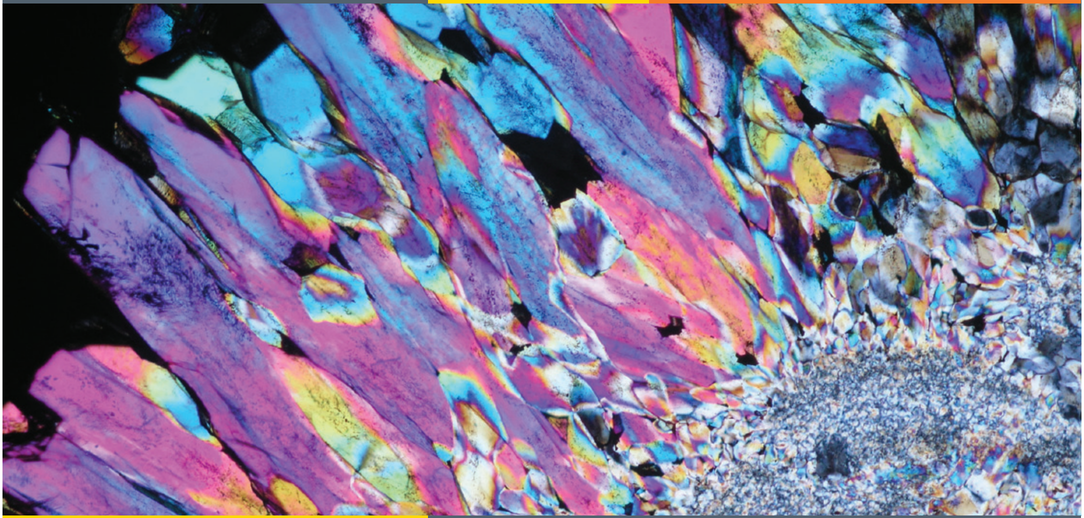
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

GEOTHERMAL TECHNOLOGIES PROGRAM



Exploration
1976 – 2006

A History of Geothermal Energy Research and Development in the United States

Cover Photo Credit

Photomicrograph of quartz sampled from a depth of 948 feet in Lake City Observation Hole-1, Lake City geothermal system, California. The image was taken under crossed nicols. The vibrant birefringence colors are due to the section being extra thick. The field of view is 0.07 inches across. (Courtesy: Joseph N. Moore)

This history of the U.S. Department of Energy's Geothermal Program is dedicated to the many government employees at Headquarters and at offices in the field who worked diligently for the program's success. Those men and women are too numerous to mention individually, given the history's 30-year time span. But they deserve recognition nonetheless for their professionalism and exceptional drive to make geothermal technology a viable option in solving the Nation's energy problems. Special recognition is given here to those persons who assumed the leadership role for the program and all the duties and responsibilities pertaining thereto:

- Eric Willis, 1976-77
- James Bresee, 1977-78
- Bennie Di Bona, 1979-80
- John Salisbury, 1980-81
- John "Ted" Mock, 1982-94
- Allan Jelacic, 1995-1999
- Peter Goldman, 1999-2003
- Leland "Roy" Mink, 2003-06

These leaders, along with their able staffs, are commended for a job well done. The future of geothermal energy in the United States is brighter today than ever before thanks to their tireless efforts.

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Preface

In the 1970s, the publicly available information about geothermal systems was woefully inadequate. The understanding of geothermal resources and the means for their optimum development was primitive. Much of the extant information was held in private company files. Lack of information meant only a few companies invested in exploration and resource development. Utilities did not understand the geothermal resource, especially the risks and costs of development, and they were therefore reluctant to sign long-term geothermal power purchase agreements. For the same reasons, financial institutions were wary of funding geothermal energy projects. Development of the large resource base in the United States, apart from The Geysers in California, was essentially stagnant. This was the environment in which the U.S. Government's geothermal research and development (R&D) program began.

The intent of the geothermal program was to understand geothermal resources, improve geothermal science and engineering technology, and ensure that information was publicly available to geothermal stakeholders, such as developers, utilities, financial institutions, regulators, and others necessary to spur development of a vital, progressive geothermal industry. As this report will demonstrate, the intent was achieved, to the benefit not only of geothermal energy development in the United States but also around the world.

This report is one of a series issued by the U.S. Department of Energy (the Department) to document the many and varied accomplishments stemming from the Government's sponsorship of geothermal research since 1976. The reports represent a history of the major research programs and projects that have had a lasting impact on the use of geothermal energy in the United States or which promise to have an impact. We have not attempted to write the definitive history of the Geothermal Program and the $1.3 billion that were expended through 2006 on geothermal research. Rather, we have brought together the collective memories of those who participated in the program to highlight advances which the participants deem worthy of special recognition.

In particular, this report examines the work done in one key area of geothermal technology development: Exploration. Companion reports cover work in other areas, including Energy Conversion, Drilling, and Reservoir Engineering. The history focuses on the period 1976-2006, when the Department of Energy was the lead agency for geothermal technology research as mandated by the Geothermal Research, Development and Demonstration Act of 1974. The earlier, groundbreaking work by precursor agencies, such as the National Science Foundation, Atomic Energy Commission, United States Geological Survey, and the Energy Research and Development Administration, is cited as appropriate but is by no means complete.

Those wishing to learn more about certain topics discussed herein should consult the references listed in the report. These sources give the reader access to a much larger body of literature that covers the topics in greater detail. Another useful source of information about the Department's geothermal research can be found in the Geothermal Technologies Legacy Collection (www.osti.gov/geothermal/) maintained by the Office of Science and Technology Information.

The budget history of the federal geothermal research program during the 30-year period documented here is included as Appendix A. That portion of the budget devoted to exploration is highlighted and amounts to about $190 million in actual dollars. Funding for work in exploration ended in fiscal year 2006 with a decision by the Department to refocus limited funding resources on higher priority needs within the Office of Energy Efficiency and Renewable Energy. That decision did not preclude future work in this area, as the needs for geothermal technology development are assessed. This report summarizes the products and benefits of that earlier research investment.

Acknowledgements

While the many contributors to U.S. Department of Energy-supported geothermal exploration research and development over the years are too numerous to acknowledge by name, we wish to mention those who participated in writing this report. The primary authors were Joseph N. Moore, Howard P. Ross (retired), and Phillip Michael Wright (retired) all of the Energy & Geoscience Institute, University of Utah. Contributing authors included Clayton R. Nichols (retired), U.S. Department of Energy; Paul Kasameyer (retired), Lawrence Livermore National Laboratory; and Joel Renner (retired), Idaho National Laboratory. Elizabeth C. Battocletti served as the report's technical editor. These persons deserve credit for assembling a history of impressive accomplishment that will continue to reap benefits for many years to come. To the individuals whose efforts are not specifically identified in this report, the Department and authors offer their sincere gratitude.

Introduction

This report summarizes significant research projects performed by the U.S. Department of Energy (DOE)[1] over 30 years to overcome challenges in exploration and to make generation of electricity from geothermal resources more cost-competitive. At the onset of DOE's efforts in the 1970s, several national laboratories, universities, and private contractors conducted exploration research. Beginning in the late 1970s, this research was undertaken largely by the Lawrence Berkeley National Laboratory (LBNL), the Lawrence Livermore National Laboratory (LLNL), and the Earth Science Laboratory of the University of Utah Research Institute (ESL/UURI). In addition, the Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), and Sandia National Laboratories (Sandia) also performed exploration research. Throughout the years, many other groups, including the Great Basin Center for Geothermal Energy at the University of Nevada, Reno, geothermal developers and consulting groups, the U.S. Geological Survey (USGS), and state geological surveys contributed to the program.

Beginning in the early 1970s, DOE supported research to develop solid scientific underpinnings and new technology to locate and characterize geothermal resources. This research has greatly advanced the state of geothermal science and technology, benefitting the development of this clean, plentiful, renewable energy resource in the United States and around the world. At the end of 2007, the installed electric generating capacity from geothermal energy worldwide was 9,728 megawatts-electric (MWe).[2] In the United States alone, the installed electric generating capacity at the end of 2008 was 2,960 MWe,[3] nearly a six-fold increase in generating capacity since the DOE Geothermal Program began. An additional 29,000 megawatts-thermal (MWt) from geothermal resources worldwide is used for bathing, space heating and cooling, agriculture, aquaculture, industrial processes, and geothermal heat pumps.[4] Despite this level of development, however, the worldwide geothermal resource base is vastly underutilized today.

DOE's goal in geothermal energy research has been to decrease the costs and risks of economically utilizing geothermal resources primarily for electrical power generation. A linchpin of DOE's approach to realizing their goals has been strong working relationships with the private sector. Program priorities have been driven by the technical barriers to economically viable geothermal development as identified by the industry, as well as the results of economic sensitivity modeling to identify those elements in the geothermal development process with the greatest potential for lowering costs and risks.

Initially, the industry identified lowering well-field costs and improving drilling technology as two high priority areas for research. DOE's geothermal drilling research and development (R&D) program is covered in a companion report. DOE supported R&D in exploration whose purpose was to more quickly locate resources in the subsurface and to more reliably site exploration and reservoir confirmation boreholes, production wells, and injection wells. The strong cooperative working relationship with the private sector has fostered efficient technology transfer, resulting in rapid implementation of research advances.

Early in DOE's program, the public information base for high-temperature geothermal areas was woefully inadequate. Lack of information inhibited new resource companies from investing in exploration and resource development, and prevented utilities from understanding the geothermal resource and the risks and costs of its development. Utilities were therefore reluctant to sign geothermal power purchase agreements. Due to this lack of information, lending institutions were also wary of funding geothermal energy projects. This was the environment in which DOE's initial geothermal R&D began in the late 1970s.

In 1977, DOE initiated the Industry-Coupled Drilling Case Studies Program, discussed more fully in Section 2.1. The objectives of this program were to: 1) accelerate exploration of new high-temperature areas by furnishing a cost-share for the drilling of reservoir-confirmation boreholes, and 2) obtain data held as confidential in company files for public release. In exchange for the cost-share, the company proposed a data package which DOE could use in its research and release in open file.

The Industry-Coupled Drilling Case Studies Program was an outstanding success in meeting its objectives. Of the 14 areas explored under the program, eight were subsequently developed by the private sector, producing 137 MWe of baseload power today. The eight areas are Roosevelt Hot Springs and Cove Fort-Sulphurdale in Utah, and Beowawe, San Emidio, Soda Lake, Stillwater, Dixie Valley, and Desert Peak in Nevada. In each of these areas, geological, geochemical, and geophysical surveys were carried out by DOE researchers to supplement the company data packages, and detailed case studies were published. The large amount of data resulting from the program, as well as other similar programs, helped utilities and the financial sector better understand high-temperature systems and feel more comfortable in dealing with geothermal developers.

While the majority of this report focuses on high-temperature geothermal resources, part of DOE's exploration program was directed toward low- to moderate-temperature resources. DOE supported exploration and resource definition for systems suitable for direct use through the State-Coupled Geothermal Mapping Program, described in Section 3.1. As a result of this program, the inventory of known geothermal occurrences in many states was vastly expanded, resulting in a more comprehensive view of the total geothermal resource base in the United States. The State-Coupled program also built state-level expertise in geothermal energy and its potential uses.

DOE exploration activities focused primarily on the western United States. However, in the late 1970s, DOE supported limited exploration of the eastern U.S., specifically verification of a geologic model developed by scientists at Virginia Polytechnic Institute and State University (VPI). In parts of the Atlantic coastal plain, granitic intrusions containing naturally occurring radioactive uranium, thorium, and potassium are known from surface outcrops. Decay of the radioactive elements in these granites produces heat. VPI researchers postulated that buried granites having similar characteristics also existed, covered by thermally insulating sedimentary rocks such as shales. If the radioactive mineral content of these granite plutons were high enough and the thermal blanket good enough, temperatures in the granites might exceed 150°C (302°F), sufficient to generate power.

DOE funded drilling of 50 wells, each about 300 meters (1,000 feet) deep, to determine geology, measure thermal gradients with depth, and calculate heat flow in the Atlantic Coastal Plain from New Jersey to southern Georgia. In 1979, a large-diameter, 1,220-meter deep well (4,000 feet) was drilled near Crisfield, Maryland to test a heat-flow anomaly detected by the VPI program. The test well encountered an aquifer with a temperature of 56°C (133°F) at total depth (TD). Although this well failed to find a commercial resource, the VPI model is still considered valid from a geologic viewpoint. Exploration to find other buried granites in the eastern U. S., followed by drill testing may be warranted in the future.

Throughout much of the 1980s, DOE did not identify geothermal exploration research as a separate program per se; exploration elements were included under the reservoir engineering program. The reasoning was that similar or identical techniques could be useful both for exploration and to delineate and characterize geothermal reservoirs. As a result, DOE funded continuous research in geological, geochemical, and geophysical techniques in geothermal areas even though that funding came from various geothermal programs.

Beginning in 1985, DOE and the U.S. geothermal industry undertook cost-shared drilling of five deep exploration core holes in the High Cascades province in Oregon. The presence of active volcanism and the high measured temperature gradients with depth in existing wells argued strongly that the area has potential for large, high-temperature hydrothermal convection systems. The theory, still widely held, was that downward migration of cold meteoric water in the Cascades Mountains suppressed surface thermal manifestations, concealing hydrothermal systems. Many occurrences of thermal springs on the margins of the Cascades were thought to be lateral outflow from these hydrothermal systems. The objectives of DOE's program were to: 1) accelerate exploration of the region by cost-sharing exploration drilling with the private sector; 2) obtain samples and data to characterize the deep hydrothermal environment; and 3) develop analytical and interpretive tools to help industry locate and evaluate geothermal reservoirs in young volcanic regions in general. The program is described in Section 2.3.

From the beginning of DOE's geothermal exploration program, industry-coupled exploratory drilling and field verification of new technology were high priorities. More recently, the DOE-sponsored Geothermal Resources Exploration and Definition (GRED) program helped to identify and verify the performance of new resources. DOE made a total of 26 contract awards under the GRED program. A total of 14 slim holes were drilled, leading to numerous production-sized wells being drilled; several of the projects have power purchase agreements associated with them. GRED I, II, and III programs are covered in Section 2.4

DOE's exploration research program also supported cooperative work with geothermal developers from other countries where the benefits of doing so were clear. In many, but not all cases, the developer involved was a U.S. company. One requirement for such support was that geothermal data and subsurface samples would be released for use and publication by DOE researchers. This research on foreign geothermal systems enabled the program to develop a much broader range of information on the nature and occurrence of geothermal energy than would have been possible from the study only of U. S. occurrences. The results of this work are presented in several sections of this report.

As a result of DOE's long history of cooperative work with the private sector, thousands of technical papers have been published in a wide variety of journals. Geothermal reports were issued by most of the DOE national laboratories, universities, state agencies, and geothermal companies. Drill cuttings and core samples obtained during the research were stored at the Geothermal Sample Library at the Energy and Geoscience Institute (EGI) at the University of Utah — currently the largest existing repository of geothermal samples, containing more than 1.3 million meters (4.3 million feet) of core and cuttings. The collection contains samples from every high-temperature geothermal system in the western United States, as well as important systems in Canada, Mexico, Guatemala, Indonesia, and the Philippines. The EGI Geothermal Sample Library has been and remains an important resource for researchers.

Accomplishments and Impacts

Table 1 summarizes the major advances resulting from DOE R&D in geothermal exploration from 1976 through 2006. They are not ranked in any particular order of importance or priority. Each has made a contribution to fulfilling the federal geothermal exploration R&D program's goals and objectives.

Table 1. Major advances resulting from the Department of Energy's geothermal exploration research and development program, 1976 – 2006

Technical Area	Accomplishment	Significance	Industry Measure
Industry Cooperative Exploration and Drilling	The industry was encouraged to move ahead with drill-testing of high-temperature geothermal areas by DOE's cost-share for drilling confirmation wells. A very large amount of new data was generated, interpreted, and released to the public. Numerous geological, geochemical, and geophysical methods were tested, adapted, and improved specifically for the geothermal environment. Samples of drill cuttings and cores from geothermal systems have been preserved at EGI, and this collection has been used by researchers from the public and private U.S. sectors and by foreign researchers.	Industry's exploration was accelerated, and the new public knowledge enabled both the utility industry and the financial sector to feel more comfortable in participating in projects for geothermal power generation. New exploration technology developed under this program has allowed the private sector to explore for, locate, confirm, characterize and drill into subsurface resources much more cost effectively than was possible before.	Industry was able to bring online 8 of the 14 geothermal power plants studied in the Industry-Coupled Case Studies Program, the initial program under this umbrella. As the program continued with the GRED program, an additional 6 sites have been explored and new power plants are being considered at several of these sites.

Technical Area	Accomplishment	Significance	Industry Measure
State Cooperative Programs	A comprehensive inventory of geothermal resources was prepared and published in the form of maps and reports for 26 states. This work expanded the number and extent of known geothermal resource areas. Geothermal expertise was developed in each of the involved states for provision of assistance to potential developers of resources of all temperatures.	The data and maps resulting from this program have spurred development of low- and moderate-temperature applications throughout the West. The maps produced by this program are used today for land-use planning by federal, state, and local governments.	The state geothermal maps provide one base used by the industry to plan geothermal exploration, and to delineate areas having geothermal potential. Direct use of geothermal resources has been accelerated in the entire western and several central states since the inception of the State Cooperative programs.
Selected Hydrothermal System Studies	Geothermal environments studied included volcanic ocean islands, the Basin and Range, the Salton trough, and the environment hosting The Geysers field, among others. DOE researchers performed exploration surveys and compiled databases allowing detailed subsurface reservoir models to be constructed for several geological environments. In conjunction with comprehensive system studies, various geological, geochemical and geophysical techniques were tested and improved.	These studies serve as a basis for understanding the character of geothermal systems in diverse geologic regimes. They also provide the necessary database for evaluating and improving exploration techniques for specific environments.	The studies have been used by industry to help guide development and management of such geothermal fields as The Geysers, Salton Sea, Dixie Valley and others.

Technical Area	Accomplishment	Significance	Industry Measure
Geological Technique Development	Researchers performed detailed geologic mapping in the Basin and Range province and demonstrated their utility to forming subsurface exploration models. Studies documented the importance of mapping the distribution of hydrothermal alteration in 3 dimensions on understanding the permeability distribution and fluid flow, and on its effect on geophysical measurements. Conceptual models of volcanic-hosted geothermal systems were developed.	Understanding the evolution and flow paths in geothermal systems is important for guiding exploration and the successful management of developed fields. Remote sensing techniques allow rapid regional and site specific collection, and interpretation of geologic information.	Industry has used these models for successful exploration in volcanic-hosted systems. Industry utilizes remote sensing techniques in ongoing exploration projects.
Geochemical Technique Analysis	Researchers developed the application of fluid-inclusion analyses to understanding the evolution of hydrothermal systems, and demonstrated the use of these techniques in forming better system models. Trace element distributions and soil gas fluxes over geothermal systems have been measured. Analyses of helium isotope distribution in the Basin and Range have been published.	Fluid inclusions are one of the few tools available to interpret the thermal and fluid chemistry history of geothermal systems. The data document a relationship between surface chemistry and active faults and indicate where hydrothermal convection is a possibility. Helium isotopes suggest that some geothermal systems in the Basin and Range may have fluid circulation from depths as great at the mantle.	Industry now uses fluid inclusion studies to determine the evolution of geothermal systems. Industry routinely uses soil surveys as an exploration tool. Helium isotope studies can be used to locate deeply penetrating fault zones. Additional benefits are likely in the future from these data.

Technical Area	Accomplishment	Significance	Industry Measure
Geophysical Technique Development	DOE researchers performed geophysical surveys in more than 50 geothermal areas for the purpose of testing and improving techniques. Computer-based modeling programs were developed for high-priority methods to quantify interpretation of geophysical data and better develop geological and geochemical models of the subsurface. Techniques developed and tested for geothermal application include seismic, aeromagnetic and magnetic, gravity, thermal, electrical, borehole geophysics, well-logging, radar, and global positioning systems (GPS).	Improvements in geophysical techniques resulting from DOE-funded research have vastly extended the capabilities of geophysical techniques to delineate and characterize geothermal systems and have improved the cost-effectiveness of these techniques.	Industry routinely utilizes the improved geophysical tools and interpretation methods for exploration. Magnetotelluric surveys have become the electrical method of choice for the exploration of high temperature geothermal systems. Their application to lower temperature systems is being tested.
Exploration Strategies	Strategies for exploration were developed and published, primarily for the Basin and Range province.	Such exploration strategies are important especially for newcomers to geothermal exploration to create exploration programs, having the highest benefit to cost ratio.	Industry has utilized many of the methods and strategies to find new geothermal resources.

Technical Area	Accomplishment	Significance	Industry Measure
National and Regional Resource Assessments	DOE co-funded USGS assessments of the geothermal potential of the United States in 1975, 1978, and 1982.[5]	These resource assessments provide industry and the government with definitive information on the amount of both identified and undiscovered geothermal energy in the United States. The assessments have included both high-temperature resources >150°C (>302°F) and lower-temperature resources <150°C (<302°F), as well as energy contained in the earth's crust to a depth of 10 km, both in magmatic systems and as a result of the normal increase of temperature with depth.	The assessments have been extensively used by the geothermal industry in making decisions about investing in geothermal energy development and in targeting exploration areas in the United States.
Magma Energy Program	DOE-funded researchers developed a theoretical basis for mining energy from magma, and did extensive field testing, including drilling a borehole into and producing energy from the lava lake underlying the crater at Kilauea Iki in Hawaii.	Energy contained in magmatic systems in the U.S. to a depth of 10 km is estimated to be between 50,000 and 500,000 Quads. If even a fraction of this enormous amount of energy could be harvested for mankind's use, the impact would be very significant.	The private sector has not yet undertaken development of magma resources.

Major Research Projects

While this document briefly discusses research done in the 1970s, primary emphasis has been placed on work done beginning in the 1980s, in 10 specific areas pertaining to geothermal exploration:

1. Early Studies.
2. Industry Cooperative Exploration and Drilling.
3. State Cooperative Programs.
4. Selected Hydrothermal System Studies.
5. Geological Technique Development.
6. Geochemical Technique Analysis.
7. Geophysical Technique Development.
8. Exploration Strategies.
9. National and Regional Resource Assessments.
10. Magma Energy Studies.

In general, the research summarized in each of these areas is cited in chronological order.

1.0

Early Studies

Spurred by the energy crisis of the 1970s, the DOE exploration technology research program evolved from consolidating individual geothermal initiatives being conducted by several federal agencies. The Department of Interior—through the U.S. Geological Survey, the Bureau of Mines, and the Bureau of Reclamation—conducted geothermal research prior to the passage of the Geothermal Steam Act of 1970. With passage of the Steam Act, along with increased interest by a nascent U.S. geothermal industry, the Atomic Energy Commission (AEC), a precursor to DOE, advanced research into geothermal technologies and established geothermal resource utilization programs at Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Idaho National Engineering Laboratory (now INL).[6]

In 1972, Aerojet Nuclear Corporation, the operating contractor for AEC at the National Reactor Test Station (NRTS) near Idaho Falls, Idaho, began exploring the potential for geothermal energy demonstration projects. Recognizing that successful geothermal site selection and reservoir characterization depended on expertise in exploration technology that AEC contractors lacked, Aerojet partnered with the USGS and Boise State University (then Boise State College) to provide technical assistance for exploration technology and resource definition research to support its demonstration project aspirations.

Some of the AEC's early work dealt with a concept to artificially create geothermal reservoirs by fracturing underground rock at depths of thousands of feet using nuclear devices. The concept originated in the Plowshare Project, a federal effort to demonstrate peacetime uses of nuclear explosives, and involved mining both the natural heat of the Earth and the residual heat from the nuclear explosion using fluids injected for heat recovery. The theory that nuclear explosions would create extensively fractured volumes of rock was shown to be false. Instead, the nuclear explosions created a cavity in the location of the explosive and greatly compressed the rocks outside the cavity with significantly reduced permeability and porosity. Little fracturing occurred outside the zone of compression. With the creation of the Energy Research and Development Administration (ERDA) in 1975, the Plowshare program was terminated before any possible geothermal application could be demonstrated. Other aspects of AEC's geothermal programs, however, were dramatically expanded, and are described in the companion report on DOE's reservoir engineering R&D program.

Geothermal programs at the National Science Foundation (NSF), the Bureau of Mines, and the Bureau of Reclamation were consolidated into the AEC to form the ERDA Geothermal Program. In 1975, ERDA and the USGS, recognizing the value of close collaboration between the two agencies in geothermal research, agreed to work together to use ERDA pilot demonstration projects as case studies in exploration technology. The Raft River Pilot Project resulted from this agreement, becoming a showcase for the development and application of USGS exploration expertise. Cooperative projects initiated at Raft River and Boise, Idaho involved significant exploration technology development and applications, and were later incorporated into ERDA. The geothermal program grew further in 1977 with the establishment of the U.S. Department of Energy (DOE), at which time federal geothermal research was transferred from ERDA to DOE.

In response to the federal government's national goal of developing alternate energy sources in the early 1970s, Lawrence Berkeley National Laboratory (LBNL) conducted a brief (1975–1979) assessment of sites in northern Nevada for a proposed geothermal electrical generation demonstration plant. Researchers thought that demonstrating the viability of geothermal power generation would encourage the private sector to move forward on its own. LBNL's program included efforts to develop and improve existing geophysical exploration methods, i.e., electrical, electromagnetic, and seismic techniques. Testing and verification of the results were conducted at various other geothermal sites as part of this resource assessment, including in Mount Hood and Klamath Falls, Oregon.

LBNL also conducted geophysical studies at Cerro Prieto in Baja California, Mexico in an integrated geophysical program under a joint U.S.-Mexico agreement. The geophysical work helped define reservoir boundaries, determine reservoir rock parameters, and launch seismic and subsidence monitoring of the Cerro Prieto field. At the same time, LLNL undertook geologic investigation of the Salton Sea field in southern California as part of a program to assist in developing energy conversion systems for the hyper-saline fluids.

During the 1970s, the geothermal industry was largely dominated by petroleum companies who were using exploration tools and techniques modified from the petroleum and mining industries. Unocal had exploration success in locating geothermal prospects with drilling of temperature gradient holes as deep as 500 meters (1,600 feet). Other exploration companies also used this technique, and thousands of holes were drilled in the western United States. Companies were looking for large geothermal reservoirs capable of 250 MWe or more of electrical generation at depths of less than 2,000 meters (6,000 feet).

2.0

Industry Cooperative Exploration and Drilling

One of the prime objectives of the DOE geothermal exploration research program was to help lower the costs of geothermal exploration and production drilling. In close cooperation with the private sector, programs were undertaken to 1) improve drilling technology; 2) more effectively select drill sites to decrease the incidence of unproductive or otherwise failed wells; and 3) share the cost of drilling, especially for reservoir confirmation wells, and thus decrease up-front expenditures. Research to improve drilling technology is covered in the companion report on Drilling. Programs to address the second and third objectives are described in this report.

2.1 The Industry-Coupled Case Studies Program

Prior to the Industry-Coupled Case Studies Program, information in the public domain about high-temperature geothermal systems was limited in two ways. First, on a regional scale, the locations of resources outside of The Geysers field in California were little known. Second, on a site-specific scale, data on the lateral extent, depth, temperature, and productivity of individual resources were largely kept private by companies. Given the competitive nature of geothermal development, this situation was entirely understandable. At the same time, however, a lack of public data caused problems for utilities with which the developers were trying to negotiate power purchase agreements since the utilities had no objective way to judge the viability of specific geothermal systems as reliable energy sources. In addition, the financial sector was reluctant to make loans for resources with which they had little information or experience.

DOE initiated the Industry-Coupled Case Studies Program in 1978 to help private industry accelerate the pace of developing high-temperature geothermal resources. The program was designed to offset high initial development costs by reducing the financial risks inherent in exploration and reservoir confirmation through cost-shared drilling with industry partners. An important additional feature of the program was the study and publication of data from high-temperature hydrothermal convection systems. In order to participate, companies had to propose a data package pertaining to the area being drilled that could be released publicly. Prior to the Industry-Coupled program, much of the data on high-temperature hydrothermal systems was proprietary and held in private company files. The program shared drilling costs for new holes and purchased data from specific prospects or wells that had already been drilled.

Under the Industry-Coupled program, DOE researchers studied specific areas and topics in-depth to aid exploration and development, assess and improve existing exploration technology, and increase general knowledge of geothermal reservoirs. The University of Utah Research Institute (UURI, now the Energy and Geoscience Institute [EGI]) at the University of Utah provided scientific expertise to the program. This group comprised scientists with mineral-industry experience who applied their knowledge to the closely related geothermal environment. Other universities and the national laboratories participated as well. All technical data obtained under the program were provided to DOE for publication. In addition, a substantial amount of previously existing data, generally emphasizing early-stage exploration in the areas in question, were acquired and published.

Geothermal investigations were conducted at 14 sites in Utah and Nevada. Exploratory wells and thermal gradient holes were drilled; new and existing geological, geochemical, and geophysical data acquired and compiled. Interpretation techniques were developed and honed on this large data set. The information was quickly published as open-file reports and later in peer-reviewed literature. As a result, more than 50 topical reports were generated, more than 12 exploration techniques evaluated, 15 deep exploration wells drilled, and 25 drilling histories written. All of the data generated during the program, including company exploration data packages and core and cutting samples from cost-shared and other wells, were released to the public. They are preserved and still available at EGI. A summary of the data placed in the public domain as a result of the Industry-Coupled Case Studies Program is presented in Table 2. A detailed inventory of these data, as well the data itself, may be obtained by contacting EGI.[7]

*Key For Companies In Table 2:

AO = Aminoil USA Inc.
EP = Earth Power Production
SR = Southland Royalty Co.
AM = AMAX Exploration
G = Getty Oil Co
U = Union Oil Co.
C = Chevron Resources Co.
P = Phillips Petroleum Co.

^ Companies active at Roosevelt Hot Springs:
Getty Oil Co., Philips Petroleum Co., Thermal Power Co., AMAX Exploration

Table 2. Publically-Available Data Gathered Under the Industry-Coupled Case Studies Program

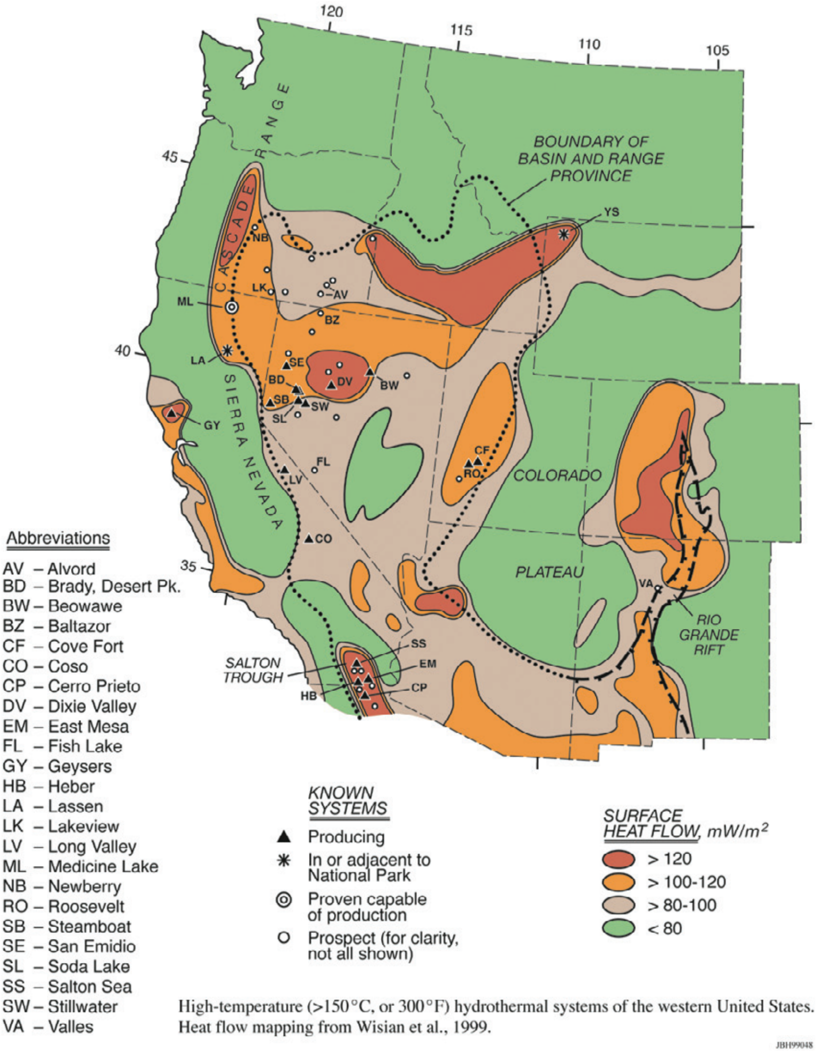
E = existing data;

X = generated from program;

R = UURI case-study investigation

	Baltazor	Tuscarora	McCoy	Leach H.S.	Colorado	Beowawe	Beowawe	San Emidio	Soda Lake	Stillwater	Dixie Valley	Desert Peak	Humboldt House	Cove Fort – Sulphurdale (UT)	Roosevelt H.S (UT)
Company*	EP	AM	AM	AO	G	G	C	C	C	U	SR	P	P	U	^
Gravity	ER	X	X	E	E	X		E		E		E	E	E	
Ground Magnetic Survey					E	X						E			
Aeromagnetic Survey	E	X	X				E				E			E	E
Electrical Resistivity	R														
Magnetotelluric Survey		RX	X	X	E		E		E	E	E	E	E		
Audiomagnetotelluric Survey					E										
Self Potential	R	X	X				E	E							
Seismic Emission Monitoring							E	E						E	X
Micro-Earthquake Surveys	E	X	X				E								
Seismic Reflection Survey (weight drop)							E		E					E	
Seismic Reflection Survey (COP 12 or 24 fold)			X	X			X	E	E						X
Geology	ER	R	R	E	R	R	R	ER	R	R	EX	E	ER	ER	RX
Geochemistry	E		R	E	R	R	R				E			ER	R
Shallow Temperature Measurement											X				
Shallow Thermal Gradient Measurements	E	EX	EX	X	EX	X		E	E	E	E			E	EX
Deep Thermal Gradient Measurements	X	X	X	X	X	X			EX		EX	E		E	
Exploration Well	X	X	X	X	X	X	E	E	E	E	X	X	X	EX	EX
Flow Test	X	X	X	X	X	X	X			X	X	X	X	X	X

Of the 14 areas studied under the program, seven currently produce electrical power. The seven are Roosevelt Hot Springs in Utah, and Beowawe, San Emidio, Soda Lake, Stillwater, Dixie Valley, and Desert Peak in Nevada. Cove Fort-Sulphurdale in Utah produced electricity between 1985 and 2003 and may be brought back online in the future. Today, 137 MWe of installed capacity exist at these 14 areas. DOE's Industry-Coupled program helped the geothermal industry move forward at a time when only very limited development activity was taking place, and contributed enormously to the amount of scientific data available in the public domain. Figure 1 shows the locations of selected geothermal systems in the Western United States (modified from[8]).



High-temperature (>150 °C, or 300 °F) hydrothermal systems of the western United States. Heat flow mapping from Wisian et al., 1999.

Figure 1. Locations of selected geothermal systems in the western United States

Two case studies from the Industry-Coupled Case Studies Program are briefly summarized below: Cove Fort-Sulphurdale and Roosevelt Hot Springs, both located in Utah.

CASE STUDY

2.1.1 Cove Fort–Sulphurdale, Utah

The Cove Fort-Sulphurdale geothermal system lies within a large thermal anomaly in the Tushar Mountains and adjacent alluvial pediment on the eastern edge of the Basin and Range Province in south-central Utah. The field differs in several respects from its sister hydrothermal system at nearby Roosevelt Hot Springs. Cove Fort is cooler, with maximum measured temperatures of 178°C (352°F); and contains a small, natural producible steam cap, a rare occurrence. In addition, young gravitational glide blocks (landslide deposits) form an effective cap rock over the eastern part of the system—a feature not recognized until UURI geologists performed detailed geologic mapping under the Industry-Coupled Case Studies Program. Surface manifestations include numerous sulfur deposits, acid-altered ground and gas seeps—features typical of vapor-dominated geothermal resources.

Between 1975 and 1979, Union (Unocal) Geothermal Division undertook exploration studies, drilling 53 thermal gradient boreholes and four deep exploration wells, the deepest to 2,358 meters (7,736 feet), in and around the surface features. Unocal proposed to release all data in exchange for DOE cost-sharing exploration expenses, and a contract agreement was subsequently reached between DOE and Unocal (non-Unocal data were not included in the agreement). Other companies holding leases surrounding Unocal's property also conducted geologic and thermal gradient surveys. All told, more than 200 thermal gradient holes were drilled in an area of 260 square kilometers (km^2), documenting a shallow thermal anomaly over an area of more than 181 km^2.[9-11]

The Cove Fort–Sulphurdale project resulted in an extensive data base that included detailed geologic mapping, geologic logging and geochemical analyses of drill cuttings, interpretation of well logs, electrical-resistivity surveys, regional gravity and magnetic surveys, and micro-earthquake monitoring. The data and studies yielded a comprehensive picture of the geothermal system that was quite different from the model initially used by Unocal to guide exploration.

Figure 2 is a photograph of the Cove Fort-Sulphurdale geothermal power plant. The facility had an installed capacity of approximately 11 MWe. The inset shows the locations of the major topographic features. The edge of the Cove Fort volcano can be seen on the skyline at the left edge of the larger image.

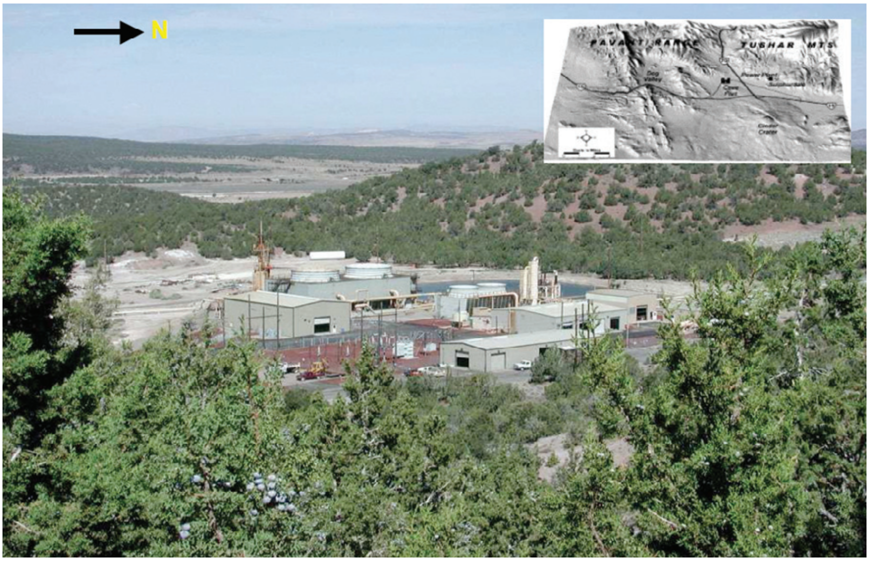


Figure 2. Photograph of the Cove Fort-Sulphurdale geothermal power plant, Utah

Geologic studies at Cove Fort-Sulphurdale discovered large-scale gravitational glide blocks, soled (bounded below) by low-angle faults, and composed of volcanic rocks that formed a cap rock over the geothermal system. Figure 3 is a geologic map of the Cove Fort-Sulphurdale geothermal area, and Figure 4 is a schematic conceptual model of the area.[7]

Over much of the system, the exposed geology was not a good indicator of what lies vertically below. The steam cap, fed by a deeper liquid-dominated resource, occurred in fractured sandstone above the water table. Areas of surface leakage were characterized by anomalously high thermal gradients, pronounced soil-mercury anomalies, intense acid leaching and deposits of native sulfur. Extrapolation of the measured shallow thermal gradients to the depth of the water table suggested that temperatures may be high enough to cause boiling under atmospheric conditions, but the gradients provided no information on the true reservoir temperature. Such large-scale gravitational glide blocks in geothermal fields, and their influence on shallow temperature measurements, had not previously been documented, although they were well known to mining companies exploring the Basin and Range province.

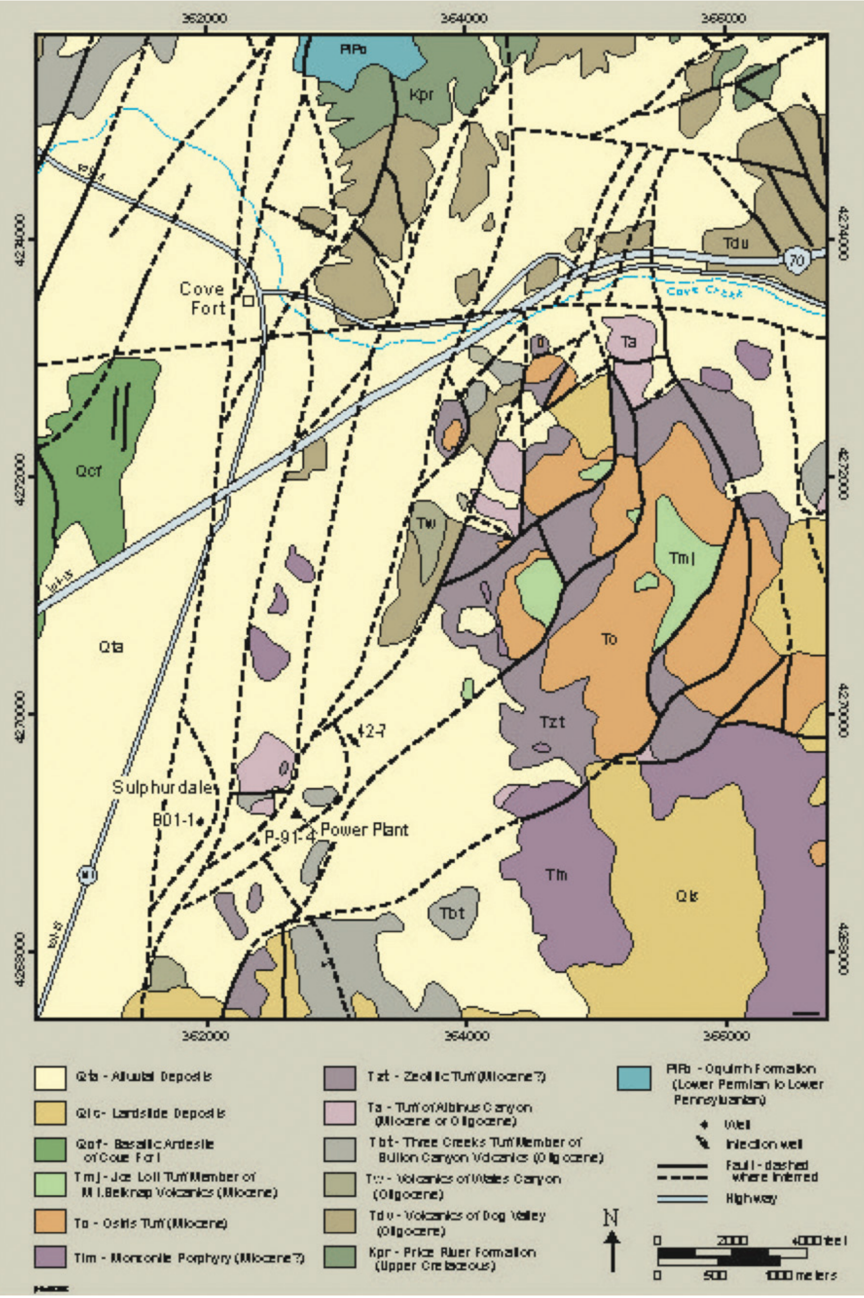


Figure 3. Geologic map of the Cove Fort-Sulphurdale geothermal area

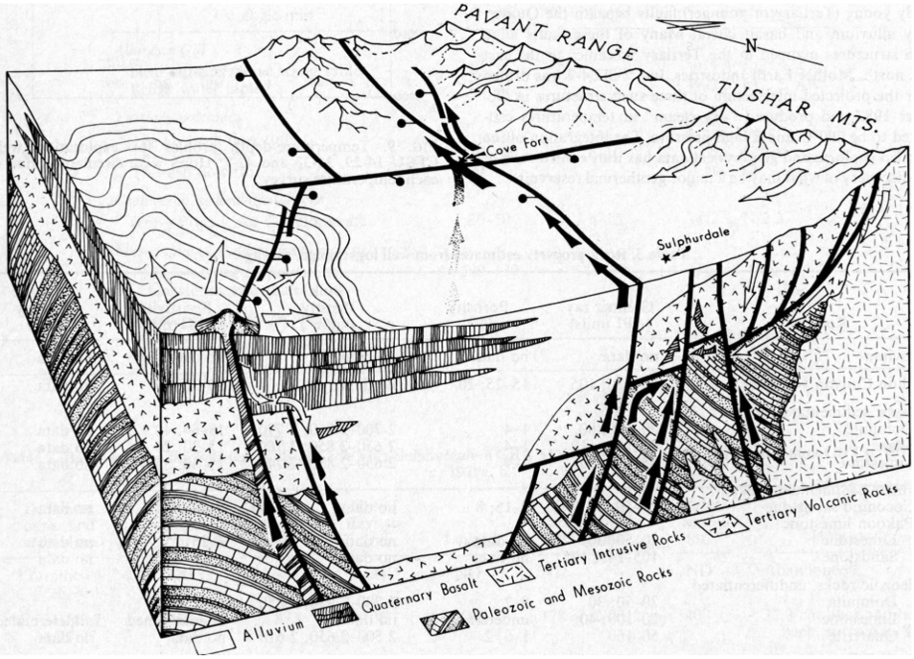


Figure 4. Schematic conceptual model of the Cove Fort-Sulphurdale geothermal area

In the studies cited above, the distribution of thermal fluids and hydrothermally altered rocks at depths to 600 meters (2,000 feet) was most clearly shown by interpretation of electrical-resistivity survey data, not presented here. Resistivities of 4 to 5 ohm-meters occur over an area of more than 5 km^2 centered on the Sulphurdale sulfur pit, an area of intense acid leaching. Narrow zones of low resistivity to the north and south appear to mark fault zones. Deep, through-going structural zones below and disconnected from the glide blocks are most clearly reflected in the magnetic and gravity data. The value of micro-earthquake data was uncertain. Most of the micro-earthquake activity occurred in swarms with focal depths of less than 5 kilometers (3 miles) in an area to the north of the main thermal features.

The Industry-Coupled data and supporting studies provided the basis for exploration and development of the Cover Fort-Sulphurdale field after Unocal concluded in 1980 that the field was not suitable for large-scale electric-power production. Mother Earth Industries, Inc. (MEI) acquired the property, initiating a new round of drilling and exploration in 1983,[10] based on the data from the Industry-Coupled program. The first well encountered a dry-steam resource having a pressure of 690 Kpa and a temperature of 177°C (351°F). However, the well blew out and had to be capped. Other wells were subsequently drilled, and a power plant was eventually installed that operated on dry steam from the resource. By 1991, however, declining pressures dictated the need for supplemental steam sources. A well was drilled into Paleozoic limestone beneath the steam cap and encountered a potentially large liquid-dominated resource at a temperature of 157°C (315°F)—the source of the steam.

Recurrent Resources purchased the Cove Fort-Sulphurdale field and plant in 2003 and subsequently decommissioned the plant. Enel North America, Inc. (ENA),[12] the subsequent owner, used data obtained under the Industry-Coupled Program in its development program to bring the field back to active production and electrical-power generation. Although exploration results have not been released, it is understood that the drilling was successful and that the results are consistent with previously developed models of the field. Resumption of power generation from this field is anticipated.

CASE STUDY

2.1.2 Roosevelt Hot Springs, Utah

Roosevelt Hot Springs is the most extensively developed and hottest geothermal resource in the eastern Basin and Range province. The system is located near the town of Milford in west-central Utah, near the border between the Basin and Range province and the Colorado Plateau province. The reservoir is developed in Tertiary granitic and Precambrian metamorphic basement rocks heated by young intrusions. The field produces 36 MWe from a combination of flash and binary plants. Figure 5 is a photograph of the Blundell geothermal power plant at Roosevelt Hot Springs. Drilling for an additional 36 MWe was proposed but not yet undertaken. Temperatures as high as 268°C (514°F) have been encountered.[13-14]

Beginning in the early 1970s, Roosevelt Hot Springs was the focus of numerous investigations by exploration companies, mainly Phillips Petroleum, Thermal Power, Getty Oil, and AMAX Exploration. Between 1977 and 1979, an extensive suite of geoscientific data from the area was made public under DOE's Industry-Coupled Case Studies Program. A wide range of geological, geochemical, and geophysical investigations was undertaken in support of the program principally by the University of Utah Department of Geology and Geophysics and UURI. Field and laboratory surveys were conducted including detailed geologic mapping,[15] new electrical resistivity surveys,[16] reflection seismic profiling,[14] a comprehensive evaluation of the reservoir fluid chemistry and its relationship to the hydrothermal alteration of the reservoir rocks and regional groundwater regime,[17] and trace element analyses of the altered rocks and soils.[18] The conclusion was reached that of all the electrical survey methods tested, dipole-dipole resistivity surveying, in combination with geologic data, provided the best representation of the resistivity structure for a given cost.[14]

The Roosevelt Hot Springs case study outlined a basic exploration strategy that could be applied in other Basin and Range areas. The study also made apparent the need for research to develop better technologies in four key areas: 1) detecting and delineating fault systems in which thermal fluids circulate; 2) evaluating the size, productivity, and feasible longevity of fracture-dominated geothermal reservoirs; 3) identifying the fluid-rock interactions and their effect on hydrothermal system evolution and fluid circulation; and 4) identifying the source of heat. While significant progress and technological advances have been made in each of these four areas as a result of DOE's geothermal exploration program, more remains to be done before routine answers to these questions can be given.[9/13]

Figure 5. The Blundell geothermal power plant at Roosevelt Hot Springs, Utah *(Photo: R. Blackett)*

2.2 Case Studies of Low- to Moderate-Temperature Hydrothermal Energy Development

To stimulate the development of direct use geothermal projects, DOE issued Program Opportunity Notices (PONs) in 1977 and 1978 for contracts in cost-shared exploration and drilling of low- to moderate-temperature geothermal systems. DOE selected 22 applicants on a competitive basis to participate in cost-shared projects. While the program was primarily directed toward evaluating the quality of the geothermal resources based on hydrologic and well-test data, a variety of geological, geophysical, and geochemical investigations was conducted to support these efforts. Case studies were published on resources at St. Mary's, South Dakota; White Sulphur Springs, Montana; Pagosa Springs, Colorado; Utah Roses and City of Monroe, Utah; and Susanville, California.[19]

At White Sulphur Springs, Montana, soil temperatures at a depth of 0.6-meters (1.9 feet) were measured, and resistivity and reflection-seismic surveys conducted. At Pagosa Springs, Colorado, dipole-dipole and dipole-bipole electrical-resistivity surveys were run.[20] Low resistivities of 30 to 50 ohm-meters were mapped along North 30° East zones that parallel mapped faults near the hot springs. Vibroseis and mercury soil surveys did not yield any additional information on the resource. At Monroe, Utah, magnetic, gravity, and dipole-dipole resistivity surveys were run, and 11 thermal gradient holes were drilled to depths up to 100 meters (300 feet).[21-22] The surveys provided information on the Sevier Fault thought to control the hot spring system. Gradient wells encountered a maximum temperature of 63°C (145°F), and production wells were subsequently drilled. The geothermal district heating system envisaged, however, was not constructed although the Monroe resource remains potentially viable.

The Utah Roses, Utah project resulted in drilling wells at the extreme south end of the Salt Lake valley, near Utah State Prison, where a resource had previously been found and was being used to heat several prison buildings. Wells drilled to depths of up to 300 meters (1,000 feet) produced geothermal water with a temperature of 88°C (190°F). Four projects are currently operating at the site. Bluffdale Flowers (formally Utah Roses) utilizes the resource to heat 250,000 sq ft of greenhouses for cut roses. At Utah State Prison, geothermal water heats 332,000 sq ft of building space. Two aquaculture operations, Hi-Tech Fisheries and Steve Davis Aquaculture, use discharge water to raise tropical fish.[23]

2.3 The Cascades I and II Cost-Shared Programs

Despite a lack of surface thermal manifestations, the Cascades volcanic province, extending roughly north-south through west-central Oregon and Washington, has long been considered to have significant geothermal potential due to its similarities to other geothermal provinces occurring along the Pacific Rim. The absence of hydrothermal manifestations was generally thought to reflect masking by downward and laterally flowing, cold meteoric water (the so-called "rain curtain"). Many thermal springs issue along the contacts of Cascades volcanic rocks with the underlying strata, indicating that deep thermal waters in the Cascades may be diverted laterally. A significant question was the nature of the underlying rocks, namely whether their permeability was destroyed by alteration or whether they were embrittled in places by higher temperatures, and therefore may sustain fractures to form a plumbing system for hydrothermal circulation. A further significant question was the thickness of the rain curtain (i.e., how deep exploration holes would have to be to reach below the influence of downward moving meteoric water).

DOE's Cascades I and II Cost-Shared Programs were designed to help answer these questions and to encourage the private sector to explore the Cascades. The effort included acquiring core and cuttings samples and lithologic, hydrothermal, geophysical and hydrologic data within and below the shallow groundwater regime; interpreting the data; and placing all data, drill samples, and technical reports in the public domain. UURI provided the technical interface between the DOE Geothermal Program and the private sector and performed much of the research, although other research groups, including Southern Methodist University and the Oregon Department of Geology and Mineral Industries, were also involved.

In Oregon, deep core holes to depths of 400 to 1,500 meters (1,300 to 4,900 feet) were drilled on the northern and southern flanks of the Newberry Caldera (N-1, N-3), on the north slope of Mount Jefferson near Breitenbush Hot Springs (CTGH-1), and near Santiam Pass in the Deschutes National Forest (SP 77-24). In addition, a well was drilled to a depth of 400 meters (1,300 feet) on the east side of Crater Lake National Park (CL-1).

Research was undertaken to describe the drilling histories and the data made available from CTGH-1, N-1 and N-3;[24] provide an analysis of the thermal data obtained from CL-1 and other nearby wells;[25] discuss the drilling history of SP 77-24;[26] and describe the thermal results[27] and the petrology, stratigraphy, and rock ages.[28]

Significantly, all of the wells yielded high-temperature gradients below the rain curtain, exceeding 65°C (149°F) per kilometer, and the thickness of the isothermal layer within the rain curtain, due to downward-moving ground water, ranged from a few meters to 500 to 700 meters (1,600 to 2,300 feet). The higher figure probably establishes a minimum limit that planners can use for exploration drilling in this volcanic province. Subsequent drilling of a production-size well at Newberry caldera by California Energy Company, Inc. (CalEnergy) found very high temperatures but no productivity in lower Cascade rocks, apparently due to limited permeability. Davenport Power, LLC drilled two additional deep wells that were reported to have found high temperature but little productivity, indicating low permeability at depth.

The Cascade Cost-Shared Programs provided very useful information for further exploration of the Cascades province. While none of the holes discovered a producible resource, there is little doubt that extensive heat sources underlie the Cascades, as proven by the active volcanism. Future exploration work in this region may eventually result in development of geothermal power generation as well as direct uses. Table 3 summarizes data available from EGI from the Cascade I and II Cost-Shared Programs.[21]

Table 3. Data available from the Energy & Geoscience Institute resulting from the Cascade I and II Cost-Shared Programs

	CTGH-1	N-1	N-3	SP 77-24	CL-1
Operator	Thermal Power Co.	GEO Operator Corp.	GEO Operator Corp.	DOGAMI* Oxbow	California Energy
Depth (meters)	1,465	1,226	1,220	928	405
Completion history	X			X	
Lithologic log	X	X	X	X	
Geophysical logs	X	X	X		
Temperature log	X	X	X	X	X
Secondary mineralogy	X	X	X		
Max. temperature, °C (°F)	96 (205)	74 (165)	57 (135)	25 (77)	107 (225)
Avg. gradient (°C/Km)	82	84	53	116 at bottom	250

*Oregon Dept. of Geology and Mineral Industries

2.4 The GRED I, II and III Cost-Shared Programs

The DOE-supported Geothermal Resource Exploration and Definition (GRED) Program ran from 2000 to 2007. DOE selected seven projects for GRED I, the first round of funding. Of the seven, about 100 MWe of resources were postulated to exist in the four projects that completed drilling. At Blue Mountain, Nevada (supported under GRED I and II) the construction of a 49.5-MWe plant was scheduled for completion by the end of 2009. The Steamboat Springs, Nevada geothermal field was enlarged due to work done under two GRED projects. Exploration continued at the Cove Fort-Sulphurdale, Utah geothermal prospect. Development of GRED projects at Glass Mountain in California was delayed due to environmental issues. Of the eight GRED II projects, a power plant was built at Raft River, Idaho, and the Bureau of Land Management leased additional land to developers at the Truckhaven, California project.

Additional information on the GRED projects is provided in Table 4 which lists the awardees and locations under GRED I, II, and III. Figures 6, 7, and 8 are maps of the GRED I, II, and III project sites. Reports for many of the projects can be found on the DOE Office of Scientific and Technical Information (OSTI) website.[29]

Table 4. Geothermal Resource Exploration and Definition Program (GRED) I, II, and III awardees and locations

GRED I	Location	State
Presco Energy, LLC	Rye Patch	Nevada
Noramex Corp.	Blue Mountain	Nevada
Utah Municipal Power Agency	Cove Fort / Sulphurdale	Utah
Calpine Siskiyou Geothermal Partners, LP	Fourmile Hill	California
SB Geo, Inc.	Steamboat Springs	Nevada
Coso Operating Company, LLC	U-Boat	Nevada
Lightning Dock Geothermal, Inc.	Lightning Dock	New Mexico
GRED II	**Location**	**State**
U.S. Geothermal, Inc.	Raft River	Idaho
Noramex Corp.	Blue Mountain	Nevada
Calpine Corporation	Glass Mountain	California
Lake City Geothermal, LLC	Lake City	California
AmeriCulture	Animas Valley	New Mexico
Advanced Thermal Systems	Fly Ranch	Nevada
Layman Energy Associates	Truckhaven	California
Northern Arizona University	San Francisco Mountain	Arizona
GRED III	**Location**	**State**
Ormat Nevada, Inc.	Grass Valley	Nevada
Earth Power Resources	Hot Sulfur Springs	Nevada
Esmeralda Energy Co.	Emigrant	Nevada
Noramex Corp.	Pumpernickel Valley	Nevada
AMP Resources	Cove Fort – Sulphurdale	Utah
New Mexico Tech	Socorro Mountain	New Mexico
Fort Bidwell Indian Community	Fort Bidwell	California
Western Geothermal Partners	Reese River	Nevada
NGP Power Corp.	Upper Hot Creek Ranch	Nevada
Arizona Public Service	Clifton	Arizona
Chena Hot Springs Resort, LLC	Chena Hot Springs	Alaska

Figure 6. Geothermal Resource Exploration and Definition Program (GRED) I project locations

Figure 7. Geothermal Resource Exploration and Definition Program (GRED) II project locations

Figure 8. Geothermal Resource Exploration and Definition Program (GRED) III project locations

3.0

State Cooperative Programs

3.1 State-Coupled Program

In 1977, DOE founded the State-Coupled Program to provide support to state agencies, national laboratories, and university earth-science groups in 26 states with known geothermal potential. The objectives of the State-Coupled Program were: 1) to fund the compilation and verification of existing geothermal information and collect new data on geothermal resource locations, depths, temperatures, and heat flow; and 2) to foster the development of state-level expertise in agencies and universities that could in turn provide technical assistance to potential developers. The State-Coupled Program's ultimate goal was to promote private-sector development of geothermal resources by making information and technical resources widely available in the states.

Gruy Federal (GRUY-Arlington, VA) coordinated the activities of eight eastern and southeastern states. LANL coordinated the Arizona and New Mexico state programs. The remaining 16 western state programs were coordinated and supported by the geothermal group at UURI. In addition, UURI provided technical and contract support services to all state resource teams, hosted annual technical and coordination meetings, and provided geophysical, geochemical, and geologic services. UURI also facilitated cooperation between the states, the USGS, and the National Oceanic and Atmospheric Administration (NOAA).

Data compiled under this program was submitted to the USGS for inclusion in the national geothermal resource database (GEOTHERM) and used in a new assessment of the low-temperature geothermal resource base.[30] In addition, each state prepared information that was converted by NOAA into state geothermal resource maps. NOAA's map-making facilities were deemed to be state-of-the-art and the staff highly skilled. The State-Coupled Program produced a series of high-resolution, high-quality geothermal resource maps and more than 80 technical reports.[31] The maps have since been used by federal, state, and local government agencies in land-use planning as well as by private companies and individuals interested in geothermal energy use. Many of the participating states still maintain local geothermal expertise, which is used by potential developers.

3.2 State-Cooperative Reservoir Analysis Program

When the State-Coupled Program formally ended with the publication of state resource maps in 1983, DOE continued to support state teams in those states judged to have the most promising resource potential and high-priority projects. New temperature and heat-flow data were obtained for the Cascades and North and South Dakota, and detailed reservoir studies were made public. A geothermal resource map for the state of South Dakota was compiled, completing the resource map base for the western United States.[32] The State-Cooperative Reservoir Analysis Program was continued at decreasing levels of support through the 1980s and finally ended in 1990.[33]

3.3 Low-Temperature Resource Program

Aware that a great deal of new data on geothermal resources had been developed, and that low- and moderate-temperature resources were still greatly underutilized, UURI, the Idaho Water Resources Research Institute (IWRRI), and the Oregon Institute of Technology's Geo-Heat Center (OIT-GHC) proposed a new low-temperature program in 1990-1991. Funding limitations restricted the program to the 10 states deemed to have the greatest potential to increase their total geothermal resource base and bring new direct-use projects online: Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Washington. The program engaged previously established state teams, leading to the further development of in-state expertise. UURI coordinated and managed the activities of the state teams. OIT-GHC provided a critical component with their state-level direct-use inventory, which they used to correlate identified geothermal resources with the nearest potential market.

Under the Low-Temperature Resource Program, a database of more than 9,278 thermal springs and wells ranging from 20°C to 150°C (68°F to 302°F) was compiled. The number of resources identified in the new assessment was 85 percent greater than previous compilations. The program emphasized geothermal resources located near potential users. In California, for example, 56 communities were identified as being located within 8 kilometers (5 miles) of a known geothermal resource with a temperature of at least 50°C (122°F).[34]

The database included the locations of thermal features, descriptive data, physical and chemical parameters, and references for data sources. Computer-generated maps were created for each state. Direct-heat use of geothermal fluids was documented at more than 350 sites, including commercial and municipal buildings, greenhouse and aquaculture industries, and major space-heating districts in California, Colorado, Idaho, Oregon, Nevada, and Utah.[35] More than 50 high-priority resource study areas were identified, along with high potential for near-term direct heat utilization at 150 new sites. The state teams recommended more comprehensive resource and preliminary engineering studies for over 50 sites to advance near-term utilization. Digital database reports on this work are available from OIT-GHC and also as open file reports for each state team listed in Table 5.[32] The increase in known occurrences is due primarily to the 1992–1994 program.

Table 5. Number of Known Geothermal Occurrences in 1995 Compared with the Number of Previously Known Occurrences, Given by State

	State PGA*	AZ 1982	CA 1980	CO 1980	ID 1980	MT 1981	NV 1983	NM 1980	OR 1982	UT 1980	WA 1981
Thermal Wells/ Springs	1995 PGA	1,003 501	979 635	157 125	912 899	267 68	455 796	265 312	2,193 998	964 315	975 368
Moderate Temp. Wells/Springs (100°C<T<150°C)	1995 PGA	0 0	32 48	0 0	20 0	0 0	16 35	10 3	88 79	3 3	1 1
Low Temp. Well/Springs (20°C<T<100°C)	1995 PGA	1,003 501	957 587	157 125	1,915 899	97 58	433 761	255 309	2,047 925	710 312	970 367
Low Temp. Resource Areas (20°C<Tres<150°C)+	1995 PGA	35 29	58 56	93 56	28 28	16 15	300 300	30 24	200 151	161 64	17 10
Direct-Heat Utilization Sites (Commercial, districts, resorts)	1995 PGA	2 0	72 54	28 24	29 20	15 2	21 8	7 0	29 23	16 9	4 0
Greenhouses, Aquaculture, Industrial Processes	1995	5	17	4	17	4	8	6	7	6	0
Areas, High Priority Resource Study	1995	4	7	6	8	5	5	12	5	7	6

* PGA = previous geothermal assessment. + Tres = estimated reservoir temperature.

4.0

Selected Hydrothermal System Studies

Throughout DOE's exploration program, opportunities to examine specific geological environments occasionally arose. Research on these specific hydrothermal environments aided the understanding of geothermal systems as a whole. Such studies were usually conducted by interdisciplinary research teams, and they resulted in a great deal of new information. Geological, geochemical, and geophysical investigations were undertaken, contributing not only to understanding the individual systems but also testing the techniques themselves. The following section highlights five topical studies conducted to evaluate five high-temperature geothermal systems and environments:

1. Ascension Island, a mid-oceanic volcanic geothermal system;
2. Coso Hot Springs, California, a continental silicic volcanic system;
3. The Geysers, California, a plutonically driven vapor-dominated geothermal system;[36]
4. Dixie Valley, Nevada, a fault-controlled deep circulation system; and
5. The Salton Sea, California, an active rift-valley system geothermal field.

At two of these sites—Salton Sea and The Geysers—a large portion of the research focussed on data from wells drilled for scientific purposes. Salton Sea geothermal well State 2-14 was the first major well drilled in a geothermal field under the U.S. Continental Scientific Drilling Program. Results from those drilling projects are discussed in this section. Additional work at these fields can be found throughout this report.

4.1 Ascension Island, South Atlantic Ocean

Strategically located in the South Atlantic Ocean near the mid-Atlantic Ridge with a volcanic origin, British-ruled Ascension Island is used primarily for military purposes. A U.S. airfield on the island is used by both the Royal and U.S. Air Forces; missiles are tracked from the island. Ascension Island is also a British Broadcasting Corporation relay station.

In the early 1980s, the U.S. Air Force (USAF) asked that DOE undertake exploration of Ascension Island to determine whether geothermal energy could generate some or all of its electrical-power requirements. The USAF was generating power by burning jet fuel in diesel generators. DOE provided supplementary support for research on the volcanic island. The exploration project included geologic mapping, geophysical and geochemical surveys, developing an exploration model, and drilling thermal-gradient and test wells.[37]

Geologic mapping documented the presence of young felsic volcanic rocks, indicating the possibility of a shallow magmatic heat source.[38] Due to the presence of young volcanic cover, aeromagnetic and electrical-resistivity surveys were conducted to locate buried faults that might be conduits for hydrothermal convection. The aeromagnetic survey identified east- and northwest-trending magnetic sources interpreted as mafic dikes emplaced along structures that fed the volcanic centers peripheral to the central core of the island.[39] Northeast-, northwest-, and north-trending magnetic signatures and low electrical resistivities (5-10 ohm-meters) were observed in the weakly magnetic central part of the island.[40] These geophysical signatures were interpreted to reflect the presence of altered rocks and possibly geothermal fluids at depth.

Seven core holes were drilled to depths of about 500 meters (1,600 feet) to obtain subsurface samples, measure temperature gradient and heat flow, and site a deep exploration test well. Test well Ascension #1 was drilled at production diameter to a depth of 3,126 meters (10,256 feet).[38/41] The well encountered a temperature of 247°C (477°F) in propylitically altered rocks at total depth (TD). A subsequent flow test showed that flow rates were sub-commercial and production could not be sustained. Temperature, pressure, gamma-ray, sonic, and dipmeter logs were run in the well. The well encountered acidic fluids at TD, indicated by high hydrogen sulfide (H_2S), carbon dioxide (CO_2), hydrogen-2 (H_2), and methane (CH_4) in the return line. As a result, the bit and bottom-hole assembly were severely corroded. The well was plugged back for a sidetrack but was lost in the sidetracking effort. The exploration program was terminated at that point by the USAF.

Many reports documented the exploration of the interesting environment on Ascension Island. The core and cuttings as well as original data are housed at EGI. The exploration project discovered and documented the existence of temperatures high enough for power generation. There remains the possibility that a permeable part of the heat source could be found by further exploration. The area would also seem to be a potential candidate for Enhanced Geothermal System (EGS) development. Further exploration may be warranted if and when development of a local energy source for baseload power generation becomes a higher priority.

4.2 Coso Hot Springs, California

Situated within the China Lake Naval Air Weapons Station in the Mojave Desert of California, Coso Hot Springs is in the largest and hottest known geothermal system in the Basin and Range province (see Figure 21). Four geothermal power plants at Coso produce about 200 MWe. Production has declined because the high production rates are drying out the reservoir. A shallow groundwater injection system to recharge the reservoir became operational in 2009.

Geologically, Coso Hot Springs shares a number of similarities with Roosevelt Hot Springs in Utah. Consequently, investigating the Coso field was a complementary test case for this class of system. Fluid circulation in both the Coso and Roosevelt fields is driven by young, shallow magma chambers that have given rise to rhyolite domes within the last half million years (my). Both reservoirs are developed in granitic rocks where fluid flow is structurally controlled by networks of interconnected fractures. Present-day surface expressions are limited to fumarolic activity. Hot spring deposits are present but the springs are no longer active, although they were in the historic past.

DOE-supported exploration research at Coso Hot Springs was conducted in the late 1970s and early 1980s—before the field was developed for power generation—and from 2005 to 2007 when the field was selected for EGS technology R&D. Work related to the Coso EGS project is summarized in the Reservoir Engineering report, a companion volume to this report. In the late 1970s, development of the Coso Hot Springs geothermal resource was just beginning. Few wells had been drilled. These early results can be compared with what is now known about the Coso system.

DOE-supported investigators[42] synthesized the results of the early geological and geophysical investigations. They examined the results of geological studies,[43] thermal-gradient mapping,[44-45] dipole-dipole resistivity,[46] and aeromagnetic[47] and seismic surveys.[44/48] Researchers found an overall correlation between the distribution of such geothermal manifestations as hot spring deposits, fumaroles and acid-altered ground, calcite- and opal-filled veinlets, with 1) heat-flow values > 42 milliwatts per square meter (mW/m^2); 2) near-surface electrical resistivities < 30 ohm-meters; 3) ground temperatures at 2 meters (6 feet) > 26°C (79°F); and 4) a magnetic low of amplitude 800 gammas. The geophysical anomalies were interpreted to express a large, high-temperature geothermal resource extending southward from the area of active thermal features where a few wells had been drilled. Investigators noted, however, that the heat-flow anomaly extended north of both other geophysical anomalies as well as the northern boundary of active thermal features. Thus, the heat-flow data might reflect northward movement of thermal fluids at shallow depth. The significance of the geophysical anomalies has since been verified with temperature and production data from more than 125 wells, some drilled to depths of near 4 kilometers (2.5 miles).

4.3 The Geysers Coring Project: The Geysers, California

The Geysers in California is one of the largest producing geothermal systems in the world, and one of the few that is vapor-dominated. The reservoir occurs primarily in a thick succession of Franciscan (Mesozoic) metagraywacke that underlies a chaotic suite of serpentinite, argillite, chert, and greenstone.[49] Formation of the modern geothermal system began with the emplacement of The Geysers felsite, a granitic intrusion that underlies the field, at 1.2 to 1.1 million years ago.[50] Figure 9 shows two block diagrams of The Geysers geothermal field. The top diagram illustrates the top of the steam reservoir; the bottom, the top of the plutonic complex (felsite).[51]

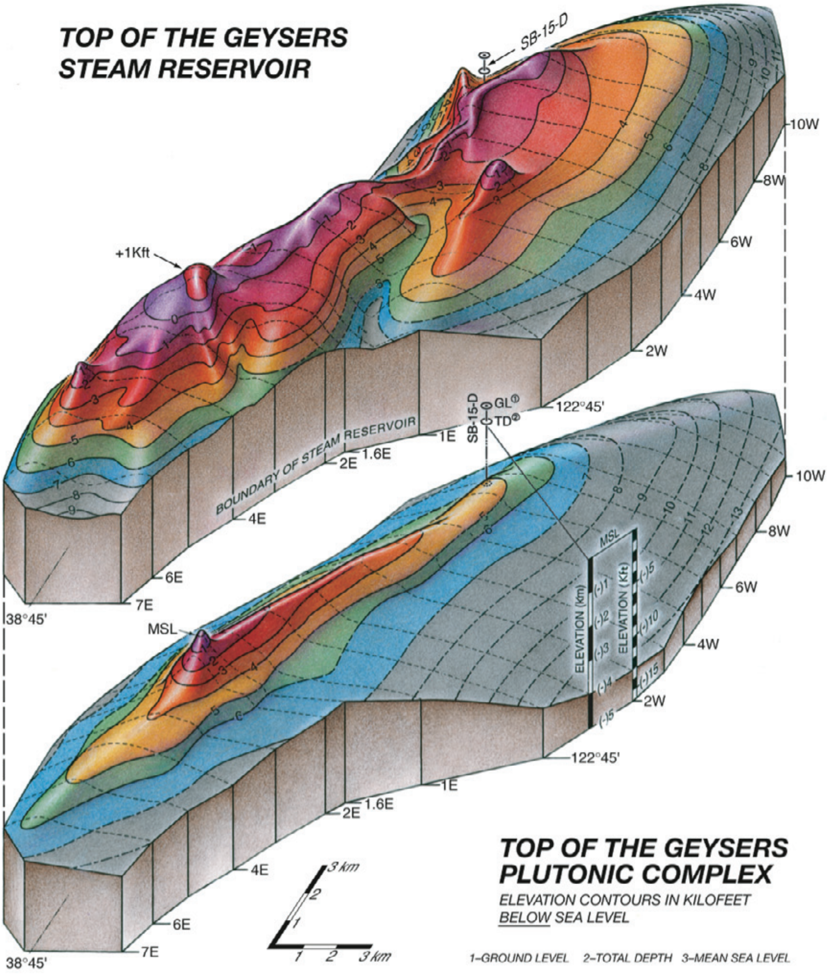


Figure 9. Block diagrams of The Geysers geothermal field showing the top of the steam reservoir (top) and the top of the plutonic complex (felsite)

When The Geysers Coring Project began in 1998, production across the field had declined from a high of nearly 2,000 MWe in 1987 to about 1,000 MWe by 1995. Stabilizing production by increasing and optimizing injection was critical. The Geysers Coring Project therefore had three main objectives: 1) to collect continuous core from the steam reservoir for scientific study; 2) to develop a better understanding of the reservoir's porosity, permeability, fluid flow, and storage; and 3) to refine existing models of the field's evolution. These goals provided valuable data and and models needed for the design and interpretation of exploration surveys in vapor-dominated systems.

Well SB-15-D was drilled in the Sulphur Bank area, in the west-central part of the field, near the northern extent of the felsite. It was completed as a sidetrack to an existing Unocal production well and cored to a TD of 488 meters (1,601 feet) below the sidetrack. Despite drilling difficulties, 237 meters (777 feet) of continuous core were collected that penetrated the transition zone between the uppermost steam reservoir and the overlying low-permeability cap rock. The well was drilled dominantly within Franciscan metagraywacke. Intrusive rocks were not encountered.

The Geysers Coring Project achieved all of its key objectives. The core from SB-15-D tripled the amount of core collected in the previous 35 years of operation from the entire field.[52] Hydrologic and reservoir properties were measured, including:

- Capillary-pressure curves and gas permeabilities,[53]
- The effects of capillarity on the electrical resistivity of the rocks,[54]
- Water adsorption at high temperatures,[55] and
- Indigenous water saturation.[54]

The Geysers field was described in a series of papers published by the Geothermal Resources Council as Special Report 17.[56] Additional details of the geologic setting and hydrothermal history of the system were presented in a further series of papers.[57-60]

Researchers[61] combined mineralogic and fluid-inclusion data from SB-15-D with observations from other wells to characterize the changes that occurred during the transition from liquid- to vapor-dominated conditions. They concluded that the geothermal system was liquid-dominated from its inception at 1.2 Ma until approximately 0.3 Ma, when the modern vapor-dominated regime formed. Others[62] documented the clay mineralogy of the core samples. The clay samples yielded potassium-argon (K-Ar) dates of 105.5 Ma to 1.5 Ma, with most falling in the range of 35.4 Ma to 19.4 Ma. Thus, these ages record a long history of thermal activity.

The thermal evolution of the system was numerically simulated.[51] The simulations were constrained by a 0.57 Ma $^{40}Ar/^{39}Ar$ age of adularia from the core,[59] vitrinite-reflectance and fluid-inclusion temperatures,[59/61] the geometry of the felsite,[57-58] and a felsite emplacement age of 1.2 Ma to 1.1 Ma.[50] Models indicate that a felsite intruded at 1.2 Ma to 1.1 Ma would have cooled below the modern reservoir temperatures encountered in SB-15-D by 0.5 Ma. Thus, subsequent heating events must have occurred. Others[63] modeled heat, fluid- and oxygen-isotope transport in the system, supporting conclusions[51] that isotopic alteration reflected multiple episodes of heating with a recent thermal pulse. Furthermore, the models suggested that the strong oxygen isotopic interchange between water and rock along the flank of the felsite reflects the influx of fluid from distal portions of the system, whereas weak alteration in the discharge zones above the felsite is limited by the presence of an unbroken caprock.

The results of this project added significantly to existing information about The Geysers field. It enabled new physical property data to be obtained which will be of continuing use for future field development, especially in reservoir engineering work. Based on project results and previously existing data, new models of the thermal evolution of the field were developed that contribute to a much better understanding of this important geothermal resource.

4.4 Dixie Valley, Nevada

Located in central Nevada, east of the Stillwater Range, the Dixie Valley geothermal system is the hottest deep-circulation system known in the Basin and Range, and it is arguably the most intensely studied. Figure 10 is an illustration of the geologic setting of the Dixie Valley geothermal system.[66-67] With an installed capacity of 63 MWe, the field has been in continuous production for nearly 20 years.

In many respects, the Dixie Valley geothermal system typifies other fault-controlled Basin and Range geothermal fields that are driven by deep circulation of ground waters. At Dixie Valley, fluid movement is controlled by the Stillwater fault zone that bounds the east side of the Stillwater Range. The reservoir is developed in Mesozoic rocks exposed in the adjacent range, specifically in Jurassic sedimentary and igneous rocks that include quartz arenite and metamorphosed ophiolitic rocks.[64-65]

Reservoir fluids are low-salinity waters with temperatures of 241°C (466°F),[66] temperatures near the upper end of most Basin and Range geothermal systems. Production depths ranged from 2.4 to 2.7 kilometers (1.5 to 1.7 miles). However, unexpected temperatures as high as 285°C (545°F) were found at a depth of three kilometers (1.86 miles) in a well five kilometers (3.1 miles) south of the producing area at Dixie Valley along the same fault zone.[67] These high temperatures demonstrated significant gaps in understanding the Dixie Valley geothermal system.

Investigations of Dixie Valley were undertaken to: 1) better characterize Basin and Range fault-bounded geothermal systems, 2) develop a better understanding of why some parts of faults are permeable and others are not, and 3) determine which exploration techniques are best suited to locating and characterizing deep, fault-controlled systems.

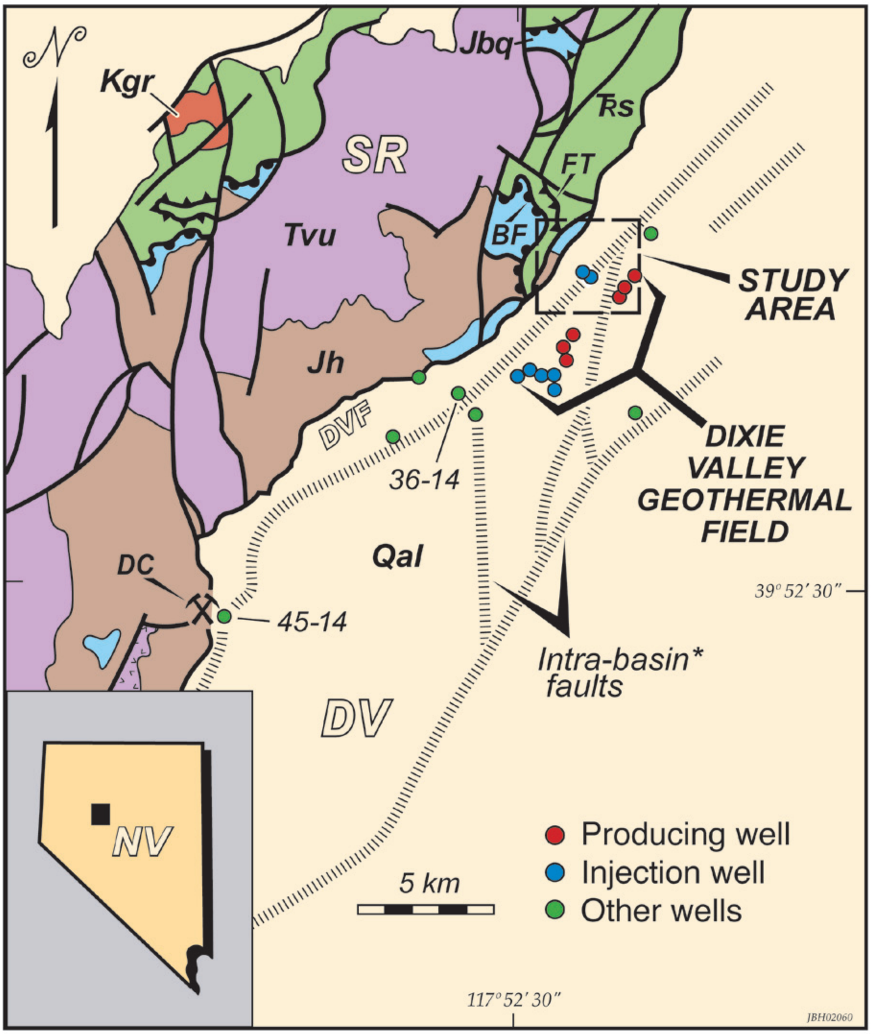


Figure 10. Geologic setting of the Dixie Valley geothermal system.

The geology of the Stillwater Range (SR) has been generalized to show the major rock types and structures. Abbreviations of rock units from youngest to oldest; Qal = Quaternary alluvium; Tvu = Tertiary volcanic rocks; Kgr = Cretaceous granite; Jh = Jurassic Humbolt igneous complex; Jbq = Jurassic Boyer Ranch Formation (quartzite); Trs = Triassic Sedimentary rocks. Normal faults are shown by the solid black or hachured lines; thrust faults are denoted by solid half circles or teeth. Other abbreviations: DC = Dixie Comstock mine; DV = Dixie Valley; DVF = Dixie Valley fault zone; FT = Fencemaker Thrust.

Recent investigations of Dixie Valley clarified the structural and thermal setting of the geothermal system to a much greater extent than previously known. Researchers considered the portion of the Stillwater fault zone extending from the production area to Dixie Hot Springs, a distance of about 30 kilometers (18.6 miles) to represent a single geothermal system. Hot springs to the north were thought to represent separate, independent geothermal systems. Researchers concluded that 1) the Dixie Valley fault zone is one to two kilometers (0.6 to 1.2 miles) wide with multiple strands, 2) production is from blind valley segments of the fault zone, and 3) the water and heat are not magmatic in origin.[67] Figure 11 shows an idealized structural model of the Dixie Valley geothermal field.[68] The presence of multiple permeable fault strands greatly increases the potential number of drill targets and reservoir size, compared to a single-fault model.

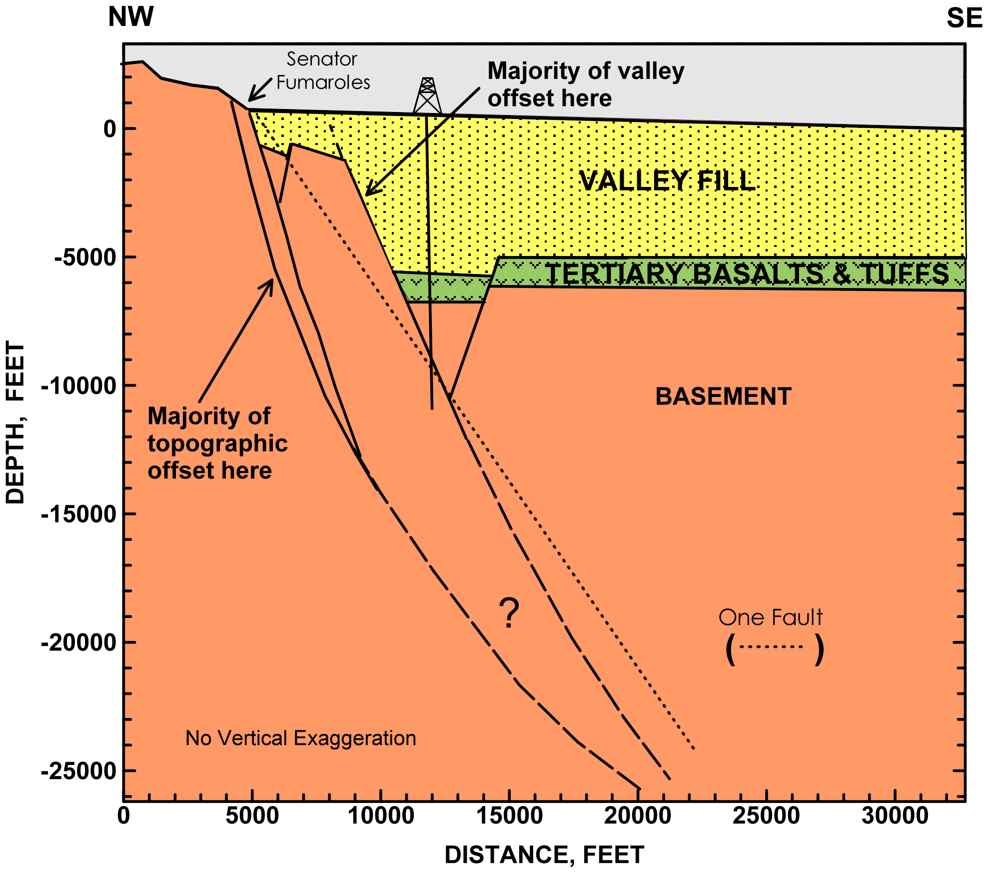


Figure 11. Idealized structural model of the Dixie Valley geothermal field, Nevada

Numerical simulation of thermal data[69-70] led to the conclusion that thermal flow has been active for the last 50,000 to 500,000 years, and must persist to depths of at least six kilometers (3.7 miles) to generate the observed temperature and heat flow values. The faults were thought to dip primarily at high angles, although low-angle faults that bound gravitational glide blocks may be present.[71] These low-angle faults, however, could not explain the thermal structure of the system.[67]

Gravity, aeromagnetic, magnetotelluric, and reflection-seismic surveys have been run over the Dixie Valley system. Of these, gravity and magnetic data were the most useful and cost effective in defining the reservoir's structural setting and fault locations.[67] The utility of the gravity data was due to the large displacement between the range and the low-density valley fill. Gravity studies may be less useful, however, in other places where displacements are less or density contrasts are lower. Aeromagnetic data, when compared to surface maps, showed that faults with a strong surface expression are marked by a strong aeromagnetic signal, but not all aeromagnetic anomalies appear to signify faults.

Magnetotelluric measurements across the geothermal field and through Cottonwood Canyon were integrated with regional-transect magnetotelluric data.[72-76] Inversion of the data revealed a deep, subvertical conductor intersecting the base of Dixie Valley from the middle crust (see Figure 12[75]). Reflection seismic surveys, while accounting for the greatest percentage of the overall geophysical survey costs, were less useful than other methods because the data were two-dimensional while the velocity setting is three-dimensional.

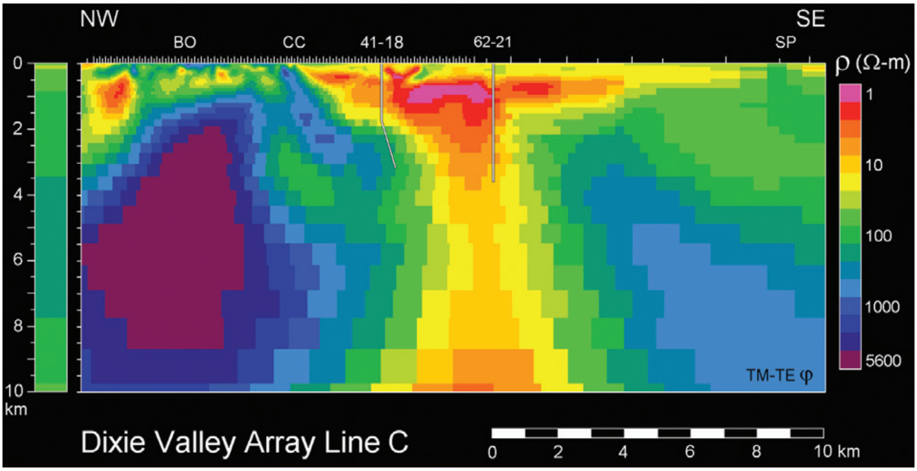


Figure 12. Magnetotelluric section across the Dixie Valley geothermal field.

(Abbreviations: BO = Boliva Mine; CC = Cottonwood Canyon; SP = Shoshone Point).

Surface geology, alteration, and hydrologic features were mapped using aerial photographs (black and white and color infrared images), hyperspectral data (HyVista's HyMap hyperspectral imagery),[77] and Airborne Visible-Infrared Imaging Spectrometer data (AVIRIS).[78] Analysis of the AVIRIS data showed that some of the buried piedmont faults are marked by concentrations of calcium carbonate and kaolinite. Interferometric synthetic aperture radar (InSAR) images[79] were used to map subsidence in the geothermal field and define a west-northwest trending lineament that may have structural significance.

Radiometric dating (carbon-14 [^{14}C], uranium-thorium [U-Th], and protactinium-231) of spring deposits recorded a long period of episodic activity and fluid flow.[80-83] This research demonstrated that hot-spring activity in the area extended over at least 100,000 years (100 kiloannum [ka]). The oldest deposits were travertine, the youngest sinters deposited at approximately 2 to 2.5 ka, a few kilometers north of the producing field. Episodes of spring activity were documented at approximately 3.6-7, 4, 5, 11, 39, 54, and 100 ka, although veins as old as 182 ka occurred adjacent to the oldest deposits. A U-Th disequilibrium age of 287 ± 16 ka was reported for a silicified zone on the Dixie Valley fault system at The Mirrors.[67]

Geochemical investigations included chemical analyses of the spring, fumarole, and well samples, and identification of the hydrothermal alteration minerals in the well cuttings. Stable-isotope analyses indicated that the thermal waters are Pleistocene in age.[84] Researchers documented elevated helium-3 to helium-4 (^{3}He/^{4}He) ratios of 0.70-0.76 in reservoir fluids.[85] While the ratios were higher than expected for a purely crustal source (0.2 Ra), they were much lower than those found in geothermal systems driven by mid- to upper-level crustal magma chambers on the margins of the Basin and Range (e.g., ^{3}He/^{4}He ratios of 2-6 Ra at Steamboat Springs, Long Valley, Coso Hot Springs, and Roosevelt Hot Springs). Investigators concluded that that the helium must be derived from deep within the crust and the crust-mantle boundary.[85] Both helium ratios and hydrothermal fluid temperatures were the highest of the known Basin and Range fault-controlled systems. The high permeabilities implied by these data are consistent with the deep through-going fault zone imaged in the magnetotelluric (MT) data.

Borehole imaging and hydraulic fracturing experiments were also undertaken, with the conclusion that production occurs where fractures were optimally oriented with a strike of N 45°E and a dip of 60°SE, and critically stressed in the present stress field.[86-87] Maximum horizontal stress varies along the fault zone and is greater to the south in the vicinity of two unproductive wells.[87] Consequently, the range-front fault appears to be severely misaligned with respect to the present stress field in the southernmost well, resulting in a fault that is frictionally stable and in which fluid flow is suppressed.

4.5 The Salton Sea Scientific Drilling Program, California

The Salton Sea geothermal field in southern California is a hot, magmatically driven hypersaline geothermal system formed in deltaic sediments deposited by the Colorado River in the Salton Trough, an actively subsiding rift basin. Several other hydrothermal systems are known in the Salton Trough province. There is significant potential for further development, both at the Salton Sea field itself and at other locations. The Salton Sea Scientific Drilling Program (SSSDP) was designed to investigate the roots of this important geothermal system and form a better understanding of hydrothermal reservoirs within the Salton Trough. It was a joint effort conducted under the Interagency Accord on Continental Scientific Drilling, a cooperative agreement between DOE, the USGS, and the NSF. Forty-one science and technology projects were funded under the SSSDP.[88]

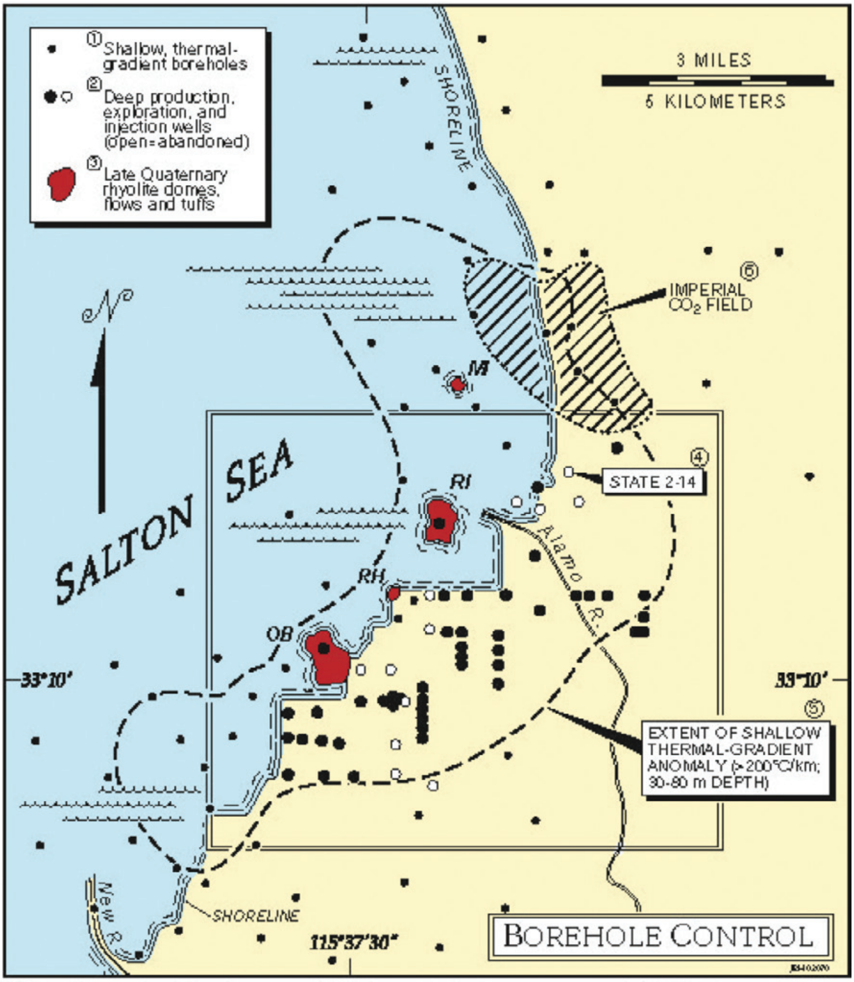
The focal point of the SSSDP was drilling a well, State 2-14, for scientific study just east of the main thermal anomaly at the Salton Sea geothermal field, to a depth of 3,220 meters (10,564 feet). Figure 13 shows the location of the State 2-14 well, other well locations and the area of a shallow thermal-gradient anomaly.[89] Drilling began in October 1985; the well was completed in 160 days.

State 2-14 achieved its initial scientific goal of investigating the subsurface thermal, chemical, and mineralogical environments of the geothermal site.[90] Due to funding limitations and location, however, the well did not reach the deep roots of the system. Nevertheless, it encountered temperatures of 355°C ± 10°C (671°F ± 18°F). Measured flow rates of 350 tons/hour demonstrated the commercial potential of the deep resource. A total of 224 meters (735 feet) of core was obtained. Brine samples with salinities of 25 weight percent total dissolved solids (TDS) were collected; temperature and downhole geophysical measurements were made. The extent of this effort was limited by severe borehole conditions below 1,800 meters (5,900 feet). State 2-14 encountered two mafic intrusions cut by veins of epidote, sulfides, quartz, and actinolite.

The Salton Sea geothermal field is an example of a sulfide-bearing mineral deposit in the process of formation. Research findings are of interest to the minerals exploration sector, as well as the geothermal exploration sector. A key finding with implications for commercial resource development was that, despite the decrease in porosity and increase in rock induration with depth, permeability-controlling fractures increase with depth.[91-92] Temperatures are high enough in the deltaic sediments to embrittle the rocks and enable them to sustain fractures. Flow-rate tests were completed through multiple flow zones at depths of 1,860 to 3,220 meters (6,120 to 10,560 feet), indicating high fluid-production rates. Results suggest productive resource potential at both shallow and deep levels.[93-94]

Drill core from the State 2-14 well demonstrated the presence of higher-grade metamorphism (low amphibolite facies) at temperatures and pressures lower than expected for that metamorphic grade.[95-97] The core samples obtained supported:

1) pioneering research studies of petrophysical properties ;[97-99] 2) analyses of sedimentary and evaporitic facies;[100-103] 3) determination of the source of salts in the brines;[101] 4) evaluation of structural relationships;[100/92] 5) identification of igneous-intrusive units;[104] 6) resolution of mineral-paragenesis and vein-deposition sequences related to ore-body emplacement;[102/105-107] and 7) identification of sulfur sources.[100-101] Evidence suggested that the system has cooled in the vicinity of State 2-14, possibly indicating that there is an older system in the same area or east of the present system.



① From Newmark et al. (1988)
② Mostly Magma Energy, CalEnergy, and Unocal
③ Robinson et al. (1976)
④ Salton Sea Scientific Drilling Project (Elders and Sass, 1988)
⑤ Modified and updated from Newmark et al. (1988)
⑥ Rook and Williams (1942); Muffler and White (1968)

Figure 13. Location of the State 2-14 well, Salton Sea Geothermal Field

Earlier work based on studies of drilling chips recovered from geothermal wells in the SSGS identified progressive metamorphism up to greenschist facies,[107-108] implying metamorphism under low-temperature conditions. Laboratory petrophysical measurements of porosity, density, and primary-wave (P-wave) seismic velocity correlated well with downhole well-logging values.[98-99] Vertical seismic profiling showed strong reflectance and scattering effects that agreed with fracture zones encountered by the borehole.[92] Innovative measurements with a high-temperature borehole gravimeter determined that high densities seen in the borehole extend a few kilometers from the borehole.[109]

As a part of the drilling program, gravity and magnetic data were combined with conductive heat-flow data to 1) refine the boundaries of the local, intense thermal anomalies responsible for the rate of heat flux for the entire Salton Trough,[90/110] and 2) confirm earlier work that inferred that the SSGS is about 10,000 years old.[95]

Further research work on the Salton Sea system is described in Section 5.1.

5.0

Geological Technique Development

Without a good understanding of the geology of a prospect area, exploration is merely guesswork. Three-dimensional geological models are the foundation of geothermal exploration and the interpretation of geochemical and geophysical signatures of geothermal systems. These models are formed from detailed geologic mapping supplemented with geochemical and geophysical data collection, both surface and subsurface. Because most geothermal fields are the result of active hydrological, thermal and mechanical processes, the geological models often include theoretical or numerical calculations of these phenomena. Initial models are tested, supplemented, and refined by further field work. The process continues until a hopefully reliable model is achieved. Detailed surface and subsurface mapping, structural analysis of faults, interpretation of satellite images, analysis and evaluation of mineral distributions, age-dating of geothermal manifestations, and many other techniques have been applied at numerous sites and wells under the DOE geothermal exploration technology development research program. The major accomplishments of these geological techniques along with their significance in reducing the cost and risk of geothermal exploration and resource development are highlighted below.

5.1 The Evolution of the Salton Sea Geothermal Field, California

The Salton Sea geothermal system is one of the largest geothermal systems in the world. Estimates of its electric generating potential exceed 2,000 MWe.[111] Because of the importance of this resource, DOE supported exploration and characterization studies of this field for over 30 years. In the 1970's, public domain electrical and thermal logs, cuttings, and available geophysical data were analyzed to provide a description of the upper kilometer of SSGS. This study quantified the thicknesses of impermeable caprock, unaltered reservoir, and altered reservoir throughout the accessible portion of the system. Wellbore temperatures were combined with thermal conductivity estimates from electric logs to estimate the variations of vertical conductive heat with depth across the drilled portion of the system. A broad area of nearly constant heatflow is underlain by a higher temperature zone with low vertical gradients, presumably caused by hydrothermal circulation.

A generalized model of this hydrothermal circulation was developed. The flow was assumed to be driven by the heat from recent intrusions (and small extrusions) evidenced by a somewhat circular magnetic anomaly. The temperature at the top of the convective zone was linearly correlated with the size of the surface magnetic anomaly at each well. If the magnetic anomaly size is viewed as a proxy for proximity to the driving force, this result suggests the fluid flow is primarily horizontal away from the intrusions. A simple kinematic model of horizontal flow was compared to the thermal data from the cap rock, and the duration of this pulse of horizontal flow was estimated. That duration is controlled by the expanse of area with nearly constant heat flow, and the abrupt transition to normal heatflow at its boundary. The range of possible ages for the system was found to be between 3,000 and 20,000 years.[119-120]

After the Salton Sea Scientific Drilling Program, DOE supported a series of studies[112-117] that provided a detailed analysis of the geology and history of the geothermal system, expanding on earlier investigations.[118-119] Researchers[120-121] based their models on the lithologic logging of more than 3,000 individual samples from 12 wells; an evaluation of geophysical logs, thermal conditions, regional and local seismicity, reservoir-fluid chemistry, and the distribution of hydrothermal minerals; and studies previously cited in Section 4.5. The following is an abbreviated summary of DOE-supported exploration R&D and results at the Salton Sea.

Thick intervals up to 400 meters (1,300 feet) of buried extrusive rhyolite were found in wells in the central part of the Salton Sea field where temperatures at depth are also highest. The thicknesses of these concealed felsic volcanics and the lack of corresponding intermediate-composition igneous rocks imply coeval granitic magmas that originated by crustal melting rather than by differentiation of gabbroic magma. Results of numerical modeling suggested that active magma-hydrothermal processes disperse energy from an intrusive complex approximately 20 km^2 in areal extent.[116] Individual plutons within this complex were estimated to be a few kilometers in diameter, at least 2 kilometers (1.2 miles) thick, with tops in the depth range of 5 to 6 kilometers (3.1 to 3.7 miles). The ages of the plutons, based on numerical models (10 to 50 ka)[116] and U-Th dating of zircons (30 ± 13 to 9 ± 7 ka)[117] suggested that the modern system is no older than a few tens of thousands of years. Analysis of the temperature profiles in wells indicated that portions of the current Salton Sea hydrothermal system are still thermally prograding, whereas other parts of the system have reached thermal maturity.

The wealth of scientific data and resulting field models developed through DOE-supported research will enable field developers to make the best decisions in further field expansion, and also be useful in the development of other thermal systems in the Salton trough.

5.2 Structural Controls on Geothermal Systems

Fluid flow within geothermal systems is often controlled by faults and fractures. DOE-funded investigations of the structural controls of geothermal systems focused primarily on determining fault distributions using a variety of field geological and geophysical techniques, including geologic mapping, remote sensing, satellite imagery, thermal infrared images, and aerial photographs. Studies were documented at Roosevelt Hot Springs,[122] Cove Fort-Sulphurdale,[123] Dixie Valley,[124] Steamboat Hot Springs,[125] and Desert Peak-Brady.[126]

The developing field of geomechanics has not yet been applied to any significant extent in geothermal research, and is a fertile field for investigation. This is especially true for development of EGS, in which the geomechanics of the area play a vital role in system development. To date, few geomechanical investigations of geothermal fault systems have been conducted due to limited availability of data. To help remedy this situation, researchers evaluated the kinematics of faults at the Karaha-Telaga Bodas field in Indonesia by analyzing image logs and determining the relative directions of movement on fault planes in continuous core samples.[127-130]

In 2000, KarahaBodas Co. Ltd gave EGI data and subsurface rock samples from the Karaha-Telaga Bodas geothermal system for research work. Subsequent analyses of structural and petrologic data showed that the base of the permeability cap is controlled by: 1) the distribution of initially low-permeability lithologies above the reservoir; 2) the extent of pervasive clay alteration that had significantly reduced primary rock permeabilities; 3) the distribution of secondary minerals deposited by descending waters; and 4) locally, a downward change from a strike-slip to an extensional stress regime, attributed to the increased thickness of the overburden. Productive fractures display the greatest tendency to slip and dilate under the present-day stress conditions. The effective base of the reservoir is controlled either by the boundary between brittle and ductile deformational regimes or by the closure and collapse of fractures within volcanic rocks located above the brittle/ductile transition.

Geomechanical analyses were also performed on wells in the Coso geothermal system. The results of this work are summarized in the companion volume to this report on Reservoir Engineering and in several other reports.[131-132] Apparently, geomechanical studies can be quite important in understanding fluid flow in specific geothermal systems.

5.3 Applied Terrestrial Remote Sensing Technology

EGI, the Great Basin Center for Geothermal Energy at the University of Nevada, Reno (GBC), and LLNL, among others performed DOE-sponsored remote sensing studies to support geothermal exploration and the geologic characterization of geothermal systems. Studies covered topics ranging from geologic mapping to the indirect identification of blind hydrothermal systems, and are grouped in four general categories: 1) geothermal exploration model development, 2) exploration for blind systems, 3) geologic characterization of geothermal areas, and 4) thermal-anomaly mapping.

5.3.1 Geothermal Exploration Model Development

DOE-supported scientists developed a knowledge-based digital geothermal exploration model that covers most of the Great Basin. The model used analysis of several spatially correlative data sets based on a geographic information system (GIS).[131] Input data included hydrothermal alteration maps and lineament-fault maps derived from LandSat Thematic Mapper™ data[132], gravity data, aeromagnetic data, geochemical data, locations of mining districts, locations of young igneous lithologic units, heat-flow data, known geothermal occurrences, and topography. Data were weighted and quantified using a GIS into a final geothermal potential map. The results indicated that known geothermal systems could be located with such a system. However, anomalies generated from such analyses always require field-verification. Use of such a technique could in principle, speed exploration-area selection and reduce costs. Such techniques can be generally applied to benefit geothermal exploration programs in any geologic environment.

5.3.2 Exploration for Blind Systems

Applying remote sensing to locate blind geothermal systems—those with no evident physical surface manifestations—focused on: 1) identifying vegetation affected by upwardly migrating geothermal gasses (e.g., H_2S and CO_2) which are vented at the Earth's surface via fault and fracture systems; 2) geochemical anomalies in soil produced from geothermal systems; 3) detection and characterization of hydrothermal-alteration mineralogy; and 4) detection and mapping surface evaporite minerals that may be related to hydrothermal convection.

Vegetation was analyzed using hyperspectral imaging—imaging which uses hundreds to thousands of spectral bands—at: 1) several Nevada geothermal sites where greasewood is the predominant vegetation, including Kyle Hot Springs, Gabbs Valley, and Dixie Valley, Nevada; 2) Cove Fort-Sulphurdale, Utah, where big sagebrush is the dominant vegetation type,[131/133-137] and 3) at Long Valley Caldera.[138]

Significant vegetal-spectral differences were found near and over Kyle Hot Springs and over faults in Dixie Valley near the current Terra-Gen Power production area. Additionally, a vegetation anomaly was detected in Dixie Valley using data from the French AVIRIS airborne hyperspectral system. The anomaly showed few visual surface effects at first, but eventually became a complete die-off of surface vegetation. The event was related to a reservoir pressure-drop that led to production-induced boiling, with venting of steam and gases in the kill area. Vegetal-spectral anomalies were also identified over a blind hydrothermal convection system, located serendipitously by mineral exploration drilling, in Gabbs Valley.[131]

For interpretation of Cove Fort-Sulphurdale data, new software was developed to automate spectral-parameter calculations for the position of the visible green maximum, the point-of-inflection of the spectral red-edge, and a ratio parameter of the spectral red-edge.[137] Anomalies were statistically determined using the standard-deviation method from the spectral parameters. The classified results were then mapped in a GIS, along with faults from geologic maps and geophysical surveys, to determine if spatial correlations existed. Researchers discovered that a significant clustering of spectral anomalies in sagebrush occurred along strike coincident with the range-front fault system. Smaller anomalies were also associated with other faults and an obvious H_2S gas seep. The anomalies were thought to be related to soil changes, such as acidification, related to gas seepage. In some small areas, flora was affected directly by degassing.

Long Valley has a large area of tree kills due to CO_2 leakage. Ground-based measurements with a hand-held hyperspectral imager showed that the method was able to detect stress caused by hydrothermal emanations before the effects were visible. However, to detect these effects from the air requires fine-enough resolution that the vegetation is homogeneous in a single pixel. A HyMap survey was flown with the desired resolution, and the plant stress was mapped. The kill area inferred from the airborne survey matched published descriptions of the kill area. The airborne survey also identified other areas of pre-morbid plant stress that may point to flow paths out of the system.[139]

Research suggested that field vegetal-spectral surveys could be useful, cost-effective tools in local exploration efforts and that airborne hyperspectral data would no doubt be useful in exploration over larger areas with moderate to dense vegetation cover. However, vegetal-spectral analysis for discovery of blind systems is a first-pass, reconnaissance exploration method, and field checking is needed to corroborate the results. This being stated, the technique can help find targets of interest that may be missed otherwise. It also has the potential to reveal unknown faults.

Soil geochemistry is often found to be affected by underlying geothermal systems. Buried fossil sinters, fumaroles, and hydrothermally altered material in faults and fractures can produce localized geochemical halo effects in soils. Hyperspectral AVIRIS data covering Dixie Valley over and near the production field were tested to determine if any such halos existed.[140-141] Evaluation of these data revealed both calcite and kaolinite anomalies that correlated with the buried piedmont fault believed to be associated with production. The fault also acted as a conduit in the development of new fumaroles during a period of decreasing reservoir pressure and boiling, indicating that the fault was permeable and in communication with the hydrothermal convection system. This suggested that the anomalies were likely related to older fumarole-related mineralization or buried hot-spring deposits along the fault. Hyperspectral data could be used in regional surveys to pinpoint similar anomalies that may lead to the discovery of new blind geothermal systems.

Hyperspectral data were also used for hydrothermal-alteration mineral mapping, another potential technique for discovery of blind geothermal systems. Successful efforts were made in Dixie Valley using hyperspectral imaging data[142-145] and at the Pyramid Lake Piute Reservation.[146] Identification and mapping of hydrothermal alteration minerals formed by fossil systems may show temperature-controlled mineral zoning, indicating where structures have been permeable in the past. Hydrothermal alteration can identify areas where further work is warranted in the search for blind systems. However, field verification must determine whether the alteration and mineralogy are recent enough to indicate current hydrothermal activity.

Hyperspectral data were also used to identify evaporite minerals that may be associated with geothermal systems.[147-149] It remains to be determined by field studies, however, whether alkali minerals identified using hyperspectral imagery are unique indicators of geothermal activity or if they have other origins.

5.3.3 Geologic Characterization of Geothermal Areas

DOE supported the testing of multispectral, hyperspectral, panchromatic, and light detection and ranging (LIDAR) techniques to characterize the geology of geothermal areas. LandSat Thematic Mapper™ multispectral data were used for structural characterization in a study that led to a new conceptual model for the structural evolution of The Geysers geothermal system in California.[150]

Investigators used Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) multispectral imagery with 15-meters to 30-meters (49-feet to 100-feet) spatial resolution, fused with digital panchromatic orthophotos (DOQs) at 1-meter (3-feet) spatial resolution, for geologic mapping.[151-152] Due to the residual spectral qualities in the fused imagery, the resultant image was found to be superior to traditional color aerial photography as a geologic mapping base. The imagery better facilitated the discrimination of lithology in areas with low or moderate vegetation cover and also aided in structural mapping. The imagery was particularly useful when draped over 10-meter (33-feet) resolution digital elevation models to create a three-dimensional scene. A good deal of mapping can be done prior to field work, thus shortening the time and cost of field geologic mapping. However, field work is still necessary to validate the results interpreted from the imagery and to help answer questions generated from the initial mapping effort.

Figure 14 shows an example of ASTER and fused imagery at the Silver Peak Range in Nevada. The top image is ASTER multispectral 15-meters (49 feet) spatial resolution data. The bottom image shows fused 1-meter imagery overlain on the original ASTER image (pixilated) for comparison. The 1-meter data corresponds spatially with the small white box in the top image. The white box encompasses an area near the mouth of Emigrant Canyon in the northern Silver Peak Range.

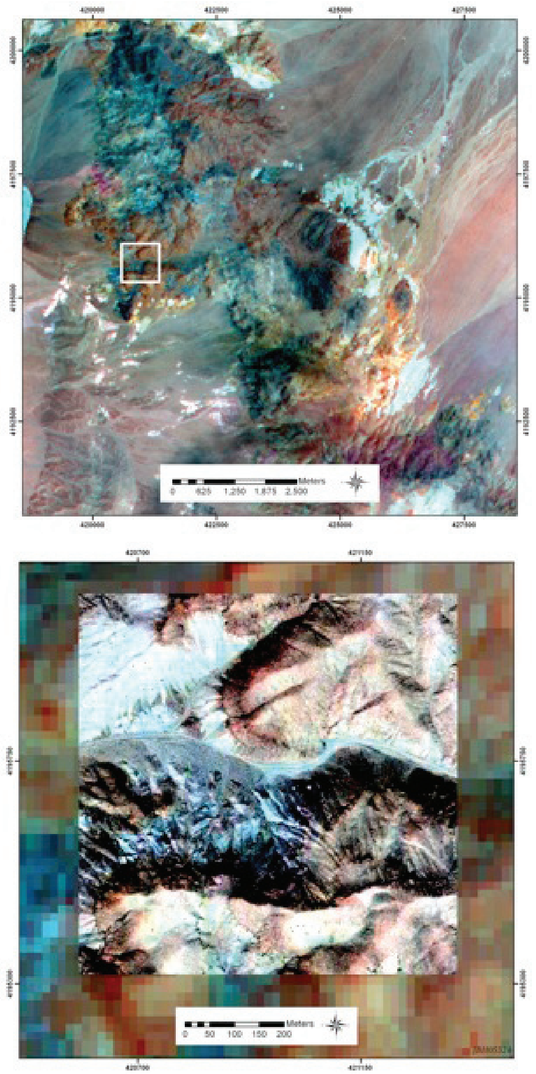


Figure 14. ASTER and fused imagery, Silver Peak range, Nevada

DOE researchers also used high spatial-resolution data for geologic characterization.[153] This research was applied to develop advanced remote sensing methods that could screen large spatial regions and pinpoint promising locations for traditional geothermal exploration and existing field expansion. Several lines of investigation were followed, including: 1) evaluating the utility of high-resolution QuickBird satellite imagery and comparing its results to airborne hyperspectral imagery results for subtle fault system mapping; and, 2) evaluating the use of LIDAR high-resolution digital elevation models (DEMs) to locate subtle fault systems.

Satellite data are useful for mapping important structures, such as cross-cutting fault systems and rotated block-fault systems, and providing an overview of the geomorphology of the exploration region. By targeting traditional geothermal exploration through terrestrial remote sensing, costs may be lowered and the probability increased in finding new geothermal power resources.

5.3.4 Thermal Anomaly Mapping

DOE supported research into airborne detection of thermal anomalies as early as the 1970s. Airborne detection would allow more extensive and rapid surveys than the standard approach of measuring heat-flow in boreholes. In one experiment, pre-dawn aerial dual-band infrared surveys of parts of Long Valley were corrected using scattered surface measurements to obtain a detailed map of true land surface temperature. This approach identified the same anomalous area as had been previously identified by standard heat flow measurements.[45/154]

In the 1990s, remotely-sensed thermal-infrared (TIR) imagery was tested in Dixie Valley, Nevada, to determine its utility in geothermal exploration and system characterization.[155-156] Data were used to: 1) map heretofore unknown thermal anomalies associated with the hydrothermal convection system, 2) calculate heat flow, and 3) develop a hydrologic model for the shallow thermal regime.

With DOE support, researchers examined the use of relatively high spatial-resolution (approximately 10 meters [30-feet]) airborne thermal infrared multispectral scanner and relatively low spatial-resolution (90 meters [290 feet]) ASTER TIR data for mapping thermal anomalies at Steamboat Springs, Nevada. They determined that the integration of calculated thermal inertia and slope corrections enhanced thermal anomalies by an order of magnitude.[157] ASTER TIR data were also used in a similar study at Railroad Valley, Nevada.[158] Use of a thermal-inertial image, which is compared to a nighttime kinetic-temperature image derived from the ASTER TIR imagery, was found to be crucial in identifying anomalies. The method facilitated mapping thermal anomalies, corroborating earlier work.[157]

Thermal-anomaly mapping using ASTER data can be applied over relatively large areas cost-effectively, potentially making it a good first-pass exploration method. However, it must be noted that other natural phenomena, such as vegetation-density anomalies associated with shallow ground water, can cause phantom thermal anomalies. Therefore, as in all remote-sensing based mapping efforts, field work is required to substantiate the results of analysis.

5.4 A Conceptual Model of Volcano-Hosted Vapor-Dominated Geothermal Systems

Vapor-dominated geothermal systems are highly prized due to their high energy value per unit of fluid produced at the surface and simpler power plant requirements. In-depth investigation of volcano-hosted geothermal systems[159-164] resulted in significant new insights into the time-temperature-composition histories of volcano-hosted geothermal systems. DOE-funded studies concluded that volcanic-hosted, vapor-dominated geothermal systems evolved from liquid-dominated resources and consequently displayed the same hydrothermal features. Thus, methods used to explore for liquid-dominated reservoirs, such as magnetotelluric and other electrical geophysical surveys, can also be used for vapor-dominated regimes.

DOE researchers developed a five-stage conceptual model to describe the formation of vapor-dominated conditions based on these studies.[162/164] Stage 1 involves the formation of an over-pressured, liquid-dominated geothermal system soon after magmatic intrusion. In Stages 2 and 3, pressures progressively decrease, and a curtain of steam-heated water develops surrounding a magmatic vapor-dominated chimney at 350°C (662°F) and 14 ± 2 MPa. The relatively low pressure near the base of the chimney causes liquid inflow adjacent to the intrusion and the development of a secondary marginal vapor-dominated zone. In Stage 4, the magmatic vapor discharged from the intrusion becomes small, vapor pressure declines; the secondary vapor-dominated zone expands above the intrusion. In Stage 5, the vapor-dominated zone floods because heat from the intrusion is insufficient to boil all liquid inflow. A more common, liquid-dominated volcanic-hosted system then develops.

As part of this investigation, more than 3,900 meters (12,800 feet) of continuous core and 14,800 meters (48,600 feet) of cuttings, along with temperature, pressure and lithologic logs, geochemical analyses including major and minor components, stable isotope compositions, ^{3}He/^{4}He ratios, and gravity and magnetotelluric data were graciously provided to DOE researchers by the KarahaBodas Co. Ltd in Indonesia. As a result of the donation of this mountain of data, Karaha-Telaga Bodas is the best documented and drilled volcanic-hosted system for which data are currently available in the public domain. Rock samples from Karaha-Telaga Bodas are stored at the EGI Geothermal Sample Library and are available for research purposes. Figure 15 shows a conceptual model of the Karaha-Telaga Bodas geothermal system in Indonesia.[164]

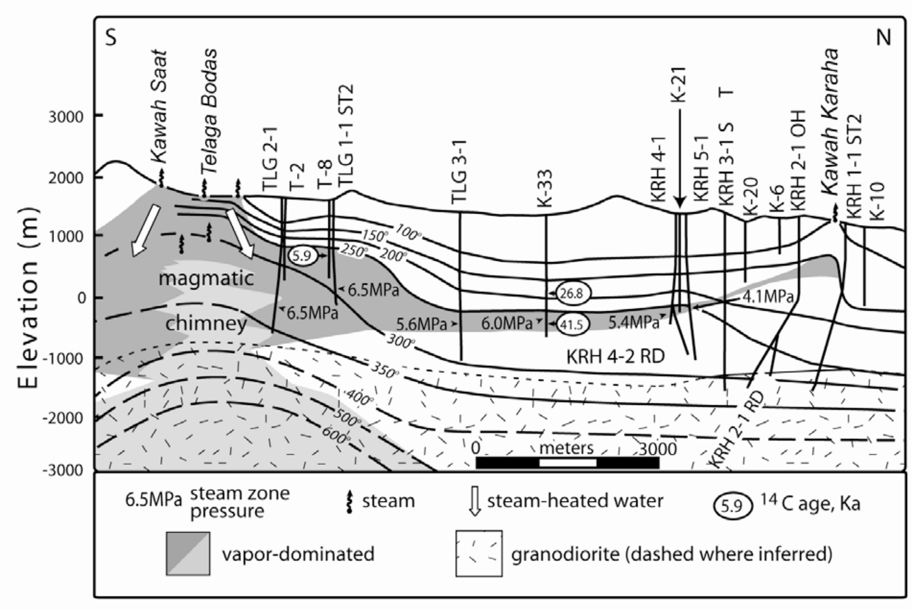


Figure 15. Conceptual model of the Karaha-Telaga Bodas geothermal system, Indonesia

5.5 Significance of Hydrothermal Alteration Assemblages

The distribution and characteristics of hydrothermal minerals within a geothermal system have a major effect on the porosity and permeability distributions and structural behavior of hydrothermal systems. Because clay minerals are electrically conductive, the geophysical signatures of geothermal systems are also dependent to a large degree on the distribution of hydrothermal minerals. Researchers concluded that five factors influence mineral deposition: temperature, pressure, rock type, permeability, and fluid composition.[165] The relative ages of the secondary minerals provides an additional dimension to understanding the evolution of geothermal activity.

Researchers supported by the DOE Geothermal Program found that the modern high-temperature thermal regime at Coso was superimposed on an earlier lower-temperature geothermal system with well-defined caprock and reservoir sections, and that the present production was from the older reservoir section.[166] This older caprock is as much as 2,500 meters (8,200 feet) thick in the eastern part of the field. The modern system may have formed very recently (see Section 5.6).

Detailed paragenetic investigations of the volcanic system at Karaha-Telaga Bodas led to the recognition of four distinct assemblages. The earliest assemblages reflected peak thermal conditions in liquid-dominated geothermal systems. With increasing distance from the heat source, the diagnostic minerals were tourmaline, biotite, actinolite, epidote, illite, interlayered illite-smectite, and smectite. Epidote, characteristic of propylitically altered rocks (temperatures > 240-260°C [464-500°F]) typically marked the top of the reservoir zone. Chalcedony, followed rapidly by quartz, was found to have the high-temperature assemblages (>250°C [482°F]) of several volcanic systems. Figure 16 is a photomicrograph from the Bulalo geothermal field, Philippines, showing chalcedony (cha) overprinted by epidote (ep) and then anhydrite (anhy).[161] Figure 17 shows the progressive formation of silica polymorphs resulting from catastrophic reservoir boiling.[164]

Chalcedony typically occurs only at temperatures less than approximately 180°C (356°F). Its appearance at high temperatures is interpreted to represent catastrophic decompression and boiling of the reservoir fluids caused by flank failure of the volcano or by faulting.[161] Such an event can trigger the formation of vapor-dominated regimes in systems with low to moderate permeabilities.

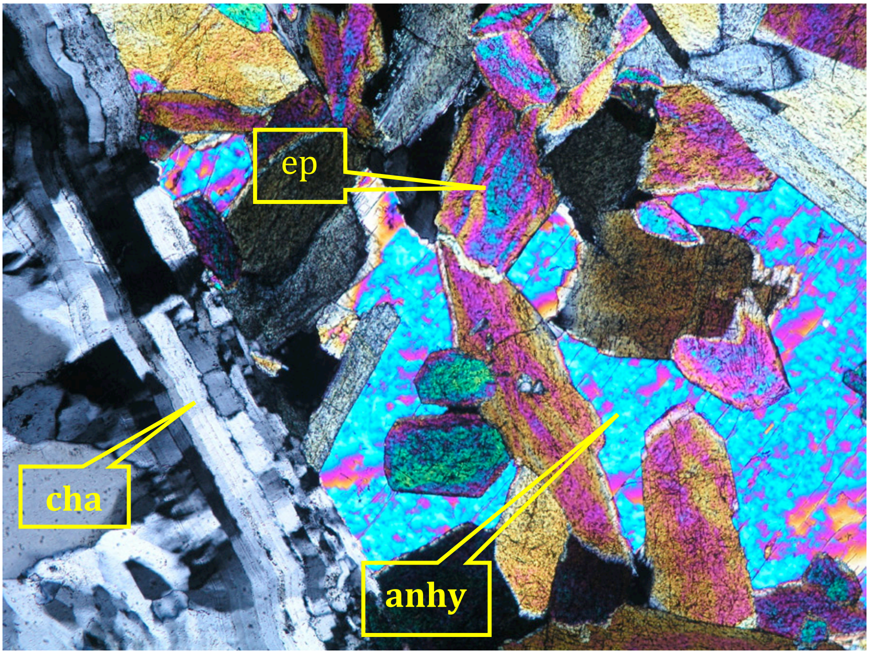


Figure 16. Photomicrograph from the Bulalo geothermal field, Philippines, showing chalcedony (cha) overprinted by epidote (ep) and then anhydrite (anhy)

The third assemblage recorded the influx of CO_2- and sulfate (SO_4)-rich steam-heated waters as temperatures and pressures declined. These fluids deposited anhydrite and calcite at shallow to moderate depths in the fractures, limiting further recharge through marginal fractures. Wairakite was deposited where steam-heated waters mixed with in situ reservoir fluids in the deeper parts of the system. In regions of low permeability that dry out completely in response to production or through the formation of vapor-dominated regimes, the final assemblage would be represented by precipitates of sodium chloride (NaCl), potassium chloride (KCl), and iron chlorides ($FeCl_x$) on rock surfaces and the discharge of hydrogen chloride (HCl)-bearing steam.

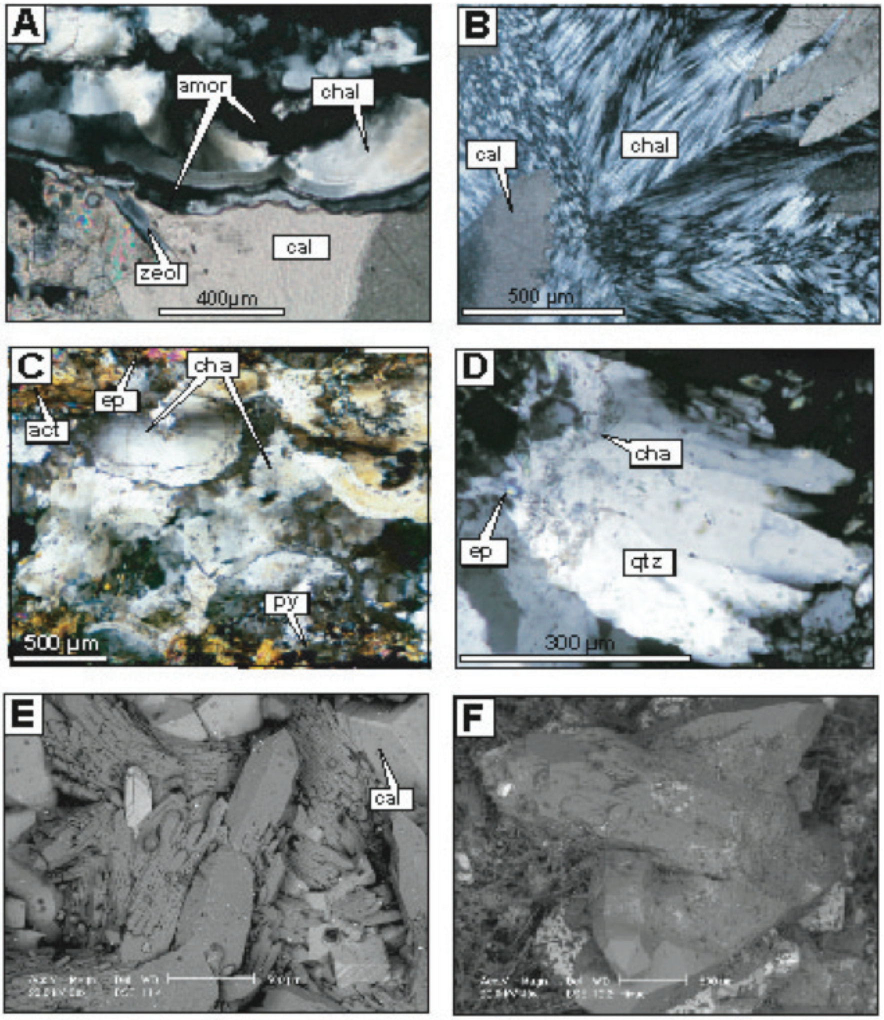


Figure 17. Progressive formation of silica polymorphs resulting from catastrophic reservoir boiling.

Photomicrographs (A-D) and scanning electron microscope (SEM) images (E, F) are from Karaha-Telaga Bodas. A) At the lowest temperatures, the silica was deposited as alternating layers of amorphous silica (amor) and chalcedony (chal). B) Chalcedony is the only silica polymorph present at intermediate temperatures (<250°C [482°F]). C-D) At temperatures >250°C chalcedony is overprinted by quartz (qtz). Traces of epidote (ep), actinolite (act), and pyrite (py) are present. E-F) SEM images of quartz after chalcedony. Calcite (cal) was deposited after quartz in E.

5.6 Duration and Age of Hydrothermal Activity

The presence of young volcanic rocks (< 1 my in age) was found to be among the best diagnostic criteria for locating potential geothermal resources. From this, researchers inferred that geothermal activity typically spanned long time periods.[167] More recent studies, however, suggested that geothermal activity was frequently episodic and that individual pulses could be relatively short-lived.

Sinter deposits at Roosevelt Hot Springs and Steamboat Hot Springs were dated.[168-169] Carbon-14 ages of organic material encapsulated in the deposits were much younger than volcanic rocks at the same locations. Dates obtained on the basal portions of two sinters at the Opal Mound at Roosevelt Hot Springs yielded ages of 1,630 ± 90 and 1,920 ± 160 y BP. Dating of a 15-meters (49-feet) thick sequence of sinter deposits at Steamboat Hot Springs suggested that activity began at approximately 11,493 ± 70 y BP. An important observation was that the transformation of amorphous silica to quartz may have occurred very rapidly, within a few thousand years, and that this transformation could not be used to estimate the age of hot spring activity.

Other studies constrained the ages of geothermal activity in two volcanic systems—Tiwi, Philippines and Karaha-Telaga Bodas, Indonesia.[163/170] Argon 40/39 ($^{40}Ar/^{39}Ar$) spectrum dating of vein adularia from Tiwi, when combined with fluid-inclusion temperatures, documented a complex thermal history that began with adularia deposition between approximately 314 and 279 ka.[170] Between 279 and 200 ka, temperatures of at least 300°C were reached intermittently in response to a short-term (e.g. 20,000 y) thermal pulse(s) or were maintained by slow cooling. A long period of quiescence lasting from 200 to 50 ka followed. The present system is no older than 10 to 50 ka. It is significant that fracture zones, which are permeable during the early phase of geothermal activity, also control fluid flow today.

^{14}C ages of altered lake beds in the volcanic-hosted system at Karaha-Telaga Bodas also documented recent thermal activity. In this case, hydrothermal and magmatic activity was found to be no older than approximately 5,910 ± 76 y.[163] Similarly, recent heating events were suggested by preliminary $^{40}Ar/^{39}Ar$ spectrum dating of rocks from Coso, indicating that the present temperatures may not have persisted for more than 10 ka.[171] In another instance, young thermal pulses at the Salton Sea were implied by zircons with uranium-thorium (U-Th) ages between 30 ± 13 and 9 ± 7 ka.[172]

DOE scientists used geochemistry in the exploration stages of a geothermal program to estimate reservoir temperatures, locate permeable fault zones, trace fluid sources, and evaluate past fluid temperatures and salinities. Toward these goals, the trace-element, stable-isotope and noble-gas compositions of soils, rocks and fluids were analyzed. Changes in the thermal and geochemical conditions within reservoirs were monitored by integrating mineral distributions with microthermometric measurements on the fluid inclusions trapped within these minerals.

Although the development of chemical geothermometers was historically done by the USGS and research groups in New Zealand and Iceland, DOE provided funds for collecting and analyzing water and gas samples. The USGS, OIT-GHC, GBC, Utah Geological Survey, and others maintain databases of geochemical analyses. These databases are updated as new information becomes available. Geothermometer temperatures, measured temperatures, and other well data can be accessed electronically through these databases.

6.0

Geochemical Technique Analysis

6.1 Trace-Element Analyses of Soils and Rocks

The application of trace-element distributions to geothermal exploration was based on the success of mineral exploration programs that had documented the presence of multi-element haloes around ore deposits. The technique was refined and further adapted for geothermal use by analyzing soils and cuttings samples from Beowawe and Colado in Nevada, Cove Fort-Sulphurdale and Roosevelt Hot Springs in Utah, The Geysers in California, and Meager Mountain in British Columbia.[173-178] These studies showed that the distribution of mercury (Hg) in soil samples could be used to map the locations of permeable structures connected to a geothermal reservoir. Other elements such as arsenic (As), antimony (Sb), and beryllium (Be) were locally enriched, but their distributions were inconsistent. At depth, anomalous concentrations of Hg were found in wells where temperatures were below 200°C (392°F) but at higher temperatures, Hg was not fixed in the rocks.[176]

Researchers reported that alkali minerals such as borates were associated with hidden geothermal systems in the Basin and Range.[179] While imagery like ASTER data could be a potentially useful exploration tool, mineralogy may also be related to the evaporation of Pleistocene playa waters with sources distant from the evaporate minerals. Field work is necessary to confirm any remotely sensed anomalies.

6.2 Soil-Gas and Gas-Flux Measurements

Researchers employed analyses of soil-gases and measurements of gas-fluxes at several geothermal sites. Analyzing radon gas at Roosevelt Hot Springs located mapped faults that communicated with the reservoir.[180] Scientists conducted a detailed mercury soil-gas survey at Desert Peak and analyzed a broad range of soil gases at Steamboat Springs and Brady's Hot Springs.[181] The Desert Peak study further demonstrated the utility of mercury surveys in tracing concealed permeable structures. Carbon dioxide (CO_2), water (H_2O), sulfur gases, boron (B), and radon (Rn) were also measured at the two other sites during the study.

Gas-fluxes were measured at Dixie Valley,[182-183] Roosevelt Hot Springs, and Cove Fort-Sulphurdale.[184] At Dixie Valley, high CO_2 fluxes were measured in an area of recent plant kill and along recently formed ground fractures at the base of the kill zone. The high flux was related to reservoir pressure declines that induced boiling of an outflow plume. In the latter two studies, fluxes of CO_2, CH_4, and nitrous oxide (N_2O) were measured. Although geothermally derived CO_2 was detected in soil gas and soil-gas fluxes, interpretation of the data was complicated by soil respiration and biological processes, especially during the summer months.

6.3 Geochemical Analyses of Geothermal Fluids

Geochemical analyses, particularly of helium isotopes, are significant potential tools in exploration for high-quality geothermal resources, beyond their application as geothermometers. The $^3He/^4He$ ratios of geothermal fluids from fault-bounded Basin and Range geothermal systems were measured to determine if a deep mantle signature was present (see Figure 18).[185-187] Researchers documented elevated $^3He/^4He$ ratios in three areas:

1. On the western margin of the Basin and Range where recent magmatic activity occurred along the Cascade volcanic chain and Walker Lane shear zone;
2. In the northwestern Basin and Range, Snake River Plain, and Idaho Batholith where there was no evidence of young volcanic activity; and
3. At isolated sites within the interior of the Basin and Range that lacked young volcanic rocks, including Dixie Valley, Black Rock Desert, Diamond Valley, and Monte Neva.

These elevated $^3He/^4He$ ratios were believed to be evidence of deep permeability and possibly deeper, higher-temperature fluid reservoirs. The results could be used to identify extensional faults with deep permeability that would be most suitable for future exploration projects.

DOE supported studies to measure the isotopic compositions of Dixie Valley waters, including deuterium (D), oxygen-18 (^{18}O), carbon-14 (^{14}C), and the ratios strontium-87/strontium-86 ($^{87}Sr/^{86}Sr$), and carbon-13/carbon-12 ($^{13}C/^{12}C$), to help determine fluid-source regions and circulation paths.[188] Researchers concluded that the thermal waters evolved from dilute valley waters, perhaps in a Pleistocene lake, 11,000 to 20,000 years ago. There was little lateral flow into the production zone; instead, most of the flow occurred upward within the Dixie Valley fault zone, which hosted the production zone.

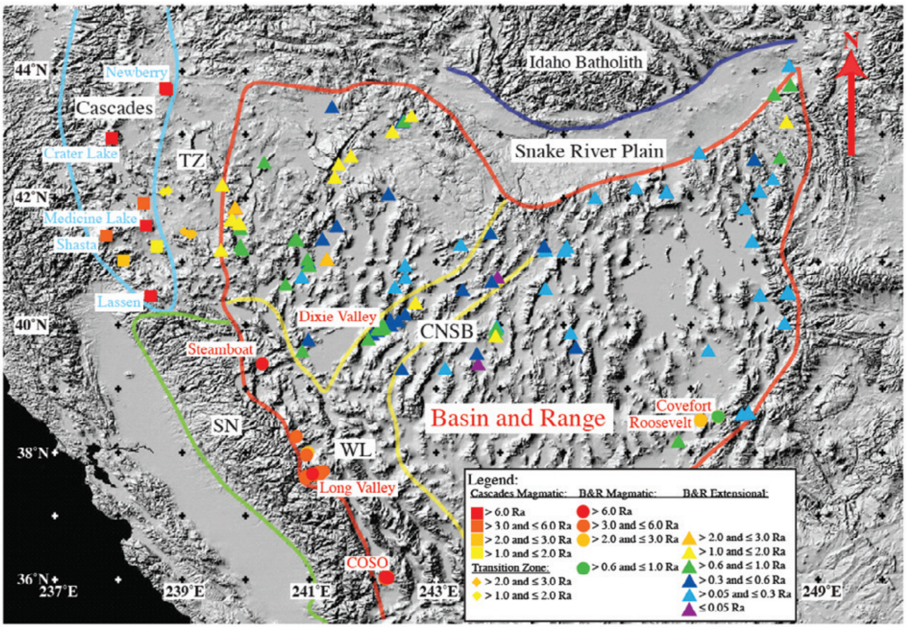


Figure 18. Map of $^3He/^4He$ ratios for Western geothermal areas, expressed as Ro/Ra (the air-corrected sample ratio normalized to the ratio in air).

Symbol shapes identify the type of thermal area. Tectonic zones are outlined: red, northern Basin and Range (B&R); yellow, the Walker Lane transtensional zone (WL) and the central Nevada seismic belt (CNSB); green, the Sierra Nevada batholith (SN); and light blue, the Cascades volcanic zone; TZ = transition zone between the Cascades, WL and B&R.

Another study analyzed concentrations of rare-earth elements in waters to assess their application as an exploration tool.[189] However, sampling and analysis of rare-earth elements from thermal systems were difficult and the results of the study were inconclusive.

Researchers analyzed the distribution of 14 chemical constituents in ground waters from the Great Basin to determine if their distributions could be useful in geothermal exploration.[190] While most of the constituents displayed some degree of correlation with geothermal activity, fluorine, boron, arsenic, and silica were found to have the highest spatial correlation with high-temperature geothermal systems.

6.4 Fluid Inclusion Studies

Fluid inclusions are micrometer-sized cavities trapped in many mineral species at the time of mineral formation. They contain samples of the liquids and vapors present within a geothermal system at different times during its evolution. Figure 19 shows examples of fluid inclusions from Karaha-Telaga Bodas, Indonesia.

Inclusions generally contain a liquid phase and a gas phase, the latter seen as a bubble under the microscope. The temperature of the inclusion's formation is considered the temperature at which heating causes the fluid to homogenize (i.e. the bubble to disappear). By freezing the fluid in the inclusion, a measure of freezing-point depression can be obtained and related to the salinity of the contained fluid. Temperatures and salinities, calculated as equivalent weight percent NaCl, can be interpreted in terms of boiling, cooling, and mixing in much the same way as chemical analyses of well and spring waters are evaluated.[191]

Researchers used fluid-inclusion data to characterize the thermal and geochemical structures of geothermal systems.[192-193] Measurements on fluid inclusions from more than 15 wells at Coso Hot Springs demonstrated that hydrothermal fluids on the western side of the field moved upward and northward from an upflow zone in the south. Present-day flow and geochemical patterns are similar to those defined by the fluid-inclusion data; fluid-inclusion salinities indicated the presence of low-salinity groundwater not present in the field today.

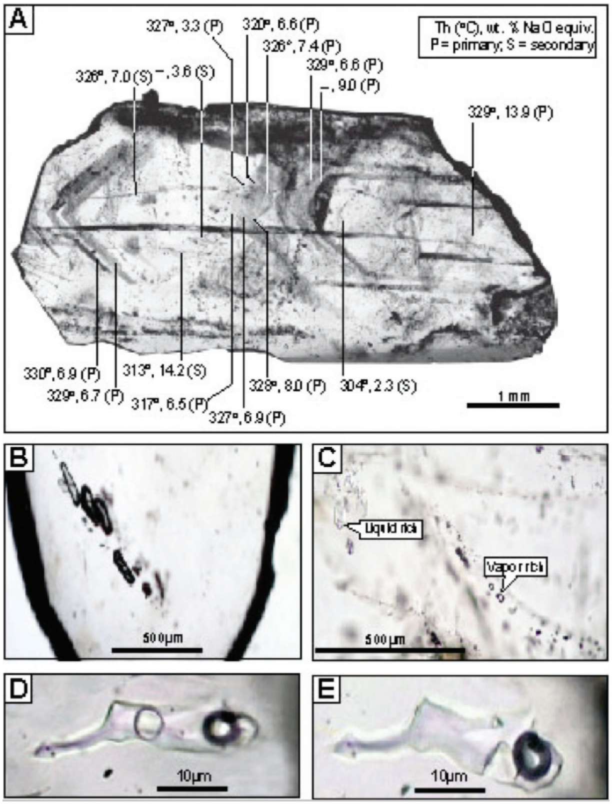


Figure 19. Examples of fluid inclusions from Karaha-Telaga Bodas, Indonesia.

(A) Homogenization temperatures and salinities of fluid-inclusion populations in a single crystal of quartz. (B) Primary vapor-rich inclusions. (C) Secondary planes of all liquid- and all vapor-rich fluid inclusions. (D-E) A liquid-rich fluid inclusion containing a daughter crystal of fluorite at room temperature (D) and after heating and cooling (E).

At The Geysers and Karaha-Telaga Bodas, fluid-inclusion temperatures and salinities provided a unique and otherwise invisible record of the transition from liquid- to vapor-dominated conditions.[163-164/194] At Tiwi in the Philippines, comparing measured and present-day temperatures provides insight into short time-scale variations and indicates that the system is hotter now than it was in the recent past (see Figure 19).[164/170]

Gaseous species trapped in the inclusions can be determined by quadrupole mass spectrometry.[195] Under the DOE-sponsored exploration R&D program, analytical techniques were refined and new interpretational methods were developed to use such information. Scientists used gas ratios as tracers to distinguish fluids derived from meteoric, magmatic, and connate sources.[196-198] Fluid inclusions that trapped boiling fluids were shown to be enriched in gases with low solubilities including methane (CH_4), hydrogen (H_2), argon (Ar), nitrogen (N_2), and helium (He).[170/198] Fluid inclusions showed that differences in the gas ratios of various fluid-inclusion populations reflected the degree of boiling and whether boiling occurred under open- or closed-system conditions.

Figure 20 shows the fluid inclusion temperatures and salinities from Matalibong-25, Tiwi, Philippines, comparing the homogenization and measured temperatures documents heating since the inclusions were trapped.[170]

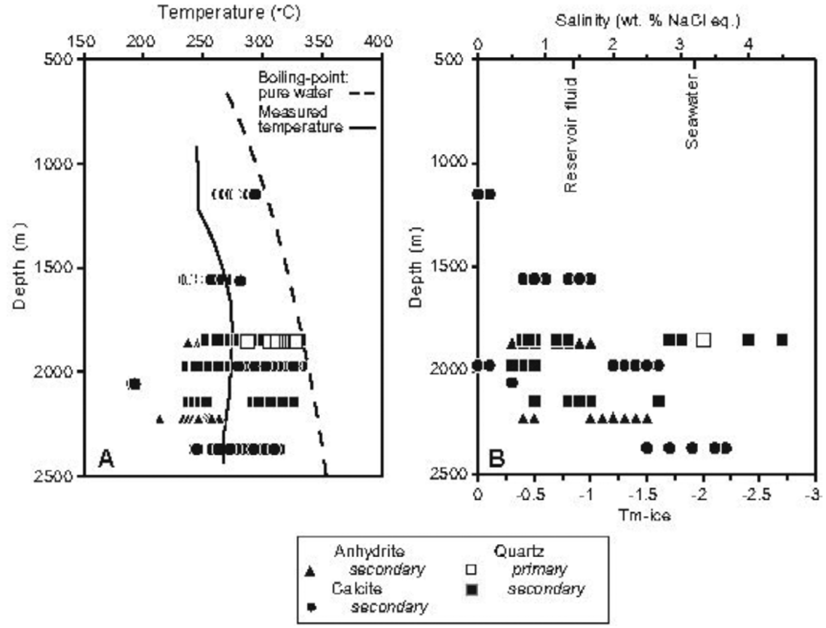


Figure 20. Fluid inclusion temperatures and salinities from Matalibong-25, Tiwi, Philippines. Comparison of the homogenization and measured temperatures documents heating since the inclusions were trapped.

7.0

Geophysical Technique Development

A large and varied array of geophysical methods is used in mineral and petroleum exploration and by earth science researchers. It was important to test many of these methods in the geothermal environment to determine which methods were useful, how they should be applied, and how they can be adapted and improved. This section documents some of these efforts.

7.1 Seismic Methods

Since the days of the AEC, the geothermal exploration program sponsored research on seismic methods related to exploration and reservoir monitoring, with research continuing to the present. The role of seismic methods in geothermal reservoir definition has been under investigation for many years as a part of the LBNL geothermal exploration technology program; a great deal has been accomplished. In the early 1970s, a primary research goal was to evaluate the several seismic techniques in general use for application to geothermal exploration. Exploration seismology is composed of several methods. Microearthquake and ground-noise surveys are most relevant to geothermal exploration. Active seismic profiling was also studied, with some success.

7.1.1 Active Seismic Studies

Reflection and, less commonly, refraction seismic surveying using explosive or pneumatically driven energy sources (active seismic surveys) are the mainstay of petroleum exploration, and have been very highly developed over many years for use in petroleum geologic environments. When accurately conducted in the right environments, the interpretation of seismic surveys can form a highly detailed and reliable picture of the subsurface structure, with resolution unattainable by most other geophysical methods. Such a picture would be highly desirable in geothermal exploration to guide drilling. However, the geothermal environment differs radically from the petroleum environment (e.g., see discussion of seismic surveying in difficult, hard-rock environments[199]).

In most petroleum basins the strata are flat or gently dipping and seismic velocity generally increases with depth. In the geothermal environment, structures such as rock contacts and faults are often steeply dipping, and the seismic velocities of the various units may not be orderly. These characteristics result in a highly complex data set that is often very difficult or ambiguous to interpret. Due to the high cost of active seismic surveys and geothermal systems' complexity, researchers and industry have conducted little research and testing of active seismic methods in geothermal environments. In most geothermal environments, the challenge of using seismic methods has been to separate the "background" natural complexity and heterogeneity of the host rock from the fracture/fault heterogeneity controlling the fluid flow. Ideally, the objective is not only to find fractures, but those specific fractures which control fluid flow.

Early in the DOE Geothermal Program, LLNL conducted a large-scale seismic refraction survey of the Salton Sea geothermal field, performed by the University of California at Riverside.[200] LBNL performed seismic studies of the Cerro Prieto, Mexico field as part of a reservoir definition and evaluation study. This work is summarized in the companion DOE report on Reservoir Engineering.

DOE funded an attempt to interpret old seismic data obtained from the Dixie Valley geothermal field utilizing modern data analysis.[201] Several active seismic studies were undertaken by industry. Although the method could help to solve specific, well-posed problems, broad use of the method was not justified. Not until a project at Rye Patch, Nevada was selected as part of an exploration solicitation in 1997 did DOE fund a new active seismic reflection study, conducted at Rye Patch, Nevada.

In 1998, a 3-D surface seismic survey was conducted over the Rye Patch geothermal reservoir to determine if modern seismic techniques could be successfully applied in geothermal environments. The intent was to map the structural features that controlled geothermal production in the reservoir. The results suggested the presence of at least one dominant fault responsible for the migration of fluids in the reservoir.[202-203] In addition to surface receivers, a three-component seismometer was deployed in a borehole at a depth of 1,200 meters (3,900 feet) within the basement below the reservoir, and recorded the waves generated by all surface sources.[204-205] Gravity, magnetic, and self potential data were also collected over the Rye Patch area. Gravity data revealed a Bouguer residual anomaly indicating a broad region of constant values bounded by steep negative gravity gradients to the northwest and southeast. The results supported the interpretation of higher density or excess mass in the central region around the wells, surrounded by less dense material (e.g., an elevated high density basement may represent a fitting model).[206]

DOE has also supported active seismic tomography experiments where portable seismometers record signals from widely spaced explosives. In the late 1980s, DOE cooperated with the USGS to generate seismic velocity and attenuation images of Medicine Lake Volcano and Newberry Crater. These images defined possible two-phase or steam drilling targets.[207-208]

In the early 2000s, researchers began developing a seismic-velocity model of the Great Basin.[209] The model consisted of simplified, rule-based representations of some of the region's crust to 50 kilometers (31 miles) depth, with more detailed characterization of geothermal areas and sedimentary basins. One goal of the project was to determine if parameters such as crustal thickness could serve as regional indicators of geothermal potential. Conclusions one way or the other in this regard were not established by this project.

7.1.2 Passive Seismic Studies

Due to their lower cost and the postulated association of seismicity with hydrothermal-convection systems, the DOE geothermal exploration program placed greater emphasis on passive seismic techniques. Early in DOE's program, researchers hypothesized that hydrothermal convection might produce detectable continuous seismic noise, providing an inexpensive means to locate fluid up-flow zones.[210]

The method, however, did not live up to its promise and has been replaced by microseismic monitoring in which advanced electronics and computing provide direction and magnitude for the seismic sources. Natural seismicity reflects the physical processes occuring within an unexploited area. DOE supported microseismic monitoring at a large number of unexploited sites, including some in Utah, Nevada, Nicaragua, Kenya, and others.[211-214] Although not all geothermal systems have microseimicity, it is sometimes helpful in exploring for systems that are closely coupled to intrusions or localized extension.

Passive recordings of earthquake signals can be used to learn much more than the locations of earthquakes; they can also be used to learn about the mechanical properties of the earth between the earthquakes and the seismographs. Passive seimic tomography is less expensive than active-source seismic tomography, particularly if the recordings are required for other reasons, such as environmental monitoring. Passive imaging has the advantage that the sources can occur below the area of interest. However, the location and time of the sources cannot be controlled, so the quality of the results is not predictable.

Scientists from LBNL conducted a seismic monitoring program over many years at The Geysers field. Although this data collection effort was driven by environmental regulations, it provided significant opportunities to test and validate exploration methods. Microseismicity associated with production and, more importantly, injection of fluids was used by LBNL to interpret injection pathways in The Geysers.[207-208/219] The same data were used by other groups to image the geological structure, saturation conditions and fracture orientations at that field.[207-208]

Groups from University of North Carolina and Duke University used the three-dimensional propagation of shear waves to infer the orientation of fractures throughout the Geysers Geothermal Field.[215-217] LLNL augmented this dataset and used it to continue the imaging work described in the Section 7.1.1 on Active Seismic Studies. Three-dimensional images of compressional wave velocity and attenuation throughout the entire geothermal field were generated.[218] The interpretation of these images is descibed in Section 7.1.1.

Techniques tested with The Geysers seismic data have been applied and developed further at other fields. At the Coso geothermal field, the crack geometries modeled with shear-wave splitting were in good to excellent agreement with drill-core data, tracer tests, locally mapped fractures, and the regional tectonic settings at both sites.[215-224] At the Coso geothermal field, the crack geometries modeled with shear-wave splitting were in good to excellent agreement with drill-core data, tracer tests, locally mapped fractures, and the regional tectonic settings at both sites.

7.2 Aeromagnetic Methods

The aeromagnetic method is a well-developed exploration technique long used by the petroleum and mining industries for both regional and prospect-scale cost-effective exploration.[221] The technique can be used for structural and lithologic mapping, basin-fill thickness determination, extension of geologic mapping under younger alluvial or volcanic cover, and direct detection of concentrations of magnetic minerals and ore bodies. Magnetic surveys, either ground or airborne, have been conducted at many geothermal areas, often with the intent of mapping decreases in rock magnetization caused by hydrothermal alteration of magnetite to pyrite.[222] Researchers discussed the determination of Curie-isotherm depths from regional aeromagnetic data, noting some of the method's limitations,[223-224] and that this technique has not proven to be useful in geothermal exploration.

Regional aeromagnetic survey data are available for many areas in the western United States. Commonly obtained at high elevations and wide flight-line spacings, however, the data may not be suitable for interpreting geologic features important to geothermal exploration at the prospect level. DOE, often in conjunction with the USGS, funded several low-level, detailed aeromagnetic surveys over geothermal areas of interest to industry. One example is the aeromagnetic surveying of the Raft River area during the initial exploration of the field.[225] The locations of faults, fracture zones, intrusive rock, silicic domes, and major alteration areas were noted on detailed aeromagnetic surveys flown at Coso Hot Springs, California;[226] at Baltazor, Tuscarora, McCoy, Beowawe, and Dixie Valley, Nevada; and at Cove Fort-Sulphurdale and Roosevelt Hot Springs, Utah. Much of this data came from Industry-Coupled Program data packages or were developed under the program.[227] Studies described the relation of interpreted aeromagnetic features closely related to the Opal Mound fault and the production zone at Roosevelt Hot Springs, Utah[228] as well as probable structural controls interpreted from aeromagnetic data at Cove Fort-Sulphurdale, Utah.[228] DOE also funded interpretative efforts and computer-program development to assist the geothermal community in more quantitative interpretations, such as complex three-dimensional modeling.[229] Such models are required due to the complex geological structure, the magnetic nature of igneous rocks, and the influence of hydrothermal alteration on the distribution of magnetite in the geothermal environment. Partly due to this project, such three-dimensional magnetic modeling is now undertaken routinely, and software for such modeling is widely available.

DOE funded the modification and upgrading of a compact, transportable "button-on" aeromagnetic survey system, donated to UURI by Kennecott Exploration, Inc. UURI used this equipment to complete regional and detailed magnetic surveys from fixed-wing and helicopter aircraft at Los Azufres, Mexico.[230] The equipment was also used at Ascension Island in the South Atlantic Ocean, where a detailed aeromagnetic survey was completed in support of the geothermal exploration program, using helicopter training missions of the British Royal Navy helicopter group.[231] In these cases, mobilization of contract survey aircraft for research purposes would have been far too expensive to allow collection of aeromagnetic data.

More recently, high-resolution aeromagnetic surveys flown over the Albuquerque basin of the Rio Grande rift, New Mexico, have demonstrated that aeromagnetic methods can successfully map concealed and poorly exposed faults in a basin environment.[232] To better understand the fault patterns near the Dixie Valley geothermal resource area, DOE contracted the USGS to acquire and process a high-resolution, helicopter-borne magnetic survey. The high-resolution aeromagnetic data showed many subtle, generally northeast-striking, linear to sinuous features that are superposed on large-amplitude anomalies produced by magnetic bedrock consisting of gabbroic-complex and volcanic rocks.[233-234] Thus, these anomalies can be used to extend faults beyond their mapped surface exposure or to infer previously unknown faults where they are covered by thin surface deposits.

7.3 Gravity Methods

The gravity method is another established geophysical technique with a history of development by the petroleum and mining industries.[221] In principle, density contrasts among rock units permit the method to map intrusive rocks, faulting, deep valley fill, and geologic structures in general. In the Basin and Range province and similar geologic settings, the gravity method was a relatively inexpensive way to determine the thickness of alluvium overlying bedrock on the pediments, and the location of covered structures. Studies discussed positive gravity anomalies related to the densification of porous sediments as a result of geothermal activity.[235-237] Regional-scale gravity data are often available from state survey projects, university theses, or USGS basin mapping activities. Gravity surveys were used in early work by LBNL in the Imperial Valley in southern California[238] and in Nevada.[238]

Regional gravity data available for Basin and Range geothermal areas often suggested buried structures, but the data were typically too widely spaced, without adequate topographic corrections, to be suitable for detailed interpretation at the prospect level. DOE supported a number of detailed studies in Industry-Coupled Program study areas. These surveys were run using a greater station density and more precise location and elevation control than is usual in regional work. Full topographic corrections were made, yielding a good data set.[239]

UURI developed interactive computer modeling programs for 2½-dimensional and three-dimensional geometries, and made these available to the geothermal industry and geophysical contractors working with the industry.[240-241] These programs were also used to enhance the geologic interpretation for a number of geothermal areas, including San Emidio[242] and the Baltazor Known Geothermal Resource Area (KGRA) in Nevada.[243]

A quantitative interpretation of detailed gravity data at Roosevelt Hot Springs, Utah noted the absence of a large displacement in the bedrock surface along any single normal fault, but rather a gradual dip to the west, and possibly several minor faults near the Opal Mound fault and outcropping range front.[228] In contrast, a detailed gravity survey of the Cove Fort-Sulphurdale area,[240] enhanced by three-dimensional modeling[244] defined the north end of the Beaver-Cove Fort graben, with 1 to 2 kilometers of low-density volcanic and alluvial fill, and a north-trending range-front fault with perhaps several kilometers of displacement, along the margin of the Colorado Plateau. Similar structural interpretations could be cited for other Basin and Range and Imperial Valley geothermal areas. Gravity surveys, in particular, were used to great advantage in helping to interpret the subsurface geology at Dixie Valley, Nevada.[68]

7.4 Thermal Methods

Several thermal methods respond directly to high rock and fluid temperature—the most direct indication of a geothermal resource. While temperature gradient and heat flow are most commonly used, shallow-temperature surveys, snow-melt photography, and thermal-infrared imagery have also been used. (See Section 5.3.4 for a discussion of the aerial infra-red work funded by DOE.) Temperature gradient holes also provide useful geological, hydrological, and occasionally geochemical information.

USGS researchers[245-247] provided much of the early database for the western United States; other work[248] related heat flow to lithospheric thickness. Francis Birch, the "grand old man" of continental heat flow studies, pointed out the need for terrain corrections to heat-flow data[249] and devised a method of making them. Other early researchers discussed the effect of terrain on heat flow,[250] the thermal effects of regional groundwater flow,[251] and reported heat-flow studies on selected geothermal resource areas.[252-253]

A large amount of temperature-gradient and heat-flow data was made available through the Industry-Coupled Program and has been incorporated into the national database. Through the State Cooperative Program, DOE drilling projects added many new data points to temperature gradient/heat flow databases. The results of several projects in the Cascades have been reported,[254-255] as well as thermal results for drilling programs in Nebraska, North Dakota, and South Dakota.[256-258]

The USGS, the geothermal industry, and DOE have supported a number of studies and data acquisition efforts to obtain exploration-quality, near-surface temperature information at reduced costs and drilling time. Research reports described the early use of 1-meter (3.3-feet) depth observations in Nevada[259] and temperature surveys at 2-meter (6.6-feet) depths.[260-261] Other work describes 3-meter (9.8-feet) deep temperature measurements that agree well with thermal anomalies outlined by deeper holes at McCoy and Dixie Valley, Nevada although seasonal temperature variations must be considered.[262] Multiple studies found that properly corrected shallow-temperature data often provided an exploration-quality outline of a resource area, substantially reducing the number of deeper temperature-gradient holes required to evaluate the resource prior to drilling exploration wells.

In addition to working with the USGS, DOE funded heat-flow and temperature-gradient studies by Southern Methodist University (SMU) and the Nevada Bureau of Mines. The SMU geothermal program collected temperature data from existing wells as the opportunity arose and temperature and heat-flow data from industry exploration programs.[263] In addition, SMU collected subsurface geologic data in order to project thermal gradients to basement. These data were used extensively in preparing the estimates of heat available in a recent Massachusetts Institute of Technology (MIT) study.[264] SMU researchers also edited a heat flow map of North America.[265] The Nevada Bureau of Mines and Geology collected and cataloged all temperature data publicly available in Nevada.[266] These data are included in the SMU geothermal database. Heat-flow studies were also performed in the Cascades by SMU.[25]

The USGS collaborated with DOE to digitize thermal data from exploration projects in the Basin and Range.[267] The Great Basin of the southwestern United States was the focus of concerted exploration and leasing activity by the geothermal power industry beginning in the 1970s. Combined, Chevron Geothermal and Phillips Petroleum Company evaluated more than 75 geothermal prospects with a potential for accessible temperatures of 150°C (302°F) or greater. Other companies assessed more than 25 other sites, bringing the total number of potentially high-temperature sites evaluated by industry to more than 100. During the summer of 1998, USGS personnel inventoried the CalEnergy holdings, and INL collected subsurface temperature data from several hundred holes. The USGS subsequently digitized the data, making them available through the USGS publication website.[268]

In the late 1970s, DOE sponsored exploration in the eastern United States through a grant to Virginia Polytechnic Institute and State University (VPI). An exploration model for possible high-temperature geothermal occurrences was proposed based on the known occurrences in the East of granitic plutons having above average internal heat generation due to radioactive decay of naturally occurring uranium, thorium, and potassium.[269-270] On the Atlantic coastal plain, rocks having low thermal conductivity, such as shales, have been deposited on top of these eroded granitic plutons, forming a thermal blanket. VPI postulated that temperatures in granite buried beneath shales might be sufficient for electrical power generation from resources at reasonable drilling depth. Through DOE contracts between 1976 and 1982, VPI analyzed available geological, gravity and aeromagnetic data to help infer the presence of buried granites, and collected additional data where needed. Anomalies were tested through gradient-hole drilling of sites having anomalously low gravity—an indication of an underlying granitic body.[271]

Fifty wells, each about 300 meters (1,000 feet) deep, were drilled to measure thermal gradients and to calculate heat flow in the Atlantic Coastal Plain from New Jersey to southern Georgia. In this way, the VPI program identified several thermal anomalies thought to be associated with buried granitic plutons. The program culminated with the drilling of a test hole about 1,200 meters (4,000 feet) deep, near Crisfield, Maryland. The temperature at depth was somewhat lower than hoped, however, and the low measured fluid flow rate was not sufficient for power generation at commercial levels. The exploration model, however, remains valid.

DOE also supported a heat-flow survey of the portion of the Salton Sea Geothermal Field that is submerged. The results are discussed in relation to the Salton Sea Scientific Drilling Project in Section 4.5.

7.5 Geophysical Well Log Interpretation and High-Temperature Tool Development

The cost of geothermal exploration and production wells is typically high. Thus, it is crucial to extract as much geologic information as possible from every well, whether production quality or not. The technology for interpreting geophysical well-log data in sedimentary petroleum environments is well-developed. Extrapolating the technology to geothermal environments has lagged. Lost circulation, poor cuttings return, and unfamiliar rock and alteration-mineral types were common obstacles to a good understanding of geothermal wells. As a result, DOE has long recognized the value of improving well-log interpretation, starting as early as 1979.[272] DOE supported an effort at UURI to develop algorithms for integrated well-log interpretation, cross-plot analysis of rock and mineral identification, and accurate depth measurement for fractures and production zones.

Interpretative efforts by geologists and experienced well-log analysts enhanced the interpretation of well logs from many geothermal wells completed under the Industry-Coupled Program, resulting in better identification and location of fractures, production zones, and host rock type. Some novel cross-plot techniques provided new insights into the presence of and earlier identification of hydrous minerals.[273] Algorithms developed during the program were released to the public domain with support provided for their use.

Geothermal exploration benefited greatly from the development of high-temperature logging tools with more robust electronics and cables. Much of this work was done at Sandia National Laboratories, and is described in depth in the companion report on the DOE R&D drilling program. In short, the development of "memory tools" with solid-state electronic memory and with temperature shielding (Dewar housings) allowed the logging of very high temperature (above 300°C [572°F]) geothermal exploration wells without the constraint of temperature-limited electronic cables to the surface. Many of the high-temperature logging tools carry the pressure-temperature-spinner combination of sensors to provide the basic information of velocity and direction of flowing geothermal fluid in a well. The experimental high-temperature acoustic televiewer developed with DOE funding and operated by the USGS acquires information on stress directions in a geothermal reservoir from the imaging of fractures on the sides of a well.

7.6 Electrical Methods

Electrical methods comprise a highly varied collection of techniques, all of which basically seek to determine the electrical properties of the subsurface in three dimensions, and sometimes, with time. Resistivity and its inverse, conductivity (how well the earth conducts electricity) are perhaps the most important of these electrical properties. Electrical resistivity anomalies are arguably the most diagnostic geophysical property of hydrothermal systems.[274] The dominant reservoir properties that determine electrical conductivity are: the presence and type of hydrothermal alteration, particularly low-resistivity clay minerals (i.e., smectite, inter-layered illite-smectite, and chlorite-smectite); the temperature and salinity of the thermal fluids; the degree of liquid saturation; the state of the reservoir fluid (steam or liquid); and the porosity and hydraulic permeability of the rock. All these reservoir properties are of direct interest in geothermal exploration and reservoir testing. Rocks containing low-resistivity alteration minerals, including clays and zeolites, and thermal fluids with increased salinities typically exhibit much lower electrical resistivity (higher conductivity) than the surrounding host rock. The 3D distribution of resistivity in the subsurface often can be interpreted in terms of these mineral and fluid properties, helping to form a picture to guide exploration and production drilling.

Electrical methods as typically used for geothermal exploration were previously developed and applied by the mining industry.[275] Techniques for measuring the electrical properties of the earth include:

1. **Galvanic resistivity**, in which electrodes are emplaced at the surface or in boreholes and used to inject current at various frequencies in certain locations, and to measure resulting voltages at other points.
2. **Induced polarization (IP)** methods, which measure the buildup and decay of chemical membrane potentials in response to an injected current. IP effects often result from metallic minerals or from clay and zeolites minerals in the subsurface.
3. **Self-potential** methods, which measure naturally occurring ~DC voltages having various causes, including subsurface fluid flow and oxidation of sulfide ore minerals, among others.
4. **Electromagnetic (EM)** methods, in which an alternating current is used to induce an electromagnetic response from the earth and from which resistivity structure can be interpreted.
5. **Magnetotelluric (MT)** methods, which measure naturally occurring electrical and associated magnetic fields that range in frequency from roughly 0.001 Hz to > 10,000 Hz. Methods using the higher parts of this frequency range are referred to as audiomagnetotelluric (AMT) methods.

Since the late 1970s, the DOE geothermal exploration research program has funded studies of almost all of the electrical methods. Consequently, these methods are routinely used in most geothermal exploration programs by industry. The sections immediately below give a sampling of the work done in the program area.

7.6.1 Galvanic Resistivity

Early geothermal characterization and exploration studies by the USGS verified the potential worth of electrical resistivity techniques in geothermal exploration.[276-277] DOE and its predecessor agencies, AEC and ERDA, funded resistivity studies of geothermal sites in the northern Great Basin related to complementary DOE geothermal R&D activities. These studies strongly indicated a need for using optimum electrode arrays and quantitative interpretation techniques.

Initial studies by UURI included evaluating various electrical resistivity arrays and new ground surveys at various sites, including Roosevelt Hot Springs.[278-283] A state-of-the-art, finite-element numerical modeling program, IP2D, was developed for the interpretation of dipole-dipole resistivity surveys in support of the Industry-Coupled Case Studies Program.[284] The IP2D modeling program was published and technical support made available. Detailed interpretations were completed for resistivity surveys at several areas and the results distributed to the geothermal industry. In addition, quantitative interpretation algorithms were developed for the Schlumberger vertical sounding (VES) array and for topographic effects on resistivity survey data.[285]

7.6.2 Electromagnetic and Magnetotelluric Methods

Electromagnetic (EM) and magnetotelluric (MT) methods are typically used to map resistivities at depths greater than 500 meters (1,600 feet). Several limitations of the methods were identified: high noise levels for natural field signals, high cost per MT station which discouraged the close station spacing needed for detailed surveys, and inadequate interpretation algorithms for complex subsurface geometries.[286-288] Recognizing these problems, DOE supported the development of improved survey techniques, including controlled-source methods, remote-reference MT observations for noise reduction, new interpretation algorithms that take advantage of ever-growing computing power, and a number of detailed demonstration surveys in support of geothermal prospects of interest to industry. Much of this work was conducted by the USGS, LBNL, and the University of Utah. The success of these efforts is reflected in the increased acceptance and use of the methods and the dissemination of results through numerous reports and major journal publications.[72-77]

7.6.3 Imaging Multi-Dimensional Electrical Resistivity

MT surveys are currently the method of choice for many exploration programs. Recent advances in data collection, resolution and interpretation, including the development of new algorithms that allow 3-D modeling of the data, have greatly improved the utility of the method. Investigations of the Coso geothermal field illustrate the current “state-of-the-art.”

In early 2002, EGI acquired a dense MT profile plus 101 five-channel MT soundings of approximately 500 meters (1,600 feet) average spacing. Figure 21 shows the Coso MT survey. The upper left image shows the location of the MT survey with respect to the geology of the Coso field. The remote reference sites are shown on the lower left; the results of the modeling on the right.[289]

In-field electromagnetic noise due to production of fluids and power generation from the Coso field combined with non plane-wave effects associated with the Bonneville Power Administration DC Intertie power line a few miles to the west necessitated novel, remote-reference MT processing techniques. The Parkfield, California MT observatory time-series data recorded 260 kilometers (161 miles) west of Coso were employed to reference the MT responses of the first field survey. The second survey utilized a reference established by Quantec Geoscience Inc. near Socorro New Mexico; 965 kilometers (599 miles) to the east with the time series linked through high-speed internet file transfer protocol (ftp).

Two-dimensional inversion of the dense array profile across the East Flank of the Coso field revealed a steeply west-dipping conductor under the west-central portion of the survey area. Subsequent 3-D finite-difference inversion by LBNL confirmed north-south continuity of the steep conductor under most of the East Flank, but not extending north of Coso Hot Springs. In cooperation with Kyushu University of Japan, EGI carried out 3-D finite difference inversions on a personal computer (PC) and replicated the main features of the steep conductor, using a half-space starting model. This low resistivity zone could represent the presence of high-salinity magmatic fluids, high-salinity residual fluids from boiling, or, less likely, cryptic acid sulphate alteration fluids, in a steep fracture network.[289]

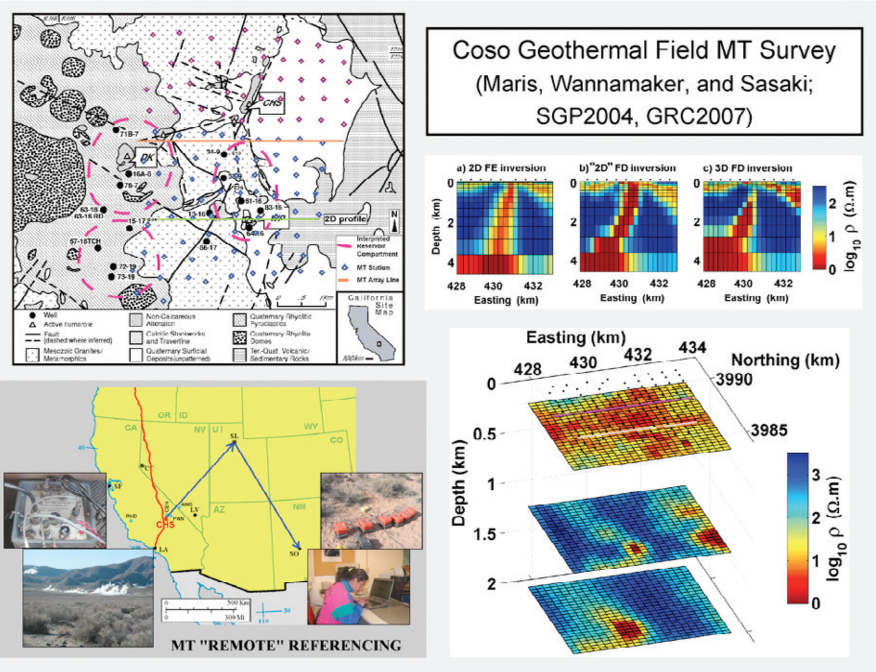


Figure 21. The Coso magnetotelluric survey

The upper left image shows the location of the magnetotelluric survey with respect to the geology of the Coso field. The remote reference sites are shown on the lower left; the results of the modeling are on the right.

7.6.4 Self-Potential Methods

The Self-Potential (SP) geophysical method is an established geophysical technique that measures naturally occurring voltage differences at the surface of the earth. SP has been used increasingly for engineering, hydrologic, environmental, and geothermal applications since the early 1970s. Researchers completed several surveys over geothermal areas in the western United States, publishing a landmark paper describing the geothermal expressions and physical property basis for these anomalies.[290] Under DOE funding, the physical basis for the geothermal SP anomalies was extended.[291] An algorithm for the quantitative numerical modeling of SP data was developed and forms the basis for many programs used by geophysical contractors and industry today. The results of a survey at Roosevelt Hot Springs, which supported the Industry-Coupled Program database for the area, were reported.[292]

The frequent association of SP anomalies with geothermal occurrences, simplicity of data acquisition, low cost, and low environmental impact of survey work indicated the method was appropriate for low- and moderate-temperature geothermal exploration. Efforts were made by the University of Utah to further develop the technique, reduce survey costs and noise levels, and improve the SP data quality for typical surveys. At Newcastle, Utah, scientists mapped a well-defined negative 108-millivolt (mV) anomaly that corresponded closely with the heat-flow distribution and was interpreted as being due to upflow of thermal fluids—lending confidence in the prospect and contributing to further development of the geothermal system.[293] Subsequent surveys were conducted in support of State Cooperative and Low-Temperature program teams in Utah and New Mexico, and in cooperation with industry at Cove Fort-Sulphurdale and Newcastle in Utah, and at Blue Mountain and Carson Lake in Nevada. The SP method continues to be used for geothermal exploration.

7.7 Borehole Geophysics Studies

Borehole-to-borehole and borehole-to-surface resistivity methods were recognized at an early stage of geothermal exploration research as a potential means of improving fracture identification and delineation. Several new algorithms using finite elements and integral equations were developed to model various electrode arrays and reservoir geometries, primarily at UURI.[294-295]

An important project in DOE's borehole geophysical research program was the development by Electromagnetic Instruments Inc. (EMI) of a high-temperature (>250°C [482°F]) borehole EM tool for geothermal exploration. The new device, termed Geothermal Borehole Induction Logging Tool (Geo-BILT), provided high-quality 3-D EM data in a single-borehole environment. With Geo-BILT, EMI collected data at a Chevron oil field in southern California during a CO_2 pilot injection project. EMI was purchased by Schlumberger and has been used in steam-flood, oil operations. Geo-BILT, however, has not yet been used in geothermal applications other than at Dixie Valley, Nevada during tool development. Figure 22 is a photograph of the Geo-BILT logging tool being deployed in an oil field.

Figure 22. The Geo-BILT logging tool being deployed in an oil field

DOE also supported the development of an innovative way to characterize fractures at a great distance from a borehole. It is well known that the level of fluid in wells fluctuates in response to earth strain due to barometric loads and to tidal forces. The tidal forces are directional and the orientation of the maximum compression varies with time. Fractured rock is more compliant than unfractured rock, and it is most compliant when the compression is perpendicular to a planar fracture. Fluid pressure fluctuations can be measured inexpensively in wells. LLNL developed an algorithm to determine fracture orientation from these observations,[296] and subsequent development and commercialization was done by Terrra Tek Research. Because this method is sensitive to the fracture orientation far from the well, it supplements near-wellbore information from televiewer logs.

7.8 Measurement of Active Deformation

Geologists have long known that recent and ongoing tectonic activity appears to be associated with geothermal systems.[297] Geothermal geoscientists have postulated that geothermal systems need to be situated in active structural regimes in order for permeability to be maintained through fracturing, and for the system to be continuously active over long periods of time. It is not known, however, whether such tectonic activity is a necessary condition for a geothermal reservoir.[298] Interferometric synthetic aperture radar (InSAR) and GPS studies were initiated to determine whether crustal movement could be measured in and around existing geothermal systems and, if so, whether that movement indicated the presence of the geothermal system.

LBNL and LLNL jointly investigated InSAR's use in geothermal exploration. Initial studies focused on the Dixie Valley geothermal field[79] as part of ongoing investigations into that geothermal system as an analogue of other Basin and Range geothermal systems. Studies found that the method could be used to monitor elevation changes within an operating geothermal reservoir. The Dixie Valley studies correlated well with geologic interpretations based on detailed surface mapping. InSAR may be useful in interpreting the geology beneath an operating field and in reservoir monitoring. The LBNL/LLNL studies were discontinued without conclusively determining the utility of InSAR as an exploration tool.

More recently, similar studies were conducted at the Steamboat geothermal field with similar results.[299] Figure 23 shows annualized InSAR surface vertical displacements at the Steamboat geothermal field in Nevada, compared to initial Fahrenheit isotherms from June 23, 2004 through November 30, 2005.[277]

A custom-designed global positioning observation system that measures strain accumulation with < 1 mm/yr accuracy was used to measure relative movement of surface rocks in the Great Basin to determine whether areas of ongoing movement indicated active geothermal systems.[300] The method may provide regional data of interest to geothermal exploration, but a very closely spaced set of receivers would be necessary in order to provide sufficient data for locating exploration boreholes. In addition, detailed studies may be valuable in determining reservoir properties during exploitation, as well as useful when siting and developing EGS.

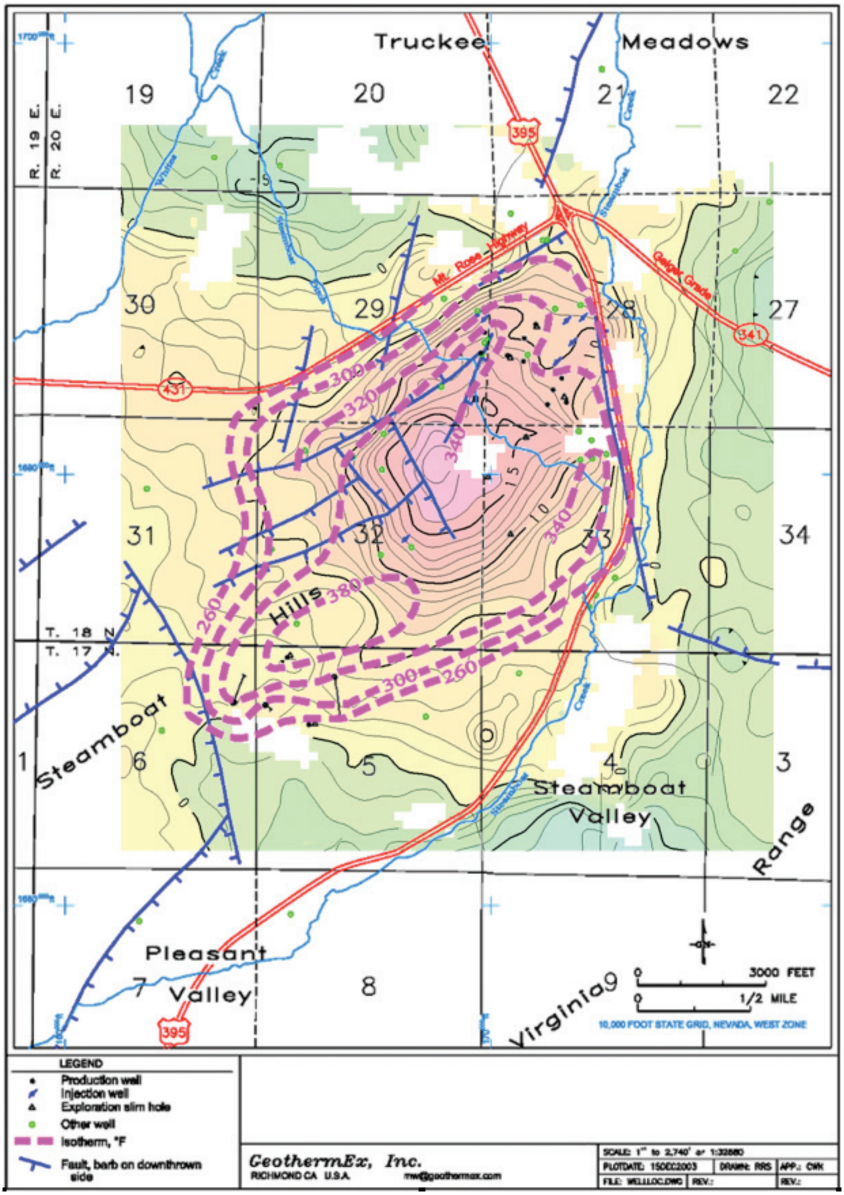


Figure 23. Annualized InSAR surface vertical displacements at Steamboat geothermal field, Nevada, compared to initial Fahrenheit isotherms (magenta heavy dashed contours) at +4,000 feet (msl).

The ground surface elevation is approximately 4,700 to 5,200 feet (msl). ENVISAT InSAR vertical downward displacement (solid color) contoured at 1 mm per year change (thin black contours) from June 23, 2004 through November 30, 2005.

7.9 Relating Geophysical Results to Properties of Interest

The geophysical techniques discussed above allow us to infer physical characteristics, such as rock density, seismic velocity, or electrical resistivity. The goal of an exploration survey is to identify economically useful attributes in the ground, such as permeability, saturation, thermal and chemical state, or cap rock structures. Consequently, an additional step is required to get from the results of the exploration survey to the identification of the useful drilling targets. DOE has supported research in three approaches to this part of the problem: 1) the development of geological and geothermal system models, discussed in Sections 4 and 5 of this report, 2) the coupling of reservoir models to geophysical exploration, discussed in a subsequent part of Section 7, and 3) laboratory, field, and theoretical studies relating the measured physical properties to the desired attributes. The third area is discussed here.

The petroleum industry has performed extensive laboratory, field, and theoretical studies of the relationship of measurable physical properties of rocks to reservoir properties. These rules have been applied to interpret geophysical data from geothermal areas. For example, at Medicine Lake Volcano, an active seismic survey produced images of seismic velocity and attenuation. Laboratory studies of Berea Sandstone during boiling were used with those images to identify a potential boiling zone.[207-208]

DOE supported research in the physical properties of materials from geothermal fields, because geothermal fields, unlike oil and gas fields, often are found in crystalline or highly altered rocks. Inferences drawn from measurements on sedimentary rocks may be misleading. This fact was quantified through measurements on core obtained from The Geysers, showing that increasing the saturation in these highly altered rocks changes the bulk and shear modulus much more than is seen for sedimentary rocks.[301-302]

This behavior is related to the structure of microcracks in the sample. The results were combined with theoretical models of the behavior of fractured solids with pressure in order to develop expected profiles of velocity and attenuation at The Geysers. Seismic tomography identified areas where the pressure and saturation effects caused deviations from this profile. The resulting anomalies correlate very well with the contours of pressure drawdown due to production.[218]

Electrical resistivity and ultrasonic velocity images and permeability measurements were made on core from the Salton Sea Scientific Drilling Project. These measurements were used to relate velocity and electrical anisotropy to permeability caused by micro cracks.[98] Additional measurements on core from The Geysers SB-15-D hole and from the Awibengkok Geothermal field identified large changes in electrical resistivity as fractured rocks undergo the boiling process.[303-304]

7.10 Coupled Reservoir Simulation and Geophysical Surveys

DOE supported research to assess the feasibility of finding “hidden” or “blind” geothermal reservoirs using a combination of existing electrical exploration methods and reservoir simulations to predict fluid flow within a geothermal system and the resulting geophysical signal generated by that flow.[305-306] Beowawe and Dixie Valley were used as test cases. The study 1) theoretically investigated the feasibility of finding “hidden” geothermal reservoirs in the Basin and Range using electrical surveys, 2) identified operating geothermal fields in the Basin and Range for which both electrical exploration surveys and adequate reservoir information are available, and 3) examined the correlation between the subsurface geothermal reservoir and the surface electrical surveys using detailed numerical modeling. The studies established the potential utility of coupling reservoir simulation and electrical surveys.

DOE also supported the development of a statistical approach to integrate the different model constraints provided by disparate geophysical, geological, and geochemical data in a rigorous and consistent manner by formal joint inversion. Researchers identified how this approach could be applied at Dixie Valley and the Salton Sea Geothermal Field.[307]

8.0

Exploration Strategies

From its earliest days, DOE recognized the importance of having and following a strategy to minimize cost and maximize success in exploring for and evaluating geothermal resources. It was important to determine which of the techniques used for geothermal exploration did not identify a geothermal system. DOE funded several geothermal companies to discuss both failed and successful techniques. Geothermal exploration strategies were developed along lines similar to those used in exploring for metallic minerals, which proved very helpful to the nascent geothermal industry. The results were presented in a series of seminal papers on geothermal exploration. These papers included case studies of individual geothermal systems, exploration strategies, the application and limitations of individual techniques, and conceptual models of geothermal systems.[13/199/227/308-312]

9.0

National and Regional Resource Assessments

In the development of any natural resource, the critical first step is the quantitative determination of the location and extent of the resource base, especially the portion of the resource base that can potentially be developed. The Geothermal Steam Act of 1970 gave the USGS the responsibility for assessing the geothermal energy resource base. DOE and its predecessor, ERDA, traditionally provided financial support to the USGS for such assessments. The landmark first assessment was published in 1975[313] and updated a few years later.[314] DOE also supported an assessment of low-temperature geothermal resources.[315] These publications remain the standard references for geothermal potential in the United States, and they have been widely used by the private sector. Over 30 years later, the initial results from a new assessment of U.S. geothermal resources by the USGS partially supported by DOE were released in late 2008.[316-317]

10.0

Magma Energy Studies

The possibility of extracting energy directly from crustal molten rock or magma was considered in the early 1970s. Beginning in 1975, the DOE Office of Basic Energy Sciences (OBES) funded the Magma Energy Research Program. A major impetus for the program was the potential size of the magma resource. In 1979, the USGS estimated that the total thermal energy in molten or partially molten rock within 10 kilometers (6.2 miles) of the Earth's surface was between 50,000 and 500,000 quads (1 quad = 1 quadrillion British thermal units [btu]).[318] In comparison, annual energy consumption in the United States from all energy sources is approximately 100 quads. Although quantifying the size and energy content of a specific magma body is problematic, using standard plant performance parameters, the calculated energy content of 2 cubic kilometers of magma would supply a 1,000 MWe power plant for 30 years.

DOE's studies of magma energy were divided into two phases: 1) the "scientific" phase (1975-1982) and 2) the "engineering" phase (1984-1990). The DOE OBES funded the scientific phase; the DOE Geothermal Program funded the engineering phase under the name "Magma Energy Extraction Program."

10.1 Magma Energy Research Program (1975 – 1982)

The scientific phase addressed whether any fundamental physical barrier to the magma energy concept existed. Approximately five years of analysis and experiments culminated with drilling into the remaining melt (at a temperature exceeding 1,000°C [1,832°F]) in Kilauea Iki Lava Lake, Hawaii, and performing energy extraction experiments in the still-molten lava. The drilling used near-conventional coring equipment, operating under the principle that enough water could be circulated into the hole to temporarily freeze the molten lava into enough solidity to be drilled. More than 100 meters (300 feet) of lava core were retrieved, and the bits and core rods were essentially undamaged. After the hole was completed, water was injected into it and calorimetric experiments measured the energy content from the steam emitted. These scientific activities were extensively documented in a number of comprehensive summary reports.[319-322] The scientific phase concluded that the magma energy extraction concept was viable. At this point, the program was transferred from OBES to the Geothermal Division.

10.2 Magma Energy Extraction Program (1984 – 1990)

The engineering phase was aimed at ascertaining the economic viability of a magma energy project, considering four specific aspects of the project's feasibility:

1. **Geophysics:** Could magma bodies at drillable depth be reliably located?
2. **Drilling:** Could the technology be developed for drilling to significant depth at extremely high temperature?
3. **Energy Extraction:** Could fluid be circulated and heat brought to the surface in sufficient quantity and for an adequate length of time?
4. **Geochemistry:** Did materials exist that could withstand the extremely high temperatures and corrosive chemicals expected to be characteristic of most magma bodies?

10.2.1 Geophysics

Several geophysical techniques can be used to explore for magma bodies, but their results are often ambiguous. For example, consider Long Valley Caldera, one of the most heavily instrumented, observed, and investigated locations in the world. One type of seismic investigation—shear-wave shadowing (i.e., the notion that a liquid or semi-liquid magma body could transmit pressure waves but not shear waves)—inferred that a magma body lay beneath the caldera at potentially drillable depth, (i.e., 5 to 6 kilometers [3.1 to 3.7 miles]) beneath the valley floor. Other seismic investigations using active refraction, primary-wave (P-wave) tomography, and teleseismic reflection, gave a general structure of the caldera, implying a major anomaly at approximately 6 kilometers (3.7 miles) under the resurgent dome.

Horizontal strain measurements showed spreading across the Long Valley dome 30 to 50 times higher than that of the San Andreas Fault system. Gravity surveys showed that the dome's center rose more than half a meter (1.6 feet) between 1975 and 1987. Both of these measurements were believed to be the result of magma inflation of a chamber beneath the center of the resurgent dome. The volume of the chamber was variously estimated from a few tens of cubic kilometers to as much as 1,000 km^3.

10.2.2 Drilling

Drilling into molten rock at temperatures exceeding 1,000°C (1,832°F) has consequences unlike conventional geothermal drilling. Many materials, and especially drilling fluids, will fail relatively quickly under these conditions. Pore fluids in the formation are expected to be highly corrosive, which is also exacerbated by the temperature. A major reason for the success at Kilauea Iki was that the hole was relatively shallow and the molten lava could be "frozen" readily by cold water pumped from the surface (this also was of great benefit in protecting the bits and core rods.) In a well deep enough to reach most known magma bodies, however, the fluid will travel for a long distance in a hot wellbore, making drilling much more difficult. Many of the predicted problems could be mitigated or eliminated by using insulated drill pipe; much of the planned technology development centered on this concept.

10.2.3 Energy Extraction

Energy extraction, as shown in Figure 24, relies on maintaining a peninsula (or column) of solidified rock protruding into a magma chamber, with liquid magma convectively circulating around the column's exterior. Immediately after drilling, the radius of this column will grow until it reaches an equilibrium value determined by the rate of heat extraction from the well. Because rock is a poor thermal conductor, any useful rate of heat extraction requires a large fractured zone to expose the heat-transfer fluid to a sufficient area of heated rock. However, there must still be a solid (although plastic) boundary to contain the process. The scenario raised questions about whether the physical model was realistic, and how energy production from a given well could be optimized.

Sandia National Laboratories (SNL) conducted several experiments using a terpene phenolic resin that softened at about 125°C (257°F). When a cooled central probe was inserted into resin heated to 160°C (320°F), simulating drilling into a magma body, it formed a highly fractured zone around the probe, contained by a plastic boundary, just as predicted for the actual magma drilling case. In the scientific phase of the program, SNL built a rock-melting furnace and test chamber to measure convective heat-transfer coefficients for molten rock. The work showed an extreme variation in viscosity with temperature.

In the engineering phase, SNL performed a convection experiment using corn syrup as a magma simulant, deriving a viscosity correction factor that could be used with standard heat-transfer models for analysis of the energy extraction.[323] SNL modeled fluid temperature variation with flow rate and combined that with an assumed Rankine-cycle power plant to provide guidelines for optimum plant production. Researchers again concluded that energy extraction from magma was feasible.

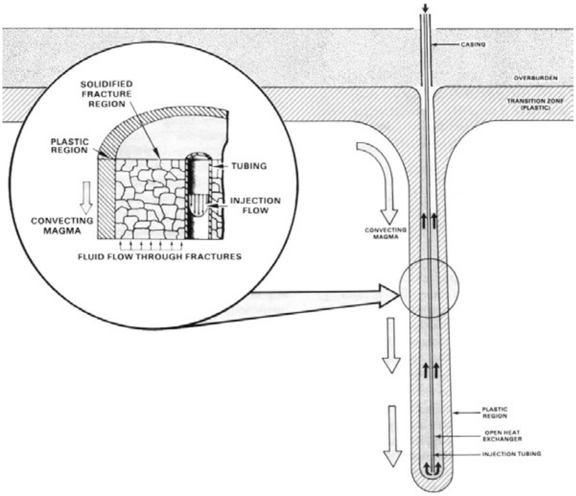


Figure 24. Schematic of energy extraction from magma

10.2.4 Materials

Corrosion-resistant materials for a downhole heat exchanger and, to a lesser degree, drilling equipment, are crucial for magma energy extraction. Material selection was complicated by the wide variation in magma compositions expected at different locations. Magma in the Long Valley Caldera, for example, is thought to be rhyolitic and therefore much different from the basaltic magma found in Hawaii—particularly with regard to the volatiles dissolved in the magma at high pressure. Rhyolitic magmas are more oxidizing than basaltic magmas. Oxidation is the principal corrosion mechanism at very high temperatures for many materials.

SNL tested a number of alloys in a re-constituted rhyolitic magma at 850°C (1,562°F) and 150 Mega Pascal (MPa) pressure. Scientists found that conventional carbon steels had an unacceptably high corrosion rate under these conditions. Several high-chromium (Cr) alloys and super-alloys were identified that gave excellent performance. Knowledge of the specific geochemistry of a potential magma energy site is critical to a successful design of heat exchangers and selection of drilling equipment.

10.3 Exploratory Well

After extensively evaluating candidate sites,[324] SNL selected Long Valley Caldera in California for an exploratory well, primarily to test the hypothesis that a magma body existed at drillable depth (6,100 to 7,600 meters [20,000 to 25,000 feet]) beneath the caldera. The International Continental Scientific Drilling Program (ICDP), with funds from the California Energy Commission, DOE, and USGS, supported the project.

The well would be drilled in four phases, ending at 6,100 meters (20,000 feet) or a bottom-hole temperature of 500°C (932°F), whichever came first. Phase 1 was drilled in 1989, reaching the planned depth of just below 760 meters (2,500 feet). Changing research priorities led DOE to close out the Magma Energy Program in 1990. Additional deep drilling at Long Valley Caldera in 1991 and 1998 reached a final depth of 3,000 meters (9,800 feet). Further discussion of Phase III drilling can be found in the companion drilling history report.

While a great deal of useful scientific information was derived from the later drilling at Long Valley, the borehole temperature remained disappointingly cool at approximately 100°C (212°F) at final depth. The conclusion was that a magma body, if any, beneath the resurgent dome is much deeper and smaller than originally hypothesized. Although there is no doubt that a substantial heat source exists somewhere beneath the caldera—a commercial geothermal power plant near the basin's edge draws 200°C (392°F) brine from a depth of less than 300 meters (1,000 feet)—the structure of the central feature is not yet well understood.

A concise but comprehensive description of the Magma Energy Program is available from the Geothermal Resources Council.[325-327] Ultimately, the inability of exploration methods to locate an accessible magma body led to the demise of this program.

Conclusion

At the beginning of DOE's geothermal R&D program, the U.S. geothermal industry was small and struggling to gain acceptance from utilities and financial institutions, which had only a rudimentary understanding of the costs and risks associated with geothermal energy projects. There was little solid data in the public domain on which reliable analyses of geothermal reservoirs as viable energy resources could be based. Reluctance to support geothermal projects financially was causing stagnation in the nascent geothermal industry. In addition, there was only limited understanding of the nature of geothermal systems and of how they could be gainfully used.

The DOE-funded research on exploration described in this report—along with the work described in companion reports on Drilling, Energy Conversion, and Reservoir Engineering—had an immediate and profoundly positive effect by stimulating development of the modern geothermal industry. This achievement was realized through performance of collaborative projects in which DOE-funded scientists and engineers from the national laboratories, academic institutions, and the private sector worked with colleagues in companies, other government agencies, and institutions in other countries to address the full range of problems inhibiting economic geothermal development. Research priorities were continually assessed and updated in close collaboration with industry to ensure that project results would be of practical use. The success of DOE's program can be seen in today's vital and progressive geothermal industry.

Over three decades, from 1976 to 2006, the Department's supported a wide range of R&D to overcome challenges in exploration with the goal of making geothermal electricity more cost-competitive. Over three decades, DOE's support of exploration R&D focused on areas such as industry and state cooperative programs, geological and geophysical technique development, geochemical technique analysis, exploration strategies and national and regional resource assessments. This work contributed to a decrease in the cost of geothermally generated electricity, and many of the government-supported technologies were adopted and commercialized by the U.S. geothermal industry.

The Department continues to support research and development activities and industry partnerships to encourage and help the U.S. geothermal community to meet these challenges, building on the technical research base of the past 30 years. This technical base provides the information and understanding necessary to create more efficient, reliable, and economic technologies, enabling the U.S. geothermal industry to compete for baseload electricity generation. Hopefully, this summary of prior work in exploration R&D will allow future geothermal developers and researchers to translate past efforts into future accomplishments.

Appendix A:

Budget history of the federal geothermal research program, 1976 – 2006

Notes on Budget Table

The following discussion is provided to clarify the meaning and intent behind the estimates given in the Geothermal Program budget table (Fiscal Years 1976 – 2006). Despite the precision of the table, the reader is cautioned not to accept the amounts quoted in any single fiscal year as a fully accurate representation of the funds spent on a given technical area. The reasons for this caution will become apparent from the notes. However, over the entire period covered by this history, the totals are considered reasonably accurate.

1. The funding history covers FY 1976 through FY 2006 inclusive. FY 1976 includes funding for the “transition quarter” in which the Federal fiscal year was advanced three months from June 30 to September 30. All funds are in current year dollars in thousands; no adjustments were made to cover the time value of money.

2. The Program budgets were divided among the four major technical research topics comprising the focus of the history: Exploration, Drilling, Reservoir Engineering, and Energy Conversion. For convenience, subsets of Reservoir Engineering---Geopressured-Geothermal, Hot Dry Rock and Enhanced Geothermal Systems—are listed separately to identify funds spent on those topics versus Hydrothermal Reservoir Engineering. The technical areas covered by these research topics are summarized in the Table of Contents of each history.

3. Additional line items are included for completeness. They lie outside the four research areas as defined, but they appear in the Program budget for extended periods. Those line items are mentioned briefly here:

   - **Capital Equipment** – Tools and equipment needed to carry out research, typically at the national laboratories, are identified as capital equipment. Over time, this line was either reported independently within each program area (e.g., equipment for Geopressured Resources) or included as an aggregate total for the entire program. The aggregate total is used in this budget table. In some instances this may lead to discrepancies in budget amounts between what is listed here and amounts given by other sources. The differences are minor, since capital equipment was typically a small percentage of the total budget for any line item.

   - **Program Direction** – This line covers the personnel expenses of DOE staff used to plan, implement, and manage the Geothermal Program. After FY 1995, Program Direction was aggregated at the level of the Office of Energy Efficiency and Renewable Energy, eliminating this line from the Program budget.

- **Baca Demonstration Plant** – This major project was planned as the first commercial-scale (50 MWe) liquid-dominated hydrothermal power plant in the U.S. The project was located at the Valles Caldera, New Mexico, as a government-industry partnership. The industry partners were Unocal Geothermal and Public Service of New Mexico. The project was canceled in 1983 after attempts to find adequate hydrothermal resources to support the 50 MWe plant were unsuccessful.
- **Environmental Control** – During the formative years of the Program, research was sponsored on a number of environmental topics that could have a detrimental impact on geothermal development. Topics studied to varying degrees included: hydrogen sulfide emissions, other non-condensible gas emissions, liquid effluents, land use, noise, induced seismicity, and subsidence. Environmental monitoring networks were established, notably at The Geysers, Imperial Valley, and the Gulf Coast, to collect data on subsidence and seismicity. Research was performed on environmental mitigation technology, especially hydrogen sulfide abatement.
- **Geothermal Heat Pumps** – While use of heat pumps had been a minor secondary topic for much of the Program's history, the topic became a major program element for a five-year period (FY 1995 – FY1999) when a large education and outreach effort was conducted to acquaint the public with the environmental and efficiency benefits of this technology. Research on heat pump technology was limited but did include advancements in impervious grouts and improved performance models.
- **GeoPowering the West** – This was an education, outreach, and technical support effort, launched in 2000 and patterned after the successful Wind Powering America initiative.
- **Other** – A potpourri of activities not covered elsewhere are included here, such as policy, planning, and analysis done by the Program and short-lived projects such as non-electric (direct use) demonstrations. These activities are not covered in this history.

4. The source of the budget amounts reported here is the annual DOE budget request to Congress, often referred to as the President's Request or the Congressional Budget Request (CBR). In most cases, the amounts shown are "Actual" funds budgeted for a given line item as stated in the CBR. The "Actual" funds are not necessarily the amounts appropriated by Congress for that fiscal year—differences can arise due to reductions, rescissions, or other adjustments to the budget subsequent to initial appropriations.
5. The CBR is submitted early in the calendar year, shortly after the President's State of the Union message, in order to give Congress the time needed to prepare appropriations bills before the start of the new fiscal year on October 1. Due to this scheduling of the CBR, "Actual" expenditures are reported with a two-year lag. For example, if we wished to know the actual amounts budgeted in FY 1989, they would be found in the FY 1991 CBR. FY 1989 would have ended on September 30, 1989, four months before the submission of the FY 1991 CBR to Congress. Sufficient time would have elapsed to allow a final accounting of FY 1989 expenditures, in most cases to the nearest dollar. This explains why

the funds are typically reported to 4-5 significant figures, rounded to thousands. Note that in this example the FY 1990 CBR would not be a source of complete information about FY 1989 expenditures because the FY 1990 CBR would have been submitted in early 1989, before the end of FY 1989. Therefore, the "Actual" funds reported in the CBR are considered the best source of expenditures for the fiscal year in question.

6. A major problem in using "Actual" CBR amounts stems from the fact that neither the Program nor the CBR were constant over the course of time. The Program's organization changed on a number of occasions during its 30-year history, and the format and content of the CBR changed as well. Probably the greatest impact on recreating the budgets for the topical research areas was the fact that in many cases the amounts spent on exploration, drilling, reservoir engineering, and energy conversion were aggregated under some generic title. For example, during the 1980s the major categories of Geothermal Program funding were: Hydrothermal Industrialization, Geopressured Resources, and Geothermal Technology Development. Hydrothermal Industrialization included sub-topics such as field demonstrations, test facilities, state resource assessments, and industry-coupled drilling. Technology Development covered many diverse research sub-topics such as hot dry rock, advanced drilling, geochemical engineering and materials, energy conversion, and geoscience. In some cases, the expenditures for these topical areas (e.g., hot dry rock) were reported, and the budgeted amounts could be properly allocated. However, the CBR did not always report "Actual" expenditures to that level of detail, and the amounts had to be inferred from the "Request" amount given in the CBR for the fiscal year in question. These amounts could become problematic when CBR formats changed or major programmatic reorganizations were instituted between the year of the "Request" and the "Actual" reporting year.

7. Another complicating factor was the merging of technical areas under a generic topical area. For example, the line item, "Geoscience Technology," subsumed the research topics of exploration and reservoir engineering. The amount of budget devoted to each element was usually not specified in the CBR. The problem is particularly vexing for budgets dating from FY 1999 when budget line items such as "University Research", "Core Research", "Technology Deployment", and "Systems Development" came into use. Fortunately, Program budget records apart from the CBR for this period are fairly complete, allowing assignment of funding to the appropriate research areas.

8. Despite the aforementioned caveats, many of the budget estimates are judged to be accurate. Geopressured-Geothermal was a unique line item in the budget that could be easily tracked from year to year in the CBR. Funding for Hot Dry Rock was reported separately for the life of that program. The same can be said for Capital Equipment, Program Direction, Baca Plant, and Geothermal Heat Pumps. Of the four research topical areas, Drilling Technology had the best record of budget representation over time, followed by Energy Conversion. Due to their technological similarities, Exploration and Reservoir Engineering could be difficult to distinguish. As stated above, the funding for the topical areas in any given year may reflect some uncertainty, but the aggregate totals over 30 years do provide a good estimate of relative funding levels.

Geothermal Program Annual Budget *($000)*

	Exploration	Drilling	Reservoir Engineering	Hot Dry Rock	EGS	Geopressured-Geothermal	Energy Conversion
1976	$6,280	$4,206		$5,274		$1,182	$21,209
1977	$9,000	$3,500		$5,280		$6,620	$22,350
1978	$17,600	$2,870		$5,400		$17,100	$40,630
1979	$31,270	$9,000	$8,500	$15,000		$26,600	$33,169
1980	$15,506	$8,800	$5,100	$14,000		$35,700	$30,294
1981	$25,224	$12,545	$6,547	$13,500		$35,600	$24,920
1982	$3,450	$3,036	$2,650	$9,700		$16,686	$28,858
1983	$2,360	$1,710	$400	$7,500		$8,400	$29,641
1984	$2,713	$2,640	$10,172	$7,540		$5,000	$1,105
1985	$3,215	$3,585	$5,623	$7,444		$5,226	$2,280
1986	$4,094	$2,415	$5,497	$7,631		$4,426	$1,250
1987	$0	$1,350	$5,595	$8,000		$3,940	$1,065
1988	$455	$1,775	$5,355	$5,770		$4,955	$1,580
1989	$0	$2,250	$4,085	$3,500		$5,930	$1,935
1990	$0	$2,140	$3,761	$3,290		$5,523	$1,601
1991	$6,925	$2,435	$5,543	$3,627		$5,884	$2,155
1992	$1,300	$2,700	$7,100	$3,600		$4,916	$5,300
1993	$2,080	$5,635	$5,517	$3,600			$4,520
1994	$2,597	$3,400	$6,466	$1,300			$6,403
1995	$5,977	$6,267	$4,620	$4,000			$5,090
1996	$8,700	$5,899	$0	$1,900			$5,200
1997	$9,818	$5,030	$0	$400			$5,900
1998	$5,600	$6,900	$4,387				$5,119
1999	$4,084	$4,934	$6,782				$4,150
2000	$1,475	$5,500	$7,025		$3,049		$3,405
2001	$2,700	$5,500	$5,600		$1,700		$4,745
2002	$3,000	$5,084	$5,336		$1,580		$4,111
2003	$4,163	$5,717			$5,915		$8,111
2004	$3,000	$6,000			$6,680		$5,226
2005	$3,534	$4,060			$6,788		$5,180
2006	$3,734	$4,128			$5,928		$3,592
Total	**$189,854**	**$141,011**	**$121,661**	**$137,256**	**$31,640**	**$193,688**	**$320,094**

Capital Equipment	Program Direction	Baca	Environmental Control	Geothermal Heat Pumps	Geopowering the West	Other	TOTAL
$704			$1,301			$2,958	$43,114
$1,500			$2,500			$2,300	$53,050
$2,500		$12,000	$3,600			$4,500	$106,200
$3,000	$663	$7,450	$516			$10,500	$145,668
$3,200	$1,100	$20,500	$1,300			$12,200	$147,700
$1,310	$2,376	$12,050	$2,600			$19,959	$156,631
$860	$1,600	$2,124	$500				$69,464
$250	$1,250					$5,963	$57,474
$0	$1,000					$100	$30,270
$400	$1,025					$900	$29,698
$481	$701						$26,495
$0	$780						$20,730
$0	$835						$20,725
$795	$826						$19,321
$426	$782						$17,523
$401	$889					$2,479	$30,338
$821	$1,000			$200			$26,937
$900	$1,000						$23,252
$873	$970		$1,000				$23,009
$886	$1,000		$967	$5,000		$4,000	$37,807
				$5,300		$2,400	$29,399
				$6,482		$2,000	$29,630
				$6,400		$288	$28,694
				$6,420		$1,780	$28,150
						$2,882	$23,336
					$1,600	$4,778	$26,623
					$3,200	$4,724	$27,035
					$3,521	$963	$28,390
					$2,738	$981	$24,625
					$3,128	$2,666	$25,356
					$2,658	$2,722	$22,762
$19,307	**$17,797**	**$54,124**	**$14,284**	**$29,802**	**$16,845**	**$92,043**	**$1,379,406**

Abbreviations & Acronyms

^{14}C	Carbon-14
^{18}O	Oxygen-18
2-D	Two-dimensional
3-D, 3D	Three-dimensional
^{3}He	Helium-3
^{40}Ar/^{39}Ar	Argon 40/39
^{4}He	Helium-4
act	Actinolite
AEC	Atomic Energy Commission
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS	Airborne Visible-Infrared Imaging Spectrometer
B&R	Basin and Range
BHA	Bottom-hole assembly
BHT	Bottom-hole temperature
BHTV	Borehole televiewer
BNL	Brookhaven National Laboratory
BPA	Bonneville Power Authority
BTC	Breakthrough curve
btu	British thermal unit
C	Precipitation/dissolution
CECI	California Energy Company, Inc. (now CalEnergy)
CFE	Comisión Federal de Electricidad (Mexico)
CH$_4$	Methane
CMOS	Complementary metal oxide semiconductor
CNSB	Central Nevada seismic belt
CO$_2$	Carbon dioxide
DC	Direct current

DEM	Digital elevation model
DOE	United States Department of Energy
DOE/DGE	Division of Geothermal Energy of the United States Department of Energy
DOQ	Digital panchromatic orthophoto
E	East
EGI	University of Utah Energy and Geoscience Institute
EGI	Energy & Geoscience Institute, University of Utah (formerly the Earth Science Laboratory, University of Utah Research Institute)
EGS	Enhanced Geothermal System
EM	Electromagnetic
EMI	Electromagnetic Instruments, Inc.
ENA	Enel North America, Inc.
EOS	Equation-of-state
ep	Epidote
ERDA	Energy Research and Development Administration
ESL/UURI	Earth Science Laboratory, University of Utah Research Institute (now the Energy & Geoscience Institute)
Fe	Iron
FeCl$_x$	Iron chlorides
Fe-Si	Iron-silicon
ftp	File transfer protocol
GBC	Great Basin Center for Geothermal Energy, University of Nevada, Reno
GDO	Geothermal Drilling Organization
GE	General Electric, General Electric Research Lab
GEA	Geothermal Energy Association
Geo-BILT	Geothermal Borehole Induction Logging Tool

GEOTHERM	National Geothermal Database
GIS	Geographic information system
GPS	Global Positioning System
GRED	Geothermal Resource Exploration and Definition
GTP	Geothermal Technologies Program
H	Hydrologic
H_2	Hydrogen-2
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
HCl	Hydrogen chloride, hydrochloric acid
He	Helium
Hg	Mercury
HTRI	Heat Transfer Research, Inc.
HWR	Hot wet rock
ICDP	International Continental [Scientific] Drilling Program
ID	Interior diameter
INL	Idaho National Laboratory (formerly called INEL and INEEL)
InSAR	Interferometric synthetic aperture radar
IP	Induced polarization
IWRRI	Idaho Water Resources Research Institute
ka	Kiloannum or one thousand years
K-Ar	Potassium-argon
KCl	Potassium chloride
KGRA	Known Geothermal Resource Area
km^2	Square kilometer
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LIDAR	Light detection and ranging
LLNL	Lawrence Livermore National Laboratory
m	Meter
M	Mechanical
Ma	Megayear
MEI	Mother Earth Industries, Inc.
MIT	Massachusetts Institute of Technology
mm	Millimeter
MPa	Mega Pascal
mV	Millivolt
MW	Megawatt
mW	Milliwatt
mW/m^2	Milliwatt per square meter
MWe	Megawatt-electric
MWt	Megawatt-thermal
my	Million years
N	North
N_2	Nitrogen
N_2O	Nitrous oxide
NaCl	Sodium chloride
NOAA	National Oceanic and Atmospheric Administration
NRTS	National Reactor Test Station
NSF	National Science Foundation
OIT-GHC	Oregon Institute of Technology, Geo-Heat Center
OSTI	Office of Scientific and Technical Information, United States Department of Energy
Pb	Lead
PC	Personal computer
PON	Program Opportunity Notice
P-wave	Primary-wave

py	Pyrite
R&D	Research and Development
Ra	Radium
Rn	Radon
ROP	Rate of penetration
RPS	Renewable Portfolio Standard
Sb	Antimony
SEGEP	Southeast Geysers Effluent Pipeline
SEM	Scanning electron microscope
SMU	Southern Methodist University
SN	Sierra Nevada
SNL	Sandia National Laboratories
SO_4	Sulfate
SP	Self-potential
SPME	Solid-phase micro-extraction
SPR	Strategic Petroleum Reserve
SRC	Super Radiator Coil
SSGS	Salton Sea Geothermal System
SSSDP	Salton Sea Scientific Drilling Program

T	Temperature
T	Thermal
TD	Total depth
TDS	Total dissolved solids
Th	Thorium
TIR	Thermal infrared
U	Uranium
USAF	United States Air Force
USGS	United States Geological Survey
U-Th	Uranium-thorium
UURI	University of Utah Research Institute (now the Energy and Geoscience Institute)
V	Volt
VES	Vertical sounding
VPI	Virginia Polytechnic Institute and State University (Virginia Tech)
w-hr/lb	watt-hours per pound
WL	Walker Lane
Zn	Zinc

References Organized by Major Research Project Area

Literature developed from DOE's Geothermal Exploration Research program is very extensive, going well beyond the references cited herein. A complete listing is beyond the scope of this report, and has not been attempted. Instead, selected additional references organized by major research area are listed below.

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