetotelluric, dipole-dipole and CSAMT responses of three-dimensional bodies in layered earths: University of Utah Research Institute Report, ESL-92004-TR/DOE/ID/12929-02, 52 p.
- Wannamaker, P. E., 1992, IP2DI - v1.00: Finite element program for dipole-dipole resistivity/IP forward modeling and parameterized inversion of two-dimensional earth resistivity structure: University of Utah Research Institute Report, ESL-92002-TR/DOE/ID/12929-01, 62 p.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Philip E. Wannamaker	Phone: (801) 584-4445
Phillip M. Wright	Phone: (801) 584-4437
Earth Science Laboratory Division	
University of Utah Research Institute	
391 Chipeta Way, Suite C	
Salt Lake City, UT 84108	
FAX: (801) 584-4453	

INTERNATIONAL COOPERATION

Marcelo J. Lippmann
Earth Sciences Division, Lawrence Berkeley Laboratory

KEY WORDS

Field case studies, liquid-dominated systems, vapor-dominated systems, technical cooperation

PROJECT OBJECTIVES

The objectives are (1) to provide industry and Department of Energy (DOE) sponsored research organizations with data on the exploration, evaluation, development, and operation phases of geothermal projects in different parts of the world; and (2) to facilitate direct contacts, data exchanges, and possible commercial relationships between United States industry and foreign geothermal companies and research and development organizations. This work provides the necessary information for geothermal exploration and development companies to learn from the experience of organizations in other countries. These studies provide a library of geothermal developments in a variety of geologic settings.

APPROACH

These objectives are attained by Lawrence Berkeley Laboratory (LBL) through the holding of technical workshops in the US and abroad and by helping to organize and sponsor visits of US and foreign engineers and scientists to meet their counterparts.

These activities are made possible through formal agreements:

DOE - Comision Federal de Electricidad (CFE) of Mexico

DOE - Ente Nazionale per l'Energia Elettrica (ENEL) of Italy

or informal technical cooperation such as:

LBL - Istituto Internazionale per le Ricerche Geotermiche (IIRG) of Italy

LBL - University of Auckland in New Zealand

LBL - National Energy Authority of Iceland

PROJECT STATUS

Background

For many years, LBL has added to its DOE-supported geothermal studies in the United States multidisciplinary studies of the vapor-dominated (VD) fields in Tuscany, Italy, and of the liquid-dominated (LD) fields in Mexico. Because of the need to acquire actual field data to test new technology and because of the support and significant interest shown by industry, LBL continues to augment the body of knowledge about geothermal systems in the United States with information about systems in other countries gained through collaborative efforts with foreign geothermal experts.

The work on these foreign fields continues to be carried out under the auspices of international agreements on geothermal energy. The cooperative activities with ENEL are part of an ongoing, and recently revitalized agreement, originally established in June 1975, between the Energy Research and Development Administration (ERDA) and ENEL. Similarly, the cooperative research on Mexican systems is part of a current DOE-CFE agreement that expires in April 1994. The original DOE-CFE agreement was signed in 1977.

During the late seventies and early eighties, this cooperative work with foreign organizations was quite active and productive. More recently however, due to smaller budgets, these efforts have been

reduced mainly to data exchange and analysis, workshops, and visits of small groups of engineers and scientists to discuss the latest data and technology developments. The informal cooperation between LBL and foreign scientists and engineers continues today as part of the Laboratory effort to keep informed and up-to-date with the latest developments in geothermal research and development.

Research Results

At the present time, two formal cooperative agreements on geothermal energy are in place (DOE-CFE and DOE-ENEL). However, due to lower funding levels during FY-1993, LBL activities have been reduced to a minimum. The work with Mexico has been restricted to modeling the effects of on-going and planned injection operations at Cerro Prieto and to data and software exchange. The cooperative work with ENEL this year, will be confined to information exchange and possible participation in a workshop.

Parallel to these formal activities, the informal contacts between LBL and foreign scientists continues. For example, scientific collaborator Dr. Franco D'Amore (IIRG, Italy) recently spent two days at LBL to discuss his work on modeling gas chemistry processes in vapor-dominated systems and heat and mass transfer in volcanic islands.

Significant improvements have been made in our understanding of the conceptual models and dynamics of vapor- and liquid-dominated geothermal systems during the last 15 years. This has been documented by many LBL technical papers and reports issued on the geologic, geophysical, geochemical, and reservoir characteristics of fields like Larderello, Italy; Cerro Prieto and Los Azufres, Mexico; Nesjavellir and Krafla, Iceland; and many others. For a complete listing please request the LBL list of publications on geothermal energy.

As the funding decreased in recent years, so did the number of publications. However, the previous level of cooperative research has permitted LBL researchers to follow the evolution of different geothermal fields as their exploitation continued. Significant changes in the characteristics of the produced fluids and in the processes occurring in the reservoirs have been documented. This project has also allowed the verification of the accuracy of modeling predictions.

Plans

As the exploitation of geothermal systems throughout the world continues, some of them exceeding 20 years of commercial operation, important data on the changes occurring in wells and reservoirs are being collected. This information, which might provide forewarning of dangerous reservoir conditions leading to decline and possible abandonment of partial or entire fields, is of great interest to the US geothermal industry. The data should be analyzed to develop predictive tools that could be used by field operators to anticipate problems that might arise as the geothermal reservoir reaches maturity (and senility).

This project on international cooperation would benefit from increased funding to continue the collection and analysis of data on foreign geothermal fields. This would allow the analysis and study of information from systems with various geologic and thermodynamic characteristics and production histories. Some of the fields that should continued to be analyzed for their response to large-scale fluid production are:

- Cerro Prieto (LD): sedimentary rocks, 20 years of production
- Larderello (VD): metamorphic rocks, more than 50 years of production
- Los Azufres (LD): volcanic rocks, 10 years of production

Los Humeros (LD): volcanic rocks, less than 5 years of production

Nesjavellir (LD): volcanic rocks, less than 5 years of production

REFERENCES

Bodvarsson, G. S., Bjornsson, S., Gunnarsson, A., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V., and Steingrimsson, B., 1991, The Nesjavellir geothermal field, Iceland, 2. Evaluation of the generating capacity of the system: *Journal of Geothermal Science and Technology*, v. 2, no. 4, p. 229-261.

Bodvarsson, G. S., Gislason, G., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V., and Steingrimsson, B., 1993, Accuracy of reservoir model predictions for the Nesjavellir geothermal field, Iceland: *Proceedings, 18th Workshop on Geothermal Reservoir Engineering*, Jan. 26-28, Stanford University (in press).

Kiryukhin, A. V., 1992, Progress report on modeling studies: Natural state conditions and exploitation of the Dachny geothermal reservoir, Mutnovsky hydrothermal system, Kamchatka, Russia: Lawrence Berkeley Laboratory report LBL-37729.

Lippmann, M. J., Truesdell, A. H., Halfman-Dooley, S. E., and Mañon, A., 1991, A review of the hydrogeologic-geochemical model for Cerro Prieto: *Geothermics*, v. 20, no. 1/2, p. 39-52.

Truesdell, A. H., Mañon, A., Quijano, L., Coplen, T., and Lippmann, M. J., 1992, Boiling and condensation processes in the Cerro Prieto beta reservoir under exploitation: *Proceedings, 17th Workshop on Geothermal Reservoir Engineering*, Jan. 29-31, Stanford University (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigator:

Marcelo J. Lippmann
Earth Sciences Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720
Phone: (510) 486-5035
FAX: (510) 486-5686

LOW-TEMPERATURE GEOTHERMAL RESOURCES

Howard P. Ross and Stefanie Colvin
University of Utah Research Institute

KEY WORDS

Low temperature, direct use, state teams, geothermal heat pumps, collocation studies, resource inventory

PROJECT OBJECTIVE

The objective of this program is to encourage increased utilization of the nation's low- to moderate-temperature geothermal resources and reduce our dependence on fossil fuels.

Specific objectives are:

- 1) to update the inventory of geothermal resources (20°C to 150°C) in the West (initially 9 states);
- 2) assist the Geo-Heat Center of Oregon Institute of Technology (OIT) in a collocation study of resources and communities;
- 3) prioritize the more favorable resources for in depth studies;
- 4) develop fact sheets and information that will encourage the increased use of geothermal heat pump (GHP) technology;
- 5) educate the public in the applications of GHPs through conferences and publications.

APPROACH

State geothermal resource teams will review and update their geothermal resource inventories which were completed as part of the USGS-DOE national assessment from 1977 to 1983. Each state will prepare a comprehensive digital database in table format and a resource map at a scale of 1:1,000,000. UURI and OIT will provide technical guidance and coordination, and University of Utah Research Institute (UURI) will complete 10 fluid chemistry analyses for each state. OIT will have the lead role in a collocation study of resource occurrence and communities (or potential users), and the states, OIT, UURI, and Idaho Water Resources Research Institute (IWRRI) will prioritize resources for more complete studies. Promising resources for near-term development will be studied in more detail when Phase 2 funding becomes available.

A complimentary, but distinct, part of the program is directed toward educating utilities, contractors, engineers, and the public about geothermal heat pump technology. This is a cooperative effort between UURI, the Geo-Heat Center (OIT), and the Idaho Water Resources Research Institute (IWRRI).

The portion of this program assigned to UURI is to produce fact sheets on commercial, residential and institutional geothermal heat pump systems already in operation, and to host a local downsite for the Geothermal Heating and Cooling Teleconferences sponsored by DOE and others. Two of these teleconferences have already been hosted, with the remaining one to be held April 28, 1993.

The fact sheet/brochures are planned to be educational to a very diverse audience. Therefore, they will be informative with case studies and photos, but not too technical in nature. The idea is to inform all targeted groups of the availability of this technology, how it works, and especially that systems are in operation all over the US and the energy efficiency of these systems.

PROJECT STATUS

Research Results

A. Low-Temperature Program

In FY 1992 State Teams were identified to complete the resource inventory for Washington, Oregon, California, Nevada, Utah, Arizona, New Mexico, Montana and Colorado. EG&G-Idaho, issued contracts to UURI, OIT, and IWRRI; and OIT completed subcontracts with many of the state teams. Subcontracts for the last two state teams, Washington and Nevada, have just recently been completed. IWRRI will complete the resource inventory for Idaho.

UURI is coordinating efforts to complete digital databases, with considerable help from the Utah team (Utah Geological Survey) which has completed a well-designed format and shared the information with other state teams. UURI has issued a revised water sampling manual and has begun analyses for the state teams. The state teams have completed a preliminary review of the interim OIT collocation listing, and several teams have completed a preliminary database listing. Other teams are in the early stages of database compilation, editing, and data verification.

B. Geothermal Heat Pump Technology

Fact Sheets: UURI has drafted two fact sheets which are presently at EG&G for clearance. These sheets are two-sided and contain both general information about geothermal heat pump systems as well as background and system information, system performance, economic analysis and benefits of the particular case study. The two selected were the Phil Albertson home in Perry, Oklahoma as a residential case study, and the Louisiana Department of Employment Security Job Service Office in Hammond, Louisiana as a commercial case study.

UURI is presently gathering information and slides for the production of three four-page brochures which will separately target residential studies, commercial/institutional studies, and utility-funded projects. As the April 28, 1993 teleconference is directed toward an audience of design engineers, we are focusing on the commercial/institutional brochure in order to have it available to downsites for this teleconference.

Heating and Cooling Teleconferences 1993: UURI hosted a downsite for the March 3, 1993 teleconference. We invited all local HVAC dealers, drilling contractors, utilities, and building contractors. In addition to the video portion of the teleconference, we invited P. Michael Wright, Technical Vice-President of UURI, to present a general overview of geothermal heat pump systems. Craig Young of Intermountain Consulting Engineers, presented information on the Gunnison, Utah hospital project that has now been in operation for over one year. The last invited speaker was Lawrence Fleming, President of PC Exploration, who spoke on drilling in Utah. He discussed available equipment, local drilling problems, and job-costing.

Plans

A. Low-Temperature Program

The state teams will complete their inventory, database listings, and resource occurrence maps in FY-93 and early FY-94. These will be reviewed and edited by UURI and OIT. OIT will complete the collocation study and with UURI and IWRRI, will prioritize resources for more detailed study. The results will be reviewed by, and discussed with, the appropriate state teams. UURI will complete fact sheets to inform Congress of the progress, and with OIT and IWRRI will solicit support for Phase 2 funding of additional states and detailed studies of the most promising resources for near-term development.

B. Geothermal Heat Pump Technology

UURI plans to host a downsite for the April 28, 1993 teleconference. We will feature local speakers, and although the target audience is to be design engineers, we will invite again utilities, HVAC dealers, building contractors and drillers. We hope to increase the size of the audience and the interaction of these distinct groups of people here locally.

Work on the four-page brochures with information on residential and utility-funded projects will begin as soon as the commercial brochure is completed.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Phillip M. Wright	Phone: (801) 584-4437
Howard P. Ross	Phone: (801) 584-4444
Stefanie Colvin	Phone: (801) 584-4423

Earth Science Laboratory Division
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, UT 84108
FAX: (801) 584-4453

DOWNHOLE SEISMOMETRY IN GEOTHERMAL SYSTEMS

Paul W. Kasameyer, Phil Harben, Steve Hunter,
Don Rock, Stephen P. Jarpe, and Steve Pratuch
Lawrence Livermore National Laboratory

KEY WORDS

Borehole seismometer, Long Valley, magma, brittle-ductile transition, micro-seismicity, high-temperature instrumentation

PROJECT OBJECTIVE

The objective of this project is to study the nature and spatial and temporal distribution of micro-seismic sources recorded underneath the center of Long Valley Caldera, in order to study the thermal and mechanical states and structures beneath this immense geothermal system. A second objective is to use this data set to assess the value of down-hole seismometry at other geothermal systems. This research is of importance to the exploration and evaluation of geothermal systems for commercial development. The success of this project in determining the reservoir fracture distribution would provide the geothermal industry with a tool to evaluate the area around an early well in a new system and to direct the later development drilling.

APPROACH

Our approach has been to design a 3-component downhole high-frequency seismic sensor to be operated at a depth of 2005 m (6740 ft) in the bottom of the cased portion of the Long Valley Exploratory Well (LVEW), and to record events through the winter of 1992-1993.

PROJECT STATUS

Background

Although many pieces of evidence point to the existence of magma, many questions remain about the state and thermal and mechanical effects of a major magma body thought to lie beneath Long Valley Caldera, in California. Numerous geophysical studies have characterized the subsurface structure at Long Valley, but almost all of them have used data from surface or near-surface sensors recording signals that have been complicated significantly by the caldera fill. By placing a seismometer package deep enough so it will record seismic data that is not contaminated by scattering and attenuation in the caldera fill, we intend to collect data to study the geologic structure and the nature of seismic sources within 10's of kilometers of the borehole, and to infer their ramifications for the thermal and mechanical state above the magma body. In addition, we may find stronger seismic evidence for a cessation of seismicity near 4 km depth, apparently due to the brittle-ductile transition, which could indicate high temperature (350 to 450°C) geothermal targets at drillable depths.

Research Results

Description:

The LVEW downhole seismometer experiment consists of four major components: the seismometer with clamping mechanism, the cable and winch assembly, the data acquisition system, and the solar 12V power system. The sensor package, which was optimized to record the high-frequency signals that do not reach surface seismometers, consists of a triaxial set of Wilcoxon high temperature accelerometers and a 10 Hz vertical geophone mounted and sealed within a high pressure casing. The sensor is mounted in a shortened version of the Geotech model 23900 borehole seismometer outer casing which is pressure sealed with O-rings and is designed for operation in pressures up to 500 bars and temperatures up to 107°C. The data acquisition system consists of a single 6-channel Reftek

Figure Captions

1. A "typical" event recorded by the LVEW downhole 3 component seismometer (top) and by a surface installation (bottom).

2. Magnitudes of earthquakes as a function of apparent slant distance from the LVEW seismometer. Hundreds of events are recorded each week.

3. An extremely short event that occurred near the LVEW. By recording high-frequency signals from these previously undetected events, we may learn new information about energy release during events and swarms in the Long Valley area.

model 72-02A data acquisition unit, an external 700 megabyte hard disk drive, a 1.2 gigabyte DAT tape recording unit, and a handheld PC programmer/controller. The Reftek records the three signal outputs from the downhole Wilcoxon sensors and three signal channels from a triaxial set of surface mounted Teledyne Geotech model GS-13 seismometers. The system was installed on October 29, 1992, and will be removed in spring of 1992.

Examples of data:

To date, only 11 days of observations have been processed, and none have been interpreted. During that time period we recorded 294 microearthquakes with apparent magnitudes greater than -0.5. Figure 1 illustrates that we are successfully capturing the anticipated differences between borehole and surface recordings at the LVEW. Compared to traditional surface recordings, the borehole seismograms (the top three in the figure) have a much higher frequency content, sharper and more definite P (compressional wave) and S (shear wave) arrivals, and a greater ratio of the direct arrival to the coda energy. These characteristics will enable us to detect and characterize seismic sources beneath the caldera, to evaluate the loss of resolution in surface data caused by the caldera fill, to evaluate models of shear-wave screening, and to add additional raypaths to inversions for seismic structure.

Figure 1 also shows that the borehole seismometer is noisier at low frequencies, a consequence of the desire to capture high frequency signals in this hot environment. Using three components, we can estimate the distance and direction of an event. Figure 2 shows the detection capability of the borehole seismometer as a function of approximate hypocentral distance from the instrument. The distances are based on S-P time differences and a uniform velocity approximation of the Earth, and the magnitudes are estimated by a local magnitude duration scale. The magnitudes agree to about 0.5 with the USGS magnitudes for common events. We are detecting magnitude zero events at a kilometer and magnitude 1 events at 10 kilometers. The borehole seismometer allows the detection of extremely local events, such as that shown in Figure 3. The P-S delay time of this event is approximately 0.1 sec. which places this event hypocenter about 800 m from the seismometer. Furthermore, the amplitude of the P-wave on the vertical component relative to the horizontal components indicates that the event was nearly directly below the seismometer.

Plans

Under our present funding, data will be collected and archived while the borehole is available and will be shared with others, but no analysis will take place. A number of research results are possible from future interpretation of data from the LVEW borehole seismometer.

- 1) We hope to conduct detailed characterization of seismic sources deep within the Long Valley Caldera. By examining moment-corner frequency variations from a large number of earthquakes recorded in this low-attenuation environment, we may identify unusual source areas associated with the onset of the brittle-ductile transition, or narrow-band events associated with the magma. These results could place significant constraints on the temperature below the borehole.
- 2) The detailed mapping of single-station locations of events could identify a cessation of seismicity as higher temperatures are reached beneath the borehole.
- 3) Examination of data is planned to locate paths with shear-wave screening that would indicate possible molten areas.
- 4) The data will be used to evaluate the contribution of the caldera fill to surface seismograms and the effect of that contribution on seismogram interpretation.
- 5) The borehole seismometer will be used to augment the earthquake locations and tomographic studies which are now based only on surface arrays.

We think that the future holds promise for borehole seismometry in geothermal systems where the right conditions exist. The present instrument could be used up to temperatures of 125°C, and will be available for cooperative projects with industry. A deep, temporarily idle hole is needed and well-cemented casing or a stable hole of known radius is preferred. We have identified (but not tested) seismometers that can function up to 250°C. One approach would be a series of piezo-electric sensors operating in the charge monitoring mode, which would avoid downhole electrical components. Development of such an instrument could result in significant improvements in the detection levels and location accuracy for micro-seismic signals associated with geothermal production and injection and could provide useful information about a geothermal field's response to exploitation.

REFERENCES

Harben, P., and Hunter, S., 1993, The Long Valley exploratory well downhole seismometer package: Design and operational characteristics: Lawrence Livermore Laboratory Report, (in preparation).

CONTACTS

DOE Program Manager:

Marshall Reed
U. S. Department of Energy, CE-122
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Paul W. Kasameyer	Phone: (510) 422-6487
Phil Harben	Phone: (510) 422-6487
Mail Code, L-208	
Lawrence Livermore National Laboratory	
Livermore, CA 94551	
FAX: (510) 422-3925	

GEOCHEMICAL MODELS OF GEOTHERMAL SYSTEMS

Joseph N. Moore
University of Utah Research Institute

KEY WORDS

Geochemical models, fluid inclusions, CO₂, steam-heated waters

PROJECT OBJECTIVE

The purpose of this project is to develop better geochemical models of geothermal systems. This work will assist the explorationist by providing the basic hydrogeochemical data needed for the development of conceptual models in different geologic environments. The availability of improved reservoir models will decrease the number of dry holes drilled during a geothermal project. The project will help the developer by providing information on the natural state of the reservoir. This information is needed to determine how the reservoir is changing as a result of production.

APPROACH

Most production wells discharge from one, or at most a few discrete zones, whereas thermal gradient wells generally do not produce fluids at all. Consequently, little chemical information is available on large portions of most geothermal reservoirs. In this project, we are applying the results of fluid inclusion, mineralogic, and isotopic investigations to obtain chemical information on those regions of the reservoir that cannot be sampled directly. This approach allows us to expand upon interpretations based on the compositions of the fluids and to assess the geochemical changes that occurred as the systems evolved.

PROJECT STATUS

Background

In the late 1980s, researchers at UURI initiated a series of geochemical studies on well-documented geothermal systems to determine if fluid inclusion investigations could be used to augment chemical data from production wells and springs. Our initial efforts focused on the geothermal systems at Coso, California, Los Azufres, Mexico, and Zunil, Guatemala. These studies, which are among the most detailed of any conducted on geothermal systems, demonstrated that fluid inclusion data could be combined with chemical analyses of the geothermal fluids to develop greatly refined hydrogeochemical reservoir models.

In support of these fluid inclusion studies, a series of computer algorithms was developed to interpret the results of the fluid inclusion measurements. These algorithms allow calculation of boiling point curves for varying salinities, gas contents, and water table elevations, pressure corrections, calculation of ice-melting temperatures from chemical analyses, and the determination of fluid inclusion CO₂ contents based on ice and clathrate melting temperatures.

Our current investigations represent a continuation of our initial efforts. The need for this work reflects the results of a 1989 industry survey which reiterated the importance of developing a better understanding of reservoir processes, properties, conditions, and boundaries in different geologic environments.

Research Results

Our investigations at Los Azufres and Zunil focussed on the behavior and distribution of CO₂ in active geothermal systems (reported by Moore and others in 1992). Features common to both geothermal

systems include a close association with active volcanism, abundant evidence of shallow boiling that is accompanied by the upward transfer of steam and CO₂-rich gas, abundant rainfall, high topographic relief and the development of secondary steam-heated waters. An important result of this study was the recognition of CO₂-enriched fluid inclusions that defined umbrella-shaped caps around the main zones of upwelling. These inclusions were found to contain between 4 and 6 weight percent CO₂. Comparison of the calculated trapping pressures with boiling point to depth curves led to the conclusion that these inclusions formed at pressures of up to several tens of bars above hydrostatic. These elevated pressures and gas contents may have developed as CO₂-enriched steam condensed in response to tectonic stress. Adams and Moore, in 1991, suggested that these conditions could occur in dead-end fractures where steam and gas collected during local boiling of the reservoir fluid.

In contrast to these volcanic-hosted geothermal systems, the Coso geothermal system is developed in an arid terrain characterized by low topographic relief (Figure 1). The chemical and fluid inclusion data demonstrate that this geothermal system consists of a well defined, asymmetric plume that originates in the southern part of the field and then spreads laterally to the north (Figure 2). As the thermal fluids move away from the upwelling center, the top of the plume rises vertically from a depth of 1500 m in the core of the system to less than a few hundred meters in the north. The geometry of the plume appears to be related primarily to the presence of a narrow zone of partially sealed, steeply dipping structures that extends the length of the field.

The results of our investigations indicate that the main features of the system's present thermal structure were already developed at the time the fluid inclusions were formed. These data show both the existence of the plume and the presence of a permeability barrier between the main production zone and the faults that fed hot spring deposits on the eastern side of the geothermal field. Comparison of the fluid inclusion and measured temperatures indicates that cooling has occurred along the top and margins of the geothermal system while temperatures have continued to increase within the core of the field. The apparent salinities of the inclusions fluids within the interior of the plume, however, were only slightly higher in the past than they are today. These compositional differences reflect dilution by ground waters and the sporadic flux of CO₂ generated by local boiling.

Cool, low salinity, ground waters extended over much of the present geothermal system during the emplacement of the thermal plume (Figure 3). Dilution of the thermal waters occurred along the margins of the plume, producing strong gradients in the compositions of the mixed waters that were preserved in the fluid inclusions. In response to dilution of the thermal fluids and heating of the ground water, clays and carbonates precipitated along the margins of the reservoir. This mineralization reduced the permeabilities of the shallow fractures and formed an effective seal over the thermal system.

Plans

Our investigations into the geochemical structure of geothermal systems will continue into FY 1993.

We will:

- 1) complete a detailed report on the geochemical structure of the Coso reservoir prior to production; and
- 2) continue geochemical and petrologic investigations of the Steamboat Springs geothermal system which shares a number of characteristics with Coso.

Figure 1. Location map of the Coso geothermal system.

Figure 2. North-south cross section of the Coso geothermal system showing the average homogenization temperatures of the samples studied. All data are in degrees Celsius. The vertical scale is in meters and shows the sample depths with respect to sea level.

Figure 3. Variations in the ice-melting temperatures of the fluid inclusions shown in Figure 2. For reference, an ice-melting temperature of -1.0 corresponds to a salinity of 1.7 weight percent equivalent NaCl.

REFERENCES

Adams, M. C., and Moore, J. N., 1990, Tectonic activity and gas flux in volcanic environments (abstract): EOS, Transactions, American Geophysical Union, p. 1675.

Moore, J. N., Adams, M. C., Bishop, B. P., and Hirtz, P., 1989, A fluid flow model of the Coso geothermal system, California: Data from fluid chemistry and fluid inclusions: Proceedings, 14th Workshop on Geothermal Reservoir Engineering, Stanford University, p. 139-144.

Moore, J. N., Adams, M. C., Bishop-Gollan, B., Copp, J. F. and Hirtz, P., 1990, Geochemical structure of the Coso geothermal system, California: American Association of Petroleum Geologists Guidebook, Coso Field Trip, American Association of Petroleum Geologists EMD #1, Moore, J. L., and Erskine, M., eds., p. 25-39.

Moore, J. N., Adams, M. C., and Copp, J. F., 1992, The geochemistry of the Coso geothermal system: Data from production fluids and fluid inclusions, (in preparation).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D. C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Joseph N. Moore
University of Utah Research Institute
Research Park
391 Chipeta Way, Suite C
Salt Lake City UT 84108
Phone: (801) 584-4428
FAX: (801) 584-4453

THERMODYNAMICS AND PHASE RELATIONS OF SYNTHETIC GRANITE MELTS

J. G. Blencoe, T. Burch, D. R. Cole, and D. B. Joyce
Chemistry Division, Oak Ridge National Laboratory

KEY WORDS

Granite, melt, albite, phase, mixing, volatile

PROJECT OBJECTIVE

This is a new project with the aim of determining the phase relations and thermodynamic mixing properties of synthetic granite (haplogranite) melts, leading to the development of a low-pressure (500 to 4000 bars) thermodynamic model for these melts. This research is of importance to geothermal exploration and development because of the need to understand and evaluate the possible contribution of heat and water from magmatic systems to associated geothermal systems. Current models of granitic magmas can not be used to accurately calculate the fluid-melt chemistry or to estimate the quantity or composition of magmatic water involved in hydrothermal systems.

APPROACH

The development of the thermodynamic model will be based on high quality phase-equilibrium, thermodynamic, and spectroscopic data gleaned from the geochemical literature, supplemented by new data to be obtained from experimental samples reacted at 500 to 2500 bars and 700 to 1000°C in an internally heated pressure vessel, and various cold-seal pressure vessel systems.

The long-range goals of this project are to (1) determine the solubility of water in haplogranite (mixture of quartz and feldspar) melts; (2) measure the equilibrium partitioning of Na and K between haplogranite melts and coexisting alkali chloride-bearing aqueous fluids; (3) ascertain the amounts and chemical compositions of silicate materials dissolved in aqueous fluids that have equilibrated with haplogranite melts; and (4) acquire new and more accurate data on the boundaries of crystal-melt phase fields in the haplogranite system.

This project is part of a program "Physical Chemistry of Geothermal Systems" at ORNL. The general objective of this program is to conduct laboratory experimental research utilizing unique facilities and expertise at ORNL for studies of selected chemical equilibria, thermodynamics of brine systems, liquid-vapor molecular and isotopic partitioning, and other phase behavior. Results allow prediction of temperature, chemistry and permeability changes in reservoirs and in plant facilities involved in the extraction of geothermal energy, and provide fundamental experimental data needed as input for geochemical models.

PROJECT STATUS

Background

There are numerous locations world-wide where it is evident that geothermal resources are linked genetically to granitic magmatism. Two phenomena that relate directly to this link are heat transfer from granitic magmas to superadjacent geothermal areas and mingling of magmatic-hydrothermal fluids with meteoric waters. In the latter event, it is important to recognize that the initial chemical compositions of magmatic-hydrothermal fluids are strongly influenced by the bulk composition and thermodynamic mixing properties of the granitic magma, and that various geochemical reactions can potentially produce significant changes in the compositions of these fluids prior to the time that they mix with circulating meteoric waters.

These and other geochemical issues pertinent to the granitic intrusion - geothermal system association have been addressed qualitatively in numerous field studies of active and fossil geothermal fields. However, complementary experimental and theoretical investigations, which are essential for quantitative modeling of igneous-geothermal processes, are few in number. A significant fraction of the data required to perform such modeling can be obtained from systematic experimental systems that serve as analogs for natural granitic rocks. It is widely acknowledged that the "haplogranite" (synthetic granite) system is an excellent geochemical analog for natural granites. This system, comprising the components $\text{NaAlSi}_3\text{O}_8$, KAlSi_3O_8 , Si_4O_8 and H_2O , has been examined experimentally by numerous investigators in the past, but the resulting data are mostly qualitative, relating principally to stable H_2O -saturated phase assemblages at fixed pressure-temperature-composition conditions.

The methods for thermodynamic modeling of albite-water melts developed by in our BES/Geosciences project titled "Geochemistry of Crustal Processes to High Temperature and Pressure" are readily extended to multi-component haplogranite systems. Only small amounts of phase-equilibrium data are required to initiate the modeling process. If phase relations are tightly constrained by experimental data, additional steps can be taken to increase the accuracy of calculated thermodynamic mixing properties for the melts.

Research Results

Experiments were initiated to determine the hypersolidus phase relations and thermodynamic mixing properties of $\text{NaAlSi}_3\text{O}_8$ - Si_4O_8 - H_2O (albite-quartz-water) melts at 2500 bars and 750 - 1000°C. Solid starting materials were high purity Amelia albite, Brazilian quartz and sodium aluminosilicate gels with compositions along the albite-quartz join. These materials were sealed in platinum capsules along with appropriate weighed amounts (2 to 6 weight percent) of deionized water. Experimental pressure-temperature conditions were achieved in an internally-heated pressure vessel. Solubilities of water in the ternary melts were measured using the vapor pit technique, whereby the presence of H_2O -rich vapor at pressure and temperature is indicated by a dimple or depression in the upper surface of the quenched melt (glass). Water solubilities were also measured independently by mass balance and manometry.

Crystal-melt equilibria were determined by reacting solid starting materials (crystalline albite plus quartz, or amorphous gel) with water. Crystal-melt reversal experiments were performed by seeding gels with small amounts of crystalline albite or quartz and noting whether the morphologies of the crystals at the end of the run indicated growth or dissolution. Results of crystal-melt-vapor experiments were used to evaluate binary Margules parameters for albite-quartz-water melts. Values for these mixing parameters are required to develop a polythermal thermodynamic model for albite-quartz-water melts at 2500 bars.

Plans

Remaining experiments on albite-quartz-water compositions will be completed at 2500 bars and 750 to 1000°C, and similar studies will be conducted on sanidine-quartz-water melts. We will also conduct experiments to determine the alkali aluminosilicate compositions of H_2O -rich vapor coexisting with silicate melts. Because dissolved silicate materials precipitate from high-pressure H_2O -rich vapor during quenching, it is necessary to develop a technique for separating this precipitate from the quenched melt (glass). We will evaluate two methods for achieving this separation; a modified "double capsule" technique in which silicate melt is enclosed within a fine platinum mesh inside a platinum "outer capsule" and a simpler technique in which no attempt is made to keep the melt and vapor separate during equilibration and quenching.

At the earliest possible time, emphasis will shift to performing crystal-melt-vapor and vapor-composition experiments on albite-sanidine-quartz-water compositions at 2500 bars, 750 to 1000°C. The results of the studies outlined above will determine whether the haplogranite system will be studied as a function of pressure in the 500 to 4000 bar range, or whether more complex melts, involving Ca-, Mg- and Fe-rich components will be studied.

REFERENCES

Blencoe, J. G., 1992, A two-parameter Margules method for modelling the thermodynamic mixing properties of albite-water melts: Transactions of the Royal Society of Edinburgh Earth Science, v. 83, p. 423-428.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

James G. Blencoe	Phone: (615) 574-7041
T. Burch	Phone: (615) 574-5034
David R. Cole	Phone: (615) 574-5473
D.B. Joyce	Phone: (615) 574-7622
Robert E. Mesmer	Phone: (615) 574-4958

Chemistry Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6110
Fax (615) 574-4961

MAPPING RESERVOIR PROPERTIES AND RESERVOIR MONITORING
USE OF NEURAL NETWORKS TO REDUCE COMPUTATIONAL AND
ANALYSIS COSTS IN GEOTHERMAL PRODUCTION AND EXPLORATION

Stephen P. Jarpe and Farid Dowla
Lawrence Livermore National Lab

KEY WORDS

Microearthquake, earthquake location, arrival time picking, neural networks, cost reduction

PROJECT OBJECTIVE

Our objective is to improve automatic microearthquake arrival time determination so that accurate microearthquake locations can be obtained at a lower cost by minimizing time-intensive arrival picking by human analysts. Success in this research project will provide significant savings in labor and expense in the analysis of seismic data. This project may lead to the use of seismic monitoring for day-to-day reservoir management and injection monitoring.

APPROACH

Our approach uses a new technology, neural networks, which can be used to reduce the repetitive analysis and computational costs of many processes. We train a neural network to "learn" the picking parameters from the human analyst and then to apply this training to new data. Success with this problem suggests that we could apply neural networks to reduce the costs of other computational problems in geothermal fields.

PROJECT STATUS

Background

Many geothermal operators use seismic networks to monitor microearthquake activity in the geothermal field. They often use microearthquake locations to track fluid movement within the reservoir and to assess the impact of injection. Earthquake locations require that the arrival times of seismic phases be identified (picked) from the ground motion records. To obtain high-quality microearthquake locations, human analysts are needed to pick the arrival times from the seismograms, resulting in significant labor costs when the number of events is large. Previous attempts to automate this process have resulted in a high rate of errors that must be corrected by the human analyst. In addition, the currently available automated algorithms are only capable of picking primary (P) arrivals, and are unable to successfully pick secondary (S) arrivals. The neural network approach was considered because it can learn by example to emulate the complex process of the human analyst, and in theory can equal the performance if enough training examples are used.

Research Results

The performance of our algorithm was evaluated using microearthquake seismograms with the arrival times of the P (primary) and S (secondary) arrivals determined by an analyst. For the P-waves, the neural network picks were compared to picks made both by an analyst and by a standard automated picking algorithm. For the S-waves, the performance was compared to picks made by 2 different analysts.

The neural network learned the process for selection of P-wave arrival times by copying the selection of a human analyst. The performance of the neural network picking algorithm was evaluated for high signal-to-noise ratio P arrivals from The Geysers geothermal field UNOCAL-NEC-Thermal (U-N-T)

partnership. For evaluating the performance, an independent set of 1500 time series were picked with the trained neural network. For comparison, the same time series were also picked with a standard automatic picking algorithm. We calculated the percentage of picks with errors greater than the sample period (.01 seconds) for both computer-based approaches. The neural net had errors outside this bound for 12% of the picks, and the auto-picker for 43% of the picks.

The automated determination of secondary arrivals is much more difficult than for primary arrivals, because of the need to recognize the onset of a signal with different frequency and amplitude than the P-wave. We trained a neural network to pick microearthquake S-arrivals using two directional components of motion at each recording site, one vertical component and one horizontal component. The data for training and testing came from the Lawrence Berkeley Laboratory deployment at the southeast Geysers. The trained neural net was tested with 490 sample 2-component seismograms that were picked by the same analyst (analyst 1) who picked the training set arrivals. In this test, 75% of the S-wave picks were within 0.05 seconds of the analyst pick. The results from this test are compared to a smaller, distinct, data set of 61 seismograms for which a second set of picks was made by another analyst, since no automatic picking routine for secondary arrivals was available. In this test, 67% of the picks were within 0.05 sec of the picks made by the first analyst we used. Therefore, the neural net performance is comparable to the performance of an independent human analyst.

Plans

We plan to complete this study by installing the neural picker at LBL and Unocal to process seismic data from The Geysers.

Other applications of neural networks to other geothermal problems:

A. Reservoir Engineering:

A neural network approach has been used to increase the speed of solving a hydrologic well optimization problem. Rogers and Dowla (at LLNL) trained a neural network to emulate a simulator for water well optimization forward calculation, with a significant increase in speed over the more complex simulator. This approach could improve the speed of similar geothermal reservoir engineering calculations where computer-intensive forward model calculations are performed repeatedly, for example, to study optimal injection-production strategies. The simplified neural net simulations allow more hypotheses to be tested for a given amount of computer time.

B. Subsurface Imaging:

The use of neural networks for solving geophysical inverse problems is being studied at LLNL. For the most part, the benefit is an increase in speed. Potential applications are gravity, seismic tomography and raytracing, electrical, and magnetic inversions.

C. Data Fusion:

An area where neural networks could have a major impact is data fusion, or finding relationships between very different types of data, when there is no deterministic model for the relationships. For example, the relationship between flow rate or steam production and chemistry, subsurface structure, injection rate, and other reservoir parameters could be determined by a neural network, and then reservoir behavior could be predicted for different hypothesized situations.

CONTACTS

DOE Program Manager:

Marshall Reed
U. S. Department of Energy, CE-122
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Stephen P. Jarpe	Phone: (510) 423-7676	FAX: (510) 422-7315
Paul W. Kasameyer	Phone: (510) 422-6487	FAX: (510) 422-3925
Lawrence Livermore National Laboratory		
P.O. Box 808		
Livermore, CA 94551		

SEISMIC IMAGING OF GEOTHERMAL SYSTEMS FOR PORE FLUID STATE

John J. Zucca, Lawrence J. Hutchings, Paul W. Kasameyer, and Brian P. Bonner
Lawrence Livermore National Laboratory

KEY WORDS

Seismic imaging, partial saturation, pore fluids

PROJECT OBJECTIVE

Our objectives are to develop methods to image the geologic structure of a geothermal field and to determine the state of the pore fluid in the matrix of the reservoir rock. In particular, we are working on ways to remotely sense the degree of fluid saturation in the rock pores. This type of information has traditionally been estimated from core samples. However, the saturation data obtained in this manner tend to have a large uncertainty since the fluid in the pores tends to flash to steam due to the drop in pressure bringing the sample to the surface. If saturation data could be reliably obtained in situ, this information could be used on a regional scale to prospect for new geothermal areas. On a local scale, this information could be used for management of existing fields. Knowledge of the amount and state of pore fluid could help answer such critical questions as: (1) What is the life of the geothermal system? (2) Which parts of the field are the most depleted? (3) What are the boundaries of the field? and (4) What effect does injection have?

APPROACH

Our approach is to use seismic imaging. The basic idea is to record the seismic waves that have passed through the region of interest, in this case the geothermal field. The source of the seismic energy can be either from controlled explosions dedicated to the seismic imaging or from local earthquakes. Data from many different sources may be used together to improve the resolution of the imaging. To get a good, well-resolved image, the sources and receivers should be well-distributed. We use variations in the patterns of arrival time and frequency content of the P- and S-waves to calculate velocity and attenuation structure respectively. P-wave (compressional seismic wave) velocity is sensitive changes in saturation, and the velocity increases with increasing saturation. P-wave attenuation is sensitive to partial saturation, and, for many rocks, attenuation increases with increasing saturation with a peak at 80% saturation. Although we have not included S-waves (shear seismic waves) in any of our analyses so far, S-wave velocity and attenuation information would greatly improve the reliability of our interpretations. This is because S-waves are not as sensitive to changes in saturation as are the P-waves. Therefore, including shear wave information should make it easier to determine if a given change in velocity is due to saturation variations or a change in lithology.

A shortcoming of our approach is that the attenuation behavior of rocks commonly found at The Geysers is not known from direct measurement. Our data on attenuation behavior is extrapolated from rocks much more porous than Geysers rocks (for example the Berea sandstone). Therefore, we have coupled our experimental field program closely to laboratory measurements of actual Geysers core samples. We plan to study the P- and S-wave velocity and attenuation properties of The Geysers matrix rock under varying degrees of saturation. We also plan to investigate the effect on these properties of introducing fractures into the samples.

PROJECT STATUS

Background

This project grew out of two previous projects which used explosive sources to image the P-wave

velocity and attenuation structure of two volcanoes in the Cascade range, at Newberry, Oregon, and Medicine Lake, California. In both these studies, high attenuation anomalies were discovered within a few kilometers of the surface in the volcanic calderas. These anomalies were interpreted as locations likely to contain partial saturation conditions in the pores, most likely indicative of boiling water. In the case of Newberry volcano, a drill hole into the anomaly gave partial confirmation of this interpretation. Our success in the Cascades led us to try the method at The Geysers where we had to adapt it to use the numerous local earthquakes as sources.

Research Results

To date we are involved in three seismic imaging experiments at The Geysers which we call Geysers I, II, and III. Geysers I is almost complete, and we have a draft paper in internal review at LLNL. This experiment used the local seismic data from the UNOCAL-NEC-Thermal (U-N-T) partnership in the center of The Geysers field. We have calculated a three-dimensional P-wave velocity image of The Geysers. Unfortunately, the parameter we used to estimate P-wave frequency content only allowed us to calculate a one-dimensional image of the attenuation. For The Geysers II and III experiments, we are attempting to overcome this problem by recording data at higher sample rates. We also hope to include S-waves in the analysis by recording three-component data. In these two experiments, we are cooperating with Lawrence Berkeley Laboratory to collect data in the southeast Geysers around two different fluid injection sites. The goal of the experiments is to carry out detailed seismic imaging around these injection wells and also to provide fast, accurate locations of the micro-seismic events associated with the injection. The collection of The Geysers II data set is almost complete at the time of the writing of the abstract (February 1993), but the analysis has not yet started. The collection of The Geysers III data is planned to begin in the Spring of 1993.

For Geysers I, our data consisted of approximately 300 earthquakes that were of magnitude 1.2 and distributed in depth between sea level and 2.5 km. Using compressional-wave arrival times, we inverted for earthquake location, origin time, and velocity along a three-dimensional grid. Using the initial pulse width of the compressional-wave, we inverted for the initial pulse width associated with the source, and the one-dimensional Q (the inverse of attenuation) structure. We find that the velocity structure correlates with known mapped geologic units, including a velocity high that is correlated with a felsite body that is known from drilling information. The dry steam reservoir, which is also known from drilling, is mostly correlated with low velocity. The Q increases with depth from the surface to the top of the dry steam reservoir and decreases with depth within the reservoir (see figure). The decrease of Q with depth within the reservoir probably indicates that the saturation of the matrix of the reservoir rock increases with depth.

Plans

We plan to continue working on The Geysers II and III experiments. We hope to be able to observe the effect of fluid injection into the reservoir, and, in the most ideal case, to observe the migration path of the fluid to determine at which point it flashes to steam. For our long-term plans, we would like to apply our method at other locations. The Salton Sea region is attractive because of its importance as a geothermal energy resource. We are currently collaborating with U.C. Santa Barbara on a project to assemble and interpret a local earthquake data set for the regional P-wave velocity and attenuation structure. After completion of this study, we would like to target specific local areas for more in-depth study.

Figure 1

Horizontal Slices through the Geysers reservoir. The image shows P-wave velocity variations from the 1D starting model. Dark indicates low velocity and light indicates high velocity. The Q for the layer is printed to the left of the image. Solid squares indicate locations of power producing units. The contour shows the intersection of the image plane with a known structure, i.e., within the contour on the upper image is the known steam reservoir, within the contour on the lower image is the known felsite body.

REFERENCES

Zucca, J. J., Hutchings, L. J., and Stark, M. A., 1990, P-wave velocity and attenuation tomography at The Geysers Geothermal Field and its relation to the steam reservoir (abs): EOS Transactions of the American Geophysical Union, v. 71, no. 43, p. 1467.

CONTACTS

DOE Program Manager:

Marshall Reed
U. S. Department of Energy, CE-122
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

John J. Zucca	Phone: (510) 422-4895	FAX: (510) 422-7315
Paul W. Kasameyer	Phone: (510) 422-6487	
Lawrence J. Hutchings	Phone: (510) 423-0354	
Brian P. Bonner	Phone: (510) 422-7080	

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA, 94550
FAX: (510) 422-3925

MICROEARTHQUAKE MONITORING AT THE GEYSERS

Ernest L. Majer

Earth Sciences Division, Lawrence Berkeley Laboratory

KEY WORDS

Seismology, microearthquake, monitoring, reservoir performance

PROJECT OBJECTIVE

The objective of the research is to decrease the operating costs of steam production and utilization at The Geysers by improving the efficiency of reinjection and in-fill well drilling. This will be accomplished by acquiring and interpreting high frequency microearthquake data to understand fluid paths, dynamics of the reservoir, and the structures controlling the steam and fluid flow. This research will significantly aid the field operations of The Geysers through providing a better understanding of the fluid flow paths through the fractured reservoir. It is possible that continuous seismic monitoring will be of use as an active reservoir management tool.

Specific objectives are:

- 1) Demonstrate the utility of high resolution, multi-component, microearthquake data (MEQ) for:
  - a) Locating high permeability paths in the reservoir;
  - b) Aid in the siting of in-fill wells;
  - c) Monitor the result of condensate injection in real time.
- 2) Develop a 3-D model of the reservoir:
  - a) P (compressional)- and S (shear)-wave velocity structure;
  - b) Poisson's ratio model;
  - c) 3-D structural model using MEQ location for inferring flow paths.

APPROACH

The approach taken in this project is to use state-of-the-art high frequency, digital microearthquake arrays to collect high resolution data sets for advanced processing. This approach provides data of a high quality not previously obtained in the monitoring of geothermal systems. Two arrays are being used to monitor seismicity at The Geysers. A 16-station array of three-component borehole seismometers located in the northwest Geysers owned by Central California Power Agency (CCPA) is unique in its dense placement of stations and in its high frequency digital coverage. A similar seismic array is being installed in the southeast Geysers for monitoring of injection activities. These arrays monitor two different geologic and geothermal environments at The Geysers.

PROJECT STATUS

A. Northwest Geysers

In March of 1990, the Lawrence Berkeley Laboratory (LBL), in conjunction with the Coldwater Creek Operator Company (now CCPA), undertook the collection, analysis, processing, and interpretation of the microearthquake (MEQ) data from the 16-station, digital, 3-component, high frequency array in place at the northwest Geysers geothermal field. To date, the processing has concentrated on data collected from the period prior to full production and injection in the NW Geysers until approximately one year after of injection began (1988). This involves detailed analysis and processing of approximately 6000 events. During this time, injection has occurred at two different sites, wells Pratti 8 and Pratti 9. Processing of the data has revealed a strong correlation between injection and seismicity. However, the seismicity resulting from injection is superimposed on a more general pattern

of seismicity related to such factors as "natural" seismicity and effects of withdrawal. At this point in time, we have a good characterization of the seismicity patterns in this area and their relationship to various reservoir parameters. The plan for 1993 is to bring the NW Geysers array back into operation, now that the legal and technical problems have been overcome, and to begin collecting a data base to compare to the 1988 data set.

B. Southeast Geysers

Several operators in the southeast Geysers region have undertaken a cooperative effort to more fully understand the mechanisms associated with reinjection activities. To date, MEQ rates and location have shown a good correlation with injection activities (M. Stark, UNOCAL, personal communication). UNOCAL is presently operating an analog array of MEQ stations in the injection region. Although this array has been very useful, our need for greater precision in location of events dictates that we install equipment for digital acquisition at higher frequency contents that provides three-component data. The work in the northwest Geysers has demonstrated the utility of multi-component, high-frequency, digital data. During the last year, LBL installed 8 stations and LLNL installed 5 stations of a high frequency array in the SE Geysers to apply this technology to an injection experiment. It has become obvious that the split array operation is not providing reliable data on a timely basis. The first order of business is to buy 5 new stations to replace the LLNL stations in order to have all of the data coming to one central recording point. This would streamline the data collection and processing. The rate of seismic activity (150 to 200 events per month) is not as high in the southeast Geysers as in other areas of the field, so it is reasonable to expect that with the split-array problem solved, the data processing could be done on a more timely basis.

Plans

Northwest Geysers

- 1) Insure that hardware and software are operational. (March 1993)
- 2) Upgrade software for modern picking, location, and inversion codes. (completed)
- 3) Process new and existing data for software testing and MEQ technique evaluation. (on-going, monthly status reports)
- 4) Monitor several injection projects for 6 to 12 weeks to understand the relation between seismicity and injection as a function of different geologic and thermal environments.

Southeast Geysers

- 1) Use high-frequency MEQ data to develop a 3-D velocity model for precise location of events. Obtain base line velocity model (April 1993) sites.
- 2) Install additional digital electronics capable of three-component, high-frequency (480 samples/second) data acquisition and telemetry at existing LLNL sites. (Start installation May 1, 1993, finish May 15, 1993.)
- 3) Correlate MEQ spatial and temporal locations with injection activities. (Start April 1993; Continue to end of project.)
- 4) Correlate source mechanisms (size, slip, moment, etc.) with injection activities and available stress information. (Start in July 1993; continue to end of project.)
- 5) Monitor changes in above parameters as a function of time.

REFERENCES

Peterson, J. E., Jr., Majer, E. L., Romero, A. E., Jr., and McEvilly, T. V., 1992, A search for production - induced changes in seismicity or velocities at the northwest Geysers geothermal field, California: [Abstract] Poster Presentation, American Geophysical Union, 1992 Fall Meeting, December 7-11, San Francisco, CA.

Romero, A. E., Jr., Vasco, D. W., and Majer, E. L., 1992, Nonlinear inversion for velocity structure at the northwest Geysers: [Abstract] Poster Presentation, American Geophysical Union, 1992 Fall Meeting, December 7-11, San Francisco, CA.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigator:

Ernest L. Majer
Earth Science Division, Mail Stop 50E
Lawrence Berkeley Laboratory
Berkeley, CA 94720
Phone: (510) 486-6709
FAX: (510) 486-5686

FLUID INCLUSION AND MINERALOGIC STUDIES OF THE GEYSERS

Joseph N. Moore
University of Utah Research Institute

KEY WORDS

Fluid inclusions, vapor-dominated systems, conceptual models

PROJECT OBJECTIVE

The objectives of this project are to: (1) characterize the thermal and chemical evolution of The Geysers geothermal system; (2) determine the origin of the corrosive HCl-bearing steam produced in the northern part of the field; (3) evaluate the factors controlling the permeabilities within different parts of the reservoir; and (4) provide constraints on the reservoir engineering models being developed for the field. Attainment of these objectives will assist the operators in mitigating the effects of corrosive steam and in developing improved conceptual models needed for future development.

APPROACH

In contrast to the information obtained from chemical analyses of the waters found in liquid-dominated geothermal systems, the composition of the steam discharged from vapor-dominated systems provides only limited insight into the chemistry and history of the reservoir from which it was derived. In this investigation, fluid inclusions and mineralogic data on cores and hand-picked cuttings were studied to establish the salinities and temperatures of the fluids that circulated through The Geysers at different times in its evolution. The samples were provided by Calpine, Coldwater Creek Operator Corporation, and UNOCAL from the caprock, normal vapor-dominated reservoir (graywacke and felsite), and from the high-temperature reservoir (Figure 1).

PROJECT STATUS

Background

Although the general geologic framework of The Geysers geothermal system was established more than 20 years ago in the classic study by White and others in 1971, a number of important questions regarding the evolution of this system have remained unanswered. For example, little quantitative information has been published on the evolution of the vapor-dominated reservoir, the characteristics of the low permeability boundaries of the reservoir, or the development of the high-temperature reservoir (unknown in 1971).

Efforts to better characterize the evolution of the reservoir, by Sternfeld in 1981 and by Moore and others in 1989, demonstrated the existence of an early liquid-dominated system with low to moderate salinities, but they provided little insight into the regional chemical characteristics of the reservoir prior to development of the vapor-dominated regime. In both of these studies, only cuttings samples were used, limiting the quality of the paragenetic data that could be obtained on the mineral relationships. The use of core in the present study has allowed us to: (1) characterize in detail the mineralogic relationships within the veins; (2) accurately establish the locations of the samples; (3) obtain mineral samples that are large enough to conduct fluid inclusion determinations of salinity and temperature; and (4) establish in a few cases the relative ages of the fluid inclusions.

Research Results

Investigations of the hydrothermal alteration and fluid inclusions in samples from two dozen wells (Figure 1) have provided fresh insight into the chemical and thermal evolution of The Geysers geothermal field. These studies document how an early magmatically-heated, high-temperature, liquid-

dominated hydrothermal system evolved into the current vapor-dominated regime.

A detailed conceptual model of The Geysers thermal system was developed by Moore in 1991 and by Moore and Hulen in 1992. This model recognizes three stages in the evolution of the geothermal system at The Geysers. The initial development of The Geysers geothermal system began with the emplacement of a composite Plio-Pleistocene felsic intrusive complex that is generally termed "the felsite". As the intrusive complex was emplaced, a liquid-dominated hydrothermal system developed (Figure 2), producing a well-defined sequence of vein minerals. With increasing distance from the felsite, and/or decreasing relative age at a given elevation, the following sequence of vein assemblages formed within the metamorphic aureole surrounding the felsite: (1) tourmaline-quartz + K-feldspar, albite, biotite, actinolite, and clinopyroxene; (2) quartz-biotite-actinolite + K-feldspar, clinopyroxene, tourmaline; (3) quartz-K-feldspar-actinolite-epidote + ferroaxinite, prehnite, calcite; (4) quartz-K-feldspar-chlorite-epidote; and (5) quartz-K-feldspar-calcite + sericite.

The early liquid-dominated hydrothermal system was characterized by strong gradients in the temperatures and compositions of the fluids. Fluid inclusion homogenization temperatures ranged from 350°C near the base of the present caprock to more than 450°C near the contact while the corresponding salinities varied from 5 equivalent weight percent NaCl to more than 26 weight percent NaCl. These high salinity inclusion fluids, which commonly contain crystals of halite, are representative of the dense magmatic brines that exsolved from the felsite and formed the tourmaline and biotite veins.

The second stage in the development of The Geysers thermal system occurred as temperatures around the felsite declined, causing the early liquid-dominated system to collapse upon itself (Figure 3). Downward migration of the low-salinity waters resulted in dilution of the fluids that were present in regions now occupied by the zone of condensation and the main vapor-dominated reservoir. These downward percolating waters deposited calcite within the fractures near the top of the present reservoir, leading to the formation of a low-permeability caprock.

The downward moving fluids do not appear to have breached the present high-temperature reservoir. Although fluid inclusion data are limited to two core samples, no evidence was observed for the circulation of fluids with moderate temperatures (around 260°C) and salinities (< 10 weight percent equivalent NaCl). Indeed, pressure corrected homogenization data suggest that the last fluids to circulate through these rocks had temperatures of at least 295°C. We suggest that the failure of the rocks in the high-temperature reservoir to cool further, as those in the normal vapor-dominated reservoir did, and the presence of measured temperatures that reach 347°C (reported by Walters and others in 1988) resulted from renewed intrusion in the northern part of the field. Furthermore, these data lead to the conclusion that permeabilities within the high-temperature reservoir are lower than those in the overlying rocks.

The present vapor-dominated regime appears to be a relatively recent feature of the thermal system (Figure 4). Fluid inclusions in the normal vapor-dominated reservoir suggest that, prior to boiling off, the precursor liquid had temperatures between 250 and 270°C and salinities of up to 7 equivalent weight percent NaCl. Boiling within the caprock produced veins of calcite and quartz. As the boiling proceeded, acidic condensate formed and was preserved as low-salinity fluid inclusions in the caprock and upper part of the reservoir. This condensate reacted with the host rocks to produce sericite and, in places, kaolin, which further reduced fracture permeabilities. Evidence of boiling within the reservoir rocks is limited to the presence of vapor-rich inclusions.

Figure 1. Locations and lithologies of the samples studied. Data from LFH-2 and SB-26 are from Sternfeld (1981). Abbreviations: NVDR = normal vapor-dominated reservoir; HTVDR = high-temperature vapor-dominated reservoir.

Figure 2. The initial stage in the development of The Geysers geothermal system. The temperatures shown in the figure are based on the fluid inclusion data. During this stage in the development of the system, the direction of fluid flow was predominately away from the intrusive contact as shown by the arrows. The diagonal lines show the regions of the thermal system through which hypersaline magmatic fluids circulated. The positions of the present vapor-dominated reservoir and caprock are shown in Figures 2-4 for reference.

Figure 3. Collapse of the initial liquid-dominate regime during the second stage in the evolution of The Geysers geothermal system. During this stage, fluid movement was dominantly toward the intrusion as indicated by the black arrows. Calcite was deposited near the top of the system in what is now the caprock and the zone of condensation. The high-temperature vapor-dominated reservoir began to develop at this time in response to renewed intrusion in the northern part of the field.

Figure 4. Initial development of the present vapor-dominated regime during the third stage in the evolution of The Geysers geothermal system. The open circles show the onset of boiling in the upper part of the system while heavy black arrows show the downward movement of acidic condensate.

The fluid inclusion and mineralogic data place important constraints on the origin of the corrosive steam. These data indicate that there have been several important differences in the evolution of the normal and high-temperature reservoirs. They suggest that the formation of corrosive steam in the deeper reservoir is related to lower permeabilities and the higher salinities of the liquid that existed in the pore space prior to boiling. These higher salinity fluids could have deposited greater concentrations of salt in the fractures as the present vapor-dominated regime developed.

Plans

The investigation described above has achieved all of its major objectives. A final report, detailing the results will be prepared. During FY-93, we will direct our efforts toward developing a better understanding of the relationships between the characteristics of the reservoir rocks and corrosive steam. This will be accomplished by chemically determining the soluble chloride contents of selected rock samples. The results of these analyses will be correlated with the lithologies of the rocks, their temperatures and depths.

REFERENCES

Moore, J. N., 1992, Thermal and chemical evolution of The Geysers geothermal system, California: Proceedings, 17th Workshop on Geothermal Reservoir Engineering, Stanford University, (in press).

Moore, J. N., and Hulen, J. B., 1992, The Geysers steam field: an evolving magmatic-hydrothermal system in northern California: PACROFI IV, Fourth Biennial Pan-American Conference on Research on Fluid Inclusions, May 21-25, p. 60.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D. C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Joseph N. Moore
University of Utah Research Institute
Research Park
391 Chipeta Way, Suite C
Salt Lake City UT 84108
Phone: (801) 584-4428
FAX: (801) 584-4453

HEAT-FLOW STUDIES IN THE AREA OF THE GEYSERS GEOTHERMAL FIELD, CALIFORNIA

Colin F. Williams, John H. Sass, and Arthur H. Lachenbruch
U. S. Geological Survey

KEY WORDS

Heat flow, The Geysers, thermal conductivity, high temperature reservoir, pressure

PROJECT OBJECTIVE

The overall objective of this project is to acquire thermal data from The Geysers geothermal field in order to develop an accurate and comprehensive understanding of the nature and evolution of the system. The primary research focus is an investigation of the High Temperature Vapor Dominated Reservoir (HTVDR) which underlies the northwestern part of The Geysers. This research project is significant to the field management of The Geysers because its findings will provide an understanding of the nature of the high temperature reservoir and an estimate of the thermal history of the field. Both of these benefits will impact the manner in which the reservoir is operated in the future.

APPROACH

The technical approach applied in this research involves the acquisition of precision, equilibrium temperature and pressure logs from idle wells in the NW Geysers. These data are combined with thermal properties measurements on cores and cuttings for a determination of the temporal and spatial variability of heat transfer above and within the steam reservoir. The field operations are performed in collaboration with investigators from Sandia National Laboratories.

PROJECT STATUS

Background

Pioneering studies of The Geysers geothermal field modeled the system as a nearly isothermal (~245°C) vapor-dominated reservoir (VDR) underlying an impermeable, liquid-filled caprock of varying thickness. In the early 1980s, exploration and development of the northwestern Geysers revealed the presence of a second, higher temperature vapor-dominated reservoir (HTVDR) underneath the VDR. Although a number of wells penetrate the HTVDR, there is little information from the HTVDR, and the nature of the VDR-HTVDR transition is practically a matter of speculation. Temperatures within the HTVDR exceed 350°C, and it could serve both as a producing reservoir in its own right and as a source of heat for re-injection into the VDR. Unfortunately, high quantities of non-condensable gases and HCl, both of which cause significant production problems, have also been associated with the HTVDR.

The absence of precision temperature and pressure data from the HTVDR severely limits research into these problems. In addition, detailed studies in the caprock and the interval between the VDR and HTVDR may reveal variations in conductive heat flow due to temporal variations in The Geysers system. Consequently, the first phase of this project has focused on the acquisition of equilibrium temperature and pressure logs from idle wells which penetrate the HTVDR.

Research Results

With the assistance of investigators from Sandia National Laboratories (R. Jacobson, P. Lysne, J. Dunn), temperatures and pressures have been measured in a number of wells in the NW Geysers. An example plot of temperature gradients, thermal conductivities and resulting heat flow in The Geysers caprock is shown in Figure 1. The pressure measurements have been forwarded to Idaho National

PT31, NW Geysers

Figure 1 - Plot showing the vertical temperature gradient, thermal conductivity and resulting heat flow for a well in the NW Geysers. Note the decrease in heat flow with depth from 450 mW/m² to less than 300 mW/m². The heat flow values are from the caprock section overlying the vapor-dominated reservoir.

Engineering Labs for inclusion into the TETRAD numerical reservoir model. The temperature data have been combined with thermal conductivity measurements on drill cores and cuttings in a vertical profile of heat flow. Rock thermal conductivity is significantly temperature-dependent, and conductivity values appropriate to subsurface conditions are determined through two methods. Room temperature conductivity measurements on cuttings are transformed to in situ values via the method described by Sass and others in 1992. Conductivity measurements on core plugs are being made in a new high temperature and pressure apparatus capable of simulating in situ conditions.

The results reveal a dramatic decrease in heat flow with depth. This decrease with depth could follow from a number of factors, including upward water flow, but it is most likely due to the time variation of heat flowing into the caprock from below. Modeling of these results is consistent with cooling or recession of the reservoir levels within the past 20,000 years, the thermal time constant of the 2 km thick caprock. If this model is confirmed by other measurements, it places significant constraints on the evolution of both the VDR and HTVDR.

Fluid inclusion studies published by Moore in 1992 document the evolution of The Geysers from a higher temperature liquid-dominated system to the present vapor-dominated system. The decrease in heat flow shown in Figure 1 may be a thermal record of this evolution. If so, then the NW Geysers vapor-dominated system (both VDR and HTVDR) is unlikely to be much more than 20,000 years old. The probable conductive heat flux from the HTVDR into the VDR is larger than that from the VDR into the caprock. If conductive heat transfer is dominant in the VDR-HTVDR transition zone, this imbalance in heat transfer between the heat flowing out of the VDR into the caprock and the heat flowing into the VDR from the HTVDR must be a transient condition. If advective heat transfer is important, as suggested by Shook in 1993, then the HTVDR may be in thermal equilibrium with the VDR. A manuscript summarizing these heat-flow results is in preparation for the 1993 Geothermal Resources Council Meeting.

Plans

Plans for the current fiscal year and beyond are divided into three phases. The first phase involves continued logging of wells at The Geysers to establish the areal extent of decreasing heat flow with depth in the caprock. This phase will also include additional thermal conductivity measurements under in situ conditions. The second phase centers on operations to clean out obstructions in the wells that penetrate the HTVDR. This procedure will enable temperature and pressure logging of the HTVDR at a number of locations, provide access for downhole fluid sampling of the HTVDR, and restore some bridged wells to producible conditions. As a possible third phase of this project, a section of the HTVDR would be cored as part of an investigation of rock and fluid properties in situ. Injection experiments into the HTVDR would also be possible at this point.

REFERENCES

- Sass, J. H., Lachenbruch, A. H., Moses, T. H., Jr., and Morgan, P., 1992, Heat flow from a scientific research well at Cajon Pass, California: *Journal of Geophysical Research*, v. 97, p. 5017-5030.
- Sass, J. H., Kennelly, J. P., Jr., Williams, C. F., and Lachenbruch, A. H., 1992, Thermal conductivity of water-saturated crystalline rocks as a function of temperature: Thermal Properties of Crustal Materials Conference, Bad Honnef, Germany, April 1-3, 1992.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Colin F. Williams	Phone: (415) 329-4881
Arthur H. Lachenbruch	Phone: (415) 329-4879
U.S. Geological Survey, Mail Stop 923	
345 Middlefield Road	
Menlo Park, CA 94025	
FAX: (415) 329-4876	

John H. Sass
U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ 86001
Phone: (602) 556-7226
FAX: (602) 556-7169

SALT EFFECTS ON STABLE ISOTOPE PARTITIONING

Juske Horita, David R. Cole, and David J. Wesolowski
Chemistry Division, Oak Ridge National Laboratory

KEY WORDS

Isotope, oxygen, hydrogen, salinity, partitioning, brine

PROJECT OBJECTIVE

The aim of this research is to determine the effect of dissolved ions on the partitioning of the stable isotopes of hydrogen and oxygen between geothermal brines and other phases, including steam and the alteration minerals formed in geothermal reservoirs. The distinctive isotopic signature of injected water has made it possible to trace the injected fluid through to production and to estimate the quantity of production that is derived from injection. This research is of importance in refining the usefulness of isotopic tracing of fluid flow and in providing better quantitative estimates of residence time and rock-water interaction.

APPROACH

The salt effect is measured directly by sampling the water vapor over salt solutions having a known oxygen and hydrogen isotope composition. Changes in the D/H and $^{18}\text{O}/^{16}\text{O}$ ratio of the vapor as a function of salinity is modeled in terms of the activity coefficient ratios of the isotopic water molecules in the brines.

This project benefits substantially from the program "Fundamental Geochemistry of Geothermal Systems" funded by the DOE Office of Basic Energy Sciences, Geoscience Program, in which more detailed, complementary studies are performed. This project is part of a program "Physical Chemistry of Geothermal Systems" at ORNL. The general objective of this program is to conduct laboratory experimental research utilizing unique facilities and expertise at ORNL for studies of selected chemical equilibria, thermodynamics of brine systems, liquid-vapor molecular and isotopic partitioning, and other phase behavior. Results allow prediction of temperature, chemistry and permeability changes in reservoirs and in plant facilities involved in the extraction of geothermal energy, and provide fundamental experimental data needed as input for geochemical models.

PROJECT STATUS

Background

The distribution of the stable isotopes of oxygen, hydrogen, and other light elements, which partition as a function of temperature and the bonding characteristics of individual phases, are widely studied in geothermal systems in order to constrain the time-temperature history of these systems, the sources and fluxes of fluids, the extent of boiling and mineral deposition from the fluids, and the temporal relationship among alteration minerals.

Cations and anions in aqueous solutions are surrounded by hydration spheres of oriented water molecules. Numerous investigations of salt solutions at room temperature have demonstrated that the D/H and $^{18}\text{O}/^{16}\text{O}$ ratios of these hydration spheres are different from the bulk water, resulting in concentration-dependent salt effects on the partitioning of these isotopes between brines and coexisting phases, such as steam and other volatiles, and alteration minerals. However, at the elevated temperatures encountered in geothermal systems, there are insufficient data or theoretical developments to predict salt effects on isotope partitioning.

The limited data available are conflicting, but indicate potentially significant salt effects in the 100 to 300°C range, leading to errors on the order of 50°C in calculated temperatures and gross misinterpretation of fluid sources and fluxes, particularly in highly saline systems, such as the Salton Sea and Guaymas Basin. Even in less-saline geothermal systems, the distillation processes associated with steam separation and mineral precipitation produce large isotopic differences. In order to model the products of distillation and condensation, very accurate isotope fractionation factors are required. The isotopic compositions of the products can then be used to constrain the nature of the phase separation processes.

Research Results

A.) Experimental Approach

Glass reaction vessels were designed in which a lower chamber containing pure water, or a salt solution made up from isotopically identical water mixed with anhydrous salts, is connected to two separate vapor reservoirs via remotely actuated Teflon valves. These vessels are placed in a thermostated water bath in which the vapor reservoirs are held at a slightly higher temperature than the brine reservoir to prevent condensation. Temperature control in the bath is better than 0.1°C. The brine solutions are stirred magnetically and allowed to equilibrate with their vapor. After one to two days, the valves connecting the liquid and vapor reservoirs are closed and the vapor samples extracted for isotopic analysis. This system is used in the 25 to 100°C range.

A similar system was constructed for operation in the 100 to 250°C range. In this system, stainless steel reaction vessels are used in which the liquid is housed in a fused quartz cup, the vapor reservoir is stainless steel high-vacuum tubing, and the remotely-actuated valves are monel bellows valves. For experiments in the 150 to 350°C range, the experimental system designed in this program for the studies of HCl volatility over geothermal brines is employed. This consists of platinum-lined pressure vessels which contain platinum capillary tubes allowing equilibrium sampling of either the liquid or the vapor phase.

Oxygen isotope ratios are determined by equilibration of the sampled water vapor with micromolar quantities of CO₂ gas at 25°C. The water is then reacted with uranium metal at 600°C to produce H₂. The CO₂ and H₂ are then analyzed for their ¹⁸O/¹⁶O and D/H ratios using a VG 903 gas-source isotope ratio mass spectrometer.

B.) Results to Date

In this project, we are studying the effects of pure salts in the system Na-K-Mg-Ca-Cl-SO₄. At the temperatures and salinities studied to date, the salt effects of complex brine mixtures have been found to be simply additive combinations of the effects of the individual pure salts. Therefore, the results summarized below refer to the pure salts.

We have studied the effects of 0 to 6 molal NaCl, KCl, CaCl₂, MgCl₂, and 0 to 2 molal Na₂SO₄ and MgSO₄ and mixtures of these salts in the 50 to 100°C range and two papers have been submitted for publication (see references). We have also determined the effect of 0 to 6 molal NaCl in the 100 to 225°C range. Our results are quite different from previous studies, which reported large and wildly-varying oxygen isotope salt effects as a function of temperature and salinity. In all cases, we have found a linear relationship between the salt effect and the molality of the dissolved salt, with the salt effect linearly increasing with salinity. Significantly, NaCl and KCl brines have essentially no effect on the partitioning of oxygen isotopes between water liquid and vapor. Salt effects are expressed as ‰ (parts per thousand) deviation of the isotope ratio of the sample from that of the vapor over pure water of identical isotopic composition. The effect on hydrogen isotopes is very similar for these salts

and ranges from 1.8 ‰ per molal salt at 50°C to 1.0 ‰ per molal at 200°C. The decrease in salt effect with increasing temperature is gradual and expected from isotope theory.

MgCl₂ and CaCl₂ have large oxygen isotope salt effects, ranging from -0.74 to -1.0 ‰ per molal from 50 to 100°C for MgCl₂ and staying constant at about -0.4 ‰ per molal to 100°C for CaCl₂. These salts have similar hydrogen isotope salt effects, around 4 ‰ per molal, with small temperature dependencies in the 0 to 6 molal range. MgSO₄ has a large oxygen isotope salt effect similar to that of MgCl₂, but a much smaller hydrogen isotope effect, about half that of an equivalent concentration of MgCl₂. This suggests that, if MgSO₄ ion pairs form in these solutions, they are probably of the solvent-separated variety, with the sulfate anion hydrated no more strongly than the singly-charged chloride anion. Na₂SO₄ exhibits a very modest hydrogen isotope effect in the 50 to 100°C range, 0.5 to 1.1 ‰ per molal, but this effect increases with increasing temperature. The oxygen isotope salt effect ranges from -0.1 to -0.3 ‰ per molal from 50 to 100°C.

These results demonstrate that significant salt effects are observed that must be taken into account in quantitative analysis of the oxygen and hydrogen isotope distributions in geothermal systems. The salt effects are very regular and can be extrapolated, but are very different from some previously reported results by Truesdell in 1974. The trends of the salt effects with temperature demonstrate that significant effects will persist to at least 250°C in geothermal brines.

Plans

Measurements of oxygen and hydrogen isotope salt effects by direct sampling of the water vapor over brine solutions will continue until we have completed studies of the system Na-K-Ca-Mg-Cl-SO₄ to 350°C and 0 to 6 molal salt concentration. We have initiated studies of brine-mineral partitioning as a function of salinity in order to demonstrate that the liquid-vapor salt effects are indicative of the isotopic activity/composition relationship of the liquid phase, and therefore applicable to any phase separation process. The mineral brucite, Mg(OH)₂, contains both hydrogen and oxygen in crystallographically similar sites and exchanges isotopes rapidly enough for useful studies in the 200 to 400°C. Work with this solid will also allow measurements of the salt effect at conditions where low salinity brines would be supercritical.

HCl is known to produce enormous oxygen isotope salt effects at low temperature, up to -0.8 ‰ per molal at 25°C. Because HCl is a prominent species in The Geysers geothermal system, we will study its oxygen isotope effect to 100°C in our glass reaction system, and in the 100 to 350°C range in the system designed for HCl volatility studies.

Bicarbonate and carbonate ion are abundant in some geothermal systems. The effect of carbonate on hydrogen isotope partitioning can be studied with the methods described above, but the solubility of carbonate salts is obviously limited. Carbonate and bicarbonate rapidly exchange oxygen and hydrogen isotopes with water, complicating the interpretation of salt effect studies. However, we will investigate methods of determining the salt effects of these ions.

REFERENCES

Horita, J., Cole, D. R., and Wesolowski, D. J., 1993, The activity-concentration relations of oxygen and hydrogen isotopes in aqueous salt solutions: II: Vapor-liquid water equilibration of mixed salt solutions from 50 to 100°C: *Geochimica et Cosmochimica Acta* (in review).

REFERENCES

Horita, J., Wesolowski, D. J., and Cole, D. R., 1993, The activity-concentration relations of oxygen and hydrogen isotopes in aqueous salt solutions: I: Vapor-liquid water equilibration of single salt solutions from 50 to 100°C: *Geochimica et Cosmochimica Acta* (in press).

Horita, J., Wesolowski, D. J., and Cole, D. R., 1992, The effect of dissolved salts on oxygen and hydrogen isotope fractionation between water vapor and brines at 50-100°C: *Water-Rock Interaction* (Y. K. Kharaka and A. S. Maest, eds.), Proceedings of the 7th International Symposium on Water-Rock Interaction, A.A. Balkema, Rotterdam, p. 999-1002.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-8076

Principal Investigators:

Juske Horita	Phone: (615) 576-4600
David R. Cole	Phone: (615) 574-5473
David J. Wesolowski	Phone: (615) 574-6903
Robert E. Mesmer	Phone: (615) 574-4958
Chemistry Division	
Oak Ridge National Laboratory	
P.O. Box 2008	
Oak Ridge, TN 37831-6110	
FAX: (615) 574-4961	

GEOHERMAL TRACER DEVELOPMENT

Michael C. Adams
University of Utah Research Institute

KEY WORDS

Tracers, tracer tests, fluorescein, rhodamine WT, aromatic acid tracers, geothermal reservoir

PROJECT OBJECTIVE

Chemical tracers are an invaluable tool for evaluating the efficiency of injection into geothermal fields. The overall objective of this research project is to identify and test compounds for use as geothermal tracers that are nontoxic, are thermally stable or have easily quantifiable rates of decay under geothermal conditions, have minimal rock-tracer interactions, are detectable at very low concentrations, are relatively inexpensive. As many of these compounds as possible should be identified because of the need for simultaneous tracers from multiple injection wells in a single tracer test. This research has importance in quantifying the amount of injected water that is recovered in production and in identifying the flow path of injected water through the reservoir.

APPROACH

The approach that we have taken in evaluating the utility of various compounds reflects the immediate need of the geothermal industry for tracers. We have focused our study on organic compounds because of the ability to quantify minute concentrations and because of the great variety of compounds available. Consequently, our methodology has been as follows:

- 1) Search the literature for compounds that may be useful as geothermal tracers, such as groundwater tracers and compounds used for high-temperature applications.
- 2) Rapidly eliminate from consideration compounds that are not suitable as geothermal tracers through interpretation of known thermodynamic data.
- 3) Evaluate the stability of the remaining candidates in laboratory tests using pressurized autoclaves at geothermal temperatures. Use a rock matrix to simulate a geothermal environment without expending undue amounts of time and resources.
- 4) Evaluate laboratory results through field injection tests of tracers to determine the relationship of our laboratory parameters to the field environment.
- 5) Refine our laboratory parameters based on the field results.
- 6) Publish information on successful and unsuccessful tracer candidate compounds.

PROJECT STATUS

Background

At the inception of the tracer development program in 1982, there were very few tracers in use by the geothermal industry, and those tracers in use lacked quantitative data on their stability. This information gap produced a lack of confidence in the results of tracer tests and considerably lowered their utility as a reservoir tool. Surveys of the geothermal industry by the DOE indicated a strong belief that tracer tests would be very valuable if stable geothermal tracers could be developed. It was on this basis that the tracer development project was founded.

In most geothermal fields, the spent, cooled brines must be injected back into the reservoir to avoid surface and ground water pollution and to maintain reservoir pressures. The locations of the injection wells within the three-dimensional network of fractures that form the reservoir are critical to the successful exploitation of the field. Properly located wells lead to higher power production from enhanced pressures, less reservoir scaling from boiling around the production wells, and reduced

thermal breakthrough. Improperly sited wells either give no pressure benefits or result in rapid thermal breakthrough. Prior to field production, only the pressure aspects of the hydrologic connections are known, not the pathways and velocities that the injection fluid will take between wells. The latter data can only be obtained by using evidence of mass transfer, such as chemical data. Introduction of a tracer into the injection-production loop is the most efficient and quantitative method of obtaining data that describe the subsurface flow of injected fluid.

We have used field tests in order to simultaneously prove the utility of tracer technology, transfer the technology to industry, and deduce additional properties of the tracers. For instance, a large-scale tracer test was conducted at the Dixie Valley geothermal system by the DOE and Oxbow Geothermal Corporation (as reported by Adams and others in 1989). Several of the aromatic acid tracers and the dye, fluorescein, were used to identify water from three injection wells during this test. Six production wells were monitored. The data from the Dixie Valley test were used to demonstrate that no significant adsorption of fluorescein took place during its transit through the reservoir. This was deduced by comparison with another tracer, benzoic acid, which was injected simultaneously with fluorescein. The effective temperature of the injection-production flowpath was deduced from comparison of the change in the concentration ratio of the two tracers during the test.

The first step in our project was to test derivatives of the best organic chemicals used as groundwater tracers. Organic compounds were used because they are not found in significant concentrations in geothermal reservoirs, and would provide the best sensitivity. Groundwater tracers were considered first because they had already been examined for environmental acceptability and toxicity. Thirty-nine of these compounds were laboratory-tested under conditions similar to those found in a geothermal environment. The experimental conditions included temperatures up to 300°C for periods of up to one month, contact with fluids of various salinities, the presence or absence of rocks, and atmospheric levels of molecular oxygen. Of the compounds tested, 24 can be used in geothermal systems with temperatures up to 200°C, 15 can be used up to 250°C, and 7 are stable to at least 300°C. Figure 1 shows the temperature range that each compound can be used as a geothermal tracer.

Research Results

The recent emphasis in this project has been to test some of the well-known fluorescent dyes for their stability under geothermal conditions. Most geothermal operators prefer a tracer that can be easily and inexpensively analyzed on site. Although the fluorescent dyes decay significantly at temperatures above 260°C, they are easily detectable using field-portable, inexpensive, filter fluorometers. Because the dyes also display finite decay in the temperature range of most geothermal systems, we have performed a series of experiments to define the reaction kinetics some of these dyes. To date we have conducted stability studies of fluorescein, rhodamine WT, amino G, and tinopol CBX.

Some of the dyes displayed variations in their decay rates that were dependent on other chemical species in the solution. For instance, the rate of decay of the blue dye, amino G, increases at low pH and in the presence of phosphate ions, as shown in Figure 2. The sensitivity of amino G to its chemical environment may make this compound unacceptable as a geothermal tracer.

Rhodamine WT is a red dye that has been used by industry in several geothermal tracer tests. However, our initial laboratory experiments indicated that rhodamine WT decays fairly rapidly, with a rate that is also sensitive to the anions present in the solution. The rate of decay of rhodamine WT in distilled water is shown in Figure 3. Evidence from groundwater tracer experiments has also indicated that rhodamine WT may adsorb to a much greater extent than fluorescein.

Figure 1. Summary diagram of the thermal stability of the compounds tested. The length of the solid lines represents the highest temperature tested in which the compound decomposed less than 20% within two weeks in either distilled or geothermal water. The dots along the line indicate the temperature at which the compound decayed less than 5% in geothermal water within the same time period. Compounds that decayed more than 5% at all temperatures tested or were not tested in geothermal water are shown as a line with no dot. Because 5% is within the experimental error, the dots indicate the temperature at which the compound can be expected to behave conservatively for a minimum of two weeks.

Figure 2. Decay rates of the blue fluorescent dye amino G in various solutions and pH's.

Figure 3. Decay rates of rhodamine WT derived from laboratory experimental studies.

Figure 4. Return curves (top two curves) and tracer ratios (bottom two curves) for the Steamboat Hills tracer test.

A field test was designed to examine both the decay rate and degree of adsorption of rhodamine WT. Both rhodamine WT and fluorescein were injected together into an injection well in the Steamboat Springs geothermal system. Ten production wells have been monitored since the injection. Although the test is still in progress, our preliminary data indicate that rhodamine is not decaying at a rate in concordance with our laboratory data. Figure 4 shows the concentration profile of the tracers from one production well during the first month of the test. Also shown are the ratios of the two tracers from the production well fluids and the theoretical change in ratios derived from the laboratory data. The lack of overlap of the two ratio curves demonstrates that rhodamine WT may not be useful as a geothermal tracer. Additional analyses are currently being conducted to test these preliminary conclusions.

Plans

Our current emphasis on fluorescent dyes reflects the requests that we have had from industry. To date, only fluorescein has proven to be stable enough for use as a geothermal tracer. However, our initial laboratory data indicate that Tinopol CBX may be stable in a moderate temperature geothermal environment. We plan on testing several others in the coming year.

REFERENCES

Adams, M. C., Benoit, W. R., Doughty, C., Bodvarsson, G. S., and Moore, J. N., 1989, The Dixie Valley, Nevada tracer test: Transactions, Geothermal Resources Council, v. 14, p. 215-220.

Adams, M. C., Fabry, L., and Moore, J. N., 1990, Comparative study of high performance liquid chromatographic parameters used for the analysis of carboxylic and sulfonic acid geothermal tracers: University of Utah Research Institute, Earth Science Laboratory Report, ESL-89013-TR, DOE/ID/12489-48.

Adams, M. C., and Davis, J., 1991, Kinetics of fluorescein decay and its application as a geothermal tracer: Geothermics, v. 20, p. 53-66.

Adams, M. C., Moore, J. N., Fabry, L., and Ahn, A. H., 1992, Thermal stabilities of aromatic acids as geothermal tracers: Geothermics, v. 21, p. 323-339.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Bob Creed
U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, ID 83402
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Michael C. Adams
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, UT 84108
Phone: (801) 584-4435
FAX: (801) 584-4453

GAS AND ISOTOPE GEOCHEMISTRY OF GEYSERS STEAM

Alfred H. Truesdell

Consultant to Lawrence Berkeley Laboratory

KEY WORDS

The Geysers, vapor-dominated, gases, isotope, reservoir liquid saturation, injection, marginal steam, flow decline, pressure decline, non-condensable gases

PROJECT OBJECTIVE

The objective of this research is to use extensive existing information on steam compositions at The Geysers to indicate the sources of steam and gas and to possibly predict expected changes in gas concentrations. This research will provide the predictions needed by the operating companies to anticipate noncondensable gas concentrations over the next several years. Because the removal of gas from steam is necessary for efficient power generation and the equipment is expensive (about \$ 1 million for each percent of gas for a 100 MW plant), estimates of gas concentration changes are important to optimize future operation of Geysers power plants.

APPROACH

Data is being obtained from steam producers including gas, isotope, and condensate compositions, three-dimensional coordinates of mean steam entry to each well and amounts of production and injection. Gas origins will be investigated through correlations of gas species and gas isotopes. Equilibrium source temperatures and liquid saturations are calculated based on gas reactions. Spatial and temporal variations in compositions and indicated temperature and saturation are correlated with production and injection.

PROJECT STATUS

Background

Partial studies of gas equilibria and more comprehensive studies of injection using isotopic indicators have been published for areas of The Geysers geothermal field. Fieldwide variations of initial steam and isotope compositions have been described and the main causes of the variations suggested. The extreme variation in gas concentration and isotope composition, from greater than 70,000 ppmv (parts per million by volume) gas and greater than +3‰ (parts per thousand) $\delta^{18}\text{O}$ in the NW Geysers to < 500 ppmv gas and < -8‰ $\delta^{18}\text{O}$ in the SE Geysers, suggests multiple sources and processes. A magmatic source for gas and steam in the NW and possibly central Geysers was suggested by Truesdell in 1991.

Research Results

A preliminary study of steam from the Northern California Power Agency (NCPA) area in the SE Geysers field has identified three main influences on gas and isotope compositions. These are: (1) original (pre-exploitation) gradients produced by the lateral movement of steam which has resulted in the production of high-gas steam near field margins; (2) injection of steam condensate which vaporizes and mixes with reservoir steam to dilute gases; and (3) a decrease in the availability of liquid in the reservoir which has decreased pressures and flow rates and increased gas.

Natural state gradients in gas and isotope chemistry result from lateral movement of steam from an upflow zone in the west-central part of the field toward zones of condensation mainly to the south and east with a smaller flow to the west. This movement was accompanied by partial condensation of steam along the flow path causing the residual steam to be enriched in gas and depleted in oxygen-18.

The occurrence of this process was also described for the Larderello geothermal field in 1979. The zones of condensation at the field margins produced by this natural fluid circulation contain sub-commercial quantities of high-gas steam. As pressures decrease during production, the marginal steam is drawn into producing zones causing an increase in gas concentrations. This effect may produce similar results to the general decrease of steam from vaporized liquid.

The injection of condensate in the center of the field greatly increases heavy isotope (D and ^{18}O) contents of steam produced, in part, from vaporization of injectate. Injection has also lowered the content of gas in the center of the field, but this effect has been overshadowed by the 1987 general change in steam characteristics discussed below. Injection is the most reliable means of increasing steam pressure and flow, but only injection into superheated zones has been consistently successful.

The most important influence on steam compositions is the sudden decrease in 1987 of the amount of steam formed by vaporization of liquid water in the reservoir. This is most clearly seen in the change in the gas concentration of steam from individual wells. Before 1987, steam from most central wells contained less than 1000 ppmv, and wells at the eastern margin contained less than 3000 ppmv. From low values in early 1987, gas contents increased rapidly to maximum values in 1990 of 2 to 6 times as much. This change is also apparent in the increase in steam saturation (y values) after 1987. The decrease in vaporization of easily available liquid in the reservoir has caused rapid decreases in pressure and steam flow throughout most of The Geysers field. This observation has important consequences for the continued productivity of the entire field and deserves further study, possibly through mathematical simulation.

Relating the production history of The Geysers to assumed distributions of reservoir steam and liquid is difficult. Pressure could be maintained by producing steam from a large volume of interconnected fractures with minimal vaporization of liquid in each unit volume, or from a smaller production volume with extensive vaporization. Similarly, declining pressure could result from an increasing distance to the source of steam or from decreasing availability of nearby liquid.

The existence of well-defined chemical patterns inherited from the natural state in the long-exploited Larderello field, and in our data for the SE Geysers, suggests a local source of steam. Rather than the exhaustion of a distant homogeneous source, the recent accelerated decline in pressure and flow at The Geysers could thus have resulted from the local disappearance of liquid held in easily accessible sites -- liquid on surfaces of major fractures, in minor fractures opening upwards, and perched liquid in structural traps. Continued production is now from existing steam and vaporization of less accessible reservoir liquid (possibly in matrix blocks) as well as from injected water and from under-exploited areas at the reservoir margins.

Plans

In the next phase of this project, data for high-temperature steam from the Central California Power Agency (CCPA) area in the NW Geysers field will be studied. Preliminary comparisons with normal steam from the NCPA area (SE Geysers) indicate that: High-temperature steam is high in gas. The gas/steam ratios (in moles gas/mole steam $\times 10^4$) average 205 (range 14 to 7800) for CCPA steam and average 12 (range 1.4 to 119) for NCPA steam. Steam at CCPA is more uniform in composition than at NCPA. For example, all CCPA steam has $\text{H}_2 > \text{CH}_4$ whereas NCPA steam has about equal numbers of analyses with $\text{CH}_4 > \text{H}_2$ and $\text{H}_2 > \text{CH}_4$. HCl is not found at NCPA, but is present in significant amounts in high-temperature steam.

Compared to normal steam, high-temperature steam is high in CO_2 (average 69 mole % of dry gas

versus 53%), similar in H_2 (14.3% for both), low in H_2S (4.1% versus 6.6%) and NH_3 (4.6% versus 6.4%) and very low in CH_4 (6.5% versus 16.2%) and N_2 (1.6% versus 4.7%). High-temperature steam is enriched in heavy isotopes. Most high-temperature steam samples (at CCPA) range in $\delta^{18}O$ from -3 to +3‰ while most NCPA samples range from -8 to -4‰. Most CCPA samples range in δD from -55 to -38‰, while NCPA samples range from -57 to -47‰. Finally, gas equilibria calculations of steam saturation (y) values and temperatures differ greatly. NCPA calculations show temperatures ranging from about 210 to 260°C and y values ranging from about 1% to 2.5%. The same calculations for CCPA high-temperature steam indicate similar temperatures (about 220 to 250°C) but y values are generally above 75% and most points fall above the grid ($y > 100\%$).

The isotope data were interpreted in 1987 to indicate a connate or evolved seawater deep fluid, while later interpretations (1991 and 1993) suggest metamorphic or magmatic fluid, which might also explain the high total gas and HCl concentrations. The gas equilibria calculations may be affected by excess H_2 from corrosion of steel well casings. Similar high-temperature fluids may underlie much of The Geysers and further study is important to estimate future gas (and HCl) concentrations. Injection of liquid into the high-temperature reservoir will increase steam pressure and flow and probably decrease contents of HCl and total gases.

REFERENCES

Truesdell, A.H., 1991, The origin of high-temperature zones in vapor-dominated geothermal systems: Proceedings, 16th Workshop on Geothermal Reservoir Engineering, Stanford University, p. 15-20.

Truesdell, A. H., Eneedy, S. L., and Smith, J. L., 1993, Geochemical studies of reservoir processes in the NCPA field of The Geysers: Proceedings, 18th Workshop on Geothermal Reservoir Engineering, Stanford University (in press).

CONTACTS

DOE Program manager:

Marshall Reed
U.S. Department of Energy, CE-122
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

LBL Contract monitor:

Marcelo Lippmann
Earth Sciences Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720
Phone: (510) 486-5035
FAX: (510) 486-5686

Principal Investigator:

Alfred Truesdell
700 Hermosa Way
Menlo Park, CA 94025
Phone: (415) 322-6135
FAX: (415) 324-4009

SOLUBILITIES AND SPECIATION OF ALUMINUM

David J. Wesolowski and Donald A. Palmer
Chemistry Division, Oak Ridge National Laboratory

KEY WORDS

Aluminum, solubility, hydrolysis, complexation, thermodynamics, hydrothermal, porosity

PROJECT OBJECTIVE

The aim of this research is to determine quantitatively and unambiguously the monomeric speciation of aluminum in natural waters over a wide range of solution compositions and temperatures. This research is of significance to the development of geothermal resources because aluminum is one of the most common elements in reservoir minerals and is involved in many hydrothermal chemical reactions. This work will be of importance to geothermal operators in allowing them to predict the changes in reservoir permeability during production.

APPROACH

The thermodynamic properties at infinite dilution and the corresponding activity coefficients of the $\text{Al}(\text{OH})_3^{-y}$ ions, their formation constants, and their complexation by organic and inorganic ligands are obtained from solubility measurements, potentiometric titrations and spectroscopic techniques. Experimental studies have focussed on the solubility of gibbsite, $\text{Al}(\text{OH})_3$, and potentiometric measurements of the formation constants of $\text{Al}(\text{OH})_2^+$ over a wide range of temperatures and salinities.

This project benefits substantially from the program "Fundamental Geochemistry of Geothermal Systems" funded by the DOE Office of Basic Energy Science, Geoscience Program, in which more detailed, complementary studies are performed. This project is part of a program "Physical Chemistry of Geothermal Systems" at ORNL. The general objective of this program is to conduct laboratory experimental research utilizing unique facilities and expertise at ORNL for studies of selected chemical equilibria, thermodynamics of brine systems, liquid-vapor isotope distributions, volatilities, and other phase behavior. Results allow prediction of chemistry and permeability changes in reservoirs and in plant facilities involved in the extraction of geothermal energy, and provide fundamental experimental data needed as input for geochemical models.

PROJECT STATUS

Background

Aluminum is the third most abundant element in the Earth's crust, following, oxygen and silicon. The predominant rock and soil minerals are aluminosilicates. Many of the active processes of interest to geoscientists, such as weathering and soil formation, contaminant transport, and geothermal alteration, are influenced by fluid buffering and permeability changes due to interaction of aluminum silicates, oxides and hydroxides with circulating aqueous fluids. The permeability of reservoir rock is obviously an important constraint on geothermal energy production and the useful lifetime of the reservoir. Rock alteration processes sometime lead to volume changes with accompanying changes in permeability in the fluid flow paths.

Reliable geothermal models are needed for predicting these processes. The thermodynamic properties of many aluminous minerals are well known, but the aqueous chemistry of dissolved aluminum remains a controversial subject, due mainly to the slow kinetics of dissolution and precipitation of aluminous phases, the persistence of polymeric species in aqueous solutions to low total aluminum concentrations, and the extremely low equilibrium solubility of aluminum minerals at near-neutral pH.

The small radius and high charge of Al^{3+} cause it to undergo a variety of hydrolysis and complexation reactions in aqueous solutions which can alter its activity, and therefore solubility, by many orders of magnitude.

In natural systems, the total aluminum concentration in solution is limited by the solubility of aluminum oxides, hydroxides and silicates, and hence the monomeric species, $\text{Al}(\text{OH})_y^{3-y}$ with $y = 0$ to 4, and their complexes with common natural ligands, are the dominant aqueous aluminum species.

Research Results

The solubility of a carefully pre-treated sample of gibbsite has been measured as a function of pH and salinity at temperatures $< 100^\circ\text{C}$ where this phase is relatively stable. These studies provide virtually the only tool to determine the thermodynamic properties of the mononuclear aluminum ions in solutions, particularly in near-neutral solutions where the solubility is at a minimum (about 1 ppb at ambient conditions). The combined results determined independently in acidic, basic, and intermediate conditions, which were controlled by the use of buffering agents, provide for the first time a fully consistent description of aluminum speciation and thermodynamics. An additional series of potentiometric experiments provided yet further independent, but consistent, data on the formation of the first hydrolysis product, namely $\text{Al}(\text{OH})_2^+$ to 125°C . Finally, the interaction of the buffering agents with the aluminum ions in solution was measured independently by potentiometric, solubility and Raman spectroscopic methods, resulting in not only a quantifiable measure of the strength of these interactions, but also an insight into the structure of these species.

The solubility of gibbsite has been measured in a variety of solutions in: (1) the system $\text{Na}^+ - \text{K}^+ - \text{Cl}^- - \text{OH}^- - \text{Al}(\text{OH})_4^-$ from 6.4 to 80°C and 0.01 to 5.0 molal ionic strength; (2) the system $\text{Al}^{3+} - \text{H}^+ - \text{Na}^+ - \text{Cl}^-$ from 30 to 70°C and 0 to 5 molal NaCl ; and (3) pH buffer solutions (acetate, tris and bis-tris) at 50°C and 0.1 molal NaCl . The aluminum concentration in the experimental solutions was determined by ion chromatography and the H^+ and OH^- concentrations by in situ pH measurement.

The results have been coupled with the best available literature data and modeled using the Pitzer ion interaction treatment. An eight parameter expression for the molal concentration quotient of the reaction $\text{Al}(\text{OH})_4^- \rightleftharpoons \text{Al}(\text{OH})_{3(\text{cr})} + \text{OH}^-$ was derived by least-squares regression, which was also found to describe precisely the results in NaOH , $\text{NaOH} + \text{NaCl}$, KOH , and $\text{NaCl} + \text{KCl}$ media within the experimental error. This expression describes adequately (generally within ± 0.1 log units) the most reliable of the literature data on the solubility of gibbsite in NaOH and KOH media to 100°C and 20 molal ionic strength. From this expression, the equilibrium constant at infinite dilution, $\log K_4$, and the stoichiometric molal activity coefficient ratio, $\log(\gamma_{\text{OH}^-}/\gamma_{\text{Al}(\text{OH})_4^-})$, can be evaluated over the range 0 to 100°C and 0 to 12 molal ionic strength at 1 bar with a precision of approximately ± 0.02 log units.

The pure electrolyte parameters b_0 , b_1 and C_f for $\text{NaAl}(\text{OH})_4$ and $\text{KAl}(\text{OH})_4$, as well as the mixing parameters for aluminate ion with OH^- , $\text{OH}^- + \text{Na}^+$, and $\text{OH}^- + \text{K}^+$ were also obtained, which are now available for input into geochemical computer codes, such as EQ3/EQ6 and the Pitzer model as exemplified in the work of John Weare at the University of California, San Diego.

The equilibrium quotients for the reaction $\text{Al}(\text{OH})_{3(\text{cr})} + 3\text{H}^+ \rightleftharpoons \text{Al}^{3+} + 3\text{H}_2\text{O}$ were modeled using both an empirical equation incorporating the Debye-Huckel term and the Pitzer ion interaction treatment, which incorporated the relevant single electrolyte and mixing parameters currently available in the literature. In the latter treatment only four parameters, including Θ_{AlNa} , Ψ_{AlNaCl} and two terms describing the equilibrium constant at infinite dilution, were needed to fit the data well within the projected experimental error of ± 0.08 log units. Significantly, no evidence for aluminum chloride

complexation was found by comparing solubility experiments in the presence of varying concentrations of sodium trifluoromethanesulfonate and sodium chloride at 50°C and about five molal ionic strength.

In order to determine the step-wise formation constants of the aluminum hydroxide species, the solubility of gibbsite was studied in the near-neutral pH range in the presence of pH buffers at 50°C and 0.1 molal NaCl. The solubility results in acidic and basic solutions discussed above indicated equilibrium gibbsite solubilities lower than those reported in the literature by as much as 0.5 log units. Consequently, it was decided to duplicate the most comprehensive previous study, which employed acetate, bis-tris and tris organic pH buffers. The molal dissociation constant of acetic acid in NaCl brines at elevated temperatures was studied previously at ORNL, but similar information was not available for bis-tris (bishydroxyethyltrishydroxomethylmethane) and tris (trishydroxomethylmethane). Therefore, these dissociation quotients were determined in NaCl media to elevated temperatures, which was limited by the thermal stability of these species. After developing quantitative ion-chromatographic techniques for analyzing aqueous solutions containing several thousand to less than 1 part per billion total aluminum, we succeeded in measuring the solubility of gibbsite in these buffers. However, it was discovered that acetate and bis-tris strongly complex Al^{3+} and $\text{Al}(\text{OH})_4^-$, respectively; tris showed no observable tendency to interact with any of the aluminum species. Quantitative determination of the stability constants of these complexes by additional solubility, Raman spectroscopic and potentiometric measurements allowed corrections to be made for the presence of these complexes.

The hydrolysis of Al^{3+} to form $\text{Al}(\text{OH})_2^+$ in NaCl brines was studied by potentiometric titrations in the hydrogen-electrode concentration cell to temperatures of 150°C in 0 to 5 molal NaCl solutions. The experimental technique involved equilibrating solutions of HCl+NaCl under the same hydrogen pressure in the two compartments of the cell, which are fitted with matched Pt-H₂ electrodes and connected by a porous Teflon frit that serves as the liquid junction. A solution of HCl+AlCl₃+NaCl of the same ionic strength is added to the test compartment from a positive displacement pump. The titration was then conducted by the addition of a NaOH+NaCl solution at the matching ionic strength from a second pump. The concentration of Al^{3+} was maintained at $<5 \cdot 10^{-4}$ molal to minimize formation of multinuclear species, as well as suppressing precipitation. The molal formation quotient of the reaction $\text{Al}^{3+} + \text{H}_2\text{O} \rightleftharpoons \text{Al}(\text{OH})_2^+ + \text{H}^+$ was determined with a precision of ± 0.08 log units in 0.1, 0.3, and 1.0 molal NaCl to 125°C. These results are consistent with the gibbsite solubility measurements at 50°C and 0.1 molal ionic strength.

Plans

Bourcier and others in 1993 determined the solubility of boehmite from 150 to 250°C and the resulting equilibrium constants are in quantitative agreement with the earlier work of Kuyunko and others in 1983. However, the even more recent solubility results of Castet and others in 1993, in acidic and near-neutral solutions at 170 and 200°C, are nearly an order of magnitude lower than the hydrolysis constants derived from the two previous studies with the difference increasing at higher extrapolated temperatures. These three studies constitute the only substantial solubility work on any aluminum phase in the 100 to 350°C range in existence today. The results of our lower temperature ($<150^\circ\text{C}$) investigations completed thus far are consistent with the work of Castet and others in 1993. Modeling projections by Pokrovskii and Helgeson in 1993 yield calculated solubilities that are intermediate between the two sets of high temperature data. Thus the need exists to establish the actual speciation at these extreme conditions.

The major problem with traditional solubility studies is the control and computation of the pH at any given condition. It is our intention to circumvent this problem by measuring the pH in situ, hence also

negating the need for buffering agents which complex the $\text{Al}(\text{OH})_3^{-y}$ species even more strongly with increasing temperature. A large-capacity (1 liter), hydrogen-electrode, concentration cell has been constructed for this purpose. This new design includes provision for sampling the equilibrated solutions via inert plumbing. It is anticipated that the solubility of boehmite will be measured from about 150 to 300°C over a range of NaCl molalities. Aluminum concentrations will be measured using the recently-modernized ion chromatograph.

REFERENCES

Wesolowski, D. J., 1992, Aluminum speciation and equilibria in aqueous solution: I. The solubility of gibbsite in the system Na-K-Cl-OH- $\text{Al}(\text{OH})_3$ from 0-100°C: *Geochimica et Cosmochimica Acta*, v. 56, p. 1065-1092.

Palmer, D. A., and Wesolowski, D. J., 1992, Aluminum speciation and equilibria in aqueous solution: II. The solubility of gibbsite in acidic sodium chloride solutions from 30 to 70°C: *Geochimica et Cosmochimica Acta*, v. 56, p. 1093-1111.

Wesolowski, D. J., and Palmer, D. A., 1992, Experimental studies of aluminum solubility and speciation in brines: *Water-Rock Interaction*, (Y. K. Kharaka and A. S. Maest, eds.), Proceedings of the 7th International Symposium on Water-Rock Interaction, A. A. Balkema, Rotterdam, p. 185-188.

Palmer, D. A., and Wesolowski, D. J., Aluminum speciation and equilibria in aqueous solution. III. Potentiometric determination of the formation constants of $\text{Al}(\text{OH})_2^+$ in 0-5 m NaCl solutions from 25 to 125°C: *Geochimica et Cosmochimica Acta*, (in press).

Wesolowski, D. J., and Palmer, D. A., Aluminum speciation and equilibria in aqueous solution. V. The solubility of gibbsite at 50°C in 0.1 molal NaCl solutions at hydrogen ion concentrations ranging from 10^{-3} to 10^{-9} molal: *Geochimica et Cosmochimica Acta*, (submitted).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

David J. Wesolowski	Phone: (615) 574-6903
Donald A. Palmer	Phone: (615) 576-5109
Robert E. Mesmer	Phone: (615) 574-4958
Chemistry Division, Oak Ridge National Laboratory	
P.O. Box 2008	
Oak Ridge TN 37831-6110	
FAX: (615) 574-4961	

GEOCHEMICAL INVESTIGATION OF HYDROTHERMAL SYSTEMS AND GEOCHEMICAL ASPECTS OF GEOTHERMAL RESERVOIR DEPLETION

Cathy J. Janik and Robert H. Mariner
U. S. Geological Survey

KEY WORDS

Fluid geochemistry, Steamboat Springs, stable isotopes, dissolved gases, water analyses, fractured granite reservoirs

PROJECT OBJECTIVE

The objective is to study changes in chemical and isotopic characteristics of reservoir fluids resulting from development of moderate- and high-temperature geothermal systems in fractured granitic rock. High-temperature geothermal systems in granitic rock have been drilled and produced for power generation at Steamboat Springs, Nevada; Coso Hot Springs, California; and Roosevelt Hot Springs, Utah. We will initially study the Steamboat Springs system because it is an expanding development and is the most accessible of the three sites. This study in cooperation with operating companies at Steamboat Springs will enhance the understanding of the granitic-hosted geothermal system and will benefit the development and management of the resource.

APPROACH

We will obtain high quality chemical and isotopic data on thermal waters and gases discharged from both deep geothermal wells and shallow groundwater wells. Periodic sample collection from a representative array of wells will be used to document changes in fluid characteristics with time and stress. Field operators will provide the physical data necessary for interpretation of reservoir conditions. Chemical and isotopic compositions of the thermal fluids will be used to determine origins of constituents, reservoir properties, fluid flow paths, and fluid-rock interaction. We will develop a geochemical model for the system, and use this model to detect changes in the system brought about by production and injection.

PROJECT STATUS

Background

Steamboat Springs is one of the classic geothermal areas in the United States due principally to the pioneering investigations of Don White in the 1950s and 1960s. Early in 1987, 3 wells began producing fluids for a 7-MW binary power plant north of Steamboat Hills. Early in 1988, a single-flash, 12-MW, steam power plant began operations with 3 wells in the Steamboat Hills. Today, there are still only 3 production wells in the high temperature ($>210^{\circ}\text{C}$) part of the system near the upflow zone, but 12 production wells are now producing moderate temperature (175°C) water from the outflow plume. Although some basic chemical data is being collected by the operators, no comprehensive chemical, isotopic, and gas composition data were collected prior to our November 1991 sampling, and an integrated geothermal model for the system has not been developed. Cooled fluids are injected at both well fields, but geysers and hot springs issuing from sinter terraces north and east of the Steamboat Hills have not been active since 1988. Declining water levels in spring vents may be related to geothermal development, a multi-year drought (1987 to 1992), and increased pumping of ground water for domestic and irrigation uses.

Research Results

All production wells have been sampled twice (November, 1991 and January, 1993), but analyses are complete only for the November, 1991 samples. The deep reservoir fluid is a slightly saline Na-Cl

(~750 mg/L Cl) water of near neutral pH. Conservative constituent ratios (Cl/Br) are constant from the high temperature geothermal wells (>210°C) to the slightly thermal (25 to 50°C) domestic wells in the outflow plume. Fluids from the moderate temperature part of the system (175°C) contain slightly less potassium, silica, and arsenic but more chloride, sodium, calcium, magnesium, and strontium than the higher temperature (>210°C) fluids. These differences are consistent with boiling of the high temperature fluid followed by partial re-equilibration with rock at lower temperatures. Preliminary dissolved gas data indicates that boiling occurs between the high temperature and moderate temperature parts of the system. Steam from this boiling has apparently heated the groundwater tapped by at least one of the shallow domestic wells because the water in this well has excess enthalpy for the amount of dissolved chloride.

Plans

To better monitor the reservoir processes and changes in the Steamboat Springs field, we will begin a semi-annual sampling routine with additional samples collected whenever new wells are brought on line. In addition to our basic samples for chemical and isotopic characterization of thermal fluids, we will (1) obtain isotopic data for Sr, B, Li, and perhaps Pb to help determine the rock types through which the thermal fluids have circulated; (2) sample a large region in the probable recharge area for stable isotopes of precipitation to establish probable recharge areas; and (3) determine ^{129}I and ^{36}Cl in the thermal waters to estimate maximum residence times of water in the Steamboat Springs geothermal system. This array of new data will be combined with data available in the literature to build a geochemical model of the system. This new model will be compared and contrasted with the previously suggested models which were based solely on basic chemical and isotopic data from thermal springs and shallow wells. Other high-temperature geothermal systems in granitic terrain will be similarly studied to ascertain what is characteristic of these systems as a type and what is unique to the individual systems.

CONTACTS

DOE Program Manager

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C., 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators

Cathy J. Janik
U.S. Geological Survey, Mail Stop 910
345 Middlefield Road
Menlo Park, CA 94025
Phone: (415) 329-5213
FAX: (415) 329-5203

Robert H. Mariner
U.S. Geological Survey, Mail Stop 434
345 Middlefield Road
Menlo Park, CA 94025
Phone: (415) 329-4507
FAX: (415) 329-4538

**BRINE (SOLUTION, SOLID, GAS PHASES) MODELING PROGRAM:
ADVANCED TECHNOLOGY TO AID IN THE ECONOMICAL DEVELOPMENT
OF GEOTHERMAL RESOURCES**

Nancy Møller, John H. Weare, Zhenhao Duan, and Jerry P. Greenberg
Chemistry Department, University of California at San Diego

KEY WORDS

Brine, gases, computer models, reservoir studies, scaling, rock-water interactions, simulation, thermodynamic data, Ph, high temperature, breakout, phase transitions

PROJECT OBJECTIVE

The objective of this program is to improve the productivity of geothermal resources by providing modeling tools for predicting and mitigating chemical problems associated with the extraction of energy from geothermal brines. These easily accessible models will provide reliable predictions of the chemical behavior of the resource (potential for scaling and gas breakout) under arbitrary conditions, thereby providing operators, engineers, and designers with the ability to rapidly analyze potential problems and to test strategies for problem abatement and resource enhancement. Our project objective also includes effective communication with the geothermal industry in order to exchange ideas and transfer technology.

APPROACH

In order to make predictions with the required precision for geothermal applications (see Table 1), it is necessary to have highly accurate models of the chemical behavior of the working fluids. Using recent developments in the physical chemistry of fluids and gases, we have shown that with proper attention to the parameterization we can develop models that accurately reproduce the measured laboratory behavior of brines, the solubility and liquid/vapor coexistence of gases, and other thermodynamic properties (such as heat content). The models have been applied to well determined production situations with remarkable success.

Table 1. USES OF A BRINE SIMULATION MODEL	
Exploration	Predict Scale Formation Predict Gas Behavior Determine Formation Water Characteristics Predict Recoverable Energy Predict History and Evolution of Resource
Plant Design and Operation	Predict Scale Formation Predict Phase Separation Simulate Chemical Treatments Test Energy Optimization Strategies Test Ways to Minimize Operations Costs Support Laboratory Simulations
Waste Treatment	Simulate Mineral Recovery Strategies Predict Environmental Hazards Simulate Reinjection Strategies

Our brine models handle the special problems of phase equilibrium predictions in complex mixtures, introduce a relatively low number of parameters, and are highly accurate and flexible. Our gas modeling approach utilizes a newly developed empirical equation which can reproduce PVT (pressure, volume, temperature) properties in both the liquid and gas phases, liquid/vapor coexistence, and other useful thermodynamic functions.

As the models are developed, they are included in a user-friendly application package called GEOTHERM which can be loaded from diskettes to PCs or Mackintosh computers. Annual workshops are given in the use of these programs to treat problems of interest to the geothermal community. An instruction manual is available.

PROJECT STATUS

Background

Many of the most significant problems limiting the economical development of geothermal power are related to the chemical properties of the high temperature and high pressure brines from which the energy is extracted. The properties of these fluids are very difficult to predict. However, if the system is near equilibrium, the properties can be calculated from the free energy, G . This is commonly written in terms of the chemical potential, μ_i , of the species i as:

$$G = \sum_i \mu_i n_i$$

where n_i is the number of moles of i . For brines, the chemical potential of each species is a complex function of the concentration of all the species in a phase. It also depends on the temperature and weakly on the pressure. For gas phases, μ_i is a rapidly varying function of the pressure. By minimizing G , subject to mass and charge balance constraints, the distribution of solids, gases, and liquid phase species can be predicted.

We have developed highly accurate phenomenological equations giving the behavior of gas, liquid, and solid phase chemical potentials. These equations are soundly based on theoretical results but contain a number of parameters that must be established from binary and ternary experimental data. This is a difficult problem, but once the parameters have been evaluated the models can be applied to the much more complicated systems common in the geothermal energy production industry. We have demonstrated that these equations can accurately describe complex brine behavior to high concentration and high temperature (0 to 250°C). Our gas phase models accurately predict behavior in the system $\text{CH}_4\text{-CO}_2\text{-H}_2\text{O}$ from 50 to 1000°C and from 0 to 1000 bars. We emphasize that for chemical models to be useful for geothermal applications they must be both highly flexible (able to treat wide ranges of variables) and highly accurate. We believe that the GEOTHERM programs are the only models presently available that meet these demanding criteria.

Research Results

The capabilities of the geothermal brine models we have developed to date are summarized in Table 2. These models will predict saturation ratios, scaling behavior, pH, formation porosity changes and gas breakout (gas separation) in production wells, throughout various brine flow and heat extraction systems and during the reinjection process.

Parameterization of the $\text{CaCO}_3\text{-SiO}_2\text{-CaSO}_4\text{-NaCl-CO}_2\text{-H}_2\text{-H}_2\text{O}$ system and of the seawater system, $\text{Na-K-Ca-Mg-Cl-SO}_4\text{-H}_2\text{O}$, is complete to high temperature (0 to 250°C) and to high ionic strength. These models will treat all the major components of seawater-type brines in addition to the important carbonate, sulfate, and silica scale-forming minerals and CO_2 solubility. A preliminary model of the

important $\text{H}_2\text{S}-\text{H}_2\text{O}$ system has been prepared for the 0 to 90°C temperature range (0 to 60 bars). When a model of the $\text{H}_2\text{S}-\text{NaCl}-\text{H}_2\text{O}$ system is complete to high temperature (T_{max} will depend on data availability) we will be able to begin the development of models of sulfide scale formation.

Model calculations compare remarkably well with both laboratory and field data. Our models typically retain the reliability of the experimental data on which they are based. For example, the present calcite and silica scaling model predicts all the laboratory data we could find for calcite, amorphous silica, and CO_2 solubility for a temperature range from 0 to 250°C within the accuracy of the measurements. Therefore, our models provide an effective means of summarizing, comparing, and validating the brine chemistry data presently available. They also provide a reliable standard of comparison for both field and laboratory measurements being collected in programs supported by DOE and other agencies.

Table 2. PROJECT PROGRESS: CAPABILITIES OF PRESENT MODELS

- ▶ Predict Behavior of Calcium Carbonate Scale Formation in NaCl and CaCl_2 Brines for $T = 0$ to 250°C (PC version available)
- ▶ Predict Solubility of CO_2 and CH_4 in NaCl Brines for $T = 0$ to 250°C (PC version available)
- ▶ Predict Solubility of Amorphous Silica Scale in Brines for $T = 0$ to 250°C
- ▶ Predict Solubilities of Scaling Minerals (Gypsum, Anhydrite, etc.) to 250°C
- ▶ Calculate Precipitation Characteristics of Rock-Water Systems Containing Na, K, Ca, Mg, Cl, and SO_4 for $T = 0$ to 250°C
- ▶ Predict Onset of Two Phase Behavior (Gas Breakout) in NaCl Brines
- ▶ Predict Solubility of Hydrogen Sulfide ($\text{H}_2\text{O}-\text{H}_2\text{S}-\text{HS}^-$) System (0 to 90°C; 0 to 60 bars)
- ▶ Predict Partial Fugacity in Mixed Gas System ($\text{CO}_2-\text{CH}_4-\text{H}_2\text{O}$) $T = 0$ to 1000°C and $P = 0$ to 1000 bars
- ▶ Predict Gas-Liquid Equilibrium in the $\text{CO}_2-\text{CH}_4-\text{H}_2\text{O}$ System

Our equation of state for the $\text{CH}_4-\text{CO}_2-\text{H}_2\text{O}$ system can predict behavior from the two phase (liquid and gas) region to the homogeneous region. We consider this to be a breakthrough in thermodynamic modeling of natural processes. We have shown that our new technology (equation of state and mixing rules) allows us to successfully model the behavior of gas-liquid systems of the compositions associated with geothermal operations as a function of temperature (0 to 1000°C) and pressure (0 to 1000 bars). This model can simulate both the single and two phase behavior of gas mixtures within experimental accuracy. We can use these models to improve predictions of gas breakout in highly pressurized formations. These models will also be used for predicting reservoir performance characteristics via fluid inclusion studies.

As an illustration of the application of the models, we consider an analysis of a geothermal well 23-5 in the Steamboat Springs geothermal field from work done in collaboration with Ted DeRocher of Yankee-Caithness. The fluids in this system contain an average of 3183 ppm CO_2 . Using the GEOFLUIDS gas solubility model in the GEOTHERM package, we can calculate the breakout pressure as a function of pressure. This is plotted in Fig. 1 below.

Plotted on the same figure are the measured temperature and pressure profiles for this well. When the curve giving the breakout pressure of the fluid crosses the well pressure curve, the working fluid will boil (boiling depth). Again using GEOFLUIDS, we can calculate the composition of the gas released in the boiling process. We find that it is very rich in CO_2 (roughly 0.3 mole fraction). With this loss

Figure 1. Calculated scaling characteristics of Steamboat Springs geothermal well 23-5 (see text for explanation).

of CO₂, the system rapidly supersaturates with respect to carbonate minerals. The saturation ratio (SR) of these minerals is calculated with TEQUIL, another program included in GEOTHERM. The results are also plotted in the figure. A mineral in equilibrium with the well water would have a saturation ratio very near 1.0. When saturation ratios reach 8 to 10, calcite scale forms. We see that scaling should occur in this well at approximately 1800 ft. This prediction is very close to the actual appearance of scale in the well (see asterisk in Figure 1). Using the model, other important quantities such as the gas/liquid ratio and the amount of scale can also be calculated.

Plans

Our goal is to complete a comprehensive brine model which will predict scaling (gypsum-anhydrite, carbonate, silica, metal sulfides) and acid-base characteristics in the system, H-Na-K-Ca-Mg-Al-Cl-HSO₄-SO₄-HS-HCO₃-CO₃-SiO₂, as a function of brine composition, ionic strength, pH, P_{CO2} and temperature (to 250°C). We plan to extend the carbonate scaling models into the carbonate-rich region (high pH) to 250°C as data allow. Inclusion of aluminum species in the models will greatly broaden their application to reservoir studies by bringing in the aluminosilicate minerals. Pressure effects on scale solubilities (to P ≈ 400 bars and above, as data allow) will be included in the model. After the model is completed to 250°C, the model will be parameterized to predict the near critical behavior of brines.

We will continue to add important gases to the GEOFLUIDS programs. We have already initiated efforts to improve gas/liquid predictions in ternary and higher order systems. We will continue to apply our models to geothermal problems and to promote the transfer of our technology to the geothermal energy community.

REFERENCES

- Duan, Z., Møller, N., and Weare, J. H., 1992, An equation of state for the CH₄-CO₂-H₂O system. I. Pure systems from 0 to 1000°C and 0 to 8000 bar: *Geochimica et Cosmochimica Acta*, v. 56, p. 2605-2617.
- Duan, Z., Møller, N., and Weare, J. H., 1992, An equation of state for the CH₄-CO₂-H₂O system. II. Mixtures from 50 to 1000°C and 0 to 1000 bar: *Geochimica et Cosmochimica Acta*, v. 56, p. 2619-2631.
- Greenberg, J. P., and Møller, N., 1989, The prediction of mineral solubilities in natural waters: A chemical equilibrium model for the Na-K-Ca-Cl-SO₄-H₂O system from 0° to 250°C: *Geochimica et Cosmochimica Acta*, v. 53, p. 2503-2518.

CONTACTS

DOE Program Managers:

Marshall Reed	Phone: (202) 586-8076
Gladys Hooper	Phone: (202) 586-1146
Geothermal Division, CE-122	
U. S. Department of Energy	
Washington, DC 20585	
FAX: (202) 586-5124	

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigators:

Nancy Möller	Phone: (619) 534-6374
John Weare	Phone: (619) 534-3286
Chemistry Department	
University of California at San Diego	
La Jolla, CA 92093	
FAX: (619) 534-7244	

INVESTIGATION OF MATRIX POROSITY IN THE GEYSERS RESERVOIR

Dennis L. Nielson
University of Utah Research Institute

KEY WORDS

Adsorption, The Geysers, image analysis, matrix porosity

PROJECT OBJECTIVE

Adsorption is potentially an important consideration when calculating reserves at The Geysers. The objective of this project is to calculate adsorbed fluid reserves using image analysis techniques. This research is important to development of conceptual models of geothermal systems and to simulation of reservoir processes.

APPROACH

In order to quantify porosity distribution and surface area available for adsorption, scanning electron microscope (SEM) images were analyzed using software developed for the interpretation of satellite imagery. This software classifies the images as either crystal or pore along scan lines and then accumulates data on pore size, total porosity and surface area of the mineral-pore interface.

We have used two different techniques to characterize porosity. The first is scanning electron microscopy (SEM) which has been used to image the mineral-void relationships inside pores. It has the advantage of not disturbing the fine textural features while being capable of high magnification. Measurement of the distribution of pores within a sample has utilized a technique known as "laser scanning confocal microscopy" (LSCM). The application of this technique requires that the sample be injected with an epoxy doped with a fluorescent dye. LSCM utilizes a laser to focus at different layers of the sample, allowing three-dimensional imaging of the pores. A convenient aspect of LSCM is that the data are recorded digitally. The remainder of this paper will discuss only the analysis of SEM images of pore interiors, the features we consider most important in determining the volume of water that could be adsorbed.

PROJECT STATUS

Background

SEM and thin-section examination of the rock matrix shows that porosity is generally not present along the margins of the original sedimentary grains. This is an important distinction between The Geysers reservoir and conventional silici-clastic hydrocarbon reservoirs. The observation of complex textures in core samples suggests that porosity measurements on core only partially describe the relationships necessary to understand reservoir storage. The pore size, size distribution and surface areas of minerals should influence adsorption and capillarity. We have based our measurements of pore characteristics on the interpretation methods described in Krohn and Thompson in 1986. We have improved upon their image analysis techniques to enable calculations of surface area as well as pore volume.

Research Results

Digital image processing of SEM data was approached as a micro-scale remote sensing and geographic information system (GIS) problem. This consisted of digitizing SEM images to incorporate 256 gray-scale levels to be used in the classification of pore space by albedo. Classifications were made by digitally overlaying GIS files, consisting of maps of the gray-scale images quantified by albedo, onto

the original gray-scale images. Details of the image analysis procedures are given in the report of Nielson and others in 1993.

Image processing was used to determine pore-space area, pore-space perimeter, solid-mineral area, the total adsorption area of the interface between the pore spaces and solid mineral, and the total length of the pixels in the image. Figure 1 is a processed image showing solid mineral as stippled, pore space as black, and an adsorbed water layer as white. At this scale, the adsorbed phase is one pixel thick which is equivalent to 7575 Angstroms.

Void space within calcite-dissolution vugs is logarithmically distributed with the greatest volume represented by the lower chord lengths. Figure 2 shows the volume percent as a function of chord length for a sample from well Prati State 12.

The objective of this exercise is to estimate the potential liquid reserves due to adsorption. Image analysis provides a measurement of the lengths of chords that traverse pore space and the length of the boundary between the solid and pore. Relative volume calculations of the percent adsorbed fluid assume that the images represented slices of rock that are the thickness of the adsorbed layer. It is also assumed that the total pore space is filled with water resulting in a simple two phase water-adsorbed water relationship. The calculated relative volume of adsorbed water is a function of the magnification of the image. The calculated volume percents were plotted against magnification and then extrapolated to 0. It was found that the actinolite-filled pores had a slightly higher adsorption capacity than epidote-filled pores. The actinolite assemblages supported a 0.005% volume adsorption at an assumed adsorption thickness of 10 Angstroms, 0.05% at 100 Angstroms, and 2.5% at 5300 Angstroms.

The conclusions from the present work are:

- 1) Image analysis provides a means for independently measuring porosity distribution and the surface area available for fluid adsorption.
- 2) Estimates of reserves, using the approach presented here, are highly dependent on the assumed thickness of the adsorbed layer. These data have apparently not been collected for the mineral phases of importance in The Geysers reservoir.
- 3) The proportion of total water adsorbed to mineral surfaces is small and would not seem to be important in the calculation of total reserves unless extraordinary adsorption thicknesses are present.

Plans

The research described above will be extended to develop further generalizations regarding the contribution of adsorbed fluids to reserves.

REFERENCES

Nielson, D. L., Nash, G., Hulen, J. B., and Tripp, A. C., 1993, Core image analysis of matrix porosity in The Geysers reservoir: Proceedings, 18th Workshop on Geothermal Reservoir Engineering, Stanford University, (in press).

Adsorption Interface
  Solid Mineral
  Pore Space

Figure 1. Processed SEM image showing an adsorbed water layer as white.

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Figure 2. Volume percent void space as a function of chord length for a sample from well Prati State 12.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Dennis L. Nielson
University of Utah Research Institute
391-C Chipeta Way
Salt Lake City, Utah 84108
Phone: (801) 584-4438
FAX: (801) 584-4453

EXPERIMENTAL STUDY OF WATER ADSORPTION ON GEYSERS RESERVOIR ROCKS

Shubo Shang, Roland N. Home, and Henry J. Ramey Jr.
Department of Petroleum Engineering, Stanford University

KEY WORDS

Water vapor, reservoir rock, adsorption, desorption, capillary condensation, hysteresis

PROJECT OBJECTIVE

The objective of the project is to measure water vapor adsorption and desorption on Geysers reservoir rocks to be able to make better reserve estimations and reservoir performance predictions. This research is of major importance to operation of The Geysers geothermal field in the prediction of the sustainable energy production. Field operators must know the role of desorption in the production of steam at present field pressures.

APPROACH

The approach being taken on this project is to establish a reliable experimental procedure to measure the quantity of water adsorbed and desorbed for various types of reservoir rock. An automatic sorptometer was ordered to our specifications to conduct the necessary measurements. Once a reliable procedure is designed and tested and the sorptometer is fully working, the routine measurements of water adsorption and desorption on different reservoir rocks will be performed.

PROJECT STATUS

Background

In vapor-dominated geothermal systems, Donald White, in 1973, proposed that water might exist as adsorbed liquid in micropores in the reservoir. Evidence from both laboratory studies and field data indicates that storage of liquid as micropore fluid is likely. Measurement of adsorption and desorption of water vapor is clearly a crucial step in determining whether adsorption is a significant storage mechanism for these systems. If adsorption is important, we must reevaluate the calculated reserves for reservoirs like The Geysers and find a better method for performance prediction.

The PMI Automated Sorptometer employed in this work is the first commercial apparatus of its kind on the market, and it has had some problems in both software and hardware operation. Considerable time was spent to identify the major software problems, and different versions of the PMI software have been tested. We started running adsorption and desorption tests when there appeared to be no major bugs remaining in the control program, and we obtained some results. However, we were not able to run tests at high temperatures, and the adsorption data we recorded at high relative pressures appeared to be unreasonably high. This set of questionable results led us to check the hardware. Surprisingly, we found that the system is not isothermal as the manufacturer claimed, and a cold spot in the system caused the problems we observed. We are now working on the hardware to improve the heating system to obtain isothermal conditions.

Research Results

Three rock samples have been analyzed initially, shallow reservoir core for The Geysers, Berea sandstone, and core from Monteverdi well #2 in Italy. These tests were performed at temperatures between 80 and 140°C. Due to the heating problem mentioned above, we decide to discard those tests conducted at higher relative pressures, particularly for higher temperatures. Our test results show that the initial condition of the rock surface has an influence on the amount of water adsorbed. This

implies the presence of a weak chemical interaction of the water molecules with rock surfaces, and suggests that water adsorption and desorption isotherms in reservoir rocks are rock-material dependent. This type of chemisorption of water on various materials was documented by Gregg and Sing in 1982, even at room temperature.

Adsorption and desorption hysteresis were observed on the three rock samples at all the temperatures tested. The low pressure hysteresis is caused, at least in part, by weak chemisorption. High pressure hysteresis is the result of structural heterogeneity of the reservoir rocks. Understanding the hysteresis phenomena is important to the reinjection process since the desorption isotherm is directly related to steam production in geothermal reservoirs.

At low relative pressures, adsorption dominates the process of water retention on reservoir rocks, and the amount of water adsorbed can be approximated by a linear function of relative pressure for all three samples. However, the linear relationship breaks down as pressure increases, and the amount of water adsorbed increases rapidly with pressure. This rapid increase in adsorption occurs at different pressures depending on the temperature and rock sample. The change in the shape of the adsorption isotherms is an indication that capillary condensation takes place, and its contribution to total water retention on the reservoir rock becomes more significant as pressure is further increased.

The magnitude of water adsorption is affected by temperature, and the effect of temperature is found to be sample dependent. The reason for the different temperature dependence is not yet clear to us.

Plans

Much work needs to be done to the experimental equipment in order to measure the amount of water adsorbed and desorbed at higher relative pressure. Once the heating system is working properly, we will concentrate on running such tests. We will continue to investigate the possibility of modifying the existing equipment to run adsorption tests at temperatures higher than 140°C. We have the possibility of working at higher temperatures with both the PMI sorptometer and with older manually-operated equipment in our laboratory. We plan further sets of measurements to test the effect of temperature on adsorption. Ultimately, we want to be able to simulate geothermal field conditions as closely as possible.

Apart from The Geysers reservoir rock, we will run adsorption and desorption tests on a range of reservoir samples. This will provide us a better understanding of the adsorption process.

There is an obvious need to develop a model to describe the adsorption - capillary condensation process. Work on this subject is in progress.

REFERENCES

Ramey, H. J., Jr., 1990, Adsorption in Vapor-Dominated Systems: DOE Geothermal Program Review VIII, April, San Francisco, CA.

CONTACTS

DOE Program Manager:

Marshall Reed

U. S. Department of Energy, CE-122

Washington, D.C. 20585

Phone: (202) 586-8076

FAX: (202) 586-5124

Principal Investigators:

Henry J. Ramey, Jr.	Phone: (415) 723-1774
Roland N. Home	Phone: (415) 723-9595
Shubo Shang	Phone: (415) 723-4745
Department of Petroleum Engineering	
Stanford University	
Stanford, CA 94305-2220	
FAX: (415) 725-2099	

MECHANICAL PROPERTIES OF GEYSERS ROCKS

Brian P. Bonner
Lawrence Livermore National Laboratory

KEY WORDS

Seismic Interpretation, fluid content, fluid migration

PROJECT OBJECTIVE

Basic rock properties data, in particular the propagation velocity and attenuation for compressional and shear waves, must be known in order to derive the most information from seismic images currently being produced at The Geysers. The overall objective of this project is to calibrate field seismic measurements in The Geysers to monitor fluid movement and changes in saturation. As part of this objective, we will measure the "seismic" properties of Geysers rocks in the laboratory to determine the relevance of previous laboratory measurements to field studies at The Geysers. Also, we will determine the effect of fractures on shear velocity and attenuation in Geysers samples. Our longer term goal is to determine if the dramatic effect of the water-steam transition (previously observed at ultrasonic frequencies) occurs at seismic frequencies in the laboratory.

APPROACH

Measurements are made with a combination of traditional high frequency methods for determining elastic properties and new low frequency methods. High frequency measurements are based on propagation of ultrasonic waves and will be done by a DOE contractor, New England Research (NER). The low frequency measurements are underway at Lawrence Livermore National Laboratory (LLNL) using a torsional oscillator which operates at seismic frequencies.

PROJECT STATUS

Background

Previous laboratory work for sandstone and granite at ultrasonic frequencies demonstrated that wave velocity and attenuation are sensitive to fluid saturation for reservoir conditions simulated in the laboratory. Although this result can be applied to the field in a qualitative way, the measurements were made at frequencies nearly six orders of magnitude higher than typical seismic frequencies and for rocks that are very different from the graywackes and felsites present at The Geysers. Recent improvements in laboratory capabilities make velocity and attenuation measurements possible at seismic frequencies and core from well NEGU-17 is available for determining the properties of Franciscan graywacke recovered from reservoir depth.

Research Results

Initial measurements of shear attenuation for Geysers graywacke from NEGU-17 between 1 and 20 Hz indicate that the attenuation for the matrix (the sample tested was free of healed fractures and large vugs) has much lower attenuation than expected from inversions of pulse rise times of p-waves (compressional seismic waves) from microearthquake sources. Attenuation (Q_s^{-1}) ranges from 1.5 to 2×10^{-3} (Q_s ranges from ~660 to 500), an unusually low value for crustal rock. The usual ratio of compressional to shear attenuation is 2 to 3, so Q_p for the graywacke would range from 200 to 300. This sample was tested in air at ambient pressure and temperature, but its microstructure suggests that the attenuation will not increase at reservoir conditions to near that required by the field data without additional damping caused either by fractures or by the water-steam transition. This preliminary measurement reinforces the hypothesis that fractures, which range in stiffness from healed to open, control the observed attenuation. Fractures in situ contribute to observed attenuation in two ways.

Either the intrinsic attenuation of the rock mass is increased by providing additional sites for energy loss, or scattering from the discontinuities occurs. It is possible in principle to separate these effects in field data by determining the frequency dependence of the attenuation. These preliminary measurements illustrate the value of laboratory measurements of mechanical properties for seismic interpretations. Further measurements, leading systematically to observations of the effects of the steam transition at low frequencies, are now underway.

Plans

A. Geysers reservoir rock:

Further laboratory measurements are planned to determine the effect of confining pressure on ultrasonic shear and compressional velocity; these tests will determine the stiffness of grain contacts and enable us to predict the change in velocity and attenuation at low frequency. Additional laboratory experiments are planned to directly determine the effect of fluid saturation on velocity and attenuation at seismic frequencies and to measure shear velocity and attenuation for fractured samples at low frequency. These tasks will be shared between LLNL and NER. When these basic measurements are complete, new low frequency experiments will be undertaken to measure the effects of the water-steam transition at reservoir conditions. Reliable estimates of fluid saturation are needed to predict the lifetime of The Geysers reservoir. A core hole to sample continuously into the reservoir is now being planned. We are investigating laboratory simulations of the process of core recovery from depth to determine if measurements of water content for recovered material will provide useful information about fluid storage in the reservoir.

B. Additional measurements:

An expanded geothermal program would allow us to extend laboratory "seismic" measurements to higher temperatures and pressures, up to and surpassing the onset of melting. Basic research on fluid flow in fractures now underway at LLNL could easily be adapted to address problems of geothermal interest. For example, we have recently demonstrated that slight offsets (fractions of a millimeter) can prop open a tensile fracture in granite even at depths of ~5 km. Future plans include a experimental and calculational study of the joint healing that occurs when a reactive fluid flows through the fracture. A verified model of reactive flow in fractures, including both dissolution and deposition, would be useful in predicting performance of geothermal resources.

REFERENCES

Bonner, Brian P., and Wanamaker, B. J., 1991, Acoustic nonlinearities produced by a single macroscopic fracture in granite: Review of Progress in Quantitative Nondestructive Evaluation, v. 10B, p. 1861-1867.

CONTACTS

DOE Program Manager:

Marshall Reed
U. S. Department of Energy, CE-122
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Brian P. Bonner

Phone: (510) 422-7080

FAX: (510) 423-1057

Paul W. Kasameyer

Phone: (510) 422-6487

FAX: (510) 422-3925

Mail Code, L-200

Lawrence Livermore National Laboratory

Livermore, CA 94550

GEOLOGY AND HYDROTHERMAL ALTERATION OF FELSIC PLUTONIC ROCKS AT THE GEYSERS STEAM FIELD, CALIFORNIA

Jeffrey B. Hulen and Dennis L. Nielson
University of Utah Research Institute

KEY WORDS

The Geysers, geology, felsite, pluton, magmatic, hydrothermal alteration, porosity, brecciation, fracturing

PROJECT OBJECTIVE

The Geysers steam field has recently been experiencing pressure declines and local generation of corrosive, acidic steam. A clearer understanding of the variables leading to these problems will help enable steam field operators to maximize present production while improving the odds of extending the limits of the resource through cost-effective exploration. This research addresses, (1) the nature, evolution, and geometry of the field's secondary porosity, and (2) the hydrothermal history of the field's host rocks and heat sources, through detailed investigation of lithology, geochemistry, hydrothermal alteration, and geochronology of the field's wholly-concealed, hypabyssal intrusive complex -- the felsite. In view of the clear connection between the felsite and ongoing geothermal activity at The Geysers, it is likely that improved understanding of the pluton and its effects will be useful in exploitation of existing reserves and exploration for additional resource.

APPROACH

To accomplish the objectives outlined above, we are applying a diverse array of geological and geochemical techniques of proven value in characterizing high-temperature hydrothermal systems as well as igneous intrusive bodies. We have acquired from the steamfield operators cuttings from 27 wells penetrating the felsite and the overlying 100 m of its contact-metamorphic halo; these samples representing more than 20 kilometers of drilling. These are logged in detail, with emphasis on lithology, hydrothermal alteration, and secondary mineralization, with appropriate support from petrographic, x-ray diffraction (XRD), scanning electron microscope (SEM), geochemical, and electron-microprobe analysis. J. N. Moore of UURI is completing complementary fluid-inclusion studies, and G. B. Dalrymple of the USGS is age-dating representative felsite samples utilizing precise $^{40}\text{Ar}/^{39}\text{Ar}$ methods. The resulting data are being plotted as a series of maps and cross sections designed for correlation with the field's variable production volumes and characteristics.

PROJECT STATUS

Background

The Geysers steam field occupies fractured intrusive and metamorphic rocks which once hosted a convective, high-temperature, liquid-dominated hydrothermal system. It is likely that this hot-water system immediately preceded modern vapor-dominant conditions, gradually "drying out" for reasons still not fully understood. The heat sources for both liquid- and subsequent vapor-dominated phases of The Geysers geothermal system have almost certainly been individual intrusions in the felsite (Figure 1A). The modern steam field forms an expanded envelope coaxial with the felsite, and key assemblages of high-temperature hydrothermal minerals show systematic vertical zonation with respect to the intrusive. Moreover, much of the field's porosity was apparently excavated by hydrothermal carbonate-dissolution within Franciscan (late Mesozoic) metagraywackes mantling the pluton (reported by Hulen and others in 1992, and Nielson and others in 1993). The potential leaching agents include mildly acidic fluids expelled from or heated by the felsite.

Research Results

Our Geysers felsite research to date has shown that the pluton is not homogeneous but rather a composite igneous body with great vertical and lateral variation in both rock type and hydrothermal alteration effects. Petrographic and geochemical studies have led to identification of three and possibly four major intrusive rock types at the top of the felsite (Figure 1B). Forming the northwest-trending "spine" of the felsite is leucocratic biotite microgranite porphyry -- a "quartz porphyry" -- containing prominent, rounded and embayed quartz phenocrysts embedded in a granophyric to micrographic groundmass. This rock contains 76 to 78% SiO_2 , and grades to the northwest into a chemically identical, leucocratic biotite microgranite. The microgranite could also be locally porphyritic, but most cuttings of the rock are <0.1 mm in diameter, precluding meaningful textural characterization.

Flanking the spine of the felsite on both the northeast and southwest is a distinctive, fine-grained, relatively unaltered biotite-orthopyroxene granite (Figure 1B). All cuttings of this rock type are highly contaminated with drill steel, rust, and other lithologies, so its chemical composition remains to be determined. This granite is encountered where the top of the felsite is deepest; the overlying hornfels is accordingly more coarsely crystalline and granoblastic, with original metagraywacke textures in general totally obliterated.

The easternmost of The Geysers major plutonic rocks is a hornblende-pyroxene-biotite microgranodiorite to microgranite. Containing up to 15% mafic minerals, this rock is mineralogically and chemically as well as texturally distinct from the other felsite phases. It appears to occur not only as a discrete pluton, but also as dikes in the leucocratic microgranites to the southwest. The dikes are more felsic and more silicified than the parent (?) pluton, containing 72% versus 64% SiO_2 .

G. B. Dalrymple has age-dated samples from three Geysers felsite cores. Two are leucocratic biotite microgranite porphyry, the third a pyroxene- and biotite-bearing granodiorite to granite. All show evidence of profound thermal disturbance, and all are apparently older than 1.3 Ma (reported by Dalrymple in 1992). In another study, Pulka reported in 1991 obtaining $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 0.952 Ma and 1.192 Ma for samples of the hornblende-pyroxene-biotite microgranodiorite (Figure 1B). It would seem that this most mafic and easternmost of The Geysers felsites is also the youngest.

In general, rocks along the spine of the felsite have been much more intensely altered than those on the flanks. Albitization (Figure 1C), silicification, and borosilicate alteration and veining, for example, are most intense in the shallow microgranite porphyry and microgranite. These effects extend upward into overlying hornfels and hornfelsic metagraywacke, where secondary tourmaline plus ferroaxinite locally account for up to 24% of the rock in the 61 m of hornfels immediately above the pluton (Figure 1D).

Detailed logging of cuttings from the felsite-penetrating wells has confirmed that magmatic- or meteoric-hydrothermal brecciation has been an important porosity-inducing mechanism at the Geysers. For example, in at least two wells, vuggy, intensely altered, fluidal-textured breccias more than 100 m above the pluton top contain felsite clasts -- evidence of violent rock rupture and upward transport of the resulting igneous debris in an overpressured fluid stream.

Virtually every Geysers felsite sample contains highly saline secondary fluid inclusions, probably representing magmatic-hydrothermal fluids circulating at pluton-top and higher elevations shortly after pluton emplacement, and J. N. Moore (reported in 1992) has identified similar inclusions in immediately overlying hornfels. The inclusions in felsite contain at least one and commonly two

In-Progress Geologic Map, Top of Felsite

- Hornblende-Pyroxene-Biotite Microgranodiorite
- Leucocratic Biotite Microgranite Porphyry
- Leucocratic Biotite Microgranite
- Biotite-Orthopyroxene Granite

In-Progress Mineralogic Map

$\frac{\text{Albite}}{\text{Total Feldspar}}$ (Upper 61m/200ft of felsite)

- > 0.5
- > 0.2 - 0.5
- < 0.2

ND = No Data

In-Progress Alteration Map: Tourmaline Plus Ferroaxinite, 0-61m/200ft Above Felsite

wt. %

- > 16
- > 8-16
- > 4 - 8
- > 2 - 4

Figure 1. Selected maps of The Geysers felsite. A - Index map (from Thompson, 1989). B - Geologic map, top of pluton. C - Albite in upper felsite. D - Tourmaline and ferroaxinite immediately above felsite.

cubic, isotropic daughter minerals, almost certainly halite and sylvite. Also locally present are up to four birefringent daughter minerals and a triangular opaque phase which could be chalcopryite. The presence of these saline, probable magmatic fluid inclusions lends credence to the concept of explosive, high-temperature, magmatic-hydrothermal brecciation as a porosity-forming mechanism at The Geysers.

Plans

Our project is approximately 60% complete at the time of this summary. We will continue to characterize previously acquired Geysers felsite, hornfels, and metagraywacke cores and cuttings utilizing the approach outlined above, and expand the work to encompass newly-acquired samples from the field's eastern and southeastern sectors. Results to date will be submitted for publication in 1993.

The degree to which these findings will be useful to Geysers steam-field operators will depend in part upon comparison of the data with presently proprietary production information. It is our hope that the new research results will not only assist the operators in mitigating current production problems, but will also help expand the steam field's ultimate yield.

REFERENCES

Hulen, J. B., Nielson, D. L., and Martin, W., 1992, Early calcite dissolution as a major control on porosity development in The Geysers steam field, California -- Additional evidence in core from Unocal well NEGU-17: Geothermal Resources Council, Transactions, v. 16, p. 167-174.

Nielson, D. L., Nash, G., Hulen, J. B., and Tripp, A. C., 1993, Core image analysis of matrix porosity in The Geysers reservoir: Proceedings, 18th Workshop on Geothermal Reservoir Engineering, Stanford University, (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, DC 20585
Phone: (202)-586-8076
FAX: (202)-586-5124

DOE Project Manager:

Robert Creed
U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, ID 83402
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Jeffrey B. Hulen
University of Utah Research Institute
391-C Chipeta Way
Salt Lake City, UT 84108
Phone: (801)-584-4446
FAX: (801)-584-4453

$^{40}\text{Ar}/^{39}\text{Ar}$ AGE DATING STUDIES OF THE FELSITE UNIT WITHIN THE GEYSERS RESERVOIR

G. Brent Dalrymple
U. S. Geological Survey

KEY WORDS

$^{40}\text{Ar}/^{39}\text{Ar}$ dating, geochronology, age, The Geysers, felsite unit

PROJECT OBJECTIVE

The objective of this research is to determine the age and integrated long-term thermal history of the felsite unit, a complex intrusion that underlies the zone of steam production. This information is important for both field management and exploration because the results should reveal whether the felsite unit is the source of heat for The Geysers field or is simply a conduit through which heat from another source below is brought into the production zone.

APPROACH

The experimental approach involves the separation of minerals, principally potassium-feldspar and biotite, from samples of the felsite unit and the overlying hornfels, irradiation of the samples with fast neutrons in a nuclear reactor, and measurement of $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the samples with a high-sensitivity, ultra-high vacuum furnace/mass spectrometer system. The age spectra are then interpreted and modeled to determine what they reveal about the age and integrated thermal history of the samples. Sample selection and data synthesis is being done in collaboration with Jeff Hulen, of the University of Utah Research Institute (UURI), who is conducting petrographic studies on the material, which was recovered from wells that penetrate the felsite unit.

PROJECT STATUS

Background

The felsite unit is a complex silicic batholith that intrudes the overlying Franciscan Complex (Late Jurassic to Late Cretaceous) and underlies The Geysers geothermal field. It is only found in the subsurface but it appears to be an elongate body whose axis trends northwest-southeast and whose surface is shallowest in the southeast part of the field.

The apparent coincidence of the heat flow anomaly within The Geysers field with the distribution of felsite within and below the zone of steam production suggests that the felsite unit may be the primary source of heat. The age of the felsite unit is not known but the available K-Ar ages (0.9 Ma to 2.7 Ma) suggest that it may be too old to be the primary source of heat for the present thermal activity. Resolution of this apparent paradox should be of interest for the purposes of both exploration and field management. If the felsite unit is young (<1 Ma), for example, then it should be hot wherever it is found. If the felsite unit is old (>1 Ma), on the other hand, then it may be relatively cold outside of the region of present production. The felsite unit also may be a complex body emplaced over a significant interval of time with both older and younger parts. Regardless of its age, the felsite unit appears to play an important role in the geothermal field and its intrusion and thermal history is of interest.

The felsite unit has been subjected to elevated temperatures, fluid and gas flow, and alteration over an extended period of time. It is, therefore, a complex system and K-Ar ages are probably of limited, if any, value. In the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum method the sample is irradiated with fast neutrons, along with a *monitor mineral* of known age, to induce the reaction $^{39}\text{K}(\text{n,p})^{39}\text{Ar}$. Following irradiation the

Ar is released from the sample in steps by incremental heating to progressively higher temperatures and the isotopic composition of the Ar released in each step is analyzed. The age of each increment is calculated from the $^{40}\text{Ar}/^{39}\text{Ar}$ ratio after determining the fraction of ^{39}K converted to ^{39}Ar by analyzing the monitor mineral and after making various corrections for interfering Ar isotopes. The result is a series of ages, known as an *age spectrum*, for the sample. The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum method has the advantage of providing information about the degree to which the system has been disturbed or contaminated. In many instances it is possible to determine a crystallization age for a sample that has lost a significant fraction of its radiogenic ^{40}Ar due to thermal or chemical (alteration) disturbance. In others it is possible to determine a minimum crystallization age for a disturbed sample. In some instances, information about the thermal history of the sample can be extracted from age spectra.

Research Results

A preliminary study of four samples of the felsite unit, recovered from three wells drilled by UNOCAL, has been completed. The purposes of this preliminary work were: (1) to determine if $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum analyses of sufficient precision could be made on feldspars from the felsite unit; (2) to determine a reliable, if only preliminary, minimum age for the felsite unit; and (3) to use the information obtained from the preliminary results to design a sensible $^{40}\text{Ar}/^{39}\text{Ar}$ research program with the goal of determining the age and (perhaps) some information about the thermal history of the felsite unit.

The preliminary experiments have resulted in precise $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the four feldspar samples. The age spectra indicate that the four samples have been disturbed by thermal events, alteration, or both. The first few gas increments of each of the spectra have high apparent ages, which is probably due to ^{39}Ar recoil from ^{40}K sites in alteration products that are visible in thin section. The overall patterns of the age spectra are more-or-less typical of samples that have undergone thermal loss of Ar, with low apparent ages in the low-temperature steps increasing to higher apparent ages in the intermediate- and high-temperature steps. The decrease in apparent age for the high-temperature steps in two of the samples is consistent with ^{39}Ar recoil effects but similar age spectra have also been found for altered samples. How much of the disturbance of the four age spectra is due to thermal causes and how much to alteration is not known but further analyses on a broader suite of samples may clarify this question. The feldspar from these samples is altered, however, and it is very likely that alteration effects are important.

It is virtually impossible for either thermal events or alteration to disturb an age spectrum in such a way that the apparent ages for the bulk of the intermediate- and high-temperature increments exceed the crystallization age of the sample, the increments at the extremes, i.e., near 100% ^{39}Ar released, excepted. A conservative interpretation, therefore, is that the intermediate- and high-temperature maxima in the age spectra are minimum ages. Accordingly, the results indicate that the crystallization age of the part of the felsite unit sampled by the three cores is at least 1.3 to 1.4 Ma.

Plans

The preliminary results indicated that further work would be productive and so a more extensive experiment was designed. Cuttings from a large number of wells that penetrate the felsite unit were examined (with Jeff Hulen of UURI) to determine which of the available samples were the least altered, and which of these would provide a good depth and geographic distribution. Samples from several depths recovered from four wells were selected. Biotite and K-feldspar are being separated from these samples. In addition, samples from the hornfels above the felsite unit have been obtained from two of these wells and also from a fifth well; hydrothermal biotite will be separated from these

samples. Finally, biotite and adularia will be separated, if possible, from two veins that intrude the Franciscan Complex. As of March, 1993, the mineral separations are about 75% completed and the first batch of these new samples will be sent to the U.S.G.S. TRIGA reactor for irradiation in late spring. Following irradiation, the samples will be analyzed. All work, including data analysis, is expected to be completed by March, 1995.

REFERENCE

Dalrymple, G. B., 1992, Preliminary report on $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating experiments on feldspar samples from the felsite unit, Geysers geothermal field, California: U.S. Geological Survey Open-File Report 92-407, 15 pp.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigator:

G. Brent Dalrymple
U.S. Geological Survey, MS-937
345 Middlefield Road
Menlo Park, CA 94025
Phone: (415) 329-4655
FAX: (415) 329-4664

GEYSERS TRACERS

Michael C. Adams
University of Utah Research Institute

KEY WORDS

Geothermal tracers, vapor-phase tracers, tracer tests, halogenated alkanes, The Geysers

PROJECT OBJECTIVE

Chemical tracers are a valuable tool for evaluating the efficiency of injection into geothermal fields. Prior to this project, only tritium was available for use in vapor-phase reservoirs. The overall objective of this research project is to identify and test nontoxic, thermally stable, chemical compounds for use as vapor-phase geothermal tracers that have minimal rock-tracer interactions, are detectable at very low concentrations, and are relatively inexpensive. This research is of importance to geothermal operators at The Geysers to identify flow paths in the reservoir and to quantify the amount of injected water that is recovered in production.

APPROACH

Our approach in evaluating the utility of various compounds as tracers reflects the immediate need of geothermal industry for vapor-phase tracers. Consequently, our methodology has been as follows:

- 1) Search the literature for compounds that may be useful as vapor-phase geothermal tracers, and evaluate the known thermodynamic data.
- 2) Inject several tracers during field tests, so that relative stabilities can be compared to laboratory data through their field relationships.
- 3) Refine our laboratory methods based on the field results.

PROJECT STATUS

Background

Production from The Geysers has significantly declined since 1988, due in part to a lack of injected water. One of the research projects requested by industry was the development of vapor-phase tracers that will work in the geothermal environment of The Geysers. The need for compounds that will trace the injected fluid through the reservoir has been emphasized by recent evidence that injection has beneficial effect on production.

Prior to our research, successful tracer tests at The Geysers used either deuterium or tritium to trace the flow of injected fluids. Although both of these tracers provided useful information, they also have certain limitations. Repeated use of tritium, which is radioactive and soluble in both water and steam, can saturate the reservoir after several tests. The use of deuterium can be enigmatic because its ratio in the injected fluid varies with the complex conditions at the power plant cooling towers. Furthermore, recent changes in operating procedures at some power plants in The Geysers have drastically changed the isotopic ration of injected water and eliminated the use of deuterium as a tracer.

We have pursued the development of tracers for use at The Geysers on two fronts. The first approach has been to test halogenated alkanes, most of which fractionate completely to the steam phase under geothermal conditions. These compounds, which are known for their high stability, and low toxicity, are available in a wide variety of chemical species. With different species available, water entering the reservoir from several injection wells can be tagged simultaneously.

The second approach is to search for compounds that will fractionate in a known ratio between the liquid and steam phases. These compounds must be sufficiently polar to be soluble in the liquid phase but have a low enough acidity to fractionate significantly to the steam phase from a high-pH boiling liquid. In addition, they must not decay too rapidly in the presence of molecular oxygen, which is present in the injection fluid at The Geysers.

Research Results

The halogenated alkanes are a category of compounds that appear to be suitable as vapor-phase tracers, and several compounds from this category have been tested in the laboratory and in the field. The first field test was performed in 1991, in the southeast Geysers by Calpine, Northern California Power Agency (NCPA), Unocal as members of the Geothermal Technology Organization in a 50/50 cost share with DOE. The tracers were injected into NCPA well C-11, which received steam condensate from both NCPA and PG&E/Calpine power plants. Two tracers were used in this field test, 324 kg of R-12 (CCl_2F_2) and 100 kg of R-13 (CClF_3). These tracers were chosen because their chemical and physical properties are among the best known of the halogenated alkanes, and because they were relatively inexpensive and available in large quantities. Forty-nine production wells were monitored during the tracer test, which lasted 51 days. The tracers were analyzed on a gas chromatograph equipped with an electron capture detector. This method yields detection limits for R-12 and R-13 of approximately 10^{-6} and 10^{-2} ppm, respectively.

The tracers were detected one day after injection in 13 out of the 16 wells sampled. By the end of the test at 51 days after injection, the tracers had been detected in 38 of the 49 wells sampled. Peak concentrations ranged from 3.2 parts per billion (ppb) to 31.1 parts per million (ppm) for R-12, and from 29 ppb to 1.7 ppm for R-13. Transit times were very rapid for some wells. Tracer was detected in fluid from wells as far away as 0.8 km from the injection well on day 1. By day 5, tracer was detected 1.6 km from the injection well. Contour maps of the peak arrival times and concentrations are shown in Figures 1 and 2, respectively. Interpretation of the data from this test indicated preferential permeability to injection flow in the northwest, southeast, and southwest directions, in agreement with unpublished isotopic studies of this region. R-13 has subsequently been used by industry in several successful tracer tests at The Geysers. Another fluorinated compound suggested by our research, SF_6 , has also been recently used as a tracer at The Geysers.

Plans

We are currently testing ethanol in our laboratory for use as a water-soluble vapor-phase tracer. Ethanol is very similar to water in its properties. The laboratory tests consist of encapsulating ethanol and distilled water in sealed quartz vials and heating them to temperatures typical of The Geysers geothermal environment. We will also conduct tests to determine the sensitivity of ethanol to molecular oxygen, and to the gases present in the reservoir of The Geysers.

A cost-shared injection test is being planned to take place at The Geysers in 1993. Several of the vapor-phase tracers and ethanol will be injected to determine their behavior under field conditions during this test.

Figure 1. Contoured R-12 peak arrival times in days produced from the data collected during the introduced-tracer test performed at the Southeast Geysers. The data have been corrected for thermal decay using an empirically-derived decay constant.

Figure 2. Contoured mass recoveries (kg) of R-12 during the introduced-tracer test performed at the Southeast Geysers. The data have been corrected for thermal decay using an empirically-derived decay constant.

REFERENCES

Adams, M. C., Moore, J. M., and Hirtz, P., 1991, Preliminary assessment of halogenated alkanes as vapor-phase tracers: Proceedings, 16th Workshop on Geothermal Reservoir Engineering, Stanford University, p. 57-62.

Adams, M. C., Beall, J. J., Enedy, S. L., and Hirtz, P., 1991, The application of halogenated alkanes as vapor-phase tracers: A field test in the southeast Geysers: Geothermal Resources Council, Transactions, v. 15, p. 457-463.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Bob Creed
U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, ID 83402
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigator:

Michael C. Adams
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, UT 84108
Phone: (801) 584-4435
FAX: (801) 584-4453

FLOW VISUALIZATION AND RELATIVE PERMEABILITY MEASUREMENTS IN ROUGH-WALLED FRACTURES

Peter Persoff and Karsten Pruess
Earth Sciences Division, Lawrence Berkeley Laboratory

KEY WORDS

Fracture flow, rough-walled, relative permeability, capillary pressure, laboratory measurement, transparent replica

PROJECT OBJECTIVE

Steam-water flow in fractures is a basic mass and energy transport process in geothermal reservoirs. The objectives of this research are to observe and understand the phenomena of multi-phase flow in rough-walled fractures, including non-steady flow; to improve the accuracy of simulators by developing and demonstrating a method to obtain accurate data for relative permeability and capillary pressure in rough-walled fractures; and to test theoretical methods for calculating such parameters from measurements of fracture aperture. Two-phase (water-gas) flow in fractures also occurs in the context of nuclear waste isolation, and the present project is co-funded by DOE's Office of Civilian Radioactive Waste Management. This research is important for geothermal reservoir management because it will provide an understanding of the physics controlling fluid flow in fractures, and it will provide the field operator with operational parameters for maximizing energy production.

APPROACH

The technical approach is to conduct small-scale laboratory experiments both in natural rock fractures and in transparent replicas of the fractures. Relative permeability and capillary pressure curves are calculated from experimental data, and aperture is measured at a great number of points by analysis of digitized images of the transparent replicas with the fracture filled with water or dye.

PROJECT STATUS

Background

Geothermal reservoirs are generally fractured, and two-phase flow conditions exist when boiling or condensation occurs, such as during water injection into vapor-dominated reservoirs. Simulator models for predicting the response of a reservoir to exploitation therefore must account for two-phase flow in fractures. Relative permeabilities and capillary pressure functions are needed as input data for these models, but such data are scarce and unreliable. Historically, this lack has been filled by the simple assumption that the relative permeability of each phase is equal to its saturation; this implies that the sum of relative permeabilities is 1, and is equivalent to saying that neither phase interferes with flow of the other. However, recent theoretical analysis by Pruess and Tsang in 1990 contradicts that assumption, and leads to the conclusion, instead, that the sum of relative permeabilities is much less than 1 at intermediate saturations, and significant phase interference occurs.

Research Results

Results from this project to date include: (1) the development of methods for preparing transparent replicas of natural rock fractures, (2) development of methods for measuring aperture in transparent replicas, and (3) visualization and measurements of two-phase flow in natural fractures and replicas. The research results have been published, and a patent application has been filed on the apparatus and method for measurement of two-phase flows in fractures.

Transparent replicas of the fractures were prepared by making silicone rubber molds of each face of

the fracture, and then pouring Eccobond 27 epoxy in the molds. The apertures of the transparent replicas were measured by light attenuation. Two digitized images of the fracture replica, one filled with water, and one filled with dye, were compared on a pointwise basis. The aperture was then calculated from the ratio of light intensity in the two images, using Beer's law.

The apparatus was designed to measure the inlet and outlet pressures of two immiscible fluids (water and gas) as they flow through a fracture. Special endcaps, modified from the design of Hassler in 1944, were fabricated to inject and receive two immiscible fluids at different pressures, so that controlled capillary pressure boundary conditions are imposed at the inlet and outlet. The wetting phase (water in these experiments) is injected to the inlet edge of the fracture through a wettable porous ceramic block, with 1 bar air-entry pressure. The non-wetting phase (nitrogen gas in these experiments) is injected directly to the fracture edge through a plenum and grooves in the porous block. Flow rates and pressures (capillary pressures, absolute pressures, and pressure drops) are automatically recorded.

A total of five flow experiments have been conducted. In each experiment, the flow rates of gas and liquid were varied to cover flow rate ratios ranging through three or four orders of magnitude. Liquid was injected at constant volume flow rate, and gas was injected at either constant mass flow rate or constant pressure. When gas was injected at constant mass flow rate, the gas inlet pressure, and inlet and outlet capillary pressures, generally did not reach steady state but cycled irregularly. Flow visualization showed that this cycling was due to repeated blocking and unblocking of gas flow paths by liquid. Such blocking apparently occurs at the point of minimum aperture along the gas flow path. When the path is blocked by liquid, gas pressure increases until it can re-invade and occupy this point; but when the gas path is no longer blocked, the gas pressure is insufficient to prevent re-invasion of the wetting phase.

We have found, for a system constrained by gas and liquid flow rates, the actual pressures and flow rates through the fracture will tend to cycle above and below the points of stable flow, where phase occupancies, pressures, and rates would be constant. The extent of over- and under-shoot will depend on fracture geometry, but also on the compressibility and transmissivity of the inlet and outlet plumbing systems. The transient response of the fracture depends on the number of available flow channels, their topology, and their pore-size and permeability distribution. There is a scale effect here because a small system with just a few discrete channels will be more prone to instability than a large system with an almost continuous distribution of flow channels.

In all experiments, the relative permeabilities calculated from flow rate and pressure data show that the sum of the relative permeabilities of the two phases is much less than 1, indicating that each phase interferes strongly with the flow of the other. Comparison of the relative permeability curves with typical curves for porous media (Corey curves) show that the phase interference is stronger in fractures than in typical porous media. This contrasts with the conventional view of fracture relative permeabilities that the sum of relative permeabilities is 1 at all saturations. Our findings support recent theoretical results for fractures conceptualized as two-dimensional porous media. Steady-state flow conditions are not easily achieved. Even when great care is taken to apply constant boundary conditions at the fracture, the two-phase flow behavior tends to create persistent instabilities and phase occupancy changes.

Plans

The laboratory work is ongoing. The results obtained so far will be confirmed by making measurements on a variety of fractures. Experiments will be done on larger samples to determine the

effect of scale and on non-horizontal fractures to determine the effect of gravity.

REFERENCES

Persoff, P., and Pruess, K., 1993, Flow visualization and relative permeability measurements in rough-walled rock fractures: Proceedings, International High-Level Waste Management Conference, Las Vegas, Nevada, Apr. 26-30.

Persoff, P., Pruess, K., and Myer, L., 1991, Two-phase flow visualization and relative permeability measurements in transparent replicas of rough-walled rock fractures: Proceedings, 16th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., p. 203-210.

Pruess, K., and Tsang, Y. W., 1990, On two-phase relative permeability and capillary pressure of rough-walled rock fractures: Water Resources Research, v. 26, no. 9, p. 1915-1926.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington D.C. 20585
Phone: (202) 586-8076

Principal Investigators:

Karsten Pruess	Phone: (510) 486-6732
Peter Persoff	Phone: (510) 486-5931
Earth Sciences Division, Mail Stop, 50-E	
Lawrence Berkeley Laboratory	
Berkeley, CA 94720	
FAX: (510) 486-5686	

FIELD AND LABORATORY STUDIES OF MAGMATIC VAPOR EVOLUTION

Philip A. Candela and Philip Piccoli
Department of Geology, University of Maryland

KEY WORDS

Magma, volatiles, partitioning, dynamics, apatite, HCl, chloride

PROJECT OBJECTIVE

The aim of this research is to develop a model for the flux of magmatic HCl and other magmatically - derived chlorides into geothermal systems. These materials can contribute acidity and total dissolved solids to the geothermal system. This research is of importance to geothermal systems as they dry out and are impacted by the production of hydrogen chloride from the reservoir and the corrosion of wells and surface equipment. The understanding developed in this project could help control chlorides and reduce the operation and maintenance costs for the geothermal developer.

APPROACH

We are combining field investigations of fossil magma-geothermal systems, laboratory studies of melt-vapor-brine equilibria, and physical and chemical modeling of magmatic devolatilization to understand the composition and flux of magmatic volatiles into geothermal systems.

PROJECT STATUS

Background

There is increasing evidence, from both the geothermal and ore deposit communities, that direct material input from magmatic systems is important in determining the composition of geothermal waters and their time-integrated rock alteration (low pressure and contact metamorphic) effects. The nature of this direct magmatic input must be determined if we are to understand the total dissolved solids and corrosive agents present in geothermal systems. The composition and flux of magmatic-hydrothermal fluids in continental geothermal environments are a function of a number of parameters including volatile phase to melt and crystal to melt partition coefficients, initial and saturation water concentrations (in low-CO₂ systems), and Cl/H₂O ratios. These parameters, in turn, are controlled by a number of properties of the magmatic-geothermal system that ultimately depend on magmatic source region, and mode of emplacement-related processes.

To understand the role of melt "volatile" chemistry, and the role of aqueous phase to melt partitioning relative to crystal to melt partitioning of chemical substances such as aqueous chlorides (including the potentially corrosive HCl) and the means of release of the magmatic aqueous phases from the pluton, we are: (1) investigating igneous apatite chemistry in the fossil remains of shallow, 99 Ma (Cretaceous) magmatic-geothermal systems in the Ritter Range, California; (2) performing experiments on the partitioning of HCl and other substances between silicate melts and two phase mixtures of chloride-bearing aqueous fluids, and between silicate melts and crystalline phases; and (3) modeling aspects of the chemistry and physics of aqueous exsolution from a felsic magmatic system.

Research Results

A. Apatite, and estimates of halogen concentrations of magma:

The concentrations of Cl and F in magmatic apatites have been measured using the electron microprobe. From these data, the corresponding fugacity (the activity corrected pressure of volatile components) ratios can be calculated given reasonable estimates of apatite saturation temperatures (AST). Estimates of halogen concentrations in the melt and the magmatic aqueous phase can be

calculated from these fugacities.

Whole rock analyses of SiO_2 and P_2O_5 have been used to make estimates of the temperature at which apatite begins to crystallize in granitic rocks. The solubility expression describing apatite crystallization in silicic systems can be modified to incorporate crystallization of all minerals and changes in the silica concentration as felsic systems mature. From the measured compositions of the apatites, we have calculated that one granitic melt contained approximately 250 ppm Cl and 700 ppm F at the first appearance of apatite (after the melt had crystallized 33%). Assuming incompatibility of the halogens prior to reaching this point, the estimated initial halogen concentrations in the melt (prior to any crystallization) is: Cl = 190 ppm and F = 525 ppm.

B. Element partitioning in melt/vapor/brine systems:

Experiments performed in our laboratory suggest that the crystal/melt partitioning exerts as strong an effect on the composition of the magmatic solutes as does volatile phase partitioning, because of the competition between crystals and the volatile phases for the metals and other substances present in the crystallizing melt.

Experiments are being performed at 0.5 to 1 kbar and 800 to 850°C to determine the partitioning of HCl and other substances between silicate melts and mixtures of a brine and coexisting vapor (the aqueous mixture homogenizes upon quench). Variations in the chloride/water ratio of the starting material produce variations in the vapor/brine phase ratios at high pressure and temperature. The composition range of our experiments approximates a haplogranitic - aqueous phase system. Calculations based on these experiments indicate that the HCl/NaCl ratio is higher in the vapor relative to the brine at 1 kbar, but that this trend is suppressed at lower pressures. The experimental data also suggest that bulk aqueous composition is a function of melt aluminosity (the ratio $\text{Al}/(\text{Na}+\text{K}+\text{Ca})$).

Generally, the more aluminous the melt, the higher the acidity of the magmatic fluids, and the higher the temperature of feldspar destruction and calcium release from wall rocks into the geothermal system. The dependence of vapor and brine compositions on melt aluminosities indicates that peraluminous ($\text{Al} > \text{Na} + \text{K} + \text{Ca}$) melt compositions will produce muscovite alteration (acidic conditions) at higher temperatures. Hydrolysis reactions act as a buffer of pH in hydrothermal fluids, and the failure of a crystallizing melt to produce hydroxyl-bearing aluminosilicates (such as micas) may maintain high acidity in hydrothermal fluids.

C. The physics of release of the magmatic aqueous phases:

High Lewis numbers (the ratio of heat to chemical diffusivity) for H_2O imply that water will accumulate within a marginal boundary layer or crystallization interval within magma chambers. This suggests that: (1) magmatic water exsolution occurring at much less than 20% crystallization, (at high initial magmatic water concentrations or low pressures), can induce the rise of bubble-laden plumes; (2) magmatic water exsolution occurring later (moderate initial magmatic water concentrations or moderate pressures), with vapor bubbles (trapped in an immobile crust) forms a spanning cluster (foam) at critical percolation through which the magmatic aqueous phase can upwardly advect; and (3) vapor exsolution occurring in an immobile crust, but with low initial water concentrations or at higher pressure such that the spanning cluster at critical percolation is not achieved, results in the dispersal of the magmatic aqueous phase through the cracking front, which follows the solidus into the pluton. In the first case, the likelihood of plume rise (relative to the rise of individual bubbles) can be evaluated by calculating the characteristic rise time for individual bubbles, according to the Hadamard-Rybczynski law, relative to the characteristic rise time for bubble-laden plumes. Calculations show, for bubbles of $r < 1$ cm, that plume rise is likely. In the second case, percolation theory indicates that a

spanning cluster of the aqueous phase on a simple three dimensional lattice is attained when the aqueous phase achieves a volume fraction of $F = 0.31$. Percolation is attained for initial magmatic water concentrations greater than 1 or 2% at 0.5 kbar and greater than 4 or 5% at 2 kbar. For lower water concentrations and higher pressures, vapor will be dispersed throughout a rather diffuse cracking front. This analysis suggests that orthomagmatic-hydrothermal fluids can be transported and focused to sites of mineral deposition near the apical regions of magma chambers by either bubble-plume rise or advection through spanning clusters of vapor bubbles.

Plans

Our future plans include the development of a combined physical and chemical model for aqueous fluid exsolution that will: (1) allow the prediction of the magmatic HCl concentration in the hydrothermal input to geothermal and volcano-plutonic hydrothermal systems; (2) allow the prediction of the concentrations of cations in the magmatic-hydrothermal input; (3) allow fluid chemistry to be predicted from drill core samples of completely or partially crystallized plutons; (4) allow the prediction of flux of magmatic fluids out of a pluton into the geothermal regime based on initial and final water concentration and pressures of devolatilization; and (5) permit the construction of a predictive combined chemical and physical model for felsic magmatic devolatilization.

REFERENCES

- Candela, P. A., 1990, Theoretical constraints on the chemistry of the magmatic aqueous phase: in Stein, H. J., and Hannah, J. L., eds., *Ore-bearing granite systems; Petrogenesis and mineralizing processes*: Geological Society of America, Special Paper 246, p. 11-26.
- Piccoli, P. M., 1992, Apatite chemistry in felsic magmatic systems: Ph.D. dissertation, University of Maryland at College Park.
- Piccoli, P. M., and Candela, P. A., 1993, Apatite in felsic rocks: a model for the estimation of initial halogen contents in the Bishop Tuff (Long Valley) and Tuolumne Intrusive Suite (Sierra Nevada Batholith) Magmas: Accepted for publication in *American Journal of Science*.
- Williams, T. J., Candela, P. A., and Piccoli, P. M., 1993, An experimental study of the hydrogen-sodium exchange between a high-silica rhyolite and a two-phase aqueous mixture: comparison of results at 1 kbar, 800°C and 1/2 kbar, 850°C: Submitted to the American Geophysical Union for Spring 1993 meeting.
- Williams, T. J., Candela, P. A., and Piccoli, P. M., 1991, An experimental determination of the constant for hydrogen-sodium exchange between a high-silica rhyolite and a chloride bearing two-phase aqueous mixture at 800°C and 1 kilobar: *EOS-Transactions of the American Geophysical Union*, v. 72, p. 308.

CONTACTS

DOE Program Manager:

Marshall Reed

U. S. Department of Energy, CE-122

Washington, D.C. 20585

Phone: (202) 586-8076

FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigators:

Philip A. Candela	Phone: (301) 405-2783
Philip Piccoli	Phone: (301) 405-6966
Department of Geology	
University of Maryland	
College Park MD 20742	
FAX: (301) 314-9661	

CORROSION MITIGATION AT THE GEYSERS

Lawrence E. Kukacka
Brookhaven National Laboratory

KEY WORDS

Acidity, coatings, composites, corrosion protection, high temperature, piping, polymers, pre-ceramics, well casing, turbine blades

PROJECT OBJECTIVE

The objective of the research is to decrease the operating costs of steam production, transmission, and utilization at The Geysers by the identification and subsequent demonstration of low cost materials of construction which will withstand the highly corrosive acidic environments being encountered in some areas of the geothermal field. This research will have significant impact on reducing the operating and maintenance cost associated with geothermal energy production at The Geysers.

APPROACH

The approach being used to meet the project objectives is to optimize polymer and polymer cement formulations, previously developed under Geothermal Division sponsorship, for specific end-use applications at The Geysers. The identification of needs, performance of prototype and full-scale field evaluations, and subsequent economic studies are performed as cost-shared activities with firms active at The Geysers.

PROJECT STATUS

Background

Increased HCl concentrations in the steam produced from geothermal wells at The Geysers have resulted in severe corrosion problems in the upper regions of the well casing where condensation may occur, in steam collection piping, and on turbine blades. Examples of corrosion in casing are shown in Figures 1 and 2. In some cases this has resulted in the shutdown of wells causing reduced steam supply and, therefore, decreases in electric power generation. Increased operating costs and safety and environmental concerns have also resulted.

Phase 1 of the project consists of the identification of specific materials problems, elucidation of the fluid environments, and the selection of candidate materials systems. Laboratory testing under simulated process conditions is then conducted to establish technical feasibility. Based upon these results, modifications to the systems are made to maximize corrosion resistance.

Phase 2 consists of small-scale field testing, and, contingent upon the results, prototype component testing.

Phase 3 consists of design studies to incorporate the technology into components, cost estimates, documentation, and the identification of potential commercial suppliers of the new technology.

If the research objectives are achieved, wells that presently cannot be operated due to excessive operating costs or environmental and safety concerns may be restarted, thereby increasing the steam supply available for electric power generation. In addition, the life expectancies of currently utilized wells and other components will be extended, thus decreasing operating costs.

Figure 1. Example of corrosion in upper region of well casing.

Figure 2. Example of corrosion in steam collection pipe.

Research Results

The emphasis of the work being performed is directed towards field evaluations of prototype and full-scale components. Tests are currently being conducted at the following locations: the Northern California Power Agency (NCPA) facility in Middletown, CA, and the Central California Power Agency (CCPA) facility in Cloverdale, CA. Results to date are summarized below.

A. NCPA Field Tests

Two 12-in. diameter "T" sections supplied by NCPA and lined at BNL were installed (see Figures 3 and 4). Both sections had a 5/16-in. thick cast-in-place polymer cement (PC) liner consisting of styrene, trimethylolpropanetrimethacrylate (TMPTMA), and Type III cement. One liner also contained 1/4-in. long graphite fibers as reinforcement.

Both sections were installed in a steam collection line late in April 1992. The steam conditions are as follows: flow rate 30,000 lb/hr, pressure 120 psi, and temperature 173°C. The first visual inspection of the liners will be made in April 1993. To date, no problems with either unit have been reported.

B. CCPA Field Tests

Four 8-in. diameter casing spool sections were installed at CCPA for evaluation. Two were lined with a nominal 0.125-in. thick layer of PC, the others with a 0.002-in. thick coating of polyphenylenesulfide (PPS) polymer that was bonded to the casing using a transition metal modified zinc phosphate conversion process. After testing, the PC sections were returned to BNL for analysis. Average field test conditions were:

Wellhead Pressure	127 psi
Wellhead Temperature	175°C
Flow Rate	62,000 lb/hr
Line Pressure	122 psi

Section S1 was installed in the most chemically aggressive CCPA well, a location where the service life of a 0.5-in. thick wall carbon steel is 14 days. After being in test for 23 days, a leak developed in the PC-lined section. The leak occurred just above one of the injection ports at the top of the section and may have been caused by backpressure which forced fluid under the PC and led to subsequent corrosion of the steel. Severe attack on the PC liner was also apparent.

Section S2 was in a slightly less corrosive environment for 52 days. Visual examination indicated very little chemical attack on the liner but some delamination from the metal substrate.

The two PPS-lined sections, identified P1 and P2, were placed into test in October 1992. To date, neither section has been internally inspected, but no leakage has been detected.

C. Laboratory Testing

Laboratory-scale testing of PPS and various PC systems continued throughout Fiscal Year (FY) 1992. These tests, which are conducted in pH2 HCl at 200°C, were performed to obtain preliminary information regarding potential field performance. To date, carbon steel tubes coated with PPS have been in test for 7 months without any apparent corrosion. PC samples exposed for 6 months exhibited increases in strength compared to the controls due to continued hydration of the cement, slight increases in volume, and increased porosity. Chemical attack due to the acidic environment was not evident.

Figure 3. 12-inch diameter "T" section supplied by Northern California Power Agency.

Figure 4. 12-inch diameter "T" section lined with 5/16-inch thick layer of polymer cement which was cast in place.

Plans

In FY 1993, ongoing cost-shared efforts with steam producers at The Geysers will be continued, a project with PG&E will be initiated, and other projects started as their needs are identified by the DOE-Industry Geysers Working Group.

With respect to the ongoing cost-shared effort with the CCPA, field exposure of Test Series No. 3 and 4 will be completed and the post-exposure analyses completed. Contingent upon the results from these tests, full-sized sections of lined well casing will be placed into test.

Monitoring of FY 1992-initiated field tests of composite lined 12-in. diameter pipe "T"s installed by NCPA in their steam collection piping will be continued. Contingent upon these results, plans for the testing of additional lined components will be developed and implemented.

Laboratory and field testing of coated PG&E turbine blade materials will commence. Both polymeric and pre-ceramic-type coatings will be evaluated. Metal surface modification techniques will be investigated as methods for enhancing the bonding of the coatings to the substrate. Contingent upon the results from the laboratory phase of the effort, a series of turbine blades supplied by PG&E will be coated and returned to the utility for field evaluation.

REFERENCES

Webster, R. P., Kukacka, L. E., and Reams, W., 1992, Development of polymer concrete liners and coatings for use in geothermal applications: BNL 48002, Sept. (Accepted for publication in American Concrete Institute Special Publication "Recent Innovations in Polymer Concrete Technology".)

Webster, R. P., Kukacka, L. E., and Reams, W., 1992, Utilization of polymer concrete composites in geothermal applications: Proceedings, Intertech Conference, Polymer Concrete and Polymer-Modified Concrete, Mar. 5-6, Newark, N.J.

Kukacka, L. E., and Sugama, T., 1991, Materials studies for preventing corrosion in condensing environments: Gas Research Institute, GRI 91/0393, Oct.

Fontana, J. J., Reams, W., and Cheng, H. C., 1987, Potential polymer concrete heat exchanger tubes for corrosive environments: BNL 38945, Proceedings, 5th International Conference on Polymers in Concrete, Sept. 22-24, Brighton, U.K.

CONTACTS

DOE Program Managers:

Marshall Reed   Phone: (202) 586-8076
Raymond LaSala   Phone: (202) 586-4198
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
FAX: (202) 586-5124

Principal Investigator:

Lawrence E. Kukacka
Brookhaven National Laboratory
Upton, NY 11973
Phone: (516) 282-3065
FAX: (516) 282-2359

VOLATILITY OF HCL DURING BRINE DRYOUT

J. Michael Simonson and Donald A. Palmer
Chemistry Division, Oak Ridge National Laboratory

KEY WORDS

Hydrochloric acid, volatility, corrosion, The Geysers, modeling, thermodynamics, acidity, chloride, brine, steam

PROJECT OBJECTIVE

The goal of this project has been to determine the likely source of highly corrosive steam from high-temperature wells at The Geysers geothermal field, Santa Rosa, California. This research is of great significance to the control of hydrogen chloride in the produced steam from the northwest Geysers area. The success of this project will allow field operators to reduce the operating and maintenance cost of corrosion control and will open to production parts of the High Temperature Reservoir which are now avoided because of HCl.

APPROACH

The problem is approached through measurements of liquid-vapor partitioning equilibria. In the first experimental study, the partitioning of hydrochloric acid between liquid and vapor phases was measured at temperatures to 350°C. Subsequent experiments have focused on laboratory measurements of hydrochloric acid volatility over acidic sodium chloride brines, and over brines containing hydrolyzable ions. These experiments serve both as model systems for the mixed electrolyte brines encountered in geothermal reservoirs, and as a method for measurement of the high-temperature pH imposed in mixed electrolyte brines by the hydrolysis of metal ions in solution.

This project is part of a program "Physical Chemistry of Geothermal Systems" at ORNL. The general objective of this program is to conduct laboratory experimental research utilizing unique facilities and expertise at ORNL for studies of selected chemical equilibria, thermodynamics of brine systems, liquid-vapor isotope distributions, volatilities, and other phase behavior. Results allow prediction of chemistry and permeability changes in reservoirs and in plant facilities involved in the extraction of geothermal energy, and provide fundamental experimental data needed as input for geochemical models.

PROJECT STATUS

Background

The production of acidic, corrosive steam is becoming an increasingly serious problem limiting the production of steam at The Geysers geothermal reservoir. Wells drilled recently in the northwest Geysers have produced steam at higher temperatures (>300°C) than usually found in the main body of the reservoir (~240°C). Often these wells produce high levels of chloride at the wellhead, with observed levels greater than 100 ppm in some cases. Owing to its high volatility, these observed levels of chloride in steam have been assumed to be due to hydrochloric acid. This acid-chloride-bearing steam is extremely corrosive to piping and well casings that leads to loss of production within a few days in severe cases. In addition, the problem of potential production of acidic steam in older wells at The Geysers, as the reservoir dries out with continued production, is of great long-term significance in the operation of the resource. A laboratory study was undertaken to determine the partitioning of HCl over both single electrolyte solutions and over brines likely to be encountered in the reservoir. This study addresses the current problem of acidic steam production in deeper, hotter wells and the projected behavior of the reservoir with further production.

Research Results

The conditions necessary for generation of corrosive steam are being investigated by static measurements of the partitioning of hydrochloric acid between liquid and vapor phases, and its relation to temperature and source brine composition. A special apparatus has been constructed for these measurements, using a thin platinum liner within a stainless-steel pressure vessel to permit studies to high temperatures on these very corrosive solutions. The apparatus is filled to approximately one-third its total volume with an appropriate HCl-containing brine, and maintained at temperature with a precise ($\pm 0.01^\circ\text{C}$) multiple-loop temperature control system. Samples of both the liquid and vapor phases are obtained at temperature through chemically-inert tubing and valves. An accurately-controlled sampling system using a positive-displacement high-pressure pump in conjunction with a second high-pressure vessel and an inert sample receiver is used to obtain vapor-phase samples without significantly disturbing the liquid-vapor equilibrium at high temperature.

Vapor-phase samples are obtained over a range of sampling rates to insure that equilibrium conditions are maintained, and that there is minimal mechanical carryover of solute as entrained liquid-phase droplets. Liquid-phase samples are obtained before and after each vapor sample in order to monitor and account for the changes in solution composition due to the withdrawal of condensed vapor from the high-temperature vessel. Sample compositions are determined by acidimetric titration and/or ion chromatography as appropriate for the particular solute concentrations observed. Where practical, experiments are carried out over wide ranges of ionic strength and acidity/salinity ratios at each temperature, to insure that the correct thermodynamic equilibrium constant is obtained from the analysis of the results. In addition to the measurement of partitioning of HCl over brines, vapor-phase samples are analyzed quantitatively to determine the concentrations of other cations from the brines present in the vapor phase, giving the volatility at high temperatures of the sparingly-volatile brine components (like NaCl). A second apparatus, consisting of a titanium pressure vessel equipped with a glass liner and fitted with inert tubing and valves, was also constructed for measurements up to 100°C . In this system a stream of nitrogen carrier gas is passed at variable, controlled flow rates through the liquid phase and the entrained vapor is condensed in an ice-cooled glass tube. Analysis of the compositions of the liquid and vapor phases in these experiments was performed as described above. At the conditions studied in these experiments, only hydrochloric acid is found to be sufficiently volatile to partition measurably to the vapor phase.

In analyzing the results, it has been assumed that HCl is negligibly ionized in the vapor phase, and significantly dissociated to ions in the liquid phase. The thermodynamic equilibrium constant for the partitioning reaction may then be written as $K = mv(\text{HCl})/[ml(\text{H})ml(\text{Cl})\gamma_{\pm}(\text{HCl})]$, where mv and ml are molalities of the components in the vapor and liquid phases and $\gamma_{\pm}$ is the stoichiometric mean ionic activity coefficient for HCl in the liquid phase. These activity coefficients, which are significantly different from unity at the conditions investigated, are known or can be estimated reliably from previous studies in this Laboratory; the activity coefficient for the neutral HCl molecule in the vapor phase is assumed to be unity. The invariance of K with observed liquid and vapor phase compositions and sampling rates serves as a check for the presence of mechanical carryover of solute, and of the accuracy of the activity coefficients. The values of K for HCl have been represented as a simple function of temperature and solvent (water) density for purposes of interpolation and extrapolation of the results to the solvent critical temperature (374°C). The measured partitioning of HCl between liquid and vapor phases, and an analysis of these results based on the thermodynamic model outlined above, have been published by Simonson and Palmer in 1993.

Experimental studies completed to date include the measurements of HCl volatility over HCl(aq) described in detail above; measurements of partitioning of both NaCl and HCl over $\{\text{NaCl} + \text{HCl}\}_{(\text{aq})}$

brines to 350°C; and measurements of partitioning of MgCl_2 and HCl over $\text{MgCl}_{2(\text{aq})}$ to 350°C. Measurements of total chloride partitioning ($\text{MgCl}_2 + \text{HCl} + \text{NaCl}$) over $\{\text{MgCl}_2 + \text{NaCl}\}_{(\text{aq})}$ are currently in progress.

Plans

In the immediate future, the measured values of partitioning of HCl and NaCl over $\{\text{NaCl} + \text{HCl}\}_{(\text{aq})}$ will be modeled in order to obtain standard-state thermodynamic partitioning constants for NaCl , and to permit calculation of total chloride partitioning over the mixed solutions. Based on a preliminary analysis of the results, significant levels of chloride in the vapor phase are expected at temperatures above 300°C. A quantitative description of our new experimental results for this system should lead to a significantly more accurate estimate of expected concentrations of chloride in steam as functions of temperature, salinity, and pH. Work has begun on a fully-speciated model for volatility of solutes at high temperature, which is expected to be needed for a reliable representation of the partitioning of the various components of mixed brines. A communication on the application of such a model to the volatility results for hydrochloric acid is in press.

Hydrolyzable cations (as Mg^{2+} and Ca^{2+}) may be of particular importance in determining the total partitioning of chloride over mixed brines due to their role in establishing or buffering the pH at high temperatures. A series of measurements has been completed on the partitioning of HCl and MgCl_2 over $\text{MgCl}_{2(\text{aq})}$ to 350°C. In the next series of experimental runs, volatilities of solutes will be measured over $\{\text{NaCl} + \text{MgCl}_2\}_{(\text{aq})}$ to 350°C. Future series of measurements will be carried out on $\text{CaCl}_{2(\text{aq})}$ and $\{\text{NaCl} + \text{CaCl}_2\}_{(\text{aq})}$ brines to complete our studies of the hydrolysis and partitioning characteristics of these solutes. A significant body of experimental measurements of excess thermodynamic properties, leading to values of activity coefficients of HCl , NaCl , and CaCl_2 to 400°C, has resulted from an ongoing program in this group sponsored by the DOE Office of Basic Energy Sciences. Measurements on $\text{MgCl}_{2(\text{aq})}$ to 400°C are currently being made under BES support. The information on excess thermodynamic properties obtained in experimental studies supported by BES is critically important to the rigorous thermodynamic description of the solute volatilities measured in this program. Additional measurements carried out at ORNL with BES support, including electrical conductance measurements leading to ion association constants for HCl , NaCl , CaCl_2 , and MgCl_2 , will also be of importance to the present program in establishing the levels of ion association in mixed brines which affect directly the partitioning of various components of the mixture between liquid and vapor phases.

REFERENCES

Simonson, J. M., and Palmer, D. A., 1993, Liquid-vapor partitioning of $\text{HCl}(\text{aq})$ to 623 K: *Geochimica et Cosmochimica Acta*, v. 57, no. 1.

Simonson, J. M., and Palmer, D. A., 1993, "A speciated model for the distribution of $\text{HCl}(\text{aq})$ between liquid and vapor phases to the solvent critical conditions: *Geochimica et Cosmochimica Acta*, (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

J. Michael Simonson	Phone: (615) 574-4962
Donald A. Palmer	Phone: (615) 576-5109
Robert E. Mesmer	Phone: (615) 574-4958
Chemistry Division, Oak Ridge National Laboratory	
P.O. Box 2008	
Oak Ridge TN 37831-6110	
FAX: (615) 574-4961	

WELL TESTING, SIMULATION, AND PREDICTING RESERVOIR PERFORMANCE

CONCEPTUAL AND NUMERICAL MODELS OF GEOTHERMAL RESERVOIRS

Gudmundur S. Bodvarsson

Earth Sciences Division, Lawrence Berkeley Laboratory

KEY WORDS

Conceptual models, numerical modeling, performance predictions, reservoir evaluation

PROJECT OBJECTIVES

The primary objectives of this project are to develop reliable conceptual models of geothermal reservoirs and to investigate how accurately numerical models can predict the long-term behavior of geothermal reservoirs. This research is of importance for providing the geothermal operators with reliable methods for prediction of energy recovery.

APPROACH

The most reliable conceptual models of geothermal reservoirs are developed by combining the known geologic structure and lithology with the exploitation history and operational knowledge gained through development. These models must then be tested against newly acquired information to see if they remain accurate descriptions of the reservoirs. The development of a numerical model for a geothermal field depends strongly on the conceptual model of the field, that is, important reservoir processes, and thermodynamic conditions, and inferred mass and heat flow patterns. The numerical model is developed by combining the parameters from the conceptual model into the mathematical expressions for their relationships. The more reliable the conceptual model is, the more accurate will be the numerical reservoir model and the more reliable will be the performance predictions.

PROJECT STATUS

Background

Numerical modeling is the most reliable method for evaluating geothermal reservoirs in terms of their capabilities to provide fluids for electrical power production, space heating, or other purposes. Current effort focuses on the development of conceptual models for vapor-dominated systems with emphasis on The Geysers. The development of more accurate conceptual models leads to the need for evaluation of the accuracy of numerical modeling for performance predictions. Various conceptual models of part of The Geysers have been evaluated using numerical modeling techniques. A model was developed of the high-temperature reservoir (HTR) in the northwest Geysers in order to study its development and evolution. This model assumes that the typical Geysers reservoir evolved from a high-temperature zone by liquid water infiltration at the top. Two dimensional cross sectional numerical models of the typical Geysers reservoir were developed in order to investigate the heat transfer and phase structure of the system. Incorporation of non-condensable gases into the numerical model to study boiling and condensation processes has been completed.

Available data to evaluate the accuracy of numerical models for predictive purposes are scarce. In the past we have used available data from the Olkaria geothermal field in Kenya to perform preliminary studies. Currently we are working with published and open file data from the Nesjavellir geothermal field in Iceland and have made comparisons of model predictions and actual observed behavior for the last six years.

Research Results

The existence of the HTR underlying the typical region in northwest Geysers has raised several important questions regarding the evolution of the system, the connectivity between the normal and high-temperature reservoirs, and their thermodynamic conditions. One conceptual model of the development of this reservoir system (1991) involves the formation of a typical (heat pipe) reservoir by water recharge from above into a HTR. The numerical model studies showed that this mechanism will develop a typical reservoir above a HTR, without a permeability barrier between the two. The results also showed high concentrations of non-condensable gases in the HTR, which is consistent with observed data.

We have investigated phase structure (distribution of water and steam) as well as flow and heat transfer behavior of two-phase geothermal systems through numerical modeling. For this investigation, a two-dimensional porous slab model was used with a non-uniform heat flux boundary condition at the bottom. Steady-state solutions are obtained for the phase structure and heat transfer behavior for cases with different mass of fluid (gas saturation) in place, permeabilities, and capillary pressures. The results obtained show very efficient heat transfer in the vapor-dominated zone due to the development of heat pipes and near-uniform saturations. For relatively high-permeability systems, single phase liquid zones prevail, with convection providing the energy throughput. For lower permeability systems, a two-phase liquid-dominated zone develops below the vapor-dominated zone, since conduction dominated heat transfer is not sufficient to dissipate heat released from the heat source. These results are consistent with observations from field developments, where most high-temperature, liquid-dominated, two-phase systems have relatively low permeabilities (such as Krafla, Iceland; Olkaria, Kenya; and Baca, New Mexico). The numerical results obtained also show a high-temperature vapor-dominated zone below a typical (240°C) vapor-dominated zone, as has recently been found at both The Geysers, California, and Larderello, Italy.

The performance of the 1986 three-dimensional numerical model of the Nesjavellir geothermal field for predicting the deliverabilities and pressure decline of the wells during the period 1987 through 1991 has been investigated. The model predicted adequately the flow rate and enthalpy transients of most wells, but over-predicted the pressure decline by 3 to 4 bars. Recalibration of the model against all natural state and exploitation data resulted in much higher permeabilities for the reservoir than those in the 1986 model (an increase of tens to hundreds of millidarcies).

REFERENCES

Bodvarsson, G. S., Gislason, G., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V., and Steingrimsdottir, B., 1993, Update of a numerical model of Nesjavellir, Iceland: Proceedings, 18th Workshop on Geothermal Reservoir Engineering, Stanford, CA. (in press).

Bodvarsson, G. S., Gislason, G., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V., and Steingrimsdottir, B., 1993, Accuracy of reservoir predictions for the Nesjavellir geothermal field, Iceland: (paper submitted to Geothermics).

Lai, C. H., Bodvarsson, G. S., and Truesdell, A. H., 1993, Modeling studies of heat transfer and phase-structure of two-phase geothermal reservoirs: (paper submitted to Geothermics).

CONTACTS

DOE Program Manager:

Marshall Reed
U. S. Department of Energy, CE-122
Washington, D. C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigator:

Gudmundur S. Bodvarsson
Earth Sciences Division, Mail Stop 50-E
Lawrence Berkeley Laboratory
Berkeley, CA 94720
Phone: (510) 486-4789
FAX: (510) 486-5686

DEVELOPMENT OF AN IMPROVED MATRIX-FRACTURE INTERACTION TERM FOR DUAL POROSITY SIMULATORS

G. Michael Shook
Idaho National Engineering Laboratory

KEY WORDS

Warren and Root model, dual porosity, matrix-fracture interaction, dual continua, volumetric flux

PROJECT OBJECTIVE

The objective of this project is to develop an improved method of simulating multi-phase (steam and water) flow in fractured porous media (reservoir rocks). In particular, an improved matrix-fracture interaction term will be developed, so matrix transients (time variations in pressure, saturation, and temperature) are better resolved. This study is of significance in the continuing effort to improve the capabilities of geothermal reservoir simulators. The benefit to geothermal field operators is great, if a simulator can be used to accurately predict the consequence of changing operational parameters at the well head.

APPROACH

The approach used in this study is a combination of analytical and numerical methods allowing for the study of the individual processes that govern flow between fracture and matrix. Successful completion of this project will improve our ability to simulate exploitation of fractured geothermal reservoirs.

PROJECT STATUS

Background

The vast majority of simulators that are used to simulate flow in fractured media employ some variation of the Warren and Root model presented in 1963. This model treats the fractures and the rock matrix as dual continua (two continuous materials with discrete properties) which occupy the same locations in space. Primary storage of fluids is in the rock matrix, and flow occurs largely through the fracture domain. Interaction between the two continua is expressed through the "matrix-fracture interaction" term in the conservation equations (conservation of mass and energy).

Matrix-fracture interaction in the Warren and Root model assumes the flow is quasi-steady state; that is, the volumetric flux (fluid flow rate) between the two continua is linearly dependent on the pressure difference between them. For incompressible fluids (like liquid water), or when the matrix blocks are small, the assumption of quasi-steady flow is reasonably good. When the fluids are highly compressible (as is vapor), or when fracture spacing is large, as in many geothermal reservoirs, the assumption of quasi-steady flow is inappropriate. Use of this assumption leads to errors in, for example, pressure response from the rock matrix, and errors in imbibition (the retention of fluid by the rock) rates of wetting fluids.

Research Results

This study involves a combination of analytical and numerical methods to develop an improved method of describing matrix-fracture flow. The analytical methods are used in deriving the relevant scaling groups used in the analysis. Conservation equations are written for an arbitrary fracture, and interaction with rock matrix is accounted for explicitly. These equations are rendered dimensionless, using a method known as inspectional analysis described by Shook and others in 1992. The dimensionless scaling groups can then be studied numerically, determining the conditions under which each of the forces impact the process. Non-dimensionalization (removing the restriction of

dimensions) of the governing equations minimizes the number of numerical studies required. A full suite of numerical studies of the process enables us to develop criteria for modifying the matrix-fracture interaction term used in the simulator.

To date, general conservation equations have been written and non-dimensionalized for compressible, isothermal flow. Inspectional analysis indicates the flow process is governed by 9 dimensionless scaling groups. Only the scaling groups for incompressible flow have been studied numerically thus far.

Plans

The next step of this project is to use the results of the numerical study discussed above in modifying the matrix-fracture interaction term in the Warren and Root formulation. For incompressible fluids, the assumption of quasi-steady flow is quite reasonable, and matrix pressure profiles are resolved reasonably well. However, saturation transients exist due to imbibition of wetting fluid from fracture into the tighter rock matrix. Comparisons of results between explicitly-represented fracture-matrix interaction and a modified dual porosity simulation will serve to evaluate the success of the interaction term modifications.

Upon completion of the work on incompressible fluids, the identical steps will be performed using compressible fluids, still under isothermal conditions. It is anticipated that insight developed in the first stage (incompressible fluids) will be extremely useful in this step. In addition to saturation transients in the rock matrix, pressure transients also exist in this case. Development of an improved matrix-fracture interaction term for compressible fluids is actually a generalization of the incompressible case.

The third step of this project involves relaxing the assumption of isothermal flow. In this case, flow of compressible fluids under non-isothermal conditions will be studied. As before, insights gained in the first two stages will be useful for the successful completion of step three.

The ultimate result of this project will be a generalized modification of the matrix-fracture interaction term used in dual porosity simulators, such that resolution of matrix pressure, saturation, and thermal transients is improved. Application of such modifications enhance our ability to accurately simulate geothermal systems in their native state and under conditions of production and injection.

REFERENCES

Shook, M., Li, D., and Lake, L. W., 1992, Scaling immiscible flow through permeable media by inspectional analysis: *In Situ*, v. 16, no. 4., p. 311-350.

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigators:

G. Michael Shook
Idaho National Engineering Laboratory
Idaho Falls, ID 83415-2107
Phone: (208) 526-6945
FAX: (208) 526-9822

Joel Renner
Idaho National Engineering Laboratory
Idaho Falls, ID 83415-3830
Phone: (208) 526-9824
FAX: (208) 526-0969

IMPROVED DUAL-POROSITY MODELS FOR SIMULATING THE BEHAVIOR OF FRACTURED GEOTHERMAL RESERVOIRS

Robert W. Zimmerman and Gudmundur S. Bodvarsson
Earth Sciences Division, Lawrence Berkeley Laboratory

KEY WORDS

The Geysers, fractured reservoirs, reservoir simulation, dual-porosity

PROJECT OBJECTIVE

The objective of this research is to develop more accurate and efficient methods for numerical simulation of the behavior of fractured geothermal reservoirs, particularly The Geysers. The resulting improved modeling capabilities will be useful to field operators in planning production schedules and finding remedies for pressure declines.

APPROACH

Our basic approach is to develop approximate analytical methods to model mass and energy flux between the fractures and the matrix blocks in two-phase geothermal systems. The resulting expressions will then be incorporated into existing simulators as the source and sink terms for the fracture gridblocks. This will eliminate the need to discretize the matrix blocks, and greatly increase the number of fracture gridblocks that can be included in a reservoir model. Finer resolution of the pressure and enthalpy distributions in the reservoir will be obtainable, and it will become possible to include larger regions in simulations. This study has important ramifications for the improvement of reservoir simulators and will lead to better capabilities of the geothermal operator to manage the reservoir and predict future production.

PROJECT STATUS

Background

Declines in reservoir pressure and steam flow rates of wells at The Geysers geothermal field have created the need for enhanced research addressing the problem of reservoir management. It is clear that over the next few years, numerical modeling of injection and other processes will play an important role in finding remedies for the production and pressure declines, and to decrease detrimental concentrations of non-condensable gases and chlorides. Numerical modeling of The Geysers field requires the use of fracture/matrix models, commonly referred to as "double-porosity" or "dual-continua" models. These types of models are costly and time-consuming to run, because they generally require at least five matrix gridblocks for each fracture gridblock. Thus, for large-scale models, a prohibitively large number of gridblocks would be required for accurate simulations.

In our research we are developing semi-analytical methods for simulating fluid and heat flow processes that occur within the matrix blocks. These algorithms will then be incorporated into numerical reservoir simulators such as TOUGH developed by Pruess in 1987 and TETRAD developed by Vinsome in 1991, to serve as source and sink terms for the fracture grid blocks. Numerical simulations will then require that only the "fracture continuum" need be explicitly discretized. Since this method will eliminate the need for having many matrix grid blocks for each fracture grid block, the number of fracture grid blocks that can be included in a reservoir model will be substantially increased. This will allow finer resolution of the pressure and enthalpy distributions in the reservoir, and will also permit larger regions to be included in simulations. Since the fracture/matrix flow will be treated analytically, this portion of the simulations will contribute negligibly to the total computational time required.

Similar approaches have been used in other areas of subsurface flow. Chase and O'Dell in 1973 used approximate analytical temperature profiles in the cap and base rock layers above and below a petroleum reservoir in the simulation of thermal recovery processes, thereby eliminating the need to explicitly discretize these layers. Pruess and Wu in 1989 used approximate profiles within the matrix blocks to develop a semi-analytical dual-porosity model for single-phase reservoirs. Zimmerman and Bodvarsson in 1989 developed an analytical expression for one-dimensional absorption of water into two-phase (air and water) matrix blocks. This expression was then incorporated into the TOUGH simulator as a source/sink term for the fractures, and used for studying hydrological problems related to the proposed underground radioactive waste repository at Yucca Mountain, Nevada. Savings in computational time of about a factor of ten were obtained for various test problems.

Research Results

The first stage in our work was the development of a fracture/matrix interaction term for single-phase flow that would be more accurate than the widely-used Warren-Root equation, but without being appreciably more difficult to program or to calculate. The Warren-Root equation assumes that the flow is linearly proportional to the difference between the pressure in the adjacent fractures and the mean pressure in the matrix block. We use a nonlinear flow equation that reduces to the linear Warren-Root equation in the long-time limit, but which is much more accurate in the short-time limit. This coupling equation for a single matrix block was tested against analytical solutions for various types of boundary conditions by Zimmerman and others in 1992, and was found to be very accurate in all cases considered.

This nonlinear interaction equation was then incorporated into TOUGH as a source/sink term for the "fracture" gridblocks. In order to avoid the numerical instabilities that are typically caused by explicit numerical solutions to time-dependent problems, and to be consistent with the internal structure of TOUGH, this incorporation was done implicitly. This means that the fracture/matrix flow that occurs over the time interval $(t, t + \Delta t)$ is calculated based on the pressures that exist at time $t + \Delta t$. The modified version of TOUGH was tested on various problems, such as one-dimensional flow into a fractured formation under constant boundary pressure and radial flow from a well under constant flowrate. Comparisons were made with analytical solutions where possible, and with solutions obtained with TOUGH by discretizing the matrix blocks into concentric shells. In each case, the new approach was found to be more accurate than the Warren-Root method, and was found to require much less computational time than the fully-discretized numerical simulations.

Since heat conduction is governed by a diffusion equation that is mathematically analogous to that governing single-phase fluid flow, the approach outlined above was extended to the treatment of conduction effects within matrix blocks, and also incorporated into TOUGH. This modified version of TOUGH was tested against the results obtained by Pruess and Wu in 1989 for the problem of cold-water injection into a radially-symmetric fractured reservoir.

The next stage of our work entailed the extension of our approach to matrix blocks under two-phase conditions, but with an immobile liquid phase. In these situations, liquid can first flash to steam within the matrix block, and then be produced from the block as vapor. This process can also be modeled by a single diffusion equation, by using the concept of the effective compressibility of a rock-water-steam mixture, along with the relative permeability functions for the steam. This version of our semi-analytical dual-porosity code was tested on a problem involving a three-dimensional block-shaped reservoir containing a single injection well and a single production well. Physical parameters for the problem were chosen to be similar to conditions found at a vapor-dominated reservoir such as The Geysers. Pressures and enthalpies computed with the new method agreed very

well with those calculated using a fully-discretized computational grid.

Plans

Our semi-analytical treatment of flow processes occurring within the matrix blocks will be extended to the general case of two-phase conditions in which both phases are mobile. The algorithms for the various flow types (single-phase, two-phase with immobile liquid, two-phase with both phases mobile, heat conduction) will then be combined into a single robust algorithm that will be able to handle all cases. These algorithms will be implemented into the TOUGH code, as an option.

We also plan to work with representatives of the geothermal industry to facilitate the incorporation of these new methods into other geothermal simulators. TETRAD currently has provisions for treating fracture/matrix interactions using the quasi-steady-state Warren-Root type approach. Incorporation of our nonlinear coupling equation should be possible in a relatively straightforward manner. This incorporation can begin with the interaction equations for single-phase flow and for heat conduction, both of which have already been successfully incorporated into TOUGH.

REFERENCES

- Zimmerman, R. W., and Bodvarsson, G. S., 1989, An approximate solution for one-dimensional absorption in unsaturated porous media: *Water Resources Research*, v. 25, p. 1422-1428.
- Zimmerman, R. W., and Bodvarsson, G. S., 1992, Semi-analytical treatment of fracture/matrix flow in a dual-porosity simulator for unsaturated fractured rock masses: *Proceedings of the 3rd International High-Level Radioactive Waste Management Conference*, American Nuclear Society, April 12-16, p. 272-278.
- Zimmerman, R. W., Chen, G., and Bodvarsson, G. S., 1992, A dual-porosity reservoir model with an improved coupling term: *Proceedings, 17th Workshop on Geothermal Reservoir Engineering*, Stanford University, January 29-31, (in press).
- Zimmerman, R. W., Hadgu, T., Chen, G., and Bodvarsson, G. S., 1993, Development of a dual-porosity model for vapor-dominated fractured geothermal reservoirs using a semi-analytical fracture/matrix interaction term: *Proceedings, 18th Workshop on Geothermal Reservoir Engineering*, Stanford University, January 26-28, (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigators:

Robert W. Zimmerman	Phone: (510) 486-7106
Gudmundur S. Bodvarsson	Phone: (510) 486-4789
Earth Sciences Division, Mail Stop 50-E	
Lawrence Berkeley Laboratory	
Berkeley, CA 94720	
FAX: (510) 486-5686	

MODELING PERFORMANCE OF VAPOR-DOMINATED RESERVOIRS

Antonio C. Correa and Henry J. Ramey, Jr.
Department of Petroleum Engineering, Stanford University

KEY WORDS

The Geysers, fractured reservoirs, reservoir simulation, adsorption, condensation, vaporization

PROJECT OBJECTIVE

The objective of the research is to develop methods to forecast production of geothermal reservoirs including the effects of adsorption and capillary condensation in the rock matrix. This research project is of value to the geothermal industry in providing better methods to accurately predict the long-term performance of production at The Geysers and other fields.

APPROACH

The project involves two distinct subjects. The first part comprises the development of relationships between the water saturation in the rock matrix and the relative pressure, including effects of adsorption and capillary condensation. The second part focus on the development of methods for forecasting production by relating the cumulative reservoir mass production to the reservoir pressure. Determination of the model parameters may be made by either type-curve matching or regression analysis of field data.

PROJECT STATUS

Background

Adsorbed or condensed water can play a major role in the development of vapor-dominated geothermal reservoirs. Recent research has supported the idea that, although a vapor gradient can exist in the reservoir, large amounts of water may be stored in the rock matrix as a dense phase, physically or chemically adsorbed on the rock surface or condensed due to capillary effects.

Adsorbed or condensed water in the rock matrix vaporizes as the reservoir pressure drops. The vaporized water feeds the fracture network and keeps the steam production at nearly constant levels during a large part of the depletion process. However, after that portion of water condensed due to capillary effects has been vaporized, vaporization of the remaining adsorbed water is not enough to maintain a high ratio between mass withdrawal and pressure depletion.

Research Results

A mathematical model yielding a relation between water saturation and relative pressure has been developed. The model considers the case where both adsorption and capillary condensation phenomena take place simultaneously. In order to develop the model, we have assumed that the porous medium can be represented by a probability distribution of pore sizes.

The influence of the temperature on capillary condensation has been investigated. A modification of the Kelvin equation which considers the inaccessibility to vapor of pores of very small dimensions has been implemented. Computational results have been presented for the log-normal poresize distribution.

Plans

The next step in the course of the project is to use the model to match experimental results of adsorption isotherms. The parameters to be found can then be used in conjunction with field data to

forecast the reservoir performance, especially for The Geysers geothermal field.

REFERENCES

Nghiem, C. P., and Ramey, H. J., Jr., 1991, One-dimensional steam flow in porous media: Stanford Geothermal Program Technical Report 132, May.

Ramey, H. J., Jr., 1990, Adsorption in vapor-dominated systems: Geothermal Program Review VIII, April 18-20, San Francisco, CA.

CONTACTS

DOE Program Manager:

Marshall Reed

U. S. Department of Energy, CE-122

Washington, D.C. 20585

Phone: (202) 586-8076

FAX: (202) 586-5124

Principal Investigator:

Henry J. Ramey, Jr.

Department of Petroleum Engineering

Stanford University

Stanford, CA 94305-2220

Phone: (415) 723-1774

FAX: (415) 725-2099

WATER INJECTION INTO VAPOR-DOMINATED GEOTHERMAL RESERVOIRS

Karsten Pruess

Earth Sciences Division, Lawrence Berkeley Laboratory

KEY WORDS

vapor-dominated reservoirs, water injection, two-phase flow, numerical modeling, grid orientation effects, production interference, The Geysers, field data

PROJECT OBJECTIVE AND APPROACH

Water injection into vapor-dominated reservoirs gives rise to a complex interplay of two-phase flow and heat transfer processes, which are further complicated by the porous-fractured nature of the reservoir rocks. Realistic and robust numerical modeling capabilities are needed for engineering design and optimization of injection systems. The objective of this project is to develop such capabilities and demonstrate them through applications to field data. This work has direct relationship to the reservoir management of The Geysers field where it is important to obtain the maximum benefit from the limited water available for injection.

PROJECT STATUS

Background

Water injection into hot permeable media containing superheated vapor induces vaporizing two-phase flow. Numerical simulators capable of handling the strong non-linearities of such processes have been available since the late 1970s. However, subsequent applications have shown that a basic capability to simulate injection-induced fluid and heat flow processes does not necessarily guarantee that realistic results may be obtained in field situations. The fact that injected water is much denser than steam causes gravitational instabilities and makes two- and three-dimensional simulations of water injection very difficult.

Research Results

The basic aspects of the behavior of injection plumes in fractured vapor-dominated reservoirs were elucidated by Calore and others in 1986. The migration of boiling injection fronts was modeled mathematically, and has been used to verify numerical simulation of the process by Pruess and others in 1987. Subsequently the strong tendency for numerical artifacts in injection modeling has been demonstrated, and guidance has been developed for obtaining stable, meaningful results by Pruess in 1991. Our most recent work has focussed on explaining very peculiar data from the southeast Geysers that document strong injection-production interference. This ongoing effort has succeeded in identifying, in a quantitative way, the main fluid flow and heat transfer mechanisms that determine reservoir response to injection reported by Pruess and Enezy in 1993. It was shown that injection plumes are complex heat transfer systems, that simultaneously consume (condense) reservoir steam in some parts while generating additional steam by boiling in others. If injection is performed at large flow rates, then the negative (steam consuming) effects will outweigh the beneficial (steam generating) processes. The important practical application of these results is that injection should be performed in a distributed manner, limiting the flow rate of water injected into each particular injection well.

Plans

The dependence of negative and positive impacts of injection on reservoir conditions and fracture geometries will be explored in more detail to aid in optimizing the use of injection in long-term reservoir management. Efforts will be made to transfer advanced simulation tools and methods for engineering applications to the geothermal industry.

REFERENCES

Pruess, K., Calore, C., Celati, R., and Wu, Y. S., 1987, An analytical solution for heat transfer at a boiling front moving through a porous medium: International Journal of Heat and Mass Transfer, v. 30, no. 12, p. 2595-2602.

Pruess, K., 1991, Grid orientation and capillary pressure effects in the simulation of water injection into depleted vapor zones: Geothermics, v. 20, no. 5/6, p. 257-277.

Pruess, K., and Enezy, S., 1993, Numerical modeling of injection experiments at The Geysers: Proceedings, 18th Workshop on Geothermal Reservoir Engineering, Stanford University, January 26-28 (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Principal Investigator:

Karsten Pruess
Earth Sciences Division
Lawrence Berkeley Laboratory, Mail Stop 50-E
Berkeley, CA 94720
Phone: (510) 486-6732
FAX: (510) 486-5686

INVESTIGATIONS INTO THE FORMATION AND LONG-TERM BEHAVIOR OF A "HIGH TEMPERATURE RESERVOIR"

G. Michael Shook
Idaho National Engineering Laboratory

KEY WORDS

high-temperature reservoir, non-condensable gases

PROJECT OBJECTIVE

The overall objective of this project is to improve our knowledge concerning the behavior of a "high temperature reservoir" (HTR) of the type found in the northwestern area of The Geysers. This study seeks to improve our predictive capability regarding HTR exploitation. This work will be of great significance if it leads to better exploitation of the large potential resource in the High Temperature Reservoir.

APPROACH

This study will be accomplished by achieving the following research goals. We will evaluate reservoir parameters and conditions that lead to the formation of the HTR as a steady-state component of a "typical" vapor-dominated geothermal reservoir. After we have determined what conditions lead to the formation of the HTR, this study will investigate reservoir response to production and injection, especially regarding long-term behavior and changes in thermodynamic properties within the HTR. This study uses numerical analysis to consider the development of the HTR in the native state and seeks to improve our understanding of the nature of such a system.

PROJECT STATUS

Background

In some portions of The Geysers in northern California, and in other vapor-dominated geothermal systems throughout the world, a zone of anomalous temperature has been observed below the "typical" reservoir. This "high temperature reservoir" (HTR) is not identifiable on the basis of geophysical or petrophysical measurements. Nevertheless, certain reservoir characteristics are associated with the presence of the HTR. For example, non-condensable gas (NCG) concentrations are reported to be typically much higher in portions of the field in which the HTR is found. The relationship between the HTR and high NCG concentrations has yet to be established, however.

Little is known about the evolution of the HTR or its long-term response to production or injection. If the concentration of NCG is, in fact, associated with the HTR, we must be able to predict future concentrations as mass is withdrawn from the HTR. Given the higher temperature found in the HTR, it is also a tempting place for injection; however, we are again without knowledge on what reservoir response may be.

Research Results

A simple one-dimensional model was recently presented that demonstrated a set of conditions leading to the formation of the HTR. This model HTR was a steady-state component of a "typical" vapor-dominated reservoir, with characteristics similar to those reported by Drenick in 1986 and Walters and others in 1988. Many questions still exist regarding HTR formation and behavior. It is not observed at a constant depth field-wide. Is it a purely local phenomenon, or does it vary vertically? In 1993, Shook showed one set of conditions that lead to its formation. How dependent is HTR formation on those specific conditions? How will the HTR respond to production, and are there

added benefits to injection into this zone, relative to injection into "typical" reservoir?

Plans

This project seeks to answer the above questions using a carefully controlled set of numerical experiments. The study can be broken down into the following sequential steps. Beginning with the model developed by Shook in 1993, a parametric study will be undertaken to evaluate reservoir parameters and conditions that lead to HTR formation. This stage of the study will identify how readily the HTR can develop in the native state. The model will then be expanded into a two-dimensional vertical cross section in order to consider areal and vertical variations in HTR behavior. The issue to be resolved here is based on the observation that the HTR is not always found at the same depth field-wide. The model will be used to determine if the HTR is absent in some portions of the field, or if its depth varies across the field. The NCG information will be incorporated at this point in order to study the relationship between high NCG concentrations and the HTR. Reservoir response to production will also be investigated, and predictive models will be compared with observed behavior. Finally, the effects of injection into the HTR will be studied in order to quantify the possible benefits of such injection.

Ultimately, this project will allow us to develop a better understanding of the behavior of the HTR and better tools to predict HTR response to exploitation. Models will be developed that quantify HTR response in order to improve reservoir management of the resource.

REFERENCES

Shook, M., 1993, Numerical Investigations into the Formation of a 'High Temperature Reservoir': Proceedings, 18th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., January 26-28 (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigators:

G. Michael Shook
Idaho National Engineering Laboratory
Idaho Falls, ID 83415-2107
Phone: (208) 526-6945
FAX: (208) 526-9822

Joel Renner
Idaho National Engineering Laboratory
Idaho Falls, ID 83415-3830
Phone: (208) 526-9824
FAX: (208) 526-0969

HISTORICAL INJECTION IN THE GEYSERS

David D. Faulder and G. Michael Shook
Idaho National Engineering Laboratory

KEY WORDS

The Geysers, injection, reservoir simulation

PROJECT OBJECTIVE

The objective of this project is to conduct numerical studies of historical injection response in areas of The Geysers reservoir. Specific goals of the study are to (1) evaluate the injection response and develop explanations for the observed response, (2) evaluate the impact of different relative permeability and capillary pressure relationships, and (3) determine if a field-derived relationship could be developed to provide general guidelines for the selection and operation of future injection areas at The Geysers. A second objective is to explore alternative injection strategies such as lower rate, distributed injection, and a decrease in the ratio of injectors to producers. This work has major importance to the siting and operation of injection wells at The Geysers. A major benefit of this work will be a strategy to provide the most effective injection with the limited water available.

APPROACH

One of the fundamental operational problems at The Geysers is that the reservoir is undergoing continual depletion of the working fluid (water) in the heat engine (reservoir). In order to prolong the economic life of the reservoir, it is necessary to optimize the utilization of the limited amount of water available for reinjection. Optimization involves the timely and rapid conversion of the reinjected water into steam and the return of this steam to nearby production wells. The approach used in this study combines an examination of the available information for an injection well and the nearby producers with the analysis of reservoir structure and interpreted flow paths.

PROJECT STATUS

Background

Reservoir simulation models of the Unit 13 area and a portion of the northwest Geysers are being developed. The Unit 13 study area incorporates an area of approximately two square miles, with over 20 production wells and two historical injection wells, see Figure 1. Attention was paid to the mapped geologic structure and shape of the reservoir. The total thickness of the reservoir model was chosen so that its upper boundary is the top of steam and its lower boundary is the top of felsite. Injection related micro-seismic response in the adjacent NCPA area strongly suggests that the top of felsite acts as a barrier to flow, at least in the southeastern Geysers.

One advantage of the Unit 13 area is that a fairly complete injection-water isotopic tracer data set exists. Deuterium and oxygen-18 were monitored in the produced steam for over eleven years, providing an important data set with which to constrain injection modeling efforts and to correlate injection-derived steam recovery. Secondly, the study area has been well documented in the literature, providing a ready source of information for comparison to model results. The specific northwest Geysers area was selected because of the presence of a high-temperature reservoir and the relatively short production history.

One of the major areas of uncertainty in reservoir simulation of The Geysers reservoir, is the selection of appropriate relative permeability and capillary pressure relationships. These fundamental fluid flow properties have not been measured or reported in the literature. Yet modeling results are heavily

influenced by this choice. If an expanded injection program is to be undertaken at The Geysers, one criterion that must be satisfied is our ability to confidently model and predict the process of reinjection, revaporization, and production of injection-derived steam.

Research Results

A. Unit 13 Area:

The initial model setup incorporated all relevant data about the study area and placed all study wells on a rate constraint to produce the correct historical mass production and injection. A three-component system (an artificial tracer was added) was used to track the movement of the in-situ steam and the water reinjected into each of the two injection wells. This allowed detailed tracking and determination of injection-derived steam (IDS) due to each well, and a method was provided for the quantitative calculation of IDS efficiency.

This initial study demonstrated that IDS efficiency is strongly influenced by reservoir shape and structure. It was clearly shown that cold water injection in a vapor-dominated reservoir results in fluid migrating down gradient on the bottom of the reservoir. This result is not surprising, however, it does explain a great deal about the observed isotopic ratios in the produced steam of wells in the Unit 13 area.

As noted above, two injection wells were utilized in the study area. The first well, I-1, started injection at the onset of the project. Five years later, injection was split with a second well, I-2, which was located down structure from I-1. The simulation results clearly demonstrated that by the time I-2 started operation, injectate from I-1 had already migrated to the area of I-2, cooling this area and greatly diminishing the effectiveness of water vaporization to steam in the second injection location.

While both wells had approximately the same cumulative mass injection, model results indicate that recovery of IDS from I-1 was approximately three to four times greater than from I-2. What this implies is that the selection of injection locations should include a consideration of the interpretation of the shape and geometry of the bottom of the reservoir and any identified low permeability areas.

The modeling of Unit 13 showed that the recovery of IDS is strongly influenced by the choice of capillary pressure that is used in the model. As stronger capillary functions were used, the recovery of IDS increased, and the model again showed that production wells recovered much more of the water injected in I-1 than that injected in I-2.

B. Northwest Geysers:

The study in the northwest Geysers is less advanced than the Unit 13 study. Initial runs have been made to establish the pre-exploitation reservoir and a limited number of runs have been made modelling the production history. Reasonable matches have been made to the data developed by GeothermEx for the Technical Advisory Group.

Plans

As noted above, this portion of the study relied on a rate-constrained approach to well rates. In order to better understand injection response an additional model study is currently underway to place all wells on a pressure constraint. This technique allows better insight into the parameters that impact IDS recovery. An excellent history match has recently been obtained using a pressure-constraint approach for all the production wells. This match utilized a Corey exponent of 2 for the relative permeability relationship. This exponent will be varied to determine its impact on the quality of the history match. A second objective is to examine alternative injection practice and locations and the

influence of rate on injection recovery. Finally, the results of this effort will be documented and reported.

REFERENCES

Faulder, D. D., 1992, Model study of historical injection in the southeast Geysers: Proceedings, 17th Workshop on Geothermal Reservoir Engineering, Stanford University (in press).

CONTACTS

DOE Program Manager:

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

DOE Project Manager:

Robert Creed
DOE, Idaho Field Office
Idaho Falls, ID 83415
Phone: (208) 526-9063
FAX: (208) 526-5964

Principal Investigators:

David D. Faulder	Phone: (208) 526-0674
G. Michael Shook	Phone: (208) 526-6945
Idaho National Engineering Laboratory	
Idaho Falls, ID 83415-2107	
FAX: (208) 526-9822	

Joel Renner
Idaho National Engineering Laboratory
Idaho Falls, ID 83415-3830
Phone: (208) 526-9824
FAX: (208) 526-0969

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