THE HAWAIIAN SCIENTIFIC OBSERVATION HOLE (SOH) PROGRAM COSTS AND HISTORY OF A SUCCESSFUL SLIM HOLE DRILLING PROGRAM

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ABSTRACT

To assess the geothermal potential of the KERZ, a fence of four holes, three of which were drilled, were sited along the long axis of the KERZ within existing Geothermal Resource Subzones. These holes were drilled by a Universal 5000 core/rotary drilling rig, and were located to provide stepout drill coverage between existing and planned geothermal production wells, and to pair the SOHs with production wells to test for permeability across the rift zone.

Successful drilling techniques and casing procedures were devised as the rock section became known and its characteristics noted. Above 270°F a complex stearate was added to the drilling fluids to maintain lubricity. Above 330°F a mixture of soda ash, high temperature polymer, complex stearate, and sepiolite virtually eliminated the high torque and vibration problems frequently associated with high temperature drilling.

The core and other data from the SOHs have proven to be extremely valuable for both active developers in siting production wells, and in the understanding of the subsurface geologic conditions. The first hole drilled, SOH-4 provided thermal and permeability conditions along the eastern portion of the True/Mid-Pacific Geothermal Venture's lease, and was instrumental in the proposed location of True's #2 site. SOH-4 was drilled to a total depth of 6,562 feet in 151 days at a direct drilling and testing cost of $1,466,848, and recorded a temperature of 583°F at a depth of 6,400 feet. The second hole, SOH-1, effectively defined the northern extent of the Puna Geothermal Venture's (PGV) HGP-A/PGV reservoir, doubled the proven reservoir size, and provided sufficient data to the lending institution for continued project funding. SOH-1 was drilled on a PGV lease to a total depth of 5,526 feet in 217 days, which included 6-1/4 days standby waiting on administrative permits, at a direct drilling and testing cost of $1,643,544, and recorded a bottom hole temperature of 403°F. The third hole, SOH-2, also was drilled on a PGV lease to a total depth of 6,802 feet in 126 days at a direct drilling and testing cost of $1,106,684, recorded a bottom hole temperature of 662°F, and may have intersected a potential reservoir at a depth of approximately 4,900 feet.

INTRODUCTION

The Hawaii State legislature, in 1988, funded a deep, slim-hole, diamond core drilling program, known as the Scientific Observation Hole (SOH) program, "to stimulate geothermal development and confirm the geothermal resources of Hawaii." This program was designed by the Hawaii Natural Energy Institute (HNEI) at the University of Hawaii at Manoa to assess the geothermal resources potential of the Kilauea East Rift Zone (KERZ) on the Big Island of Hawaii. The program is funded by the Hawaii Department of Business, Economic Development, and Tourism, and managed by HNEI.

The Scientific Observation Hole (SOH) program was designed as a multifaceted effort to assess the geothermal resources potential of the Kilauea East Rift Zone (KERZ) on the Big Island of Hawaii, to provide geological data useful in evaluating the commercial development of the KERZ, and to serve as long term monitoring sites for temperature and groundwater pressure conditions along the KERZ. Although much work remains to be done, the SOH program was successful in providing both geothermal developers on the Big Island with vital details of the subsurface geology of the KERZ, and in initiating the geothermal assessment of Hawaii. The SOHs, as well as the State of Hawaii HGP-A well, currently are monitored for pressure, with plans to expand monitoring to another well and to include temperature measurements at all the stations.

The SOH drilling provides the first extensive core ever taken in Hawaii. Continuous core yields invaluable tangible information to geologists and other earth scientists concerning the evolution of the Hawaiian volcanoes in general and the Kilauea East Rift Zone in particular. In addition, analysis of the SOH core provides unique information concerning the evolution of the East Rift Zone through periods of volcanic aggradation, erosion, sedimentation, mass wasting, intrusion, and subsidence to its current state.

The immediate value of the SOH program has been to evaluate the extent of a commercially viable geothermal resource along the East Rift Zone. The SOHs compliment geothermal exploration and production drilling currently underway. Study of core samples aids in understanding the interrelationship of porosity and permeability, primary and secondary minerals, and alteration in a geothermal system. Temperature surveys and geophysical logs provide information on the extent and nature of the system. Detailed descriptive logs, data bases, and the archiving of core for future study provides a powerful long term reference tool for geologists involved in current and future geothermal production drilling operations.

The SOHs now are serving as long term observation sites. From these sites, changes in water level are monitored to determine the effects of natural changes within the KERZ, and of long term commercial geothermal production. In the future, temperature, seismic, and water chemistry data also may be collected.

PROGRAM DESCRIPTION

The SOH program was planned and implemented by HNEI, a division of the School of Ocean and Earth Science and Technology, at the University of Hawaii at Manoa to provide an assessment of the geothermal potential of the KERZ on the Big Island and the Haleakala Southwest Rift Zone (HSRZ) on the island of Maui within existing Geothermal Resource Subzones (GRZ). The SOH program was initially funded to drill six SOHs to a nominal depth of 4,000 feet, four on the Big Island and two on Maui, to "confirm and stimulate the geothermal resources development in Hawaii." Initial attempts to permit the two SOHs on Maui met with such intense local opposition, that the two holes scheduled to be drilled in the HSRZ were withdrawn from further consideration during this phase of the program (Olson et al., 1990). Figure 1 shows the location of the volcanic features, the KERZ, and areas with geothermal potential on Maui and Hawaii (Thomas et al., 83). The location of the SOHs, the GRZs, as well as the production wells drilled by PGV and T/MPGV are shown on Figure 2.

<u>Contractor and Equipment</u>:

Tonto Drilling Services, Inc. of Salt Lake City, Utah won the request for bids for the drilling phase of the Scientific Observation Hole program, and provided an experienced crew with geothermal experience and a Universal 5000 rotary/core drilling rig to undertake the project. The Universal 5000 drilling rig, at the time of the program, was one of only two such units built, and turned out to be uniquely suited for the requirements of the SOH project.

Tonto's Universal 5000 drilling rig is mounted on a 3-axel trailer, is road legal, and weighs approximately 94,600 pounds.

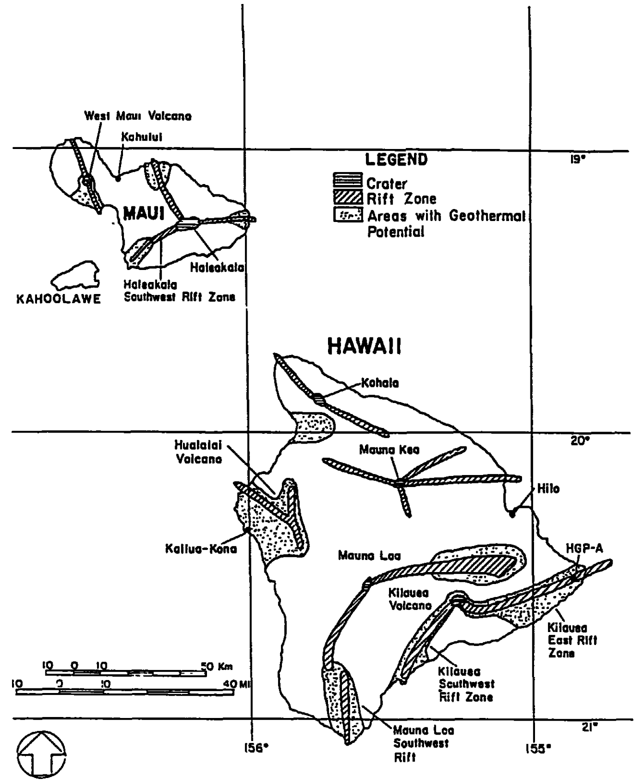

Figure 1. Volcanic features and areas with geothermal potential on Maui and Hawaii.

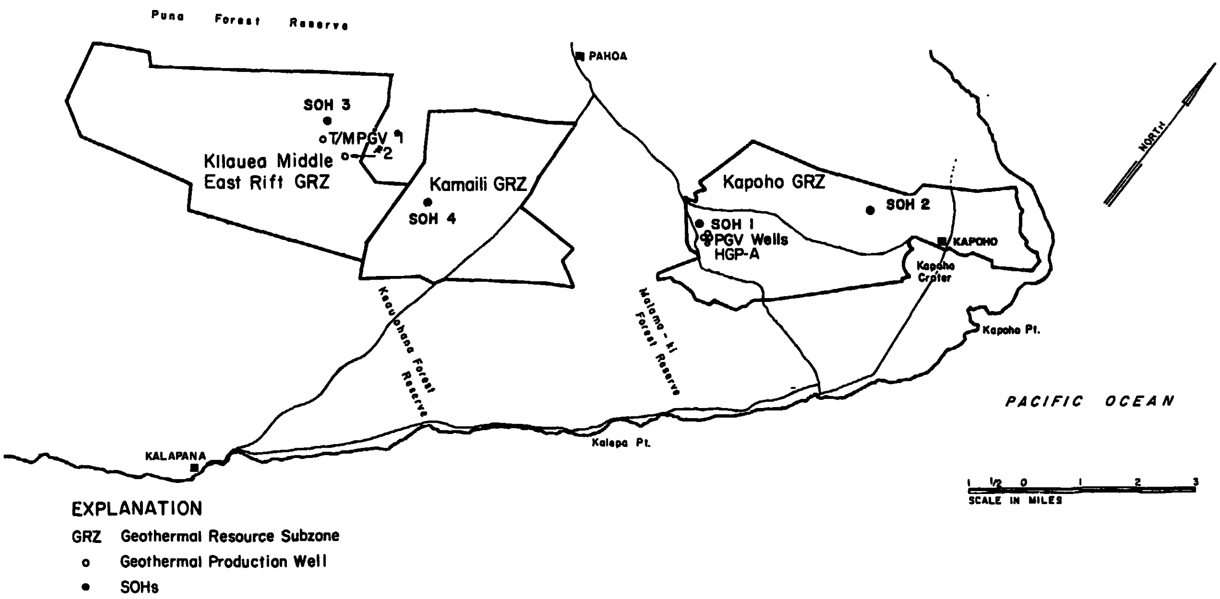

Figure 2. Location of SOHs, production wells, and geothermal resource subzones.

A self-elevating jack-up system permits raising the rig and placing a 10-1/2 foot substructure under the mast. The substructure carries the weight associated with drilling, serves as a working floor, and permits the above ground installation of blow out prevention (BOP) equipment.

Specifications of the Universal 5000 drill rig include:

a. Rotation head hoisting capacity of 100,000 pounds.
b. Main hoist capacity of 88,000 pounds (single line, 1-3/16 inch cable).
c. Rotation head pull down of 30,000 pounds.
d. Rotation head speed variable from 0 to 2,250 RPM.
e. Maximum rotation head output torque of 6,630 foot pounds.
f. Wireline winch with 18,000 feet of 3/8 inch wire rope and a full drum pull to a maximum of 1,500 feet per minute.
g. Hydraulic system consisting of axial and radial piston pumps and motors designed as three independent open loop circuits.
h. A 56 foot mast with a 40 foot rod pull and stacking capacity.
i. Hydraulically operated and self energizing casing and rod slips.

Depth rating of the Universal 5000 depends on the size of drill rods used, drilling conditions and other factors. For NQ drill rods (2-3/4 inch OD), which were used to complete all of the SOHs, the theoretical maximum depth is greater than 17,000 feet. Regular size NQ bits produce a 2-63/64 inch diameter hole. However oversize NQ bits, which opened a 3.040 inch hole, were used on the SOHs.

Core Drilling Program:

The SOH drilling program, as originally permitted, specified core drilling from the surface to total depth in each hole, the installation of a 200 foot section of 13-3/8 inch conductor casing, running 9-5/8 inch surface casing to a depth of 1,000 feet, and 7 inch casing to a depth of 2,000 feet (Deymonaz, 90, 91, and 92). This plan subsequently was modified as drilling and thermal conditions, and rig capabilities in the KERZ became known. To permit the installation of 13-3/8 inch, 9-5/8 inch, and 7 inch casing strings in the upper 2,000 feet of the SOHs, the holes were first core drilled, then opened with rotary bits or hole openers (Olson and Deymonaz, in press). After casing was cemented, core drilling resumed and continued to total depth.

In order to reduce overall drilling costs, coring in the cased portion of SOH-2 was omitted and the upper 1,907 feet was rotary drilled in a single pass. Rotary drilling was then scheduled to continue until conditions favorable to efficient core drilling were encountered. Attempts at core drilling involved the installation of a retrievable casing sleeve, which permitted the resumption of rotary drilling.

A casing sleeve is necessary to prevent excessive lateral movement of the drill rods. Unlike heavy rotary drill pipe, rods used in core drilling are relatively light with thin walls. Rod failure will occur rapidly if the rods are subjected to high speed rotation without proper lateral support.

Based on information gained in drilling SOH-1 and SOH-4, it was determined that core drilling was efficient and cost effective in most subaerial volcanic sections and in submarine volcanic and intrusive rock which have undergone extensive thermal alteration and secondary mineralization.

However, submarine volcanic rock which has not undergone extensive thermal alteration is extremely difficult to core drill in the East Rift Zone. The pervasive fracturing and abrasive nature of the rock dramatically shortens bit life by causing rapid deterioration of the bit face and inner and outer bit gauge, reduced core recovery, hole stability problems, and excessive trip time. Thermal alteration serves to both reduce the abrasiveness and bonds the rock into a cohesive mass which is easily cored with excellent core recovery. The most obvious example of the change in rock character is the increase in bit life from generally less than 30 feet in unaltered submarine volcanic rock to 600 to 1,000 feet in altered intervals.

The subaerial/submarine volcanic boundary is variable and dependent upon the amount of subsidence and/or normal faulting and the sea level at the time of deposition. The occurrence of hyaloclastite and/or carbonate reef material were the determining factors used to identify the top of the submarine volcanic section. At higher elevations the volcanic pile is thicker and hence more subsidence was anticipated. However, the thickness of subaerial volcanic rock at the SOH-4 site was surprising. Table 1 summarizes surface elevations and relative depths below mean sea level to the first occurrence of submarine volcanic rock.

Table 1
SOH Subaerial/Submarine Contact Depths
(Depths in Feet)

Hole	Subaerial Surface Elevation	Subaerial Volcanic Thickness	Contact Depth M.S.L.
SOH-4	1,195	5,554	-4,359
SOH-1	620	2,551	-1,931
SOH-2	270	1,680	-1,410

Bottom hole temperature (BHT) measurements were made on a regular basis while drilling each of the SOHs. In each of the holes, increase in bit life occurred when measured BHTs exceeded 175^{o} - 200^{o}F and a high positive thermal gradient was established. The increase in temperature and change in lithologic character of the rock suggest the presence of a definitive boundary between the permeable section containing relatively cool shallow aquifers, and the relatively impermeable section with thermally altered volcanic rocks, elevated temperatures, and low porosity and permeability.

Downhole Temperature Measurements:

Bottom hole temperature measurements were obtained by lowering a maximum reading thermometer (MRT) in a pressure tight container attached to the inner tube overshot. Failure to enclose the MRT in a pressure tight container results in erratic measurements, erroneously high temperature readings or broken thermometers due to the hydrostatic pressure of the mud column squeezing or breaking the reservoir bulb on the thermometer. When recovering core, the overshot with the enclosed MRT was lowered on a wireline until it latched onto the ten foot long innertube containing the core. On BHT runs, the overshot was left in position for approximately 5 minutes before retrieving the innertube. These readings, which were taken at intervals of approximately 100 to 150 feet, provided temperature measurements 10 to 15 feet off bottom, and 20 to 40 minutes after pumping was halted. The precise time and distance from bottom varied depending on hole depth and distance the bit was lifted off bottom prior to making a recovery run.

Deep core drilling presents a unique set of circumstances when drilling in a geothermal environment. The low pump rates (10 to 20 gpm), and small annular space (less than 0.15 inch) and thousands of feet of thin walled drill rods create an excellent heat exchanger. Even when formation temperatures, and possibly downhole circulating mud temperatures, exceed 600°F, drilling mud discharge temperatures remain nearly unchanged.

Even though surface mud discharge temperatures do not reflect elevated formation temperatures, bottom hole temperatures which occur minutes after circulating pumps are shut down are usually near equilibrated formation temperatures. An exception to this occurs if drilling fluids migrate outward from the bore hole in the vicinity of the measurement. If this occurs, BHT measurements may be depressed depending on the volume of fluids lost and the geometry of the fluid migration.

Drilling of three SOHs indicates that within areas of high formation temperature along the East Rift Zone, permeability is limited, and restricted to isolated fracture zones. Most of the fractured intervals encountered in the higher temperature section of the SOHs, however, appear to have low overall permeability. This situation generally prohibits the movement of drilling fluids outward from the bore hole and results in reasonably accurate measurements of formation temperatures during drilling operations.

When the rig had moved off the SOH sites, temperature measurements were made with Kuster instruments after the holes had reached thermal equilibrium. Attempts to measure downhole temperatures (or other geophysical measurements) electrically produced unsatisfactory or incomplete results due to instrument damage or failure. Equilibrated temperatures surveys for the SOHs are given in Figure 3.

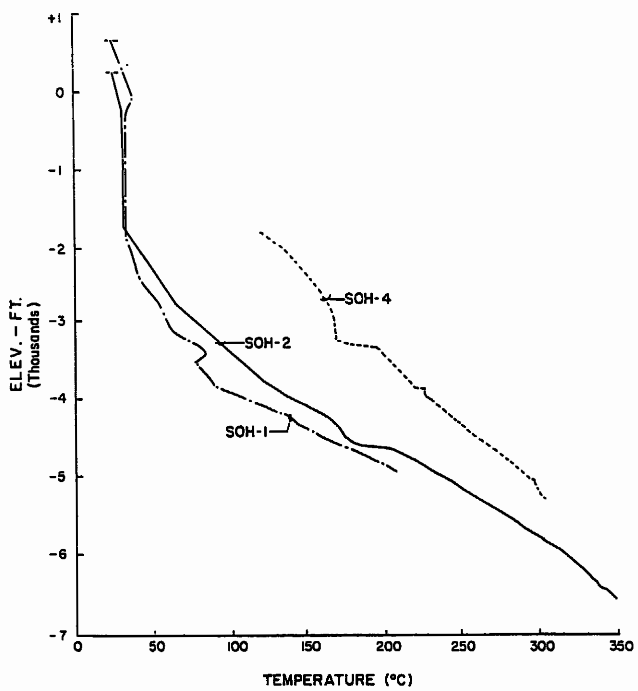

Figure 3. SOH elevation vs. temperature.

Mud Program:

Severe problems related to drilling fluids were anticipated in drilling the higher temperature intervals of the SOHs, and much thought was given to designing a mud program capable of operating at the expected high temperatures. Perhaps due to the care in planning, no severe mud related problems were encountered during the program. Nevertheless, the mud program, casing procedures, and drilling techniques continually were modified and improved as the rock section became known and its characteristic noted. At relatively shallow drilling depths, above 2,000 feet and at temperatures usually below 212°F, thin mixtures of mud and lost circulation material or cement in lost circulation zones, provided satisfactory drilling results. At temperatures above 270°F a complex stearate was added to the drilling fluids to maintain lubricity. Above 330°F a mixture of soda ash, high temperature polymer, complex stearate, and sepiolite virtually eliminated high torque and vibration problems frequently associated with high temperature drilling. This mixture gave satisfactory results in temperatures as high as 662°F, with no indication of significant mud property deterioration.

Noise Restrictions and Abatement Procedures:

Noise generated by round-the-clock drilling operations was a primary concern expressed by County of Hawaii officials, and this concern was reflected in the regulations governing drilling operations. County restriction accompanying the drilling permit limited noise levels at the nearest residence to a maximum of 55 dBA during daylight hours (defined as 7 a.m. until 7 p.m.) and 45 dBA at night. These noise levels were not exceeded at any of the three SOH sites during 18 months of drilling. Complaints, however, were routinely filed by protestors simply because the resident could hear sounds generated at the drill site regardless of measured noise levels.

A program of noise level monitoring was continued throughout the SOH program with monitoring stations at the drill site and at the two nearest residences. Solar powered, analog strip chart recorders provided a continuous and permanent record of noise levels, but proved to be less than ideal due to frequent mechanical and insect related problems (Olson and Deymonaz, 92). For future noise monitoring efforts, a digital recording system with radio transmission to a central station system should be deployed.

During drilling operations, the rig and ancillary equipment were relatively quiet, with noise levels generally less than 60-65 dBA at the drill site. Although it is not possible for drilling operations to be completely inaudible, one of the SOH program's goals was to eliminate as much "nuisance level" noise as possible. Subsequent to winning the bid, the Universal 5000 drill rig was extensively modified for geothermal work and to meet the stringent noise level limitations mandated by the county of Hawaii. The drilling contractor, working with an acoustical consultant, made extensive modifications and additions to the equipment. These equipment alterations reduced noise levels to within the limits specified by Hawaii County during most drilling operations and weather conditions. From the initiation of the SOH project in December 1989, an ongoing effort was made to further minimize sources of noise as they were identified. This effort was undertaken by Tonto and SOH personnel. Technical advice was provided by the acoustical consultant. Some of the measures taken included:

a. Completely surrounding the main power plant, a 410 HP General Motors diesel unit, with a sound dampening enclosure.

b. Constructing sound absorbing duct work over air intake and discharge areas around the engine compartment. The ducts were designed to both absorb sound and direct it upward away from the residences.
c. Modification of ancillary equipment normally powered by small gas or diesel engines, to hydraulic motors, working off the rig hydraulic system.
d. Conducting an acoustical survey at each site to determine unique conditions of sound "broadcasting" from the rig, and to position movable equipment to block or buffer the sound.
e. Installing the 5 x 7 duplex mud pump and diesel power unit in a 20 foot sound insulated shipping container.
f. Enclosing the main hydraulic hoist and sheave assembly at the top of the mast with sound dampening panels.
g. Erecting sound dampening panels around the front of the drill rig and adjacent to other sources of noise. Panels were moveable so each site could be custom fitted to meet sound emissions at each specific site.
h. Installation of large "hospital type" mufflers on the rig engine.
i. Enclosing the substructure with sound dampening panels.
j. Lining pipe rack slides with plywood to prevent metal on metal noise as rods and casing are lifted to the rig floor.
k. Enclosing the rig floor with heavy wind walls and doors.
l. Locating each drill site as distant from existing residences as practical within selected target areas, utilizing topography and vegetation to buffer or block sound wherever possible, and positioning equipment to minimize noise directed at residences.
m. Running equipment at lower speeds during night time operations to reduce noise levels.
n. Suspension of night time operations during periods of unfavorable atmospheric conditions when work involved excessive noise such as cementing and tripping.

EVOLUTION AND COSTS OF THE SOH DRILLING PROGRAM

The SOH drilling program was intended to be as flexible as possible due to the lack of any previous core drilling in the KERZ. As originally planned and funded, the holes were to be drilled to a maximum depth of 4,000 feet and were not to be pumped or flow tested. For this reason the casing plan, as originally conceived, was kept to a minimum, and designed for blow out control only. As planned, a short conductor pipe would be cemented to a depth of 100 feet and light weight 4-1/2 to 7 inch casing set to a maximum depth of 2,000 feet. If an indication of abnormal temperatures was encountered above a depth of 2,000 feet, drilling would be halted and 7 inch casing would be cemented to the bottom of the hole. Drilling would then continue and 4-1/2 inch casing would be cemented to approximately 2,000 feet if necessary.

This drilling and casing plan is similar in design to many geothermal observation holes drilled on the Mainland, although Mainland regulations usually require casing to be set to only 10 percent of the planned depth of the holes. The entire SOH would be core drilled and intervals to be cased opened to a maximum diameter of 8-1/2 inches by rotary techniques.

As the permitting for the first hole, SOH-4, progressed, local and state regulators, citizens, a potential geothermal developer, and other parties became involved in the specifics of designing the drilling and casing plan. The end result was a committee designed, inappropriate plan requiring multiple strings of heavy, large diameter casing in the upper 2,000 feet of the hole. Although never intended to produce fluids, the upper portion of SOH-4 was designed as a production well!

Consequently, the drilling of SOH-4 was severely hampered by the unreasonable requirements for multiple, large diameter, heavy weight casing in the upper 2,000 feet of the hole. The drill crew, while experienced in core drilling and small diameter rotary drilling, had never seen, let alone drilled with 17-1/2 inch equipment. A large diameter hole on a core drilling operation is typically 6 to 7 inches.

Nevertheless, the final requirements for SOH-4 specified 200 feet of 17-1/2 inch hole with 13-3/8 inch 61 pound per foot casing, 1,000 feet of 9-5/8 inch 40 pounds per foot casing, and 2,000 feet of 7 inch 35 pound per foot casing. These sizes do not present a problem for a production size rotary drill rig, but the Universal 5000 core rig, which is one of the largest core drilling rigs ever built, has only 10 to 15 percent of the horsepower, torque, and lifting capacity of a production rotary drill rig. The 7 inch casing string, for example, had a hanging weight of 70,000 pounds, which left a very small operating margin considering the 88,000 pound rating of the rig's main hoist. It is a credit to the Tonto drilling crew that they were able to safely and successfully complete that portion of SOH-4.

DRILLING RESULTS

SOH-4 was drilled to a total depth of 6,562 feet in 151 days at a direct drilling and testing cost of $1,466,813 (Deymonaz, 90). As a result of the over engineered casing plan, approximately $250,000 in additional cost were incurred. The upper 2,000 feet of SOH-4 cost approximately $794,00 to drill, while the lower 4,562 feet, cost $672,848 to complete and log. Table 2 gives a breakdown of the SOH drilling costs, and Figure 4 gives a graphical presentation of the drilling cost breakdown. Figure 5 plots the depth/time relationship for the SOHs, and Figure 6 plots the depth/cost relationship.

The second hole, SOH-1, was drilled to a total depth of 5,526 feet in 217 days at a direct drilling and testing cost of $1,643,544. For SOH-1, the casing plan was modified, with casing requirements reduced to 200 feet of 9-5/8 inch casing, and 2,000 feet of 7 inch casing. Again, the hole was core drilled from surface to TD (Deymonaz, 91). The upper 2,000 feet of SOH-1 was completed at a cost of about $537,000. Drilling performance of the upper portion of the hole showed substantial improvement over the results from SOH-4. Core drilling of the lower portion of the hole below the casing, from 2,000 to 5,526 feet, however, encountered very difficult drilling conditions, and required 156 days to complete and log at a cost of $1,106,544.

As shown in Table 1, SOH-4, had a 5,554 thick section of subaerial volcanic rocks. The subaerial section of SOH-1, however, was only 2,551 feet thick. Drilling the subaerial volcanic rocks in SOH-1 and SOH-4 presented no exceptional problems in core drilling. The submarine volcanic rocks encountered at depth in SOH-4 were hot and sufficiently thermally altered to present no problems in coring. The submarine volcanic, sedimentary, and intrusive rocks in SOH-1, however, were relatively cool and had not undergone extensive thermal alteration. These rocks proved to be extremely difficult to core. The broken and abrasive nature of the formations resulted in short bit life, poor recovery, and short core runs, which slowed progress to a few feet per day. Bottom hole temperatures began increasing below a depth of approximately 4,500 feet and by 4,900 feet conditions for core drilling were similar to those encountered in SOH-4.

Table 2
SOH Drilling Expenditures

SOH-4 Activity	
Site construction, MOB & Setup	42,297
Core 101mm (0-112 ft) in Type II	13,703
Open hole to 17-1/2" (0-112 ft)	53,847
Casing (13-3/8" 0-112 ft) cmt/rig BOPE	31,886
Core 101mm (112-1, 008 ft) in Type II	65,930
Open hole to 12-1/4" (112-992 ft)	283,609
Casing (9-5/8" 0-992 ft) cmt/rig BOPE	53,617
Core 101mm (1,008-2,000 ft) in Type II	89,452
Open hole to 8-1/2" (992-2,000 ft)	78,311
Casing (7" 0-2,000 ft) cmt/rig BOPE	82,249
Core HQ (2,000-5,290 ft) in Type II	326,956
Core NQ (5,290-6,562 ft) in Type II	205,311
Completion & testing	139,680
Total	$1,466,848 or $223.54 / ft

SOH-1 Activity	
Site construction, MOB & Setup	42,916
Core, open to 12-1/4" (0-202 ft)	35,129
Casing (9-5/8" 0-202 ft) cmt/rig BOPE	31,843
Delay, County of Hawaii permits	29,061
Core 101mm (202-1,995 ft) in Type II	136,457
Open hole to 8-1/2" (0-1, 996 ft)	175,593
Casing (7" 0-1, 996 ft) cmt & rig BOPE	93,149
Core 101mm (1,995-2,671 ft) in Type II	84,463
Fish, ream over stuck drl rods & open hole to 5-5/8" (1,996-2,671 ft)	201,709
Core 134mm (2,671-3,022 ft) in Type I	73,047
Casing (4-1/2" 0-3,022 ft) & spot cmt	23,026
Core HQ (3,022-4,325 ft) in Type I	360,154
Core NQ (4,325-4,880 ft) in Type I	165,440
Core NQ (4,880-5,526 ft) in Type II	93,549
Completion & testing	98,008
Total	$1,643,544 or $297.42 / ft

SOH-2 Activity	Cost ($)
Site construction, MOB & Setup	66,170
Drl 12-1/4" hole (0-202 ft)	35,192
Casing (9-5/8" 0-202 ft) cmt/rig BOPE	18,548
Drl 8-1/2" hole (202-1,904 ft)	227,442
Casing (7" 0-1,896 ft) cmt/rig BOPE	98,555
Core HQ (1,909-2,044 ft) in Type I Rx	27,997
Rotary 5-7/8" hole (2,044-2,785 ft)	51,062
Core HQ (2,785-2,830 ft) in Type I Rx	18,261
Rotary 5-7/8" hole (2,830-4,103 ft)	89,978
Casing (4-1/2" 0-3,022 ft) uncemented	22,733
Core HQ (4,103-4,988 ft) in Type II Rx	97,760
Core NQ (4,988-6,802 ft) in Type II Rx	243,716
Completion & testing	109,259
Total	$1,106,684 or $162.70 / ft

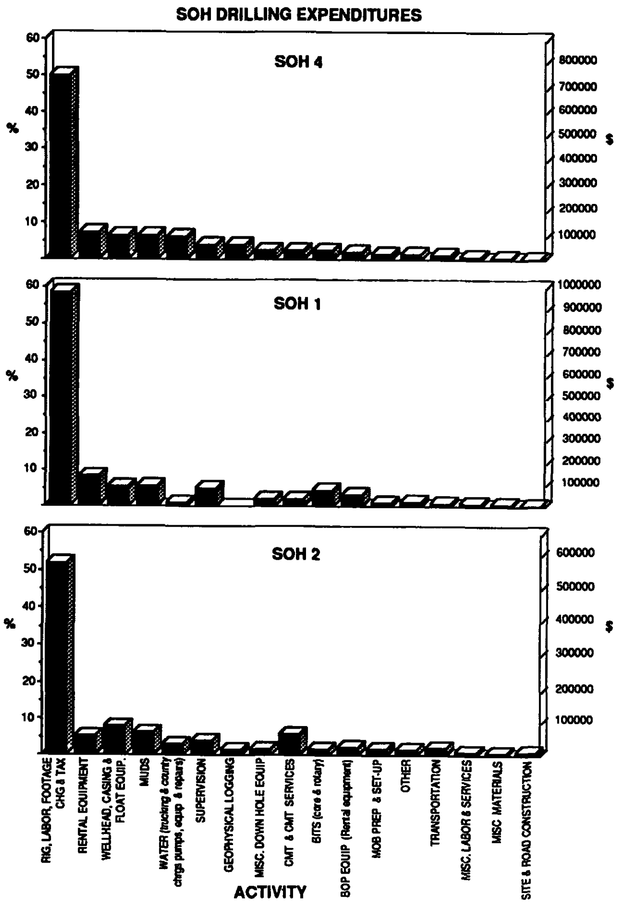

Figure 4.

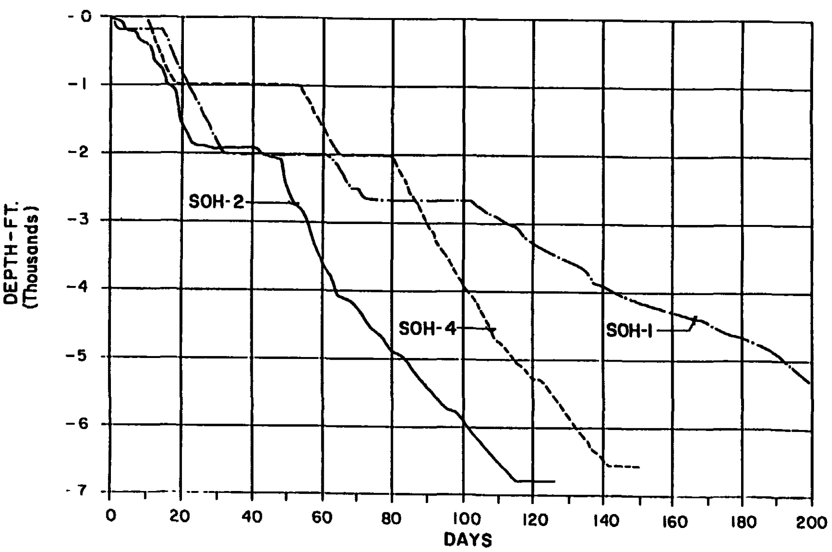

Figure 5. SOH drilling performance vs. time.

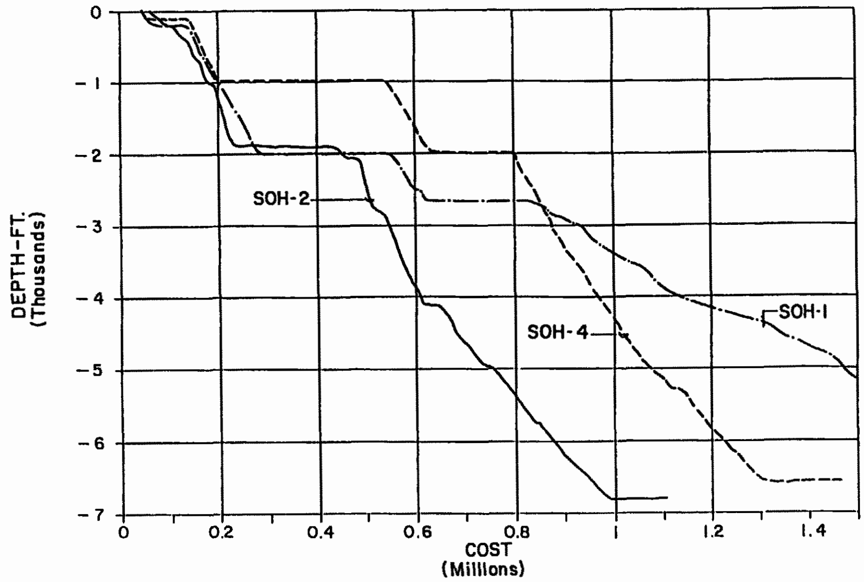

Figure 6. SOH drilling performance depth vs. cost.

With the experience gained in SOH-1 and SOH-4 the drilling plan was modified for the third hole, SOH-2. Core drilling in the upper 2,000 feet was omitted to reduce drilling costs by approximately $100,000. The casing program resembled SOH-1 except a lighter (23 pounds per foot vs. 35 pounds per foot) 7 inch casing was used. Additionally, extra drill collars and a larger mud pump were used during rotary drilling. Below 2,000 feet, thermally unaltered submarine basalt similar to that in SOH-1 was encountered, and drilling proceeded with small diameter rotary bits. During this interval two runs were made to obtain sample core, but as the samples did not indicate favorable coring conditions, the cored sections were reamed out and rotary drilling continued until thermally altered basalt was encountered at a depth of 4,103 feet. Coring resumed at this depth and continued to the bottom of the hole without incident. A removable casing sleeve was used during the coring intervals in the rotary hole, which permitted the removal of the casing sleeve and resumption of rotary drilling as required (Deymonaz, 92).

With the exception of a dogleg in the hole at a depth of 1,880 feet, and problems with drilling rods twisting off at this depth, SOH-2 progressed rapidly, and was completed to 6,802 feet in 126 days at a direct drilling and logging cost of $1,106,684. As coring the upper 2,000 feet probably would have prevented the dogleg and eliminated approximately $200,000 in delays, caused by reduced drilling performance, fishing costs, and material losses, the elimination of coring from this interval probably resulted in an estimated net additional cost of about $100,000. In future SOH type holes, consideration should be given to redrilling with rotary equipment to straighten any intervals with doglegs, or to core drilling from the surface and opening the upper intervals to be cased with rotary methods. This should insure a straight hole, and, in addition, provide valuable core samples for the analysis.

Expenditures directly related to drilling activities for SOH-2 totaled $997,000, or $147 per foot. Logging and completion brought the total cost to $1,106,684 or $162.70 per foot for SOH-2. Based on experience gained in the drilling of the first three SOHs, a realistic goal for future holes of this type, completed and logged to a depth of approximately 6,500 feet, should be about $975,000 or $150 per foot.

SUMMARY

The SOH program broke new ground by drilling deep core holes into an active basaltic rift zone in a region in which no core drilling had previously been attempted. SOH-2, which was drilled to a depth of 6,802 feet, is one of, if not, the deepest and hottest geothermal core hole drilled, with a maximum temperature of 662^{o}F recorded at a depth of 6,782 feet.

The SOH program was undertaken to provide an additional dimension to the exploration and knowledge of Hawaii's geothermal resource potential and the geologic history of the Hawaiian volcanoes. The holes were not designed to be used for production purposes, or flow testing, and as such, could not be expected to provide data regarding brine chemistry or reservoir potential. Nevertheless, a separate program funded by the Electric Power Research Institute (EPRI) studied the possibility of providing preliminary producibility potential by injecting fluids into the completed holes. As the temperature of the permeable zones and the pressure required to inject the fluids were known, it is possible to calculate possible flow rates of a production sized well.

As fluid or gas discharges from the holes were specifically prohibited in the permits, the SOHs could not provide any information regarding reservoir chemistry or composition. The holes, however, did provide information of drilling conditions, and the subsurface geology, temperature, and permeability above and within potential geothermal reservoirs. The collection of nearly 15,000 feet of core for current and future study and analysis is a unique and valuable contribution to the process of understanding and properly developing Hawaii's geothermal resource. The holes will also provide a long term service as monitoring sites to evaluate natural changes within the KERZ, and the regional effect of commercial geothermal development on the resource.

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