**COMPARATIVE ANALYSIS OF CORE DRILLING
AND ROTARY DRILLING IN VOLCANIC TERRANE**

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PREFACE

In the early 1970's, there was a small debate that seems particularly appropriate today. At issue was the question of exploration strategy on a national scale. At that time, there were only two principal factions. One group insisted that the latest generation of surface geophysical techniques, including seismic, gravity and electro-magnetic surveys would, if properly implemented, economically provide adequate, large-scale, subsurface information when calculated on a cost-per-square-mile basis. The other group contented that, although the surveys incorporate a large territory, some interpretations were based more on imagination than seismic noise. This group recommended drilling wells on one-mile centers to a nominal depth of one-mile, throughout the country. This plan would provide detailed and "unambiguous" subsurface data that could be pieced together revealing the puzzle that has kept so many of us employed.

Recent interest in subsurface conditions has prompted national drilling programs for a variety of reasons: assessment of mineral resources, determination of earthquake hazards, study of tectonic and magmatic processes near continental borders, and more. There are a variety of organizations involved with formulating and implementing the national policy including: the National Science Foundation (NSF) and its Continental Scientific Drilling Program (CSDP), which is managed by Deep Observation and Sampling of the Earth's Continental Crust (DOSECC, Inc.); the U.S. Department of Energy (DOE), including the Office of Basic Energy Sciences (OBES), and the Geothermal Technology Division (GTD); the U.S. Geological Survey (USGS) and most of the National Laboratories. In the context of this report, there are two separate but related subprograms; those

associated with the Thermal Regimes Panel of the CSDP and those associated with evaluation of geothermal resources, which is managed largely by DOE, GTD.

This project began ostensibly as a homework assignment, a comparison of core and rotary drilling rates, records and costs in volcanic terrane. This assignment was approached with a fairly good background in drilling. Members of the Division of Earth Sciences have been involved in drilling, completion and testing more than 50 geothermal exploration and production wells in Nevada and California during the past eight years. Drilling was incorporated into most regional geothermal assessment programs with excellent results. Out of necessity, the strategy included preparation of drilling specifications, contracting and drilling-project management. It should be noted that none of these holes was drilled with a core-rig; either rotary-air or rotary-mud drilling was used.

When this report was begun, it was believed that core drilling only recently was making inroads into what had been an area largely monopolized by rotary-air and rotary-mud drilling techniques. Also, it was thought that, although core drilling had advantages, the costs, in most cases, prohibitive. However, this investigation revealed that core-drilling was used in Yellowstone Park in 1929, and was widespread in some industry drilling programs between 1981 and 1983. Much of this information was unavailable to the public and most of the detailed information remains proprietary. On the basis of data obtained, a report was assembled that "documents what the industry already knew 5 years ago." Drawing on historical information on core drilling, and the rash of recently completed "scientific core holes" , a variety of costs, conditions and recommendations are presented for future core-drilling programs. It is

concluded that, regardless of what appear to be high cost-per-foot, core drilling has significantly more advantages than traditional rotary-mud drilling in hard, highly-fractured geothermal reservoirs and volcanic environments. Like any commodity, cost of drilling on a per-foot basis involves many factors, core drilling costs per se are a single, highly predictable part and may represent as little as 50 percent or as much as 90 percent of the total cost. Substantial reductions in overall cost may be achieved by reducing the amount spent on non-core drilling activities.

It should be recognized that, in the course of preparing this report, the investigation lead to National Laboratories, geothermal development corporations, state and county agencies, and various universities. The authors appreciate the opportunity to have questioned technical personnel most familiar with core drilling from the scientific perspective. Drilling specifications vary from area to area and program to program. Therefore, an important distinction should be made concerning the end-use of core and core holes. The degree of commonality between an "industry" core hole and a "scientific" core hole may be very small, but this distinction may factor heavily into drilling costs. This distinction is important to consider when reviewing the cost data presented.

Although this type of report may appear to be duplication of effort, in that some of the technical information may have been published in another format, the scope of this work is unique and complements related efforts.

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INTRODUCTION

Initially, the goal of this report is to compare and contrast penetration rates of rotary-mud drilling and core drilling in young volcanic terranes. It is widely recognized that areas containing an abundance of recent volcanic rocks are excellent targets for geothermal resources. Exploration programs depend heavily upon reliable subsurface information, because surface geophysical methods may be ineffective, inconclusive, or both. Past exploration drilling programs have mainly relied upon rotary-mud rigs for virtually all drilling activity. Core-drilling became popular several years ago, because it could deal effectively with two major problems encountered in young volcanic terranes: very hard, abrasive rock and extreme difficulty in controlling loss of circulation. In addition to overcoming these difficulties, core-drilling produced subsurface samples (core) that defined lithostratigraphy, structure and fractures far better than drill-chips. It seemed that the only negative aspect of core drilling was cost. The cost-per-foot may be two to three times higher than an "initial quote" for rotary drilling. In addition, penetration rates for comparable rock-types are often much lower for coring operations.

This report also seeks to identify the extent of wireline core drilling (core-drilling using wireline retrieval) as a geothermal exploration tool. The tables, maps, and case history sketches will assist with plans for future drilling of significantly more core holes in young volcanic areas throughout western North America. Suggestions for solving typical "top-hole" problems, such as reaming, setting casing and installing and testing blow-out prevention equipment (BOPE) are described.

Finally, a general philosophy, albeit ex-post-facto and empirical, of drilling, exploration and use (of geothermal resources) is discussed. As a general rule, when drilling in young volcanic rocks (or similar terrane), where downhole pump installation is not planned, a core-rig is likely the most suitable for drilling in terms of both cost and effectiveness.

BACKGROUND

Historical perspective on core drilling

Core-drilling with wireline core retrieval in volcanic terrane for scientific and commercial purposes is not a new development. In the last decade, however, it has become an increasingly widespread exploration technique used to delineate geothermal resources and evaluate "thermal regimes." The appearance of increased use is, in fact, quite misleading. Scientific core-drilling in geothermal environments can be traced back to 1929 and the Carnegie expedition to the Norris basin, in what is now Yellowstone National Park. Commercial applications are more difficult to trace because most records are proprietary and unpublished. The data available show that core-drilling by private industry was widespread in selected volcanic areas from 1981 through 1983.

At approximately the same time, a national Continental Scientific Drilling policy was being established. The policy, endorsed by the U.S. Congress, essentially identified deep-drilling into the earth's continental crust as a bona fide scientific endeavor that can be used and functionally woven-into existing energy and mineral assessment efforts being pursued by the Departments of Energy, Interior, and Defense.

This study is limited to core-drilling activities in the western United States. The regional extent of these core-drilling activities is illustrated in Figure-1. Although core-drilling sites in Alaska are not shown, they are fully described in Table-1, along with a lengthy and detailed history of core-drilling activities in volcanic (geothermal) terranes in the western United States. A core-hole in Hawaii, that involved drilling into the still molten part of the Kilauea Iki lava-lake, was not

1. Thermal Power Co., Cascades Temperature Gradient Hole No. 1, (CTGH-1), Mt. Jefferson, Oregon
2. GEO-Newberry, GEO N-1, Newberry Crater, Oregon
3. GEO-Newberry, GEO N-1, Newberry Crater, Oregon
4. U. S. Navy, Geothermal Test No. 1, (GT-1), Fallon NAS, Fallon, Nevada
5. U. S. Navy, Kirman Lake No. 1, (KL-1), Kirman Lake (Bridgeport), CA
6. Sandia National Laboratories, Research Drilling Office No. 8, (RDO No. 8), Shady Rest (Mammoth), California
7. Phillips Petroleum Co., Phillips Long Valley Nos. 1 & 2, (PLV-1 & 2), Long Valley, California
8. Sandia National Laboratories, Inyo Dome, Long Valley, California
- *9. DOE, Salton Sea Scientific Drilling Project, (SSSDP), State 2-14, CA
10. Los Alamos National Laboratory, Valles Caldera Nos. 1 & 2, (VC-1 & 2), Valles Caldera, New Mexico

* Conventional coring, all others wireline-coring

Figure-1. Map of western United States showing selected recent volcanic centers and core-drilling sites.

included because of the highly specialized nature of the project and lack of technical and cost data. Table-2 chronologically summarizes the development of rationale leading to present National drilling policies.

TABLE-1

HISTORICAL PERSPECTIVE ON CORE-DRILLING IN AREAS OF RECENT VOLCANISM
IN THE WESTERN UNITED STATES AND ALASKA

YELLOWSTONE NATIONAL PARK, WYOMING

DATE	ACTIVITY
1929-30	<p>In conjunction with studies of thermal phenomena, the Geophysical Laboratory of Carnegie Institute in Washington, D.C. drilled two core-holes into the geyser basin at Yellowstone Park. The first hole was begun in September, 1929, using a drill bit made of hastellite alloy. A 1.75-inch core was retrieved. This core-hole was drilled in the Upper Geyser basin to a depth of 406-ft. Pressure and temperature were measured during the course of drilling (Fenner, 1936).</p> <p>The second hole was drilled in the Norris basin in August, 1930. Drilling proceeded relatively smoothly to a depth of 246-ft when unexpected high-pressure (250-psi) was encountered. The drilling pad was "fortified with cement and iron tie-rods and steam was allowed to discharge to the atmosphere." According to Fenner (1936), "When an attempt was made to resume drilling, the feed water pumped down failed to reach the bottom. Some of it was forced out through the threaded joints of the pipes and the remainder was vaporized. This was remedied with great difficulty....These great pressures and high temperatures rendered every phase of the work difficult and slowed down progress very greatly. After twenty feet more had been drilled a succession of new difficulties brought the operation to a final stop."</p>

Data from examination of core, and downhole temperature and pressure profiles, were eventually combined to produce one of the first detailed descriptions of the operation of a geyser system. Although core-recovery was low by oil-field standards, samples and data were adequate to meet researchers needs.

1967-68 Thirteen research holes were drilled in the principal thermal areas of Yellowstone National Park. Drilling was accomplished with a truck-mounted, diamond-bit drilling rig, with wireline for withdrawing cores through the drill-rods. This allowed nearly continuous coring, greatly increased efficiency of drilling operations, and facilitated downhole temperature measurements. Hole-depths ranged from 215 to 1,088 ft and the total footage drilled was 6,802-ft. This was the most thorough scientific drilling program attempted at the time. Scientific objectives were carefully identified prior to drilling, well sites were carefully located, and safety was a foremost consideration. Drilling problems included controlling wellhead-pressure, excessive drill-rod wear from not lubricating the rods for fear of pollution, and implementing corrective actions, while combating high pressure, high-temperature steam flows. One technique used during the drilling program was daily measurement of downhole temperature, prior to drilling additional footage. This resulted in a more accurate temperature-depth profile that reflected pre-drilling, subsurface temperature conditions. However, more time was required to complete the coring of the hole. The practice of drilling for a specified time period, usually 8-hours, tripping (removing) the drill-rods from the hole to allow temperature

equilibration, then measuring bottom-hole temperature prior to drilling, is often used in scientific coring operations. This may account for differences in per-foot contract costs for core-drilling (White and others, 1975; Barger and Beeson, 1984).

STEAMBOAT HOT SPRINGS, NEVADA

DATE

ACTIVITY

1950 The following information is paraphrased from White (1968). °The U.S. Geological Survey contracted for the diamond core-drilling of 8-holes, with a total footage of 3,316 ft. Recovery of core exceeded 90 percent of the footage drilled. Although this method is superior to others in producing core for petrographic study, introduction of cold water required additional time for attainment of thermal and fluid-composition equilibria. Temperatures measured in diamond-drill holes are somewhat less reliable than those measured in churn-drill holes (cable-tool holes). The objective of these physical and chemical measurements was to learn as much as possible about this spring system in four dimensions, including time. Cable-tool drilling introduces no foreign water, except when a hole is too dry. Therefore, this method is superior to all others in providing the opportunity to obtain excellent bottom-hole temperatures and water samples, as drilling progresses. The original nature of the rocks must be interpreted from broken rock-fragments. The normal practice is to drill 8-hours per day and 5-days per week. This study demonstrated that thermal equilibrium in churn-drill holes is generally approached

within several degrees Centigrade, after a layover of 16-hours. Closer approaches to thermal equilibrium were indicated by repeat measurements made over weekends without drilling.'

In addition, White (1968) lists typical problems encountered during drilling, including: hole caving, excessive steam-pressure, loss of drilling fluid (LCZ), and stuck core-barrels.

CASCADE RANGE

Newberry caldera, Oregon

DATE

ACTIVITY

-
1977	The USGS completed a small diameter, wireline core-hole on the northeast flank of Newberry caldera, the Newberry No. 1. The drill-bit penetrated and recovered a variety of rock types, including pumice, cinders, breccia, tuffaceous sediments, ash-flow and ash-fall deposits, and basaltic to andesitic lava-flows ranging in thickness from 1 to 230-ft. The total depth (TD) of the hole was 1266-ft. Only small amounts of formation fluid was encountered. Mud-circulation could not be maintained and caving was common. The drill-pipe got stuck and the hole was subsequently abandoned (Sammel, 1981).
1978	The USGS spudded Newberry No 2 on the floor of Newberry caldera. The first 1017-feet of this hole were drilled by the rotary-mud method, to allow reduction of hole diameter latter in the drilling operation. The interval from 335 to 1098-ft was drilled as an offset, and is known as Newberry No. 3. (Sammel, 1981).

1979-81 Newberry No. 2 was deepened, by additional wireline-coring operation to a final depth of 3221-ft. Permeability in massive flow-rocks was low, but breccia zones, volcanic sediments and fractured venticular inter-flow zones were very permeable. Loss of drilling fluids was 90 to 95-percent, with little or no formation water shallower than 2000-ft. (Sammel, 1981).

1985 GEO-OPERATOR drilled the GEO N-1 core-hole as a cost-shared project with the DOE. The hole was rotary-mud drilled (with a core-rig) to 459-ft and cored HQ to a TD of 3772-ft (Cascades Newsletter, 1987).

1986 GEO-OPERATOR drilled the GEO N-2, core-hole. All data are proprietary.

GEO-OPERATOR drilled the GEO N-3, core-hole as a cost-shared project with the DOE. The hole was drilled by the rotary-mud technique, with a core-rig, to a depth of 426-ft. The hole was then drilled with a wireline core-rig, HQ-size to a depth of 1735-ft, where the drill-rods stuck. Subsequently, the hole was lost below 1604-ft. The drill-rods were cemented in-place and drilling continued, NQ-size, to a total depth of 3772-ft. Core recovery was approximately 95-percent in solid geologic units (massive flows), but decreased to a low of 50-percent in flow-breccias and fractured obsidian (Cascades Newsletter, 1987).

Medicine Lake, California

1983-84 Medicine Lake Volcano has been described as a bimodal, Quaternary-age shield volcano, located in the southern Cascade Range of northern California. The area is characterized by extensive lava flows that range in composition from basaltic to rhyolitic (Ciancanelli, 1983). In addition, intense faulting has produced a widespread network of fractures and fissures that provides an excellent potential geothermal reservoir rock and a significant drilling problem. Nine core-holes, ranging in depth from 2142 to 4009 ft were drilled by Phillips Petroleum Corp. to determine the hydrogeologic nature of the suspected geothermal reservoir. Previous efforts in the area, reported by Ciancanelli (1983), included extensive geologic mapping, both structural and petrologic, and a soil-mercury geochemical survey, completed in conjunction with Republic Geothermal, Inc. Although much of the core-hole data are proprietary, some cost and penetration-rate information were made available for this study by Joe Beall of Geysers Geothermal Co. Parts of this data-package are shown in Appendix 2. The core-drilling strategy included use of a high-pressure, high-volume rotary-air drilling rig: 1250 cubic feet per minute at 500 psi. By comparison, the standard air-package employs 600 cfm at 250 psi. The drilling plan specified air-drilling the top 10 to 15 percent of the hole, setting surface casing and installing BOPE, and proceeding to target depth with HQ-size diamond bits. Core-cost ranged from \$58 to \$99 per ft, while surface-cost (air drilling) ranged from \$33 to \$101 per ft.

Mount Jefferson, Oregon

1986 Thermal Power, Inc., cost shared a 4800-ft core-hole with the US DOE. See text (case studies) for details. Data were provided by Joseph Iovenitti, Thermal Power Company, and Phillip "Mike" Wright, University of Utah Research Institute.

LONG VALLEY CALDERA, CALIFORNIA

DATE	ACTIVITY
1982	Phillips Petroleum Co. drilled the PLV-1 core-hole in three stages. In the first stage, a rotary rig was used to complete the upper 433-ft. "This stage is characterized by high cost due to continuous lost circulation." Numerous cement-plugs were set in this interval. In the second stage, a core-rig was used to a depth of 1834-ft. Circulation was never achieved, but drilling proceeded quickly and relatively inexpensively until soft, sticky clays were encountered at 1774-ft. In the third stage, the hole was deepened to 2211-ft. The drill-string twisted-off at 1899-ft and the hole was completed with tubing inside the twisted-off drill-rod to a total depth of 2198-ft (Benoit, 1984).

The PLV-2 core-hole was drilled by Phillips Petroleum to a total depth of 1978-ft. Rotary-mud drilling was not used on this hole. (Benoit, 1984).

According to Benoit (1984), "PLV-1...has demonstrated that core drilling is a more effective technique than conventional rotary drilling in the hard, highly permeable, near-surface rocks in the western part of the [Long Valley] caldera."

Stage-1 of PLV-1, the rotary-drilled section, cost Phillips about \$100,000 and took 3 to 4 weeks to complete, using a Gardner-Denver 1500 drill-rig. There were tremendous lost circulation zones, many of which required plugging with cement. On the other hand, PLV-2 was drilled entirely as a core hole probably cost a total of \$100,000 (Dick Benoit, personal communication, 2/27/87).

When asked how to complete the upper part of the hole to accommodate the BOPE, Benoit suggested using PQ-size bits (or larger) to the required depth, then drilling to total depth with HQ or NQ-size bits.

1983 Eichelberger and others (1984) completed a 492-ft vertical core-hole through Obsidian Dome in the Inyo Dome area of California. "The first hole was conceived as a relatively low-cost, shallow, vertical hole to investigate structure and gas chemistry of Obsidian Dome. The hole was also intended to address problems of diamond coring and wireline retrieval of rock from the flow and underlying stratigraphy in order to design properly the later, more expensive holes.....Coring was required to meet the scientific objectives of the hole ('to characterize and compare the thermal, chemical, and mechanical behavior of magma in the contrasting environments of caldera fill and crystalline basement')..Further, conventional rotary-mud drilling, that relies on return fluid-flow to bring cuttings to the surface, would have been impossible in the highly fractured dome...The cost was about \$52 per ft of which \$11 per ft was drilling fluid. The only significant drilling problem was unstable hole conditions in the non-welded Bishop Tuff, which eventually necessitated casing."

- 1984 Eichelberger and others (1985) completed two slant core- holes in the Inyo Domes area. Described by the authors as "a modest effort," the holes were drilled at a sufficient angle to penetrate both the conduit and associated dike at Obsidian Dome (conduit hole is RDO No.2b; dike hole is RDO No. 3a). Plans for these holes were based upon data from the previous vertical hole and were designed to address the same scientific objectives. The holes were drilled with a combination of HQ and NX-size bits to depths in excess of 2000 ft. The principal difficulties "can be attributed to the hard but highly fractured character of the rock, lack of fluid circulation, and the slanted orientation of the hole. Glacial till, clay-rich basaltic cinders, fractured basalt flows, and fractured granitic basement all posed problems." The total drilling cost was \$420,700 for a total of 4767-ft (approximately \$88/ft).
- 1986 The RDO No. 8 core-hole was completed at Shady Rest, near Mammoth Lakes. See case studies text for details.
- 1986 Rundle and others (1986) proposed "Deep drilling to the magmatic environment in Long Valley Caldera." ...A large number of geophysical experiments, conducted by several hundred investigators of the past few years, clearly indicate that a major body of magma exists within the central part of the caldera at drillable depths of 4-5 km. Plans are underway to drill toward and eventually into this magma body." ..."Tentative plans call for drilling to 6000 ft. ..in fiscal year 1987; to 12,000 ft. ... in FY 1988; to 15,000 ft. ... in FY 1989; and as much deeper as makes sense until FY 1991.....Immediately at the end of each phase

of drilling, a small core drilling rig would be brought on site, and approximately 200-300 feet of slim core would be returned (size PQ: core diameter = 3.3 in.)." The total proposed depth is 20,000 feet. Cost estimates for this hole, apparently to be rotary-mud drilled, were not provided. However, estimates for a core-hole this deep are presented in the SUMMARY section of this report.

ALASKA

Unalaska Island

DATE

ACTIVITY

1981-82 One of the most unusual opportunities to use diamond-core drilling in young volcanic rocks is described by Carey and others (1983) and Isselhardt and others, (1983).

"The Alaska Power Authority contracted with Republic Geothermal, Inc. in 1981 to explore Makushin Volcano on Unalaska Island, Alaska, for geothermal resources. The two year, \$4.7 million contract included geological, geochemical, and geophysical exploration and the drilling of three, 1,500-foot temperature gradient holes in 1982, and the drilling and testing of one 4,000-foot small-diameter geothermal exploration well and one 2,000-foot temperature gradient hole in 1983. All the holes and the well have been or will be drilled with a wireline diamond core drilling rig supported entirely by helicopter..." No associated cost data were available and there is certainly no sound way to

comparatively evaluate this operation with rotary drilling. The principal advantage of using a core-rig appears to be largely logistical (and cost) and the requirement to minimize environmental impact.

Katmai National Park

DATE	ACTIVITY
1986	Eichelberger and Hildreth (1986) proposed a core-drilling program at Katmai, in the Valley of Ten Thousand Smokes. "History's largest rhyolitic eruption (the only historic one in the United States) took place 74 years ago in the Katmai region of the Alaska Peninsula." The scientific objectives and drilling plan are modeled after work completed in Inyo Domes area of the Long Valley Caldera. A two-phase drilling program was proposed. Phase-I consisted of core-drilling four, 1000 to 1300 ft holes at various locations on the ash flow sheet; estimated cost was \$750,000 (\$143 to \$190 per-foot). Phase-II involved drilling a 4265-ft continuous-core-hole to determine temperatures in the intrusive vent. Estimated cost for this phase was \$1,000,000 (\$235 per ft).

VALLES CALDERA, NEW MEXICO

NOTE: Valles Caldera is the focus of at least two major geoscientific programs: Hot-Dry Rock (HDR) geothermal energy, at the Fenton Hill site and, most recently, an investigation of magmatic and hydrothermal processes near Sulfur Springs. Core-drilling has been an essential part of the HDR research and development program (Pettitt, 1974). Unlike HDR, the

magmatic program is conducted under the auspices of the Thermal Regimes Panel of the Continental Scientific Drilling Program. The history of drilling activity, and scope of the new program are fully described by Goff and Nielson (1986). The new drilling program includes contributions from Los Alamos, Sandia, Lawrence Berkeley and Battelle Northwest National Laboratories, the U.S. Geological Survey, and collaborators from seven major universities. The program incorporates research and development, detailed scientific objectives (science plan), and a work-statement that includes components for planning and coordination, permits, contracting, preliminary examination, information dissemination, and curation of core and cuttings. Estimated drilling costs for at least six core-holes are projected for fiscal-years 1986, 1987 and 1988. Estimates are also included for scientific support staff, experiments and analyses and science management. Two core-holes have already been drilled under the new program; VC-1 was drilled in 1984, inside the southwestern rim of the caldera, to a depth of 2808-ft; VC-2b was drilled in 1986, at Sulfur Springs in the western caldera moat, to a depth of 1731-ft. The primary objectives of core-hole VC-1 were to: 1) core through the youngest rhyolite flow within the caldera, 2) obtain structural and stratigraphic information near the intersection of the ring-fracture zone and precaldera Jemez fault zone, and 3) penetrate a high-temperature hydrothermal outflow plume near its source (Goff and Nielson, 1986). The total cost for this core-hole was \$239,000, approximately \$85-per ft. The purpose of core-hole VC-2b was to penetrate the interface between vapor-dominated and hot-water-dominated systems within the western ring-fracture system. The total cost of core-hole VC-2b was \$182,000, approximately \$105-per ft.

TABLE-2

CHRONOLOGY OF THE DEVELOPMENT OF RATIONALE
FOR A NATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

DATE	PROGRAM DESCRIPTION
1975	<p>The Shoemaker Workshop, sponsored by the Carnegie Institute, recommended three topical areas for systematic drilling:</p> <ol style="list-style-type: none"> 1. State and structure of the continental crust 2. Mechanisms of faulting and earthquakes 3. Hydrothermal systems and active magma chambers <p>(Source: F. Goff and D. Nielson, 1986)</p>
1978	<p>A workshop on continental drilling for scientific purposes was held at Los Alamos, New Mexico and reported by the U.S. Geodynamics Committee in 1979. The meeting focused on the scientific value of current and planned efforts of federal agencies and industry and how to supplement those efforts with holes drilled solely for scientific purposes. Four major areas of interest were addressed:</p> <ol style="list-style-type: none"> 1. Basement structures and deep continental basins 2. Thermal regimes - geothermal systems 3. Mineral resources - ore-forming processes 4. Earthquake mechanisms and faulting

The recommendations for sample and core repositories were:

1. Establish a unified, coordinated system of regional archives.
2. Establish a standard operating procedure for participating agencies.
3. Provide federal support to existing state archives, to upgrade service and ensure conformance with established procedures.

(Source: F. Goff and D. Nielson, 1986)

1979 DOE, OBES, established a CSDP and funded the Workshop on Core and Sample Curation. The National Academy of Sciences, National Research Council established the Continental Scientific Drilling Committee (CSDC), chaired by E.M Shoemaker, in order to:

1. interface with the scientific community;
2. identify drill-holes of opportunity for the scientific community;
3. receive interests and objectives in drilling into the earth's crust from the scientific community;
4. provide broad policy guidance to the national CSDP; and
5. review, on request, agency CSD programs.

(Source: S. Goff and Heikan, 1981)

1981 The workshop on Core and Sample Curation for the National Continental Scientific Drilling Program was held to discuss the best means of handling, distributing and advertising samples and data collected through continental scientific drilling program activities. (Source: S. Goff and G. Heikan, 1981)

PENETRATION-RATE vs. ADVANCE-RATE

Penetration-Rate

Penetration-rate is conceptually defined as an instantaneous rate of drill-bit ingress (in units of length/time) into a geologic formation, independent of accessory operations or problems encountered (i.e., bit-change, pulling core, stuck-rod, etc.). If careful monitoring procedures are conducted and related drilling parameters, such as weight-on-bit, rotation, and mud-pumping rate, are held constant, penetration-rate may be used to compare and contrast selected mechanical properties of various geologic formations. This information may then be used to compare relative drilling costs.

Advance-rate

Advance-rate takes into account penetration rate and all other operations that take place on the drill-pad. These other operations include rigging-up and -down, mixing mud, changing bits, pulling core and rod, as well as typical problems that occur, such as stuck drill-rod, twist-offs, etc. It is usually reported by the driller as total-feet drilled in a twenty-four hour period (feet per day). This rate reflects many factors, only one of which is the mechanical properties of a geologic formation.

CASE STUDIES

The original purpose of this report was simply to compare and contrast core and rotary drilling-rates, economics, and overall drilling effectiveness in areas containing young, volcanic rocks. Information in this case studies section was the initial extent of this work. As the investigation proceeded, however, it became clear that such a limited view would result in mere duplication of daily drilling logs and sundry reports. The scope of the report was then expanded beyond this "core" material in order to present an historical perspective and attempt to forecast costs based upon the assembled records.

Most of this information is derived directly from daily drilling logs that were recorded by the driller. Additional data were gathered from contractors and technical personnel concerned with the geoscientific aspects of core-drilling projects. The information on the rotary-drilled holes was derived from open-file reports.

Tables in this section are summarized versions of the daily drilling report that also contain hourly drilling rates and daily drilling costs. Graphs showing a history of project activities and pie diagrams illustrating how time was allotted during the project are also provided in this section.

CHINA LAKE NAVAL WEAPONS CENTER No. GT-1

FALLON NAVAL AIR STATION

FALLON, NEVADA

The China Lake Naval Weapons Center, Geothermal Utilization Division (GUD), is charged with evaluating the geothermal resources of selected U.S. Navy lands to determine those areas having potential for developing energy self-sufficiency for base operations. GT-1 is one of a series of temperature-gradient and observation holes drilled at Naval Air Station (NAS), Fallon, Nevada. Pre-drilling activities began on May 8, 1986, and represent a very small part of the project time-budget total, because the site was prepared previously and water for drilling was available from a nearby irrigation canal. Daily drilling reports were provided by GUD personnel and are summarized in Table- 3.

Rotary drilling of a 5.625-inch hole commenced on May 9 and was completed on May 11 at a total depth of 600-ft (fig-2). Five-hundred feet of soft, unconsolidated lake sediments were drilled in the first 24-hours. Reaming with a 9.875-inch bit then commenced and continued, through May 11, to a depth of 600-ft. Six-inch steel casing was set and cemented in place. BOPE was set and tested on May 15.

Rotary drilling with a 5.625-inch bit resumed on May 16 and a total of 770-ft were drilled in 24-hours. The 5.625-inch hole was completed to 2000-ft on May 18. Non-drilling activities, including conditioning the hole, setting casing, setting BOPE and rigging-up for coring, occurred from May 19 through May 22. Coring, using an HQ-size bit commenced late on May 22 and continued until June 15. Coring ceased at 4485-ft because the core-shoe split. Minor problems with lost-circulation and stuck rods occurred in the interval from 2000 to 2345-ft, when a bit-change was required. From May 26

TABLE-3

Summary of Daily Drilling Reports, GT-1

Day	Date	Hours Drilled	Hours Other	Feet Drilled	Depth (feet)	Rate (ft/hr)	Daily Cost (\$)
1	May 08	0	9	0	0		0
2	May 09	19	5	500	500	26.31	27500
3	May 10	5	19	110	610	22.00	6050
4	May 11	0	24	0	610		0
5	May 12	0	10	0	610		0
6	May 13	0	12	0	610		0
7	May 14	0	16	0	610		0
8	May 15	0	24	0	610		0
9	May 16	22	2	770	1380	35.00	42350
10	May 17	16	8	200	1580	12.50	11000
11	May 18	17	7	420	2000	24.70	23100
12	May 19	0	24	0	2000		0
13	May 20	0	24	0	2000		0
14	May 21	0	24	0	2000		0
15	May 22	7	17	77	2077	11.00	4235
16	May 23	18	6	195	2272	10.83	10725
17	May 24	11	13	73	2345	6.63	4015
18	May 25	13	11	75	2420	5.76	4125
19	May 26	18	6	71	2491	3.94	3905
20	May 27	10	14	51	2542	5.10	2805
21	May 28	24	0	121	2663	5.04	6655
22	May 29	23	1	146	2809	6.34	8030
23	May 30	24	0	124	2933	5.16	6820
24	May 31	21	3	101	3034	4.80	5555
25	June 1	4	20	13	3047	3.25	715
26	June 2	24	0	131	3178	5.45	7205
27	June 3	24	0	156	3334	6.50	8580
28	June 4	23	1	125	3459	5.43	6875
29	June 5	23	1	165	3624	7.17	9075
30	June 6	24	0	185	3809	7.70	10175
31	June 7	10	14	63	3872	6.30	3465
32	June 8	22	2	122	3994	5.54	6710
33	June 9	23	1	149	4143	6.47	8195
34	June 10	7	17	45	4188	6.42	2475
35	June 11	11	13	50	4238	4.54	2750
36	June 12	19	5	121	4359	6.36	6655
37	June 13	2	22	21	4380	10.50	1155
38	June 14	14	10	85	4465	6.07	4675
39	June 15	4	20	20	4485	5.00	1100
40	June 16	0	24	0			
41	June 17	0	24	0			
42	June 18	0	21	0			
43	June 19	0	11	0

Figure-2. History of project activities at GT-1, Fallon, Nevada.

to June 1, 614-ft were cored and the average advance-rate was 102-ft per-day. Between 3047 and 3872-ft (the next bit change), the average advance-rate was 137-ft per-day. During the next two days, the average advance-rate was 134-ft per-day. A new bit was installed to increase the penetration rate through hard basalt.

From 4188-ft to total depth, the average advance-rate was only 59-ft per-day. Problems with broken wireline and split coring-shoes accounted for the poor performance.

Figure-3 shows activity breakdown, as percent of total-time. Core-drilling consumed 42-percent of the time. Rotary-drilling accounted for only 11-percent, even though 45-percent of the total depth interval (4485-ft) was drilled using the rotary method. Bit-changes and lost circulation accounted for 21-percent of the total time. It is interesting to note that non-drilling activities accounted for nearly one-half (47-percent) of total project time.

Figure-3. Rig-operations, activity-breakdown for core-hole GT-1, Fallon, Nevada.

CHINA LAKE NAVAL WEAPONS CENTER No. KL-1

KIRMAN LAKE, CALIFORNIA

The Marine Corps Mountain Warfare Training Center is located approximately 3-miles north of core-hole KL-1, drilled by the Navy's Geothermal Utilization Division (GUD) on the basis of surrounding geothermal activity and a fault-trend revealed during routine geophysical surveying. Pre-drilling activities commenced on August 28, 1986. Daily drilling reports are summarized in Table-4 and the history of project activities is shown in Figure-4. Drilling began with a 7.875-inch hole completed to a depth of 6-ft; 8-ft of 6-inch steel conductor was then cemented in place on September 1. A 5.625-inch hole was rotary-drilled to 325-ft and 4-inch steel casing was set and cemented. Non-drilling activities associated with setting and testing the BOPE occurred from September 7 to September 13.

Coring, using an HQ-size bit, commenced on September 14 at a depth of 325-ft. Coring ceased on September 24, due to inclement weather, at a depth of 2062-ft. The average daily advance-rate from 325-ft to 2062-ft was 165-ft per-day. Coring resumed on September 25 and ceased on October 4 at a depth of 3004-ft. The average advance rate from 2062-ft to 3004-ft was 94-ft per-day.

The percent-activity diagram presented in Figure-5 shows core-drilling accounted for 56-percent of the total time at the site. Rotary-drilling the upper 325-ft, 11 percent of the drilled-depth, only consumed 7.35-percent of the total time. Rotary-drilling with a 5.625-inch rock bit, between 192 and 325 ft, resulted in an advance-rate of 133-ft per-day.

The most significant factor shown in Figure-5 is the percent of time expended in making repairs (11%). This is atypical for drilling programs examined in this study.

TABLE-4

Summary of Daily Drilling Reports, KL-1

Day	Date	Hours Drilled	Hours Other	Feet Drilled	Depth (feet)	Rate (ft/hr)	Daily Cost (\$)
1	Aug 28	0	12	0	0		0
2	Aug 29	0	10	0	0		0
3	Aug 30	0	12	0	0		0
4	Aug 31	1	11	6	6	6.00	330
5	Sept 1	6	6	29	35	4.83	1595
6	Sept 2	0	12	0	35		0
7	Sept 3	18	6	78	113	4.33	4290
8	Sept 4	0	15	0	113		0
9	Sept 5	12	12	79	192	6.58	4345
10	Sept 6	18	6	133	325	7.38	7315
11	Sept 7	0	24	0	325		0
12	Sept 8	0	17	0	325		0
13	Sept 9	0	12	0	325		0
14	Sept 10	0	10	0	325		0
15	Sept 11	0	6	0	325		0
16	Sept 12	0	11	0	325		0
17	Sept 13	0	10	0	325		0
18	Sept 14	12	12	108	433	9.00	5940
19	Sept 15	22	2	130	563	5.90	7150
20	Sept 16	19	5	130	693	6.84	7150
21	Sept 17	24	0	170	863	7.08	9350
22	Sept 18	20	4	160	1023	8.00	8800
23	Sept 19	24	0	190	1213	7.91	10450
24	Sept 20	24	0	197	1410	8.20	10835
25	Sept 21	20	4	173	1583	8.65	9515
26	Sept 22	24	0	200	1783	8.33	11000
27	Sept 23	24	0	188	1971	7.83	10340
28	Sept 24	15	0	91	2062	6.06	5005
29	Sept 25	16	6	89	2151	5.56	4895
30	Sept 26	24	0	116	2267	4.83	6380
31	Sept 27	13	7	56	2323	4.30	3080
32	Sept 28	16	8	80	2403	5.00	4400
33	Sept 29	18	6	106	2509	5.88	5830
34	Sept 30	22	2	131	2640	5.95	7205
35	Oct 1	24	0	111	2751	4.62	6105
36	Oct 2	20	0	87	2838	4.35	4785
37	Oct 3	18	6	85	2923	4.72	4675
38	Oct 4	17	7	83	3006	4.88	4565
39	Oct 5	0	18	0	3006		0

Figure-4. History of project activities at KL-1, Kirman Lake, California.

Figure-5. Rig-operations, activity-breakdown for core-hole KL-1, Kirman Lake, California.

SANDIA NATIONAL LABORATORIES RDO No. 8

SHADY REST, CALIFORNIA

This core-hole was a cost-shared effort that included contributions from the California Energy Commission, Sandia National Laboratories - Research Drilling Office (RDO) and Mono County, California. The hole was ostensibly drilled to evaluate the geothermal resource potential for space-heating the town of Mammoth Lakes. The National Laboratories' interests were to obtain core from this part of Long Valley Caldera, and to obtain subsurface temperature data and fluid samples.

Pre-drilling activities commenced on May 5, 1986, and continued to May 7. The daily drilling reports and history of project activities are shown in Table-5 and Figure-6, respectively. The hole was spudded on May 7 with a 7.375-inch bit and drilled to a depth of 303-ft on May 9. PQ-size casing was installed to a depth of 303-ft and cemented in place. BOPE was installed and tested on May 10. Coring using an HQ-size bit commenced on May 10 and continued to May 19 (1496-ft). There were minor problems with lost circulation and drill-rods sticking. The average advance-rate for the period was 126-ft per-day (5.3-ft/hr)

Between 1496 and 1752-ft, when the bit was changed, the advance-rate was only 73-ft per-day (3-ft/hr), because of caving problems. After the bit-change at 1752-ft, coring continued for 24-hours. The drill-rods were pulled to change the bit and a temperature survey was attempted. The temperature tools became stuck in the hole, but were eventually retrieved by backwashing the hole. Coring resumed on May 25 at 1834-ft and advanced only 208-ft before a new bit was needed. From May 27 to 30, 314-ft were cored (4.36-ft/hr), before a new bit was installed. The average rate of advancement was 90 feet per day (3.8 ft/hr). Coring ceased at a depth of

TABLE-5

Summary of Daily Drilling Reports, RDO no. 8

Day	Date	Hours Drilled	Hours Other	Feet Drilled	Depth (feet)	Rate (ft/hr)	Daily Cost (\$)
1	May 05	0	9	0	0		0
2	May 06	0	11	0	0		0
3	May 07	19	4	160	160	8.29	12000
4	May 08	23	1	125	285	5.26	9375
5	May 09	4	20	15	300	3.75	1125
6	May 10	6	18	24	324	4.00	1800
7	May 11	20	4	71	395	3.55	5325
8	May 12	23	1	211	606	8.88	15825
9	May 13	22	1	125	731	5.55	9375
10	May 14	23	1	235	966	10.00	17625
11	May 15	21	2	165	1131	7.58	12375
12	May 16	23	1	110	1241	4.78	8250
13	May 17	15	9	80	1321	5.33	6000
14	May 18	23	1	128	1449	5.44	9600
15	May 19	10	13	44	1493	4.19	3300
16	May 20	9	14	48	1541	5.05	3600
17	May 21	22	1	128	1669	5.75	9600
18	May 22	23	1	70	1739	2.97	5250
19	May 23	14	9	52	1791	3.52	3900
20	May 24	11	12	40	1831	3.55	3000
21	May 25	21	2	79	1910	3.67	5925
22	May 26	21	2	129	2039	6.07	9675
23	May 27	15	9	82	2121	5.46	6150
24	May 28	14	9	80	2201	5.51	6000
25	May 29	23	1	102	2303	4.34	7650
26	May 30	11	13	42	2345	3.81	3150

Figure-6. History of project activities at RDO No. 8, Mammoth Lake, California.

2346 feet on May 30, 1986.

Activities by percentage time of the total project for HQ coring to 2346 feet are shown in Figure 7. Of the percentage time drilling (coring and rotary), 89 percent of the drilling time was coring for 87 percent (2043 feet) of the Total Depth of the hole. The largest percentage of time for non-drilling activities was for bit changes (12 percent) and "other" (7 percent). The "other" category included temperature surveys and logging, which were not performed during the drilling phase of other core holes considered in these case studies. The total percentage of time coring was 65.5 percent of the total project time which indicates a very high efficiency.

*Includes waiting on cement, temperature surveys and logging.

Figure-7. Rig-operations, activity-breakdown for core-hole RDO No. 8, Shady Rest, California.

THERMAL POWER COMPANY No. CTGH-1

MOUNT JEFFERSON, OREGON

This project was a cost-shared effort between the U.S. DOE/GTD, and Thermal Power Company of California. It is one of a series of core-holes drilled in the Cascade Range to develop methods for evaluating thermal regimes and geothermal resources masked by low-temperature "rain curtains." Daily drilling reports are summarized in Table-6 and the history of project activities is shown in Figure-8. A 12.25-inch hole was spudded on June 7, 1986, and drilled to 35-ft. An attempt was made to set 10.75-inch steel casing to total depth. However, the casing hung-up at 12 feet and would go no deeper, even after re-drilling the hole with the 12-inch bit. The rig was moved and a second conductor-hole was drilled to 35-ft. Two more failed-attempts were made to set the 10.75-inch casing. Finally, on June 9, 35-ft of 10.75-inch conductor-casing was set and cemented in place.

An 8.75-inch bit was used to drill-out the cement plug and deepen the borehole to 517-ft. The hole was conditioned with drilling fluids and a borehole geophysical survey was completed. Seven-inch steel casing was set to 488-ft and cemented in place. The cellar was dug and the BOPE was installed on the 7-inch casing. The BOPE test was delayed until June 18 because of a faulty pipe flange on the BOPE. A 6-inch bit and one joint of 4.5-inch drill-rod was left in the hole at 527-ft. On June 21, a 4.5-inch coring-guide casing was set to 527-ft. Coring began with an HQ-size bit on June 22 at 527-ft. A bit change was required at 859-ft on June 27. Coring continued to 962-ft when drill-rods were pulled out of the hole for lubrication and inspection. Upon running-in the hole, the core-barrel stuck at 962-ft. While attempting to retrieve the barrel, the wireline broke.

Coring resumed on June 28 and continued to a depth of 1271-ft. A bit

TABLE-6

Summary of Daily Drilling Reports, CTGH-1

Day	Hours Drilled	Hours Other	Feet Drilled	Daily Rig Cost (\$)	Rig Cost (\$/ft)	Depth (feet)	Rate (ft/hr)	Daily Cost (\$)	Total Cost (\$/ft)
1	5	5	35	1736	49.6	35	7.00	17552	501.48
2	3	11	0	1325		35	0.00	2175	
3	0	9	0	1125		35		3232	
4	9	2	185	3096	16.7	220	19.47	6646	35.92
5	11	1	200	2993	14.9	420	17.39	4078	20.39
6	9	3	97	1711	17.6	517	10.21	3011	31.04
7	0	19	0	2375		517		12696	
8	0	9	0	1000		517		1550	
9	0	12	0	1500		517		2050	
10	0	11	0	1375		517		4125	
11	0	8	0	1000		517		3255	
12	0	12	0	1500		517		2050	
13	0	17	0	2125		517		5703	
14	2	17	10	2250	225.0	527	5.00	4205	420.50
15	0	13	0	1625		527		5070	
16	22	2	70	2291	32.7	597	3.18	3921	56.01
17	24	0	97	2943	30.3	694	4.04	5194	53.54
18	19	4	80	2991	37.3	774	4.10	6476	80.95
19	24	0	85	2579	30.3	859	3.54	4360	51.29
20	21	3	59	2165	36.6	918	2.80	3536	59.93
21	13	11	44	2335	53.0	962	3.38	3640	82.72
22	20	4	121	4004	33.0	1083	6.05	5409	44.70
23	24	0	162	5483	33.8	1245	6.75	6963	42.98
24	15	9	71	3528	49.6	1316	4.73	5258	74.05
25	24	0	137	4647	33.9	1453	5.70	6277	45.81
26	24	0	137	4894	35.7	1590	5.70	6274	45.79
27	23	1	100	3670	36.7	1690	4.34	5150	51.50
28	24	0	75	2752	36.6	1765	3.12	4257	56.76
29	6	18	10	1117	111.7	1775	1.66	2547	254.70
30	0	0	53	0	0.0	1828		3375	63.67
31	24	0	89	3266	36.6	1917	3.70	4646	52.20
32	24	0	81	2972	36.6	1998	3.37	4452	54.96
33	24	0	85	3551	41.7	2083	3.54	4981	58.60
34	24	0	98	4106	41.8	2181	4.08	5636	57.51
35	24	0	105	4400	41.9	2286	4.37	5880	56.00

Table 6. (continued)

Day	Hours Drilled	Hours Other	Feet Drilled	Daily Rig Cost (\$)	Rig Cost (\$/ft)	Depth (feet)	Rate (ft/hr)	Daily Cost (\$)	Total Cost (\$/ft)
36	8	16	50	2095	41.9	2336	6.25	3575	71.50
37	9	15	32	1340	41.8	2368	3.55	3370	105.31
38	24	0	98	4106	41.8	2466	4.08	5636	57.51
39	19	5	69	3046	44.1	2535	3.63	5566	80.66
40	16	8	59	2770	46.9	2594	3.68	4300	72.88
41	23	1	114	5348	46.9	2708	4.85	6878	60.33
42	24	0	101	4681	46.3	2809	4.20	6211	61.49
43	24	0	103	4774	46.3	2912	4.29	6304	61.20
44	15	9	68	3152	46.3	2980	4.53	4682	68.85
45	24	0	89	4501	50.5	3069	3.70	6031	67.76
46	24	0	104	5388	51.8	3173	4.33	6918	66.51
47	24	0	96	4973	51.8	3269	4.00	6503	67.73
48	22	1	86	4543	52.8	3355	3.82	6023	70.03
49	24	0	106	5492	51.8	3461	4.41	6972	65.77
50	23	1	101	5723	56.6	3562	4.29	7203	71.31
51	21	3	79	4763	60.2	3641	3.76	6243	79.02
52	23	1	80	4821	60.2	3721	3.47	6301	78.76
53	1	23	2	1982	991.0	3723	2.00	3462	1731.00
54	23	1	88	4621	52.5	3811	3.74	6101	69.32
55	23	1	90	4787	53.1	3901	3.91	6267	69.63
56	23	1	81	4880	60.2	3982	3.52	6360	78.51
57	23	1	80	5379	67.2	4062	3.47	6859	85.73
58	23	1	81	5609	69.2	4143	3.52	7089	87.51
59	13	10	60	4187	69.7	4203	4.44	5667	94.45
60	0	0	0	0		4203		1480	
61	0	24	0	0		4203		1180	
62	0	24	0	1500		4203		2680	
63	0	24	0	3000		4203		4180	
64	0	24	0	1500		4203		2680	
65	4	20	23	3057	132.9	4226	5.75	4487	195.08
66	13	10	53	3545	66.8	4279	3.92	4425	83.49
67	23	1	92	6170	67.0	4371	4.00	7550	82.06
68	23	1	79	5315	67.2	4450	3.43	9095	115.12
69	23	1	80	5320	66.5	4530	3.40	6700	83.75
70	22	1	90	6347	70.5	4620	4.00	7827	86.96
71	23	1	80	6365	79.5	4700	3.47	7745	96.81
72	18	6	60	4875	81.2	4760	3.33	6185	103.08
73	13	11	40	3120	78.0	4800	3.07	4400	110.00
74	0	48	0	12750				53455

Figure-8. History of project activities at CTGH-1, Mount Jefferson, Oregon.

change was required at this depth on June 30. Coring continued to a depth of 2336-ft and 100-percent core-recovery was reported without drilling returns. The wireline broke, again, while pulling the core-barrel, and it was necessary to pull out of the hole to retrieve the core-barrel and change the bit. Coring resumed on July 13 to a depth of 2466-ft when the wireline broke again. The wireline was repaired and coring continued to a depth of 2594-ft (with the core-barrel sticking at 400-ft). Coring proceeded to a depth of 3723-ft on July 29, where the bit was replaced. Coring resumed on July 30 and proceeded to 4203-ft when the drill-rods broke. The breaking of the HQ-size core-drilling-rods resulted in a three-day shut-down while waiting for NX-size core-drilling-rods. There was difficulty in retrieving the HQ-size core-barrel on August 8 and 9. The HQ-size core-head was drilled-out with the NX-size bit, and coring continued to a depth of 4226-ft. The drill-rods were pulled-out of the hole for a bit change, and coring resumed on August 11 and continued until August 17 (4700-ft). A minor delay was required for repair of the wireline and core-barrel. Coring resumed for one-day (100-ft), then was shut down because of high fire-hazard on August 18.

Drilling crews returned on August 30 to install NCC (3.5-inch) core-rods to a depth of 4205-ft as a liner. The hole was conditioned and cooled with drilling fluids for geophysical logging. The rig remained on-site through September 7, when the BOPE was removed and the site vacated.

Because of the format of the daily drilling reports, it was difficult to determine the specific non-drilling activities performed. Figure-9 shows the percent-distribution of drilling and non-drilling activities. Only 3-percent of the total time was spent rotary-drilling to a depth of 527-ft. This depth is 11-percent of the total depth. Coring accounted for 56-percent of total project time.

Figure-9. Rig-operations, activity-breakdown for core-hole CTGH-1, Mount Jefferson, Oregon.

LITHOLOGIC EFFECTS ON ADVANCE-RATE AND PENETRATION-RATE

Information from the CTGH-1 core-hole provided the most complete data on the effects of rock-type on drilling rate. Figure-10 shows the advance-rate and instantaneous penetration-rate for a sequence of basaltic-andesite between the depths of 3630 and 3960-ft. The advance rate was slightly less than 4 ft/hr, while instantaneous penetration rates averaged 8 ft/hr. The maximum penetration-rate was 11-ft/hr after a bit change, but rapidly returned to rates of 8 to 9-ft/hr.

A comparison of coring and rotary-drilling for similar rock-types is shown in Figure-11. The left side of the figure shows coring rates from Figure-10 compared with rotary-drilling rates from 50 to 380-ft.

The average advance-rate for rotary-drilling was 16.5-ft/hr, as compared to an average advance-rate for coring of less than 4-ft/hr. Figure-12 shows the advance-rate and instantaneous penetration-rate while coring through the interval 2560 to 2890-ft. This interval was selected for comparison of variations in advance-rate and penetration-rate for various lithologies. Bit number-6 had been in-use since 2336-ft and was changed at 3720-ft, 830-ft past the interval shown on Figure-12.

It is readily apparent that the penetration rate for rotary-drilling is 4-times greater than the penetration-rate for coring in similar rock-types. The instantaneous penetration-rate for rotary-drilling exceeded 30-ft/hr for 73-percent of the interval examined, and exceeded 60-ft/hr for 24-percent of this interval. Conversely, the instantaneous penetration-rate for core-drilling peaked at 11-ft/hr and averaged only 8-ft/hr. Penetration rates were highest in lapilli tuff, andesite breccia and the upper part of basaltic-andesite, where rates exceeded 10 ft/hr.

Figure-10. Comparison of advance-rate and penetration-rate for coring in basaltic-andesite, CTGH-1.

Figure-11. Comparison of advance-rate and penetration-rate between coring and rotary-drilling in basalt and basaltic-andesite, CTGH-1.

Figure-12. Comparison of advance-rate and penetration-rate in coring various lithologies, CTGH-1.

There are distinct variations in penetration rate for units described as volcanic breccia. Lithologic descriptions indicate the lower volcanic breccia unit is fractured. This may explain the higher rate of penetration. The decrease in penetration-rate in the interval 2750 to 2846-ft would be typical of a massive-flow with vesicular top and massive welding at the base.

Advance-rate is less sensitive to changes in lithology than penetration-rate. The advance-rate ranged from a low of 3-ft/hr to a high of 5-ft/hr.

To ascertain the impact of bit-change on penetration-rate, 6-intervals in various lithologies, where bit changes occurred, were studied. Figure-13 shows the advance-rate and penetration-rate for intervals; (a) 530 to 640-ft, (b) 2270 to 2380-ft, and (c) 4180 to 4290-ft. Bit No-1 showed increased rate of penetration from 530 to 570-ft, followed by a significant decrease signifying the need for a new bit. Bit No.-2 showed a slight increased rate of penetration, but did not surpass the 11-ft/hr attained with Bit No.-1. In Figure-13, a bit change is shown at 2336-ft that resulted from a decreased penetration rate above this depth. The new bit increased the penetration rate to a maximum of 10-ft/hr at a depth of 2380-ft. A bit-change (Bit No.-8) was required because the HQ-size core-rod sheared-off and coring was resumed with NX-size rod. The life of bit No.-8 was limited to a distance of only 40-ft because the HQ-size core-bit (No.-7) had to be drilled-out (C in fig.-13). NX-size coring continued with bit No.-9. Penetration-rates using the smaller-diameter bit were similar to those attained with the larger HQ-size bits, never exceeding 10-ft/hr in basaltic-andesite (A and B, fig.-13).

Figure-14 shows in detail, the advance-rate and instantaneous penetration-rate for 3-intervals where bit-changes occurred; (a) 820 to 930-ft,

Figure-13. Effects of bit-change on advance-rate and penetration-rate in CTGH-1 core-hole.

Figure-14. Effects of bit-changes and lithologic contacts on penetration-rate in the CTGH-1 core-hole.

(b) 1240 to 1350-ft and (c) 1720 to 1830-ft. A bit-change (no.-3) in A of Figure-14 shows increased penetration-rate in a dacite unit, from 5 to 11-ft/hr. Also, the effects of a new bit and lithology are apparent in B of Figure-14. Bit-4 was installed for drilling the basal part of the volcanic breccia-unit at a depth of 1270-ft. A penetration-rate of 12-ft/hr was maintained until the top of an andesite-flow was encountered at about 1300-ft. The penetration-rate increased to 25-ft/hr and remained greater than 20-ft/hr in the upper part of the flow. These high rates of penetration undoubtedly result from the intense fracturing recorded in the lithologic log. Figure-14C shows the combined effects of a dull bit and competent rock at the base of an andesite-flow. Bit no.-4 had been in use since 1270-ft, and the instantaneous penetration-rate was decreasing and approaching the advance-rate. Upon changing to Bit no.-5, the penetration-rate increased to 11-ft/hr in a volcanic breccia, and remained between 8 and 10-ft/hr in an Andesite unit. A description of the volcanic rocks, fractures and associated features in the CTGH-1 core-hole is given in Table-7.

TABLE-7

Description of fracture-zones encountered in core-hole CTGH-1

CORE DEPTH (ft)	ROCK-TYPE	FRACTURE FEATURES	MINERALIZATION FEATURES	CORE RECOVERY (percent)
560	Basalt, basaltic andesite	Minor	White and pink clay on fracture-surfaces	NR
854	Dacite	Highly fractured 75 to 80°,	Pink and brown clay on fracture-surfaces	NR
1138	Basalt	Minor	Light orange-pink clay on fracture-surface	100
1291	Andesite	Highly fractured largely vertical, variable with depth (30-45')	Pale, orange-pink clay commonly coats fracture-surfaces; clear-white, tabular mineral (very fine) in veinlets and on fracture-surfaces	100
1570	Volcanic breccia	Minor	Pale blue, blue-grey clay on fractures with zeolite and iron oxide	NR
1647	Andesite	Platy fractures at 45° angle	Light brown, dark green-grey clay coats fracture-surfaces, also with limonite and pyrolusite	100
1666	Volcanic breccia	Minor, variable direction	Zeolites on fractures	100
1694	Andesite	Prominent, and locally intense, 45° angle	Clay on fracture-surfaces	100

TABLE-7 (continued)

1781	Volcanic breccia	Minor	Zeolites on fracture-surfaces	NR
1798	Andesite	Minor	Green-grey clay on fracture-surfaces	NR
1820	Volcanic breccia	Minor	Slickensides on fracture-surfaces	100
1826	Basaltic andesite	Few fractures, 40 to 50° angle	NR	100
1969	Volcanic breccia	Minor	Shear common on fracture-surfaces	100
1979	Basaltic andesite	Highly fractured and brecciated at 15, 40 and 80° angle	Clay and zeolites on fracture-surfaces	100
2317	Volcanic breccia	Irregular, often with waxy, sheared surfaces	Green clay on fracture-surfaces	100
2453	Andesite	Local fractures and brecciation	NR	100
2550	Andesite	Local, intense fractures	Green, grey and white clay on fracture-surface	100
2586	Crystal lapilli tuff	Light shearing	Dark green and pale blue clay on fracture surfaces	100
2657	Andesite breccia	Minor	NR	100
2726	Basaltic andesite	Tectonic brecciation with minor movement in brecciated interval; light to moderate fractures	NR	100

TABLE-7 (continued)

2042	volcanic breccia	Light to variable fracturing	Rare zeolites on fracture-surfaces	100
2965	Basaltic andesite	Generally light, locally intense in dense lavas, 45° angle common	Silica in veinlets and voids, white-blue, replaces clay	100
3360	Basaltic andesite	Moderate, locally intense zones; flows more fractured than breccia; variable direction, near vertical.	Green-blue clay common on fracture-surfaces, silica also common	100
3920	Basaltic andesite	Moderate, more common in flows than breccia, variable direction, high angle most common	Green-blue clay common on fracture-surfaces, silica replaces clay on fracture-surfaces, iron-oxide stains follow fractures	100
4480	Basaltic andesite	Concentrated in flows, fracture-surfaces often sheared	Green-blue clay, silica and zeolites on fracture-surfaces; yellow-orange iron-oxide stains follow fractures, with hematite and serpentine on fracture-surfaces.	100

CHEVRON RESOURCES, KOSMOS No. 1-9

A slim hole (6.25-inches) was drilled by Chevron Resources in 1978 in the San Emidio Desert of Washoe County, Nevada. This was the only slim-hole drilled by the rotary method, with available information on drilling rates. The hole was cased with 7-inch casing to 500 ft and drilled to a total depth of 5367 ft. The average advance-rate for the total depth of the hole was 6.4-ft/hr. This varied considerably in the upper part of the hole, where unconsolidated sediments were penetrated. Examples of advance-rates for several intervals are shown in Table-8. Advance-rates ranged from 41-ft/hr in sands and gravels to 3-ft/hr in slate. In the interval between 2562 and 2845-ft, the advance-rate averaged 6-ft/hr in claystone and siltstone. However, this interval also included spent tripping-out, coring and tripping into the hole.

TABLE-8

Advance-Rates for Various
Lithologies in the Kosmos No. 1-9 Well

Interval Drilled (ft)	Material and Activities	Advance Rate (Ft/Hr)
610-997	clayey sands	25
1308-1432	sands & gravel	41
1906-1980	sands & gravel included bit-change	15
2562-2845	claystone & siltstone included a 10-ft core	6
5066-5165	slate included bit-change	3

It would appear that advance-rates for coring and rotary drilling are similar. Table-9 shows the average advance-rate for core-holes studied and the rotary-drilled slim-hole (Kosmos 1-9). Average advance-rates range from 3.66 to 6.37 ft/hr.

TABLE-9

Comparison of average advance rates

Drill Hole	Average Ft/Hr	Drilling Method
Fallon, No. GT-1	6.29	coring
Shady Rest, RDO No. 8	5.19	coring
Thermal Power, CTGH-1	3.66	coring
Kirman Lake, KL-1	6.37	coring
Kosmos No. 1-9	6.40	rotary

COMPARISON OF CORING VS. ROTARY-DRILLING
FOR THE KOSMOS 1-9 and FALLON GT-1 HOLES

Figure-15 shows a comparison of drilling records for the Kosmos, 1-9 and Fallon, GT-1 holes. It is readily apparent that coring-rigs are not capable of drilling sufficiently large-diameter holes to set surface casing in a single operation. At Fallon, a 5.625-inch hole was rotary drilled to a depth of 610-ft and then reamed to 9.875-inch to allow for the installation of 6-inch casing. In addition, more than 50 work-hours were expended installing and testing the BOPE. This amounts to about 7 working days to drill through the cement following the BOPE test. At the Kosmos 1-9 hole, however, the hole was drilled to 500-ft, casing was set, cemented, and the BOPE was tested in only 4-days. When progress on the two holes is compared at a depth of 2000-ft, the difference between the Kosmos 1-9 and GT-1 is again reflected in the time required to set casing, and install and test the BOPE.

The advance-rate for rotary-drilling below 3750-ft is comparable to the advance-rate for coring at similar depths. Below 3750-ft, slate and quartzite were penetrated in the Kosmos 1-9 hole. These rocks are comparable in hardness to the massive basalts penetrated in GT-1; therefore, the advance-rates are similar for both rotary-drilling and coring.

Figure-15. Comparison of advance-rates for rotary-drilling and coring.

CORING COST-ANALYSIS

Coring-costs vary from site to site and from surface to total depth at various sites. Costs also vary as a function of core-size, drilling operations criteria, materials used and among individual contractors. As with many specialized fields that are directly related to ongoing research and development, costs are subject to radical fluctuations.

To ascertain the relative costs for each of the core-holes, this study began by examining cost-per-foot and total project costs. Although there is some common ground, none of the core-holes in these case studies was drilled under identical conditions. The obvious differences in location and type of equipment used are far less important than project goals and overall scientific objectives. For example, the least expensive hole for which we have detailed information, on a per-foot basis, is GT-1 (\$43/ft), which was drilled essentially as a temperature-gradient hole under relatively benign conditions. Borehole VC-2a, which was briefly discussed in Table-1, cost approximately \$105/ft, and was a "scientific borehole" drilled under the auspices of the CSDP Thermal Regimes Panel, which has developed a strict protocol for all drilling operations (Goff and Nielson, 1986). This protocol includes maintaining on-site staff including a Principal Investigator, Chief Scientist and Chief Engineer. In addition, obtaining geophysical logs of the borehole during drilling operations, obtaining magnetically-oriented core and specialized core-handling procedures are also practiced. This hole was drilled in a hydrothermally active area, replete with acid hot-springs and extensive lithologic alteration. These conditions required additional measures to assure the success of the drilling project and personnel safety. The net effect was a substantial increase in total project cost, when compared to a core-hole like GT-1,

which was drilled with a minimum of on-site science-officers and no downhole measurements taken during core-drilling.

Figure-16 shows the cost per-foot-cored for the six sites for which information was available. Thermal Power Company's CTGH-1 was the only site with daily and cumulative cost-data (Table-6) permitting examination of the rate of increase in drilling cost with depth. The average cost-per-foot, in 500-ft intervals below 1000-ft, is shown. The width of the curve (parallel-diagonal lines) on Figure-16 indicates the range in cost-per-foot for the interval cored. Costs-per-foot for other core-holes in this study were based upon total cost divided by total depth, and included rotary-drilling.

The high front-end costs incurred in setting casing, cementing and waiting-on-cement for CTGH-1 are displayed in Figure-17. Above 1000-ft, the high cost-per-foot reflects problems in setting 4.5-inch casing to 527-ft. Nearly one-third (29-percent) of the total cost had already been incurred when the depth of 1000-ft was reached (22-percent of the total-depth cored). At a depth of 2000-ft, or 44-percent of the total-depth cored, approximately 45-percent of the total costs were expended.

The lowest cost-per-foot on a flat-rate basis was \$43.50/ft for the Fallon GT-1 core-hole. The reason for this low-cost was the fact that the first 2000-ft of the hole were drilled by the rotary method in soft to moderately-hard lake sediments. On-site operations were relatively straight-forward and geophysical logging was conducted at the completion of core-drilling.

The Kirman Lake KL-1 core-hole cost \$54-per ft, which falls within the range of costs derived from analysis of the CTGH-1 core-hole for comparable depth. Again, no geophysical logging was conducted during drilling of the Kirman Lake core-hole.

Figure-16. Comparison of cost, on a per-foot basis, for selected core-holes.

Figure-17. Percent of total project cost as a function of depth for core-hole CTGH-1.

The other core-holes shown on Figure-16, Shady Rest (RDO no. 8) and the Valles Caldera core-holes VC-1 and VC-2a, were drilled as part of the CSDP. In the case of RDO no. 8, temperature-gradient surveys were made routinely during coring operations. Likewise, geophysical logging during drilling and taking oriented-core contributed to the increased cost for VC-1. As previously stated, VC-2a was drilled in an area of acid hot-springs and relatively high temperatures, which also increased total project cost. It is interesting to note, however, that drilling records for VC-1 and KL-1 (fig-18) indicate that both were completed in approximately the same number of days to a comparable depth of 2800-ft.

On the basis of cost-depth data, Thermal Power core-hole CTGH-1 was \$80/ft when total depth was reached. Figure-19 shows the variation in cost-per-foot for drilling. This diagram was generated on the basis of cumulative cost-per-foot data, as opposed to interval cost-per-foot data represented in Figure-16. The high costs at 1000-ft include non-drilling costs, such as casing, cementing, logging and waiting-on-cement. These initial front-end costs decrease with further drilling. Drilling without mechanical problems can reduce the per-foot-cost to as low as \$74. The increase in cost-per-foot below 4000-ft resulted from a twist-off of BX-size core-rod and waiting for new NX-size rod. Additional charges for stand-by time and logging accrued during the August 18 through September 6 period, increasing the final cost to \$91/ft.

Figure-18. Total depth vs. total days for 5 core-holes.

Figure-19. Variation in cost-per-foot (*cumulative), as a function of depth, for core-hole CTGH-1.

PROBLEMS IN CORE-DRILLING

Some of the most serious core-drilling problems in "thermal regimes," and those that contribute substantially to cost, are associated with drilling and completing the shallower section of the hole. The "top" of the borehole must be drilled large enough to accommodate the 4 to 6-inch diameter casing required for installation of blow-out prevention equipment (BOPE). This is generally accomplished by fitting the core-rig with a tri-cone bit and drilling with the rotary-mud technique. The advantage of this is having only one rig on-site, thus offering the economy of one mobilization charge. Also, in environmentally sensitive areas, the number of major equipment moves over fragile roads is reduced. The disadvantage is that most core-rigs are not designed for effective rotary-mud drilling, even under ideal conditions. Typical problems arising as a result of using core-rigs include the following:

1. little or no capability for getting weight-on-bit for initial penetration
2. limited capacity for using large diameter bits (6 to 8 inches) required to set adequate surface-casing and BOPE
3. limited mud-pumping capacity (when drilling by rotary-mud method) to control lost-circulation zones
4. limited capacity to lift and set heavy, large diameter (6 to 8 inch) casing
5. limited capacity to install heavy BOPE, limited driller-experience in setting and testing BOPE
6. limited driller-experience and rig-capacity to pressure-grout (cement) surface-casing for use with BOPE

There are several methods available to successfully and economically complete the upper part of a core hole. Several methods will be discussed in detail and their relative merits evaluated. The most promising methods are:

1. Conventional rotary-mud or rotary-air drilling
2. Cable-tool rigs
3. Large-capacity rotary-air drilling
4. Large-diameter core-drilling
5. Reverse-circulation drilling
6. Use of the latest generation of lost-circulation materials (LCM) with items 1 or 5

Other problems that occur in the course of core-drilling include lack of penetration and twist-offs associated with clay (a product of the hydrothermal-alteration of volcanic rocks), lack of hole-stability in fractured rocks (which results in no hydrostatic support from the drilling-fluid) and unintentional deviation of the hole from vertical. Some of these problems may be remedied by adjusting drilling-fluid composition, changing from diamond-bit to drag-bit, or casing-off bad sections of a hole. But these are site specific drilling problems that should be addressed at the drill site. The solutions to problems such as excessive drill bit and drill rod wear, thermal breakdown of drilling fluids, and lack of retrieval of core in fracture zones are being investigated by the US DOE and by the geothermal industry.

COMPARATIVE DRILLING TECHNIQUES

ROTARY-MUD DRILLING

With the possible exception of cable-tool drilling in some parts of the country, this is the most popular and most widely-available drilling technique in the United States. Truck-mounted rotary-rigs are versatile; they can drill to depths of 4000-ft (or more). They are used to drill water wells, oil and gas wells, and geothermal wells. Their popularity increased several years ago when it was learned that they could be successfully used to complete shallow-depth temperature- gradient holes much more quickly than larger rigs that required some assembly. Rotary-mud drilling relies entirely on the return (circulation) of drilling-fluid (mud) to the surface. If circulation is lost, the mud will not return to the surface. Without circulation, drill-chips fall to the bottom of the borehole, accumulate around the drilling assembly and "stick" (bind) the drill-string. This is a significant problem in subsurface areas where highly-fractured rocks occur.

CABLE-TOOL DRILLING

A cable-tool is a long, narrow, chisel-shaped hammer, attached to a long, steel cable (hence the name) that is pounded continuously into the ground to produce a hole. It is more a digging technique than a drilling technique, because no rotation is involved. The cable-tool method was invented by the Chinese and has been used to dig wells, worldwide, for the past 4000-years. It is an economic, simple and highly-available borehole-producing operation. It has the advantage of not requiring circulation of

fluid to produce the hole. Broken rock at the bottom of the hole is removed by "bailing". In many areas that contain abundant coarse glacial till, boulders, fractured and fissured rocks, and caverns, it may be the only method available to complete a hole.

ROTARY-AIR DRILLING

Rotary-air drilling rigs use compressed air as the circulation fluid instead of "mud". This technique offers many advantages over mud-drilling including: higher rates of penetration, especially in dense, consolidated rock; reduced bit-wear; reduced formation damage by drilling fluids; low water requirements; and minimized swelling associated with clays. There are two major disadvantages associated with this technique: the inability to control blowouts and the inherent ability to produce massive amounts of water while drilling through water-bearing formations. The advantage of this method is the use of a light-weight fluid (air or foam) to circulate and remove cuttings from the hole.

REVERSE-CIRCULATION DRILLING

Reverse-circulation drilling was developed to overcome problems of severe lost-circulation and borehole stability. It is in some ways a hybrid between mud-only and air-only drilling; a drilling fluid is always circulated, but is assisted to the surface by air-lift. One major difference is, as the name implies, that the direction of circulation is the reverse of conventional mud or air drilling. Instead of pumping air down the hollow drill-stem and up the annulus, mud falls down the annulus and is sucked-up through the drill-stem (like soda through a straw) with an air-lifting arrangement. Many lost circulation problems can be overcome with

reverse-circulation drilling. As a rule of thumb, when experience and intuition suggest that cost for rig-time and materials will exceed that of conventional drilling by 50-percent (or more), on a quoted per-foot bid, reverse circulation drilling is the appropriate choice.

LARGE-DIAMETER CORE-DRILLING

A continuously-cored hole (surface to bottom) is very desirable, because it provides a complete, vertical lithologic sample from ground-surface to total-depth of a hole. Drill-chips from the top part of a hole may provide some continuity, but a continuous column of rock is the goal of most scientific drilling programs currently underway. Starting the hole with a large-diameter core-bit may be advantageous for several reasons: it allows setting casing of adequate size for BOP equipment; it may be conducted through zones of lost circulation; and it returns core to the scientific investigator. Bits are available to produce a borehole 6 to 10-inches in diameter, large enough to accommodate casing suitable for use with bladder-type BOPE.

EXPERIMENTAL LOST-CIRCULATION MATERIALS

Experimental lost-circulation materials are being developed to assist with drilling and completion of large-diameter geothermal production wells. Conventional LCM includes wood fibers, cotton-seed hulls, shredded plastic, paper, dried horse manure, ground battery casings and, disposable baby diapers (infant-size works best). Newer products include polymers and co-polymers mixed with clay, sand or cellulose. The Geothermal Resources Council Bulletin (January, 1987) describes a "high-tech LCM."

A rigid polyurethane foam originally developed as a temperature- tolerant packing for electronics is now being considered as a very good material for preventing lost circulation of drilling muds into the surrounding rock formations. Characteristics of the material show particular suitability for drilling operations in geothermal environments..Its characteristics allow its use to plug the many fractures and voids present in geothermal formations."

A more rigorous description is presented by Polk and others (1985).

The judicious application of LCM, especially the latest generation products, in conjunction with either conventional rotary- mud or reverse-circulation drilling rigs, provides another technique for successfully completing the upper part of core-holes.

CORING-COST PROJECTIONS

On the basis of cost-data provided in the various case studies, cost projection to geologically "interesting" depths have been developed. Although projected costs in this study are to a maximum depth of 21,500-ft, deep and ultra-deep drilling programs have been proposed to 32,000-ft by the geologic community (Table-10).

TABLE-10

Proposed Scientific Drilling Programs

Project	Proposed Depth
Upper Crust/CICSCO	3,200 to 6,400-ft
Creede Mining District	9,500 to 15,000-ft
Appalachian ultra-deep hole	32,000-ft
Long Valley Caldera	20,000-ft

Additional drilling programs have been informally proposed for drilling targets ranging in depth from 10,000 to 20,000-ft. The cost-projection data presented are for continuous coring with wireline retrieval, which is presently not feasible for core-hole depths greater than 10,000-ft. Therefore, the data are considered to provide a conservative estimate of core-drilling costs to be expected for the various proposals listed in Table-10.

Table-11 presents cost estimates to a total depth of 21,500-ft, based on a 12-percent incremental increase for each additional 500-ft of drill core. Twelve-percent is the average cost-increase for Thermal Power's

TABLE-11

Twelve-percent incremental cost estimate
for a core-hole drilled to 21,500-ft

Depth (ft)		Cost (\$/ft)	Increase Cost (\$)	Interval Cost (\$)	Cumulative Cost (\$)
From	To				
500	1000	30.00		15000	15000
1000	1500	35.00	5.00	17500	32500
1500	2000	37.00	2.00	18500	51000
2000	2500	40.00	3.00	20000	71000
2500	3000	45.00	5.00	22500	93500
3000	3500	53.00	8.00	26500	120000
3500	4000	60.00	7.00	30000	150000
4000	4500	67.20	7.20	33600	183600
4500	5000	75.26	8.06	37632	221232
5000	5500	84.29	9.03	42147	263379
5500	6000	94.41	10.11	47205	310585
6000	6500	105.74	11.32	52870	363455
6500	7000	118.42	12.68	59214	422670
7000	7500	132.64	14.21	66320	488990
7500	8000	148.55	15.91	74278	563269
8000	8500	166.38	17.82	83192	646462
8500	9000	186.35	19.96	93175	739637
9000	9500	208.71	22.36	104356	843993
9500	10000	233.75	25.04	116879	960873
10000	10500	261.80	28.05	130904	1091778
10500	11000	293.22	31.41	146613	1238391
11000	11500	328.41	35.18	164206	1402598
11500	12000	367.82	39.40	183911	1586510
12000	12500	411.96	44.13	205981	1792491
12500	13000	461.39	49.43	230698	2023190
13000	13500	516.76	55.36	258382	2281573
13500	14000	578.77	62.01	289388	2570962
14000	14500	648.23	69.45	324115	2895077
14500	15000	726.01	77.78	363009	3258086
15000	15500	813.14	87.12	406570	3664657
15500	16000	910.71	97.57	455358	4120016
16000	16500	1020.00	109.28	510001	4630018
16500	17000	1142.40	122.40	571202	5201220
17000	17500	1279.49	137.08	639746	5840966
17500	18000	1433.03	153.53	716515	6557482
18000	18500	1604.99	171.96	802497	7359980
18500	19000	1797.59	192.59	898797	8258778
19000	19500	2013.30	215.71	1006653	9265431
19500	20000	2254.90	241.59	1127451	10392883
20000	20500	2525.49	270.58	1262746	11655629
20500	21000	2828.55	303.05	1414275	13069904
21000	21500	3167.97	339.42	1583988	14653893

core-hole CTGH-1 from 500 to 4000-ft. Table-12 provides a 10-percent projection to the same total depth. Both data-sets are illustrated in Figure-20. Ten-percent was chosen because front-end costs associated with near-surface completion do not accurately reflect subsequent cost data.

Continuous wireline coring has not yet been attempted in volcanic terrane at depths greater than of 10,000-ft. For such a hole, coring costs alone would be approximately \$1,000,000. Total project costs would range from \$1.8 to \$2.2 million.

In 1985, an estimate was made for continuous wireline-coring of the Salton Sea Scientific Drilling Project well for the U.S. Department of Energy, San Francisco Operations Office, for the interval from 6,000 to 10,000-ft. It should be noted that coring with wireline retrieval has never been attempted in a geologic environment as "hostile" as that found in the Salton Sea Geothermal Field. The report to DOE estimated that HQ-size core could be recovered (the probability was 50-percent) during 64-days of drilling at a cost of \$810,000. The estimates in this study range from \$540,000 (10-percent) to \$650,000 (12-percent) for core-drilling in this interval. Although not proposed, the total project-cost for a continuous, wireline core-hole to 20,000-ft in the Long Valley Caldera would be \$14 to \$20 million.

TABLE-12

Ten-percent incremental cost estimate
for a core-hole drilled to 21,500-ft

Depth (ft)		Cost (\$/ft)	Increase Cost (\$)	Interval Cost (\$)	Cumulative Cost (\$)
From	To				
500	1000	33.00	3.00	16500	16500
1000	1500	36.30	3.30	18150	34650
1500	2000	39.93	3.63	19965	54615
2000	2500	43.92	3.99	21961	76576
2500	3000	48.31	4.39	24157	100734
3000	3500	53.14	4.83	26573	127307
3500	4000	58.46	5.31	29230	156538
4000	4500	64.30	5.84	32153	188692
4500	5000	70.73	6.43	35369	224061
5000	5500	77.81	7.07	38906	262967
5500	6000	85.59	7.78	42796	305764
6000	6500	94.15	8.55	47076	352840
6500	7000	103.56	9.41	51784	404624
7000	7500	113.92	10.35	56962	461587
7500	8000	125.31	11.39	62658	524245
8000	8500	137.84	12.53	68924	593170
8500	9000	151.63	13.78	75817	668987
9000	9500	166.79	15.16	83398	752386
9500	10000	183.47	16.67	91738	844124
10000	10500	201.82	18.34	100912	945037
10500	11000	222.00	20.18	111003	1056041
11000	11500	244.20	22.20	122104	1178145
11500	12000	268.62	24.42	134314	1312459
12000	12500	295.49	26.86	147745	1460205
12500	13000	325.04	29.54	162520	1622726
13000	13500	357.54	32.50	178772	1801499
13500	14000	393.29	35.75	196649	1998149
14000	14500	432.62	39.32	216314	2214463
14500	15000	475.89	43.26	237946	2452410
15000	15500	523.48	47.58	261741	2714151
15500	16000	575.83	52.34	287915	3002066
16000	16500	633.41	57.58	316706	3318773
16500	17000	696.75	63.34	348377	3667150
17000	17500	766.43	69.67	383215	4050365
17500	18000	843.07	76.64	421536	4471902
18000	18500	927.38	84.30	463690	4935592
18500	19000	1020.11	92.73	510059	5445651
19000	19500	1122.13	102.01	561065	6006716
19500	20000	1234.34	112.21	617171	6623888
20000	20500	1357.77	123.43	678888	7302777
20500	21000	1493.55	135.77	746777	8049554
21000	21500	1642.91	149.35	821455	8871010

Figure-20. Projection of baseline core-drilling costs to a nominal depth of 20,000-ft. HQ-core 10 and 12-percent increase for each 500-ft of cored hole.

SUMMARY

Core-drilling in recent volcanic environments is widespread, both temporally and spatially, throughout the western United States. Historically, many shallow-depth temperature-gradient holes (500 to 1000 ft) were completed with rotary-mud or rotary-air drilling rigs. However, recent interest in thermal regimes and hydrothermal resources within young, volcanic terranes has resulted in near-universal application of core-drilling rigs in scientific and commercial exploration programs. The principal advantage, successfully completing a borehole under conditions of extreme lost-circulation, was essentially established more than 50 years ago in the Norris basin of Yellowstone National Park. The prevalence of core-rig use in penetrating volcanic-hydrothermal regimes is attributable to efficiency, economy, and multiple uses of both the core and borehole.

The coring-costs reported here vary widely from base-costs (rig-time costs), that are shown to increase exponentially with depth. This departure from base-costs is the result of cumulative effects associated with the following major factors:

1. using coring-rigs as rotary-mud rigs in near-surface hole completion,
2. using specialized equipment and material while drilling in hostile environments (high-temperatures, acid springs)
3. obtaining geophysical logs during drilling operations,
4. taking oriented-core,
5. slant or directional-drilling, and
6. problems associated with equipment-failure (stuck-rod, twist-offs, etc.).

Some of these cost-factors may not be eliminated, because they have either been identified as an intrinsic part of the drilling plan (2, 4 and 5 above) or they are an essentially unavoidable aspect of drilling activities (6). Unfortunately, some may be the of poor planning (1) or questionable use of rig-time (3). The ultimate utility of taking downhole measurements while drilling is underway is debatable. White (1968), and White and others (1975) suggest that "true" temperature-profiles are obtained by measuring bottom-hole temperatures in regular increments of time or depth, as drilling progresses. For shallow-depth holes (500 to 1000 ft) that are relatively stable (not subject to caving), this may be appropriate. On the other hand, deeper holes (2000 to 5000 ft) involve considerably higher equipment-investment and, in highly fractured rock, involve much higher risk of loosing an unstable hole. Boreholes that are unsupported by drill-rod or mud are subject to caving, clay-swelling and bridging. All of these may exclude wireline-logging operations. In addition, many core-drillers are reluctant to allow anything but drill-rods in an uncompleted and unstable borehole. On the other hand, such measurements may only account for 10-percent of the project budget, and, therefore, constitute an entirely justifiable operation. Resolution of this problem is ultimately the decision made at the drill-site by the principal investigator and driller.

Table-13 shows the relative cost of some of the most recent core-drilling projects. No two projects are alike, therefore there can be no direct correlation among the costs shown. Figure-21 shows the total project costs as a function of depth, for several core-holes. Most of the projects cost between \$50 and \$100 per-foot, depending on the extent of problems encountered while drilling, depth, and amount of time required for borehole measurements during drilling operations.

TABLE-13

SUMMARY OF DRILLING RESULTS FROM SELECTED SCIENTIFIC CORE HOLES

Hole No/ Depth (feet)	Project Operator	Drill Site	Start/ Completion Date	Principal Lithology	Core Size/ Amount	Total Cost (in \$1000) \$/core-ft
KL-1 3004	US Navy China Lk.	Kirman Lk, CA	08/28/86 10/04/86	Andesite porphyry	HQ 2679	\$166 \$55/ft.
GT-1 4495	US Navy China Lk.	Fallon NAS, NV	05/08/86 06/19/86	Basalt	HQ	\$224 \$50/ft.
RDO no.8 2346	Sandia Nat. Lab	Mammoth Lks, CA	05/07/86 05/30/86	Rhyolite/ Bis. Tuff	HQ/NQ	\$176 \$75/ft.
CTGH-1 4800	Thermal Power	Mount Jeffersn, OR	06/07/86 09/07/86	recent volcanics	NC/NX	\$439 \$91/ft.
GEO N-1 4000	GEOOC/ DOE	Newberry Crater, OR	08/00/85 10/00/85	recent volcanics	HQ 3545	\$350 \$88/ft.
GEO N-2	GEOOC	Newberry Crater OR	1986	recent volcanics	proprietary	
GEO N-3 4000	GEOOC/ DOE	Newberry Crater OR	1986	recent volcanics	HQ?	\$290 \$72/ft.
VC-1 2809	Los Alms. Nat. Lab.	Valles Caldera, NM	09/01/84 09/03/84	recent volcanics	HQ/NQ 2800	\$239 \$85/ft.
VC-2a 1731	Los Alms. Nat. Lab.	Valles Caldera NM	1985/86	altered volcanics	HQ?	\$182 \$105/ft.

Figure-21. Total project costs as a function of depth.

The question of whether core-drilling is the proper choice, rather than rotary-drilling, in young, volcanic terranes has neither been directly answered nor addressed. There may not be a satisfactory answer, because under the circumstances, there may be no choice. In addition, and perhaps because of the inherent difficulties, there are few examples of deep, slim-hole rotary-drilling projects in volcanic areas. At Mt. Hood, Oregon a scientific hole drilled by the U. S. Geological Survey and U. S. Department of Energy in 1979, and subsequently deepened in 1980 to 4000-ft, is estimated to have cost \$1,500,000 (\$375/ft). This was a production well (six to seven inch diameter hole), and the cost reflects the scope of the project. Several other wells were drilled on the flanks of Mt. Hood, but cost and technical data were not immediately available. Bloomquist and others (1985) estimate that rotary drilling costs in the Cascades will range from \$115/ft, for a 2000-ft slim-hole to \$83/ft for a 6000-ft test-well. On the basis of data available, a core-hole drilled to 2000-ft should cost \$60 to \$75/ft.

CONCLUSIONS

1. Core-drilling has been used as an exploration tool for geothermal resources in volcanic terrane for at least 50-years.
2. The recent, apparent popularity of using core-drilling rigs in what had been an area monopolized by rotary-mud rigs results from several factors:
 - Commercial or Industrial interest in volcanic areas for geothermal electric power potential
 - A National program for investigating the continental crust using deep drilling and coring, especially in "thermal regimes"
 - Recognition that, although rotary-mud drilling may be feasible, it is difficult and often impossible to successfully and economically complete a hole in hard, fractured, volcanic-rock formations
3. In the cases studied, core-drilling proceeded relatively smoothly throughout the length of the borehole. Significant problems were encountered while completing the upper parts of holes in preparation for installation of blow-out prevention equipment. The major problem was using a coring rig as a rotary rig. Six other "top-hole" completion methods are described.
4. Penetration-rates and advance-rates during coring operations are sensitive to lithologic differences and bit-changes. In hard rock, there is little difference between core-drilling and rotary-drilling advance rates.

5. In highly-fractured rocks, core-drilling proceeded smoothly through zones of lost-circulation with recovery rates of 50 to 100-percent. Rotary drilling is generally not practiced in zones of extreme lost circulation because drill chips are not recovered and the risk of sticking drill-rod in the hole is very high.
6. Average costs for core-drilling, on a per-foot basis, range from approximately \$45 to \$105/ft. Costs are shown to increase with depth, amount of specialized equipment required and degree of borehole science practiced during drilling. The cost of actual core-drilling operations range from 40 to 60-percent of total project cost.
7. Cost-reductions may be realized if recommended "top-hole" completion methods are used, and if logging core-holes during drilling is curtailed.

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ADDITIONAL SOURCES OF DATA

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APPENDIX

1. Geothermal Wells drilled under U.S. DOE Industry-Coupled Program
Industry-coupled drilling program well summary
Year-drilled vs. cost per-foot
Total Depth vs. Total cost
2. Exploration Wells drilled at Medicine Lake, California
(data courtesy of J. Beall, Geysers Geothermal Co. and included unabridged)
Medicine Lake wells drilled in 1983 & 1984
Medicine Lake wells: depth vs. days
Medicine Lake wells: depth vs. cost
3. Notes on the lithology of core-hole KL-1, Kirman Lake, California

DEPARTMENT OF ENERGY

INDUSTRY-COUPLED DRILLING PROGRAM WELL SUMMARY

No.	WELL DESIGNATION	COMPL. DATE	TOTAL DEPTH (ft)	TOTAL COST (\$ X 1000)
1	CFSU No. 42-7	3/78	7,750	2,061
2	CFSU No. 31-33	7/78	5,200	1,263
3	CFSU No. 14-29	7/79	2,620	1,063
4	KGRA No. 52-21	5/78	7,515	1,000
5	Campbell, E-2	3/79	8,060	1,300
6	Desert Peak, B-23-1	5/79	5,641	1,400
7	Debraga No. 2	5/79	6,946	621
8	Dixie Fed. No. 45-14	7/79	9,012	1,400
9	Dixie Fed. No. 66-21	9/79	9,780	1,700
10	Tuscarora No. 66-5	4/80	5,430	2,000
11	Beowawe No. 85-18	5/80	5,927	1,000
12	USA No. 11-36	6/80	8,565	1,000
13	USL No. 44x-10	5/81	7,965	1,300

COST
PER
FOOT
— \$ X 100 —

MEDICINE LAKE WELLS DRILLED IN 1983 & 1984

Legend

- ▨ RIG
- ▨ LABOR & DIST
- ▨ BOPS
- ▨ WATER HAULING
- ▨ DEV TOOLS
- ▨ CORING FT/DRILL-DAY
- ▨ CORING FT/LOCAT-DAY

MEDICINE LAKE WELLS: DEPTH VS DAYS

MEDICINE LAKE WELLS: DEPTH VS COST

NOTES ON THE LITHOLOGY OF CORE-HOLE KL-1, KIRMAN LAKE, CA

Kirman Lake hole: Samples taken at 488, 2290, 2303, and 2323 feet below the surface (courtesy of U.S. Navy Geothermal Utilization Group, China Lake, CA) are nearly identical on both a megascopic and microscopic scale.

Hand sample: Andesite porphyry consisting of medium-grained plagioclase and pyroxene (augite ?) phenocrysts in a matrix of fine-grained plagioclase and pyroxene. No visible quartz, some indication of magnetite. Color is light grey to light green on cut (core) surface, darker green and spotted-white on broken surface. Plagioclase phenocrysts, euhedral and lathe-like, vary in size from 2 to 5-mm, some as large as 7-mm. Pyroxene phenocrysts vary in shape from euhedral squares to anhedral masses from 1 to 3-mm. Larger masses appear to enclose some plagioclase lathes. Naturally fractured surfaces, occurring in the 2300 to 2325-ft interval, cut core at angle of 46-60 degrees (from horizontal axis). Fracture-filled with white, non-carbonate material, may be clay or talc. Naturally fractured surface at 2303-ft contains red-colored mineral in addition to white mineral described above. Slickensides are also evident on this surface.

Thin section: Phenocrysts: The large euhedral plagioclase phenocrysts are andesine showing extensive Carlsbad twinning. Sericite or related hydrothermal alteration evident on some exterior edges, and in planes both parallel to and orthogonal to twin-

planes. These crystals account for 70-percent of the total number of phenocrysts.

Smaller and less abundant pyroxene crystals, probably augite, account for about 25-percent of the phenocrysts. They are distinguished by relatively high relief, lack of parallel-extinction and petrogenic association. Parts of most crystals have been altered to clay.

Matrix: The fine-grained part of this rock is 80 to 90-percent lathes of plagioclase (andesine), many highly altered. Magnetite phenocrysts are next in abundance (5 to 10-percent). Pyroxene and carbonate material is rare (less than 5-percent).

COMPARATIVE ANALYSIS OF CORE-DRILLING AND ROTARY-DRILLING IN VOLCANIC TERRANE

Work performed under Contract No. DE-AP03-86SF16609

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