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Scientific Drilling

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SCIENTIFIC DRILLING IN HYDROTHERMAL TERRAINS; THE VC-2B PROJECT

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ABSTRACT

The extraction of scientific data from deep hydrothermal systems is difficult due to limitations in drilling and logging technology. Large drilling rigs such as that used in the Salton Sea Scientific Drilling Program (SSSDP) produce large-diameter holes that allow use of insulated logging tools but core extraction is expensive. Alternately, diamond-core drilling can produce nearly complete core recovery at a reasonable cost but limitations in slim-hole logging technology preclude some downhole measurements. Diamond coring was chosen for the VC-2B project, Valles Caldera, New Mexico, due to a need for top-to-bottom core traversing an entire hydrothermal system. The hole was completed to a depth of 1.76 km with 99.2% core recovery at a cost of 1.61 million dollars. High resolution temperature logs indicated numerous aquifers and a bottom-hole temperature of 295°C. It is estimated that a similar 3-km deep hole would cost three million dollars.

The VC-2B project illustrated a need for the development of coring and logging technology. This need could be met through a developmental effort involving all scientific drilling programs.

I. INTRODUCTION

Scientific drilling programs, and especially those in thermal regimes, present engineering challenges that can influence a program's scientific return. Thus it is important that geoscientists contemplating drilling programs be aware of the engineering constraints and any options that exist. This point is emphasized by the drilling activity itself due to its cost.

Two decidedly different drilling technologies have supported scientific activities. The first technology utilizes the "rotary" drilling machinery that is common to the hydrocarbon production industry. This machinery is large and it is the least expensive way to make large-diameter, deep holes. Unfortunately, when this equipment is used to take core, costs mount since the entire drill string must be removed from the hole after each core run. Thus the hole evaluations are often dependent on a suite of downhole logs. These logs are derived from service industries supporting hydrocarbon production and often are not calibrated for application to non-sedimentary formations.

The second drilling technology evolved in the mining industry and it is commonly called called "diamond-core drilling." The prime purpose of this technology is to take core and this is accomplished by removing the core from the hole by means of a wireline without removing the drill string. Another advantage is that the rigs are relatively small so the mobilization costs are relatively low and the environmental impact to a drilling area is minimized. Disadvantages are that the produced holes are too small for many logging tools, particularly if the hole is hot, and available rigs and drill strings are of limited strength. This latter point can be important in volcanic formations that often present difficult drilling conditions.

The United States Continental Scientific Drilling Program (CSDP) has used technologies from both the diamond coring and rotary drilling industries. The Salton Sea Scientific Drilling Project (SSSDP) used a large rotary rig to drill and spot core a hole to 3.2 km at which point the temperature exceeded 350°C (Elders and Sass, 1988). Likewise, the Cajon Pass Drilling Project rotary drilled its first phase to 2.12 km (Zoback, et al., 1988), has advanced the hole to 3.5 km in a second phase and drilling is planned to 5.0 km.

A contrasting example is provided by a series of eight scientific holes that have been drilled in geothermal regions of the Valles Caldera, New Mexico, and Long Valley Caldera, California, (Eichelberger, et al., 1984; Eichelberger, et al., 1985; Goff, et al., 1987; Wollenberg, et al., 1987; Goff and Gardner, 1988; Gardner and Hulen, 1988-1989). All holes utilized diamond coring technology since top-to-bottom core was the prime scientific need of the projects. The most ambitious hole, the VC-2B hole in the Valles Caldera, bottomed at 1.76 km with a hole diameter of 76 mm. Core recovery exceeded 99% and the bottom hole temperature is 295 degrees centigrade. The only detailed logs run in this project were for temperature and hole deviation. An extensive logging operation was part of the scientific plan (Gardner and Hulen, 1988) but could not be implemented due to a lack of slim-hole, high-temperature logging tools. Including site preparation and initial logging operations, the cost of this project was about 1.6 million dollars.

The purpose of this paper is to provide insight into the capabilities and limitations of diamond coring as applied to scientific drilling projects and the discussion will be limited to coring capabilities presently available in the United States. The stated purpose will be accomplished primarily by investigating the VC-2B project although other projects, especially work within the Ocean Drilling Program, will be noted as the need arises. Readers interested in similar studies of rotary-drilled holes are directed to papers by Elders and Sass, 1988, and Wickland, 1988. Some discussion of foreign drilling strategies is given by Elders, 1989.

No attempt will be made to compare diamond coring and rotary drilling other than to note that these technologies possess distinctly different merits. However, a scientist contemplating a drilling program must be aware of these differences and take into account that while both top-to-bottom coring and detailed downhole measurements can be accomplished, budgetary constraints can make them mutually exclusive. Hopefully this situation can be rectified in the future.

II. HOLE VC-2B

The VC-2B Project is one in a series of scientific holes put forth by Principal Investigators at Los Alamos National Laboratory and the University of Utah Research Institute (Goff and Nielson, 1986). The purposes of VC-2B and its companion hole VC-2A (Hulen, et al., 1988; Goff, et al., 1987) was to study from top-to-bottom an active hydrothermal system where minerals are being deposited. Logs cannot supply the requisite information so both wells were diamond cored. Pristine fluid samples were also desired, so the wells were designed to allow for limited flow of hot fluids and steam. Both holes were funded by the Department of Energy/Basic

Energy Sciences/Geoscience and the field operations were conducted by its Geoscience Research Drilling Office at Sandia National Laboratories.

The planning phase of any project is an iterative process in which a best solution is sought taking all factors into account. While briefly stated here, the pre-drilling interactions between the Principal Investigators, the Drilling Office, and the drilling industry required a period of two years to complete. In addition to the scientific requirements given above, factors that entered into the design were cost, availability of drilling equipment, safety, and permit constraints. The decision was complicated by unknown drilling conditions and uncertainties in the target depth.

The VC-2B project was intended to reach Precambrian rocks at an estimated depth of 1.5 to 2.0 km. While this depth is well within the capability of diamond core drilling, high temperatures and unconsolidated formations could cause difficulties with the light drill strings commonly used in mining applications. In a response to a request for drilling quotations, Tonto Drilling Services of Salt Lake City proposed to core the hole with a heavy-duty drill string using a Universal 5000 drill of Australian design and manufacture. This proposal was accepted.

A prime factor influencing the design of VC-2B was the permitting constraint that the surface casing string be cemented at 10% of the final hole depth. Since remedial action to a short surface casing is expensive, one commonly sets this string deeper than is thought necessary. Then the hole can be extended if scientifically justifiable. For design purposes, the depth of VC-2B was chosen to be 2.13 km (7000 feet). The final depth of VC-2B was determined by the scientific goals.

A photograph of the VC-2B operation is given in Figure 1 and a schematic of the hole as it was completed is illustrated in Figure 2. The drilling stages of VC-2B are given in Table 1. The "planned hole" and drilling schedule differed only slightly from that actually achieved and most changes were made for scientific reasons. This success is attributed to the project being relatively free from drilling problems. Such problems were averted by using strong drilling rods, a drilling rig that allowed precise control of the rods and an experienced drilling team.

Some drilling delays were caused by difficulties with the fluids circulated to remove cuttings and to lubricate the interface between the rods and the formation. In diamond coring operations, these "muds" consist of polymeric materials and clays, usually bentonite or sepiolite. This system usually works well at low temperatures. However, at temperatures above about 250 degrees centigrade, the polymers break down and the clays can thicken. Several high temperature polymers were employed, but none worked well. Domestic polymers lost both viscosity and lubricity and one imported polymer lost lubricity. The manifestation of the lubricity was that the rods could be easily turned at low speed, but rod chatter and torque increased significantly at normal drilling speeds. Low speed operation degraded the efficiency of the bit so that penetration rates decreased in the latter part of the effort. Ultimately, however, it was found that massive amounts of a drilling lubricant mitigated the problem. A plot of depth versus time is given in Figure 3.

Lost circulation is a phenomenon where drilling fluids are pumped downhole, and instead of circulating to the drill bit and back to the surface, the material flows into the formation. While diamond core drilling can proceed without circulation, it wastes expensive drilling fluids. Additionally, environmental problems can arise it circulation is not maintained and the loss of fluid pressure in the hole can lead to blow-out conditions. It also causes difficulties when permit constraints require that cement be circulated through the entire casing-formation annulus to isolate subterranean aquifers. Remedial action for lost circulation involves pumping granular material such as walnut shells, ground-up battery casings, refractory materials and cement into the formation fractures. Since the rod-to-formation annulus is small in diamond core drilling, the size of the pumpable grains is limited. Thus lost circulation problems can be hard to mitigate.

A major lost-circulation zone was intersected by the VC-2B hole at about 286 m (940 feet). Treatment of this zone with battery casings, mica and walnut shells was partly successful. The problem was not vigorously attacked, however, since the casing to 215 m (707 feet) provided for control of the well, and the use of lost circulation materials in the mud system increased the probability of sticking the rods. Various other loss zones were intersected throughout the operation and major zones can be seen apparent on the temperature log, Figure 4. While these zones did cause a loss of some fluid, about 50% circulation was maintained once casing was set to 638 m (2092 feet).

The cementing materials were high temperature, retarded cements with lightening agents so that the downhole pressures were insufficient to fracture the formation. All cementing operations were performed by a service contractor. Cement was lost into the fracture zone at 286 m when the CHD-134 rods were set for casing, see Figure 2. The top of this cement was tagged by pumping cool water down the outside of the CHD-134 rods and then noting the depth of cooling inside of the rods by use of a temperature log. Only a small amount of cement was used when the CHD-101 rods were set as casing since it was feared that cement would seal small fluid entry points thereby precluding sampling of the aquifer fluids.

The mud circulation system was about an order of magnitude smaller than that commonly used in rotary drilling operations. It consisted of a primary 4.4 liter/sec (70 gpm) pump, a back-up pump and a 3.8 cubic meter (1000 gal) steel tank. This system was configured so that it could be operated remotely if an accident precluded access to the rig floor. About 560 cubic meters (3.4 acre feet) of water was pumped from a nearby stream and about 80% of it was used in actual drilling. A 38 cubic meter (10,000 gal) storage tank gravity fed the two 0.7 cubic meter (180 gal) mixing tanks. An emergency 230 cubic meter (60,000 gal) lined pond was maintained half full capacity with fresh water. If an uncontrolled flow occurred, this water could be used to cool the well, or the pond could be drained quickly and the well affluent directed into it. Typical mud flow rates were 1.6 liters/sec (25 gpm) while drilling and 4.4 liters/sec (70 gpm) while pumping down a new core tube. Return mud temperatures were less than 10 degrees centigrade above the input temperature. Temperature and flow rate data were recorded to a computer-based data acquisition system for use in heat-flow calculations. A lubricator was part of the core retrieval system. Thus pressure could be maintained on the hole, except when a new rod was added to the drill string. Since some fluid could always be maintained in the hole, pressurization was not a problem.

Blow-out-prevention equipment was rented from an oil field service company. It consisted of a pipe ram, a blind ram, and an annular preventer. This equipment is heavy and bulky, at least by diamond coring standards. In the VC-2A project, it was placed in a cellar below the rig. This cellar trapped poisonous hydrogen sulfide gas. To avoid this problem, prevention equipment used in VC-2B was mounted above ground and the rig was elevated to accommodate it. Occasionally hydrogen sulfide did flow from the well. Seven gas monitors were placed in the vicinity of the operation which activated appropriate alarm systems. Gas concentrations were also recorded along with the heat-flow information. All project personnel were trained in first aid, CPR, the use of Scott air packs and emergency procedures. Local authorities were informed of the activities and the pilots of the local helicopter evacuation team were given an on-site briefing. Procedures for access to dangerous areas were part of the project management plan which functioned smoothly throughout the 100 day effort.

Virtually all core was recovered (99.2%). The lost core was primarily from the upper 50 m of the hole that penetrated land slide material. Initially the core was taken in 5 foot (1.52 m) sections in order to facilitate handling the 134 mm-diameter core tube in the lubricator. A 10 foot (3.05 m) tube was installed when 101 mm-diameter coring was initiated and at 1451 m the tube was lengthened to 20 feet (6.1 m). The longer tubes improved the penetration rate as can be seen from Figure 2. However, the longer tubes are fragile and cumbersome and best used only after core recovery times become significant.

Temperature logs were obtained using a four-terminal platinum resistance thermometer configured into a slim tool. Power and signals were transmitted on a seven conductor, 6.4 mm diameter logging cable (three conductors were not used). This cable and the associated modified cable head have a temperature rating of about 310 degrees centigrade. Temperature measurements were recorded to disk at 15 cm intervals. Plots of logs on an expanded scale indicate many flow zones that are undiscernible on the scale of Figure 4. Such data were used in the VC-2A project to identify zones for fluid testing (Goff, et al., 1987).

Surveys to document deviation of the hole were a permit requirement and were made with an insulated single-shot tool at about 500 foot intervals. The maximum deviation of the hole from vertical was 1.2 degrees. A slim hole televiewer (150°C temperature rating) was used below the 215 m casing into the lost circulation zone at 285 m where a slough zone forced termination of the run. While the televiewer log was not a primary scientific objective its use demonstrated a capability for orienting the core as well as imaging the well bore. Its use is recommended in future operations.

The total cost of the VC-2B project was 1.61 million dollars. This cost encompassed all field activities conducted during the drilling phase of the project and it includes taxes and Sandia administrative costs. It does not include scientific work other than that mentioned in this paper or support for scientific and Drilling Office personnel associated with the project. Future operations should benefit from this work in that some equipment was amortized in the VC-2B project and the well design is universal. A breakout of various costs is given in Table 2. (Table 2 costs include taxes, but are not cumbered by the Sandia administrative costs.) Costs directly associated with drilling VC-2B as a function of hole depth are plotted in Figure 5.

III. CONCLUSIONS

The coring phase of the VC-2B project was a success in that most scientific objectives were achieved on schedule and within the pre-drilling budget. Objectives that were not obtained resulted from deficiencies in the existing high-temperature, slim-hole logging technology. The drilling technology applied to VC-2B is readily transferred to other programs in geothermal or hydrocarbon formations. This technology is adequate for holes up to 3 km in depth. The cost of a 3 km scientific hole in an environment similar to that of VC-2B is estimated to be 3 million dollars, a figure that includes development of some new technology but that does not include taxes and administrative costs.

The VC-2B Project pointed out a need for improvement in the control of fluids used in diamond coring systems. Specifically better high temperature drilling fluids, lost circulation materials and cementing operations must be developed. We note that similar problems confront the rotary drilling industry. However, differences arise due to the small rod-to-formation annuli associated with diamond coring.

One cannot fail to note the unfortunate situation that forces investigators to choose between excellent core recovery at a reasonable cost and the ability to conduct experiments downhole. Advances in coring and/or logging technology are needed to rectify this situation. Budgetary constraints imposed upon the CSDP and the depressed state of domestic extractive industries mean that new techniques are not likely to be available for some time. However, if joint efforts between the CSDP and other programs such as the Ocean Drilling Program (ODP) could be instituted, better technology could be available in the not-too-distant future.

In this vein, we note that the Downhole Measurements Panel of the ODP has recommended that deficiencies in slim-hole, high-temperature logging tools be the subject of a workshop involving all scientific drilling programs (Worthington, 1989). Furthermore, the ODP is installing a diamond-coring system aboard the JOIDES RESOLUTION that uses equipment from the VC-2B project (Storms, 1988; Harding, et al., 1989). This system involved cooperative work between the Drilling Office and ODP engineers at Texas A and M University, and most recently this team has used the ODP system to take core in the Magma Energy Exploratory Hole, Long Valley, California. So far these inter-program contacts are informal. It would seem that they should be formalized and expanded.

IV. ACKNOWLEDGEMENTS

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Table 1. Drilling Operations, VC-2B Corehole.

Drilling Day	Drilling Operation
0 to 5	Mobilize rig to site, set up and spud hole using CHD-134 (134 mm) core barrel.
6 to 11	Core to 173 feet, ream hole to 16.5 inches, set and cement 10.8 inch casing, install and test BOP, and hang 6.6 inch casing to reduce rod whip.
12 to 24	Core CHD-134 to 707 feet, ream hole to 9.9 inches, set and cement 6.6 inch casing, install and test BOP.
25 to 43	Core CHD-134 to 2092 feet, cement the CHD-134 rods in place as casing (no cement returns). The top of the rods was set 12 feet below the surface so that they could expand freely during flow tests.
43 to 88	Core CHD-101 (101 mm) to 5567 feet, cement the bottom 370 feet of the 101 rods to the formation and hang in tension from the surface to counteract thermal expansion effects during flow tests.
89 to 94	Core NQ (76 mm) to total depth at 5780 feet, remove rods leaving open hole at the bottom of the well.
95 to 100	Demobilization and clean up.

Table 2. Project Costs

1.	Rig rental and rig materials	$471 thousands
2.	Labor and per diem, drilling crew	233
3.	Site preparation and other construction	154
4.	Drilling rods and casing	152
5.	Drilling fluid additives	141
6.	Mobilization and demobilization (a)	134
7.	Miscellaneous including logging services	61
8.	Cementing services	55
9.	Bits and reamers	36
10.	Hydrogen sulfide safety	10
	TOTAL	$1,447 (b),(c)

(a) Includes shipping rig from Australia.
(b) Does not include 11% Sandia administrative costs.
(c) Subject to Department of Energy audit.

FIGURE CAPTIONS

Figure 1. Drilling operations for Continental Scientific Drilling Project, VC-2B. The hole is located in the southwest moat of the Valles Caldera, New Mexico. The drilling project obtained top-to-bottom core penetrating an entire hydrothermal system.

Figure 2. Schematic drawing of the completed VC-2B corehole. Details of the hole are listed in Table 1. A lost-circulation zone above 940 feet precluded cement returns to the surface where the CHD-134 rods were set in place. These rods were set below surface level to allow for thermal expansion if the well flowed.

Figure 3. Hole depth as a function of drilling days for the VC-2B operations. The drilling rate initially increased as the crew became more familiar with the operation and when longer core tubes were introduced. The rate decreased as the hole deepened due to a longer time spent retrieving core, an increase in rock toughness and a breakdown of the polymeric drilling fluids at high temperature.

Figure 4. Temperature log of the VC-2B corehole. The preliminary lithologic data were obtained from an examination of the core (Hulen and Gardner, 1989). The perturbations in the log are due to an influx of relatively cool drilling fluids into permeable zones. They mark candidate zones for fluid sampling.

Figure 5. Hole cost as a function of drilling day. The step discontinuities represent cement and casing costs. The costs do not include either Items 7 and 10 of Table 2. or the Sandia administrative costs.


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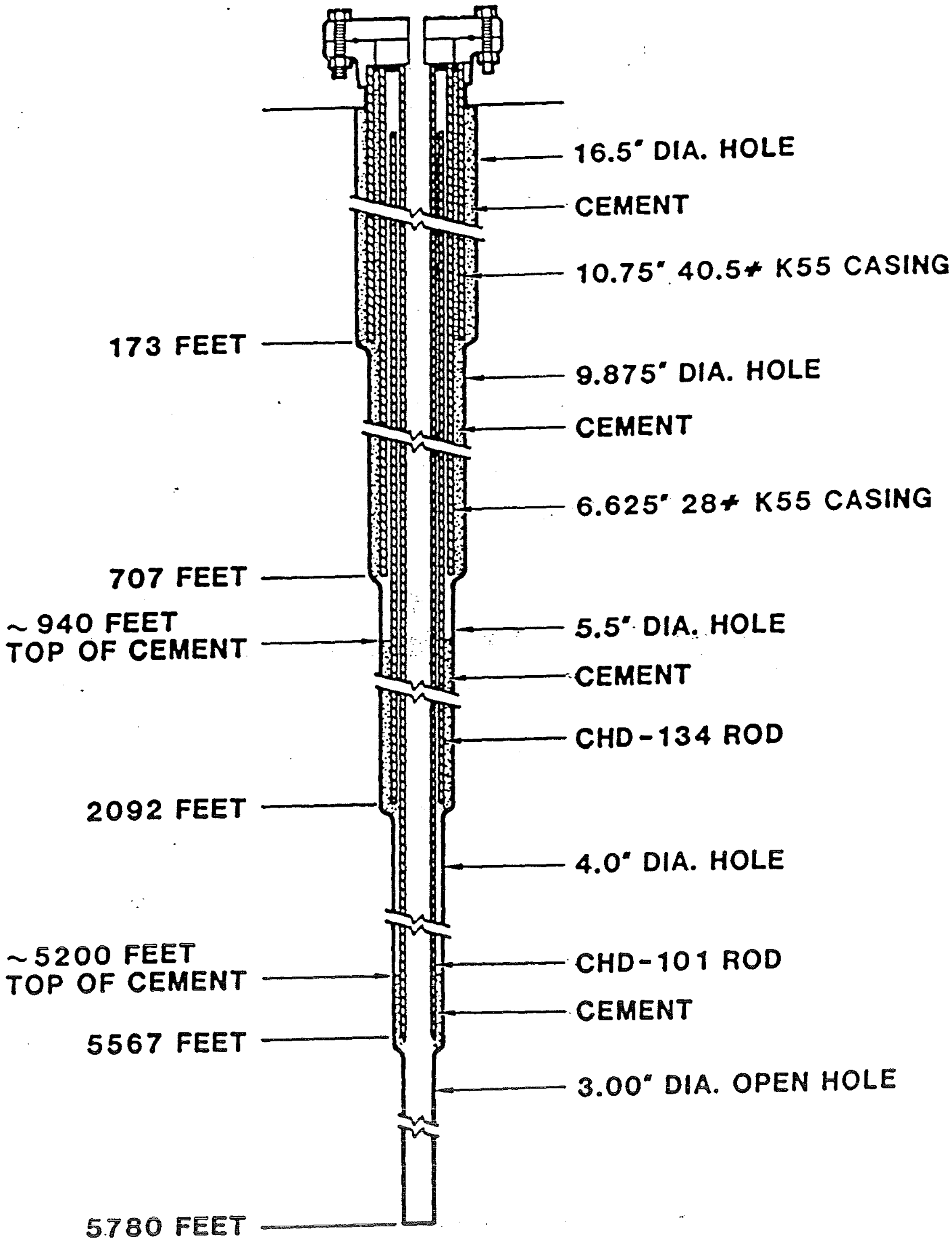
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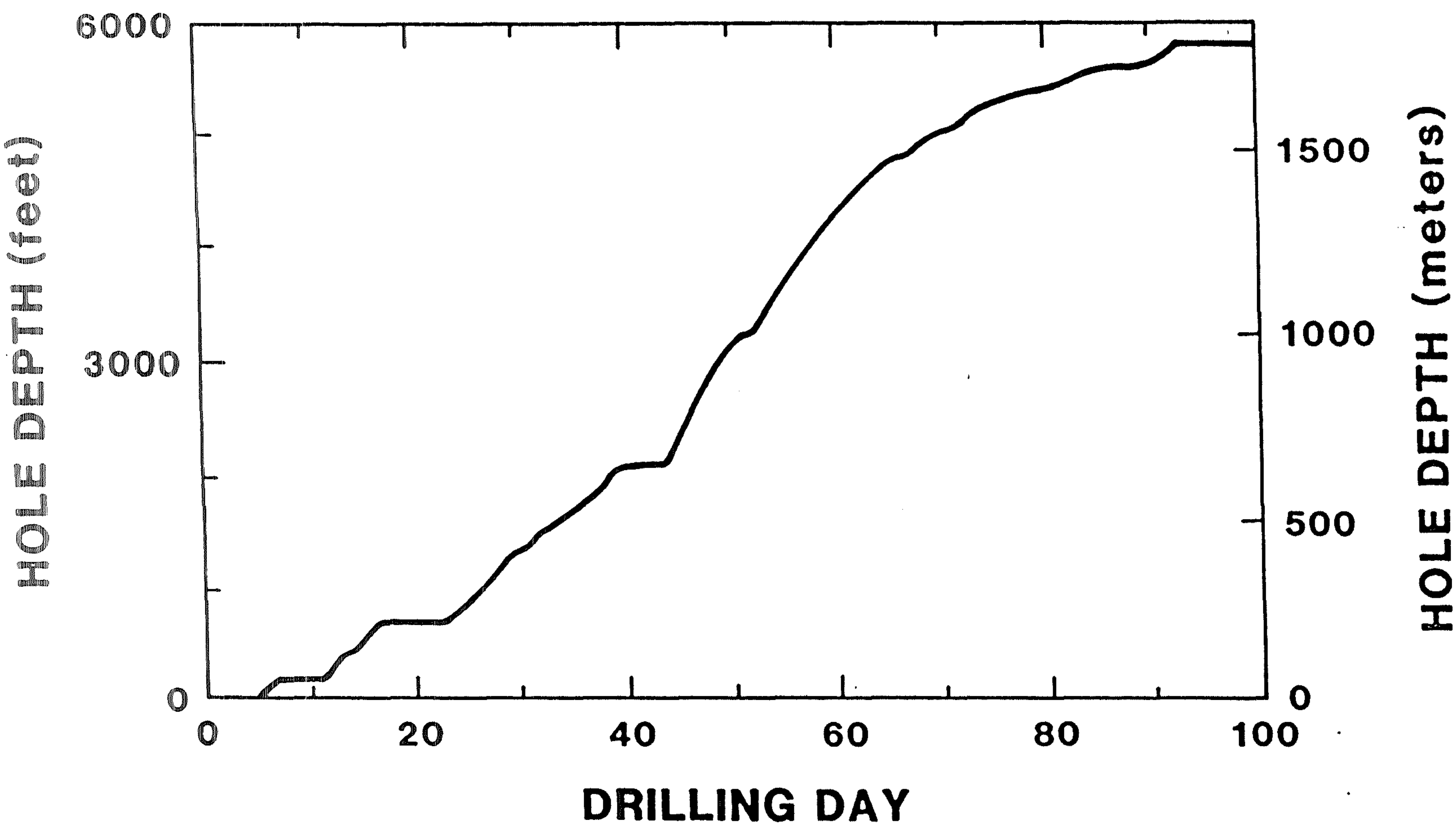
10.75" 40.5# K55 CASING
173 FEET
9.875" DIA. HOLE
CEMENT
6.625" 28# K55 CASING
707 FEET
~940 FEET TOP OF CEMENT
5.5" DIA. HOLE
CEMENT
CHD-134 ROD
2092 FEET
4.0" DIA. HOLE
~5200 FEET TOP OF CEMENT
CHD-101 ROD
CEMENT
5567 FEET
3.00" DIA. OPEN HOLE
5780 FEET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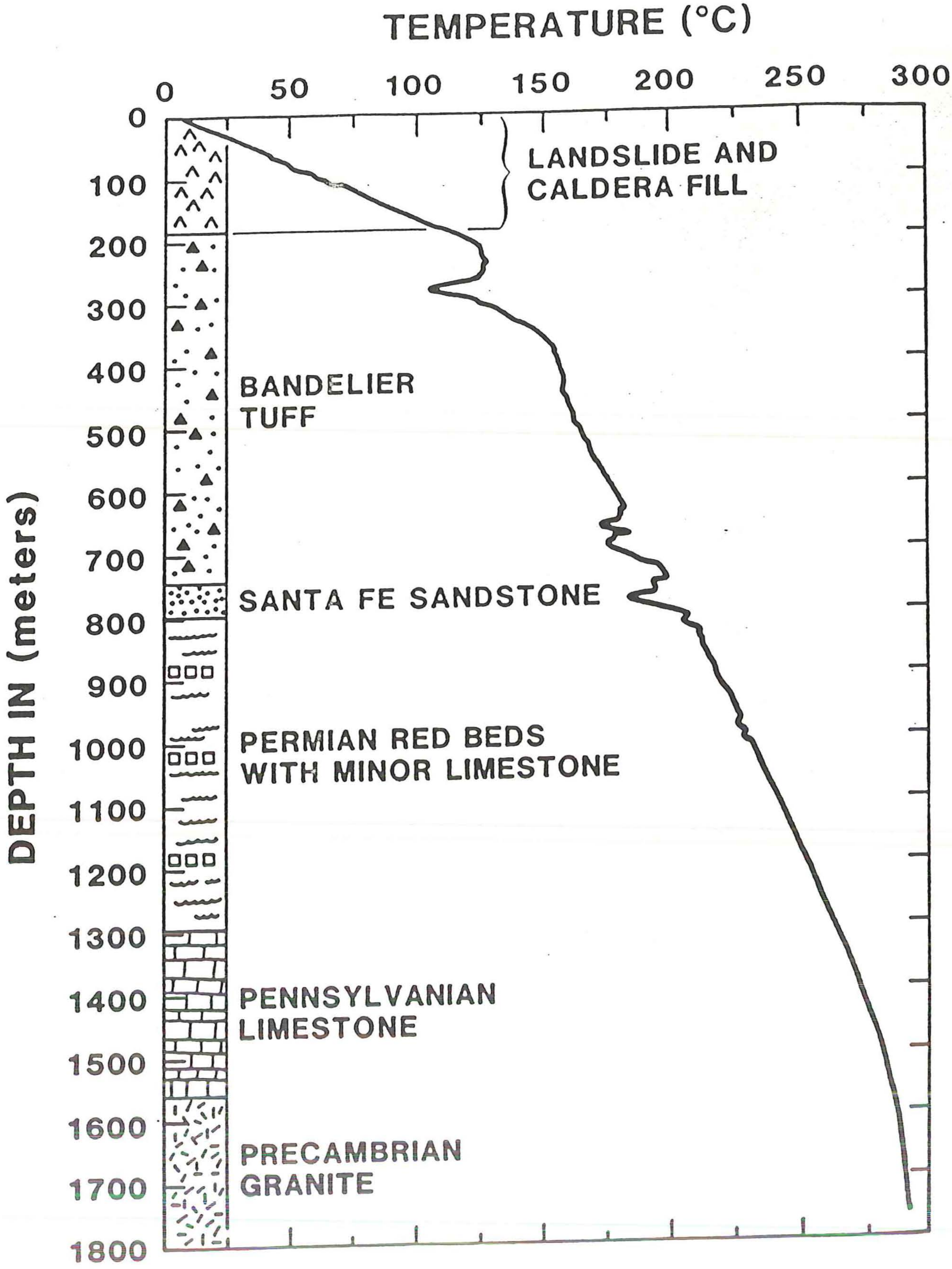
DRILLING DAY



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1200
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1700
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LANDSLIDE AND CALDERA FILL
BANDELIER TUFF
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PERMIAN RED BEDS WITH MINOR LIMESTONE
PENNSYLVANIAN LIMESTONE
PRECAMBRIAN GRANITE

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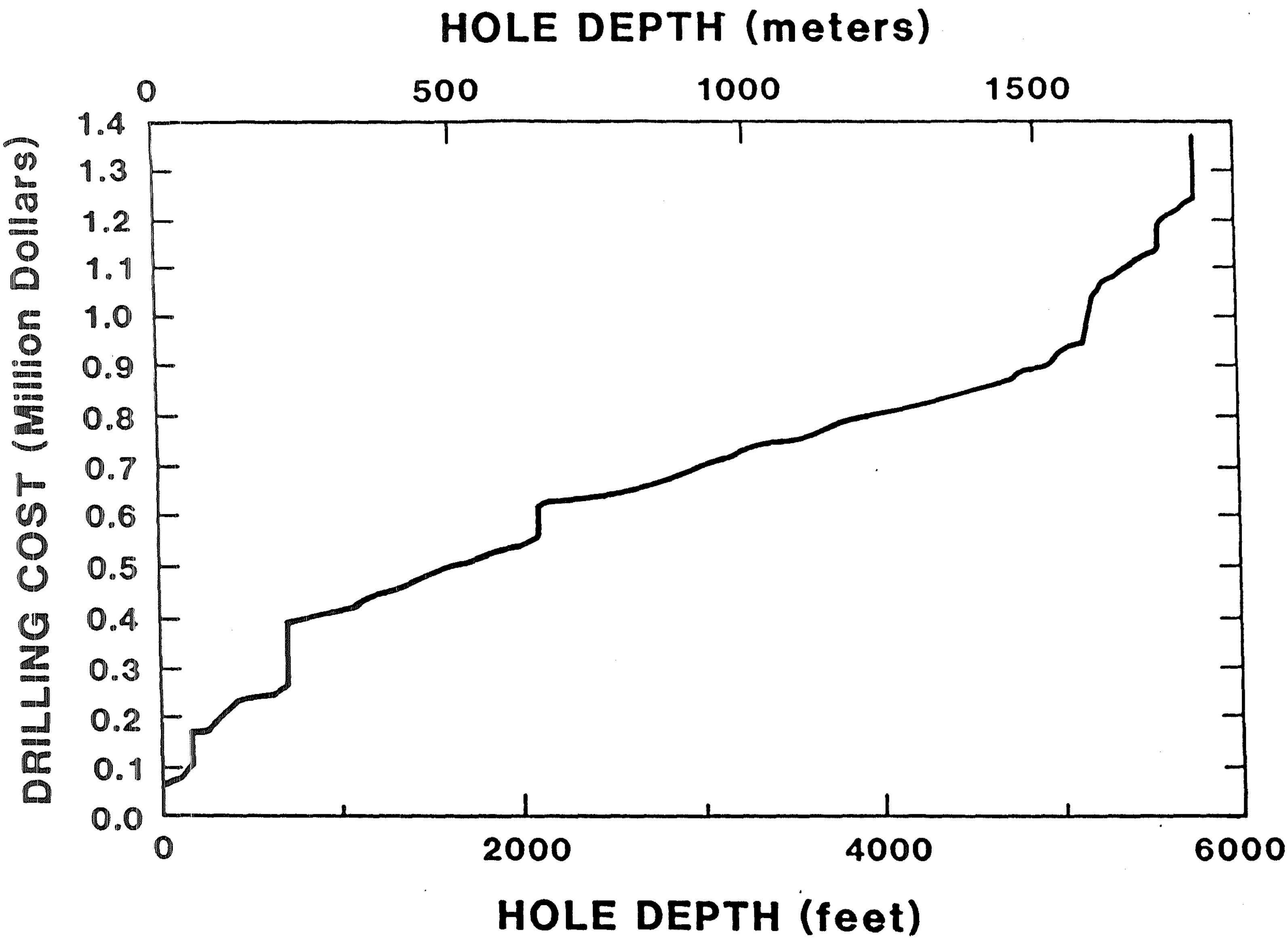
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1.3
1.2
1.1
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0.6
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0.4
0.3
0.2
0.1
0.0
DRILLING COST (Million Dollars)
0
2000
4000
6000
HOLE DEPTH (feet)