Geological Society of Malaysia – Circum-Pacific Council for Energy and Mineral Resources
Tectonic Framework and Energy Resources of the Western Margin of the Pacific Basin
November 27 – December 2, 1992, Kuala Lumpur, Malaysia

Deep, slim hole, diamond drilling program proves effective for geothermal assessment in Hawaii

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Abstract: 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 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.

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 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 130°C (270°F) a complex stearate was added to the drilling fluids to maintain lubricity. Above 165°C (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.

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 2,000.1 m (6,562 ft) and recorded bottom hole temperatures of 306.1°C (583°F) at a depth of 1,950.7 m (6,400 ft). 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 to a total depth of 1,684.3 m (5,526 ft) and recorded a bottom hole temperature of 206.1°C (403°F). The third hole, SOH-2, was drilled on a PGV lease to a total depth of 2,073.2 m (6,802 ft), recorded a bottom hole temperature of 350.6°C (663°F), and may have intersected a potential reservoir at a depth of approximately 1,490 m (4,900 ft).

INTRODUCTION

The Hawaiian Islands are located above a geologic "hot spot" in the earth's mantle that has been volcanically active throughout the past 70 million years. The Big Island of Hawaii has an obvious, large potential for geothermal energy resources, both for electrical generation and direct utilization. Since the drilling of the HGP-A well in 1976, the construction of the HGP-A, 3 megawatt geothermal demonstration electrical power plant in 1980, and the discovery of the adjacent Puna Geothermal Venture (PGV) reservoir along the eastern portion of the Kilauea East Rift Zone (KERZ), geothermal potential on the Big Island has been assumed to be in the range of 500 to 700 megawatts (Thomas, 1987).

The Scientific Observation Hole (SOH) program was planned and implemented by the Hawaii Natural Energy Institute, 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 1,200 m (4,000 ft), 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 the island of 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; Olson and Deymonaz, 1992a). Figure 1 shows the location of the volcanic features, the KERZ, and areas with geothermal potential on Maui and Hawaii. The location of the SOHs, the GRZs, as well as the production wells drilled by PGV and T/MPGV along the KERZ are shown on Figure 2.

Prior to the initiation of the SOH program, preliminary geothermal surface exploration was completed during the work that resulted in the Geothermal Resources of Hawaii Map, (Thomas *et al.*, 1983). Active volcanoes and obvious geothermal heat sources were known, rift zones were identified and mapped, and areas of geothermal potential defined. Parts of the KERZ had been studied by mapping the surface geology, and by surface geophysical and geochemical surveys. The immediate area at and surrounding the State of Hawaii HGP-A 3 megawatt demonstration electrical power plant had been tested by seven production size geothermal wells. Of these, the HGP-A well had produced at a rate of about 2.5 megawatts for approximately six years, three wells had intersected an economically viable reservoir, but had not been adequately flow tested and could not be produced due to casing damage. Two wells were hot but dry, and were shut in without undergoing extensive flow testing. The remaining well intersected a meteoric recharge zone, and although productive, was not thought to have sufficient temperature for electrical generation. Surface geochemical and geophysical exploration techniques gave results which could not be interpreted to define subsurface

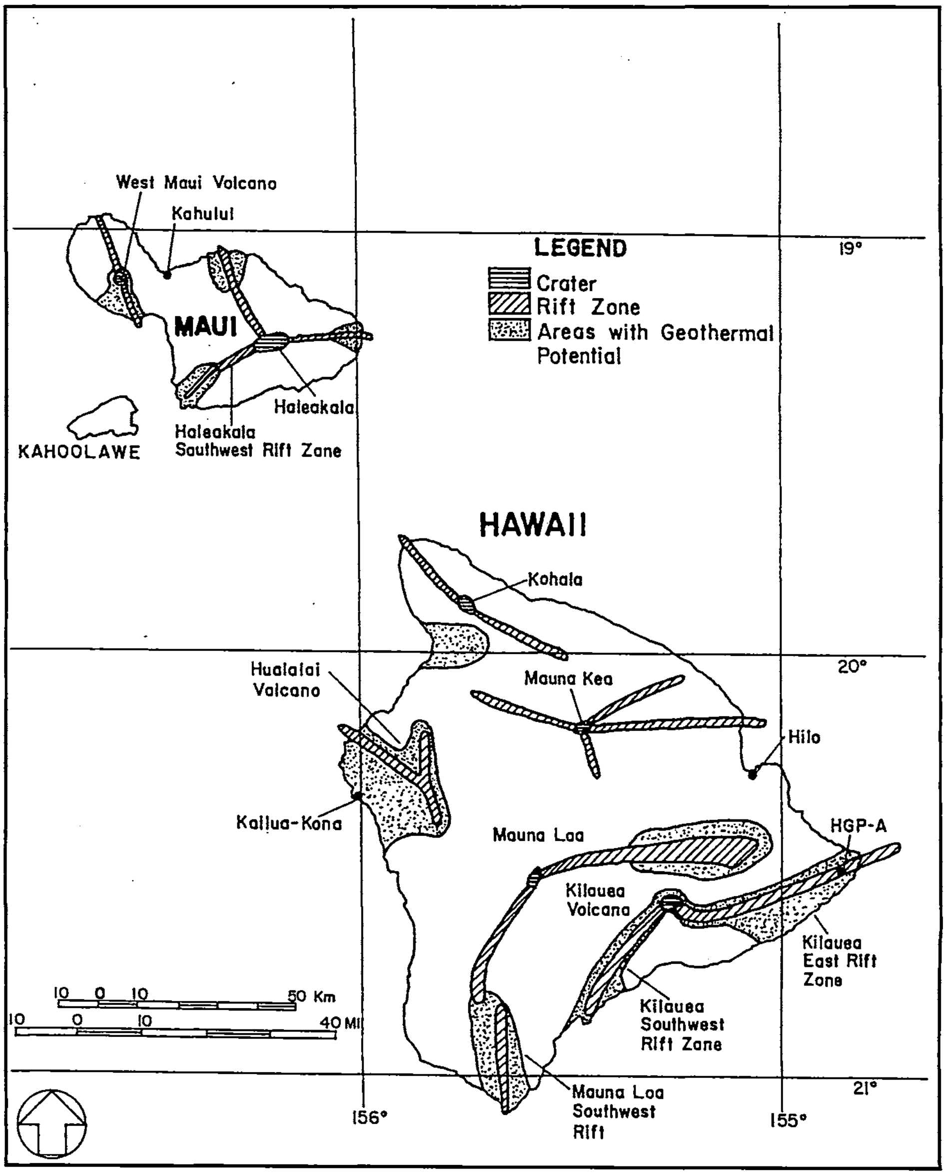

Figure 1. Volcanic features and areas with geothermal potential on Maui and Hawaii. After Thomas *et al.*, 1983.

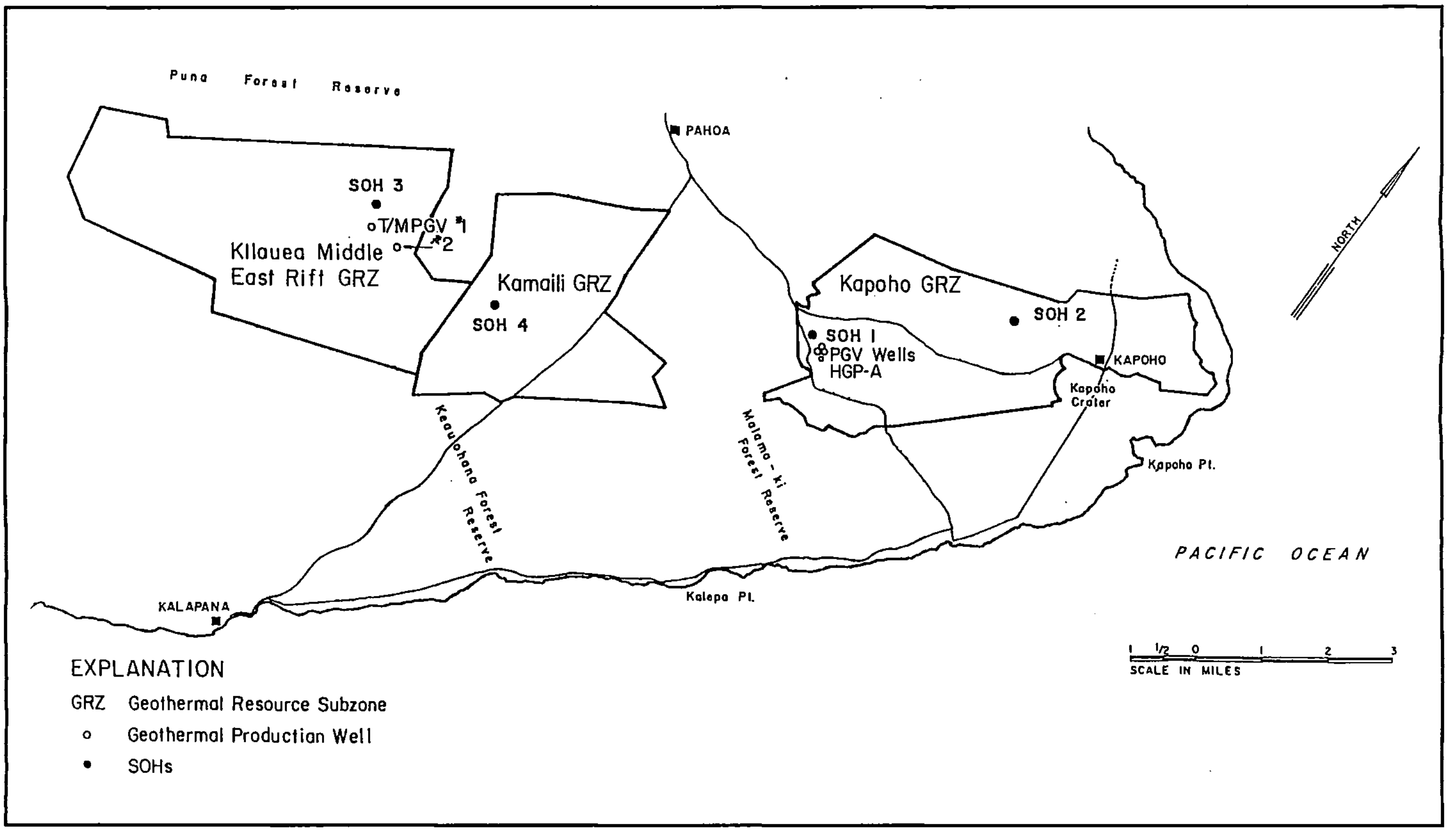

Figure 2. Location of the Geothermal Resource Subzones, production wells, and the SOHs on the big island of Hawaii.

drilling targets. Temperature surveys of the exploration wells indicated that shallow temperature gradients holes drilled to less than 600 m (2,000 ft) could not define drilling targets, and as the cap rock above the reservoir in the HGP-A area was at a depth of about 900 m (3,500 ft), drilling to a depth of approximately 1,200 m (4,000 ft) would be needed to identify other potential reservoirs in the area. The State of Hawaii, however, was interested in quickly assessing the geothermal potential of the KERZ, and so it was determined that the assessment could be accomplished most economically and efficiently by drilling a number of deep, scientific observation holes to a nominal depth of 1,200 m (4,000 ft) within the known resource areas along the KERZ.

As the SOH drilling program expected to meet with considerable environmental and community opposition during the permitting process, a primary consideration in designing the project was to minimize the environmental and sociological impact. This was achieved by selecting equipment and drilling techniques so that operation would require only a limited work area (less than 1/3 acre), would be as quiet as possible, would have low water consumption, would not require a high volume of heavy truck traffic, and would be conducted in a professionally safe manner with as little impact on the neighbouring community as possible. Prior to selecting the sites, several aerial reconnaissances of the KERZ were made to obtain a feel for the regional geology, topography, existing road network, vegetation, and use patterns; and to determine the location of residences and possible access roads. Possible drill site locations then were carefully selected, based on results of prior work in the area, and checked on the ground to eliminate the need for new road construction, to reduce environmental impacts, to maintain as much distance as possible from residences, and to use the natural terrain to reduce the visual and audible impact on the community. State regulations and land zoning restricted drilling to existing Geothermal Resource Subzones (GRZ). During the public permit hearings, extremely restrictive conditions were place on noise, fluid emissions, and operating activities, and pumping or flow testing of ground water and reservoir fluids was prohibited. Bailing fluid samples from the SOHs was not effective, and because of the operating restrictions it was not possible to collect uncontaminated water or reservoir samples, (Olson and Deymonaz, 1992b).

Tonto Drilling Services Inc. of Salt Lake City, Utah was chosen as the drilling contractor for the SOH program. Tonto provided a crew experienced in geothermal core drilling and a Universal 5000 rotary/core drilling rig to undertake this project. The Universal 5000 drilling rig was, at the time of the SOH program, one of only two such units in existence, and was uniquely suited to the drilling conditions encountered during the program. The rig was extensively modified for geothermal work and to meet the stringent noise level limitations mandated by the county of Hawaii. Figure 3 is a picture of the Universal 5000 rig at the SOH-2 site.

The drilling rig is mounted on a 3-axle trailer and weighs approximately 42,900 kg (94,600 lb). A self-elevating jack-up system permits raising the rig and placing a 3.2 m (10.5 ft) high substructure under the mast. The substructure carries the weight associated with drilling, serves as a working floor, and permits the above ground installation of blowout prevention equipment (BOPE).

Depth rating of the Universal 5000 depends on the size of the drill rods used, drilling conditions, and other factors. For NQ drill rods, which were used to complete the SOHs, the theoretical maximum depth is over 5,180 m (17,000 ft). Hole size drilled with an NQ bit is 75.7 mm (2.98 inches) in diameter.

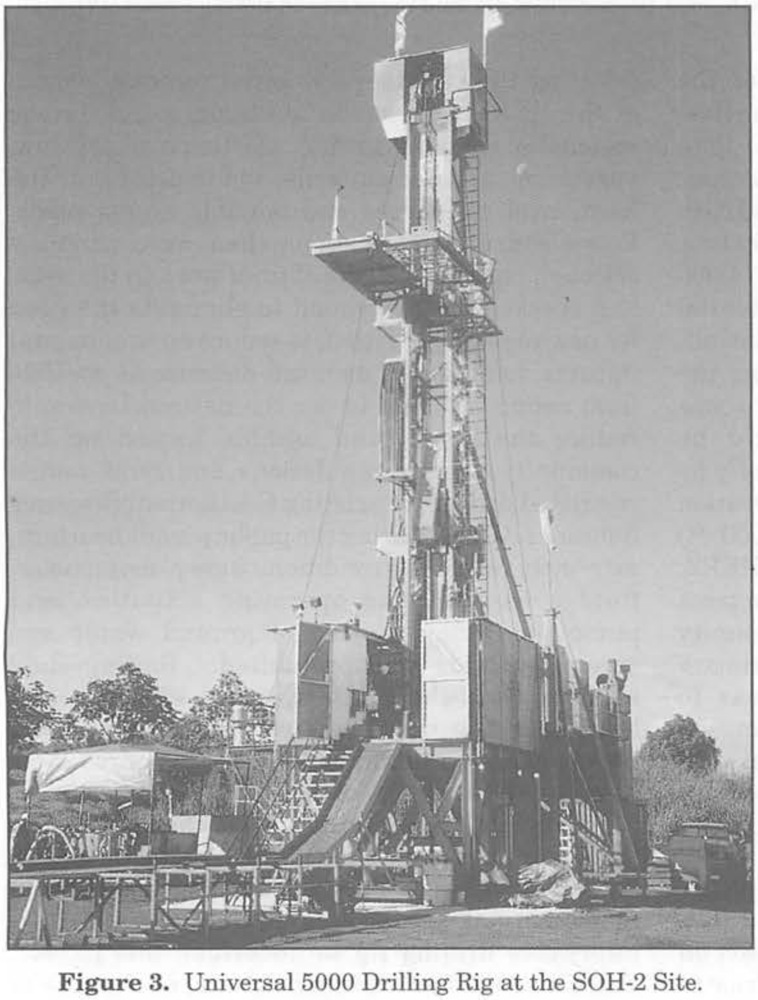

Figure 3. Universal 5000 Drilling Rig at the SOH-2 Site.

SOH-DRILLING-PROGRAM

Because of the parallel fracturing and diking along the KERZ, permeability, initially, was assumed to exist along the axis of the rift. Cross-rift permeability was basically unknown and untested, and was thought to be restricted to areas of cross fracturing or related to structures, such as subsurface plugs or buried volcanic necks, which could cause local fracturing across the rifts.

To most efficiently assess the KERZ, the SOH drill sites were laid out in a fence along the KERZ. Two of the SOHs were step-outs at a distance from any previous drilling to assess untested segments of the rift, and two of the SOHs were "paired" with existing or planned production wells to test cross rift permeability conditions. The SOH program also was designed to be more practical, rather than totally academic, and attempted to emphasize the drilling of as many holes and as much footage and ground truth as possible, rather than the collection of basic scientific information. In addition, an attempt was made to obtain indications of reservoir potential by injection tests after the well had been drilled by calculating possible flow from a production sized well at the same site from the measured downhole temperature, and the pressure required to pump a known volume of water down the hole during injection.

Despite continuous opposition from well organized and funded, highly sophisticated, special interest groups, the SOH program was highly successful and met the University of Hawaii's stated mission of providing scientific information and technology transfer to the private sector for utilization and commercialization, and to stimulate private development of Hawaii's geothermal resources. After the completion of three holes, effective techniques were devised to drill slim rotary and core holes to depths in excess of 2,070 m (6,800 ft); thermal continuity at depth along the KERZ was established; the northern boundary of the HGP-A/PGV reservoir was defined; and a potential geothermal reservoir in a previously untested area discovered. Although all the necessary permits were approved for the fourth hole, SOH-3, the State of Hawaii decided to defer the drilling of SOH-3 until additional SOHs could be permitted with amended provisions to allow pumping or flow testing of the holes to obtain fluid groundwater and reservoir samples.

Drilling problems were anticipated with the possible high temperatures that were expected to be encountered, and much thought was given to designing a mud program capable of operating in these austere conditions. A satisfactory program was designed as the program progressed with minimum experimentation, and successful drilling techniques, casing procedures, and drilling fluids mixtures were devised as the rock section became known and its characteristics noted. At relatively shallow drilling depths, above 600 m (2,000 ft) at temperatures usually below 100°C (212°F) thin mixtures of bentonite and polymer, with thicker mixtures of mud and loss circulation material (LCM) and/or cement in loss circulation zones, provided satisfactory drilling results. At temperatures above 130°C (270°F) a complex stearate was added to the drilling fluids to maintain lubricity. Above 165°C (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 350°C (662°F).

SOH-4

The first hole drilled, SOH-4, was drilled to a total depth of 2,000.1 m (6,562 ft), and recorded a bottom hole temperature of 306.1°C (583°F). Although evidence of fossil reservoir conditions were found, no zones with obvious reservoir permeability were encountered. No problems were encountered in core drilling the upper section of subaerial basalt flows and dikes. However, severe rotary drilling problems with lost circulation and reaming were encountered in the upper 610 m (2,000 ft) of the hole, resulting in large drilling cost overruns.

The initial drilling and casing plan called for opening the core hole to 17½ inches in diameter to a depth of 30.5 m (100 ft) and cementing 13⅜ inch casing to the bottom of the hole. This was accomplished at first by opening the hole by drilling with an 8½ inch bit, followed by a 12¼ inch bit, and finally with a 17½ inch bit, because the drill rig did not have sufficient torque to open the hole to full width in one pass. Each time circulation was lost, drilling stopped and circulation was regained with high viscosity mud and LCM, and the casing was set without trouble after straightening a dog-leg with a bottom hole assembly utilizing a 17½ inch roller reamer. The hole was then cored to a depth of 306.9 m (1,007 ft). This interval was then opened to a diameter of 12¼ inches by first drilling with an 8½ inch bit followed by a 12¼ inch bit. This interval encountered multiple lost circulation zones which were plugged by high viscosity mud and LCM or with LCM and cement. Upon opening the hole to 12¼ inches, however, circulation was usually lost at the same intervals as encountered with the 8½ inch bit, resulting in much lost time cementing and waiting on cement. It was soon discovered that the rig had sufficient torque to open the hole to 12¼ inches in one pass, and that the hole would stay open after loosing circulation for an additional 45 to 90 m (150 to 300 ft by drilling slowly ahead and conditioning the hole carefully. Subsequently the hole was opened, and 9⅝ inch casing set and cemented in this manner. The hole was then cored to a depth of 609.6 m (2,000 ft) and then opened to 8½ by slowly and carefully drilling blind for 45 to 90 m (150 to 300 ft) through lost circulation zones instead of cementing whenever circulation was lost, and by using thin cement mixtures to regain circulation. A 7 inch surface casing was then set and cemented, and core drilling proceeded with only minor problems to the bottom of the hole in a heated section of submarine basalts. Figure 4 shows the drilling/casing plan used in drilling SOH-4.

At a depth of approximately 1,220 m (4,000 ft), State officials approved the deepening of the hole to a depth of approximately 2,000 m (6,500 ft) because temperatures of 200°C (400°F) or higher had not been recorded during drilling. At this time, the other scheduled SOHs also were targeted to depths of approximately 1,825 to 2,000 m (6,000 to 6,500 ft). Total direct drilling costs for SOH-4 are US$1,466,848, or US$733.38 per meter (US$223.54 per foot).

As a rule, core drilling costs, usually expressed as footage charges, tend to increase with depth, even if hole size is reduced which results in lower bit costs, due to increased trip time for core recovery and bit changes, and for other problems, such as increased risk of twist-offs associated with depth. Drilling performance is shown graphically for depth versus cost for all the SOHs in Figure 5, and for depth versus time for all the SOHs in Figure 6. The temperature gradient of SOH-4 and the other SOHs are shown in Figure 7. The drilling activity cost summary for SOH-4 and the other SOHs are shown on Table 1.

Interestingly enough, SOH-4 was initially considered to be a "failure" by State officials because the bottom hole temperature was not as high as the 358°C (676°F) encountered in the State HGP-A well, because of the large cost overrun, as compared to the cost estimated for the original 1,200 m (4,000 ft) depth planned for the hole, and because the hole did not encounter a reservoir. This resulted in renewed efforts to educate the officials to the realities of drilling economics, programmatic goals, and expected results.

SOH-1

The second hole, SOH-1, was drilled to a total depth of 1,684.3 m (5,526 ft) and recorded a bottom hole temperature of 206.1°C (403°F). The drilling and casing plan for the upper 610 m (2,000 ft) was modified, utilizing the experience gained in the drilling of SOH-4, by omitting the 13$^{3}/_{8}$ inch and the lower 305 m of 9$^{5}/_{8}$ inch casing, and using 7 inch casing from the surface to a depth of 610 m (2,000 ft). Figure 8 shows the revised drilling/casing plan used in drilling SOH-1 and SOH-2. The revised drilling/casing plan resulted in rapid progress with only infrequent and minor drilling problems, and cost savings of approximately US$240,000 as compared to SOH-4 at a similar depth. When coring resumed below the casing, however, very severe drilling problems were encountered due to highly fractured, cool (<38°C or <100°F), submarine basalt, sands, and dikes, in the interval between 610 and 1,370 m (2,000 to 4,500 ft), resulting in short bit life, short (15 to 45 cm or 6 to 18 inches) core runs, stuck drill rods and massive cost and time overruns. The fractured submarine basalt and dikes broke off during drilling into small fragments around and in front of the bit, and rolled about the drilling surfaces, wearing the bit face matrix and gouging out the diamonds. The exterior gauge of the bits was reduced and the interior gauge enlarged resulting in short core runs which was caused by sticking drill rods and rock stuck in the core barrel. This resulted in the necessity of frequent redrilling of the hole to reach bottom. Bit life averaged between 3 and 6 m (10 to 20 ft), and resulted in constant tripping of the rods to replace bits. Below 1,370 m (4,500 ft) the temperature increased rapidly, resulting in normal drilling runs, core recovery of nearly 100%, and long bit life, due to fracture filling or bonding of the fractures by thermal metamorphism.

Total drilling costs for SOH-1 are extremely high at US$1,643,544 or US$975.80 per meter (US$297.42 per foot), which caused the hole to be stopped approximately 300 m (975 ft) short of the its targeted depth.

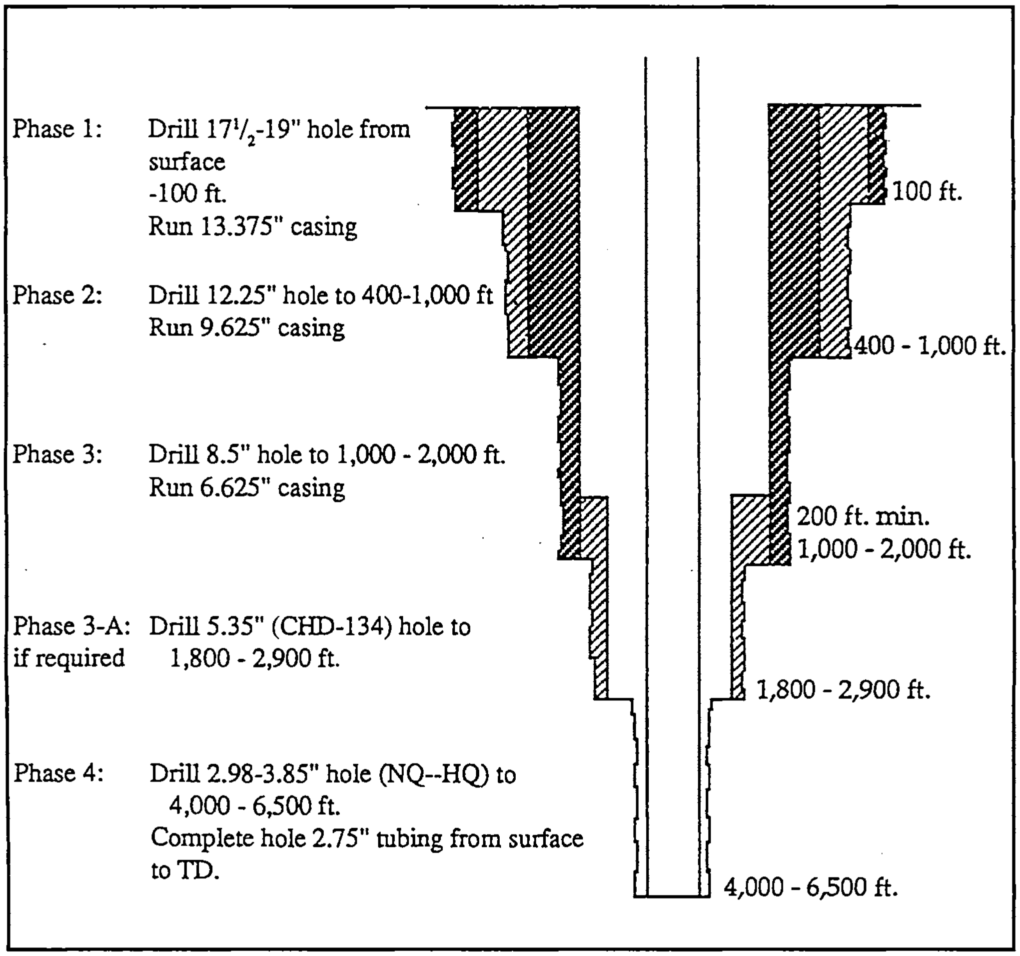

Figure 4. SOH-4 casing plan.

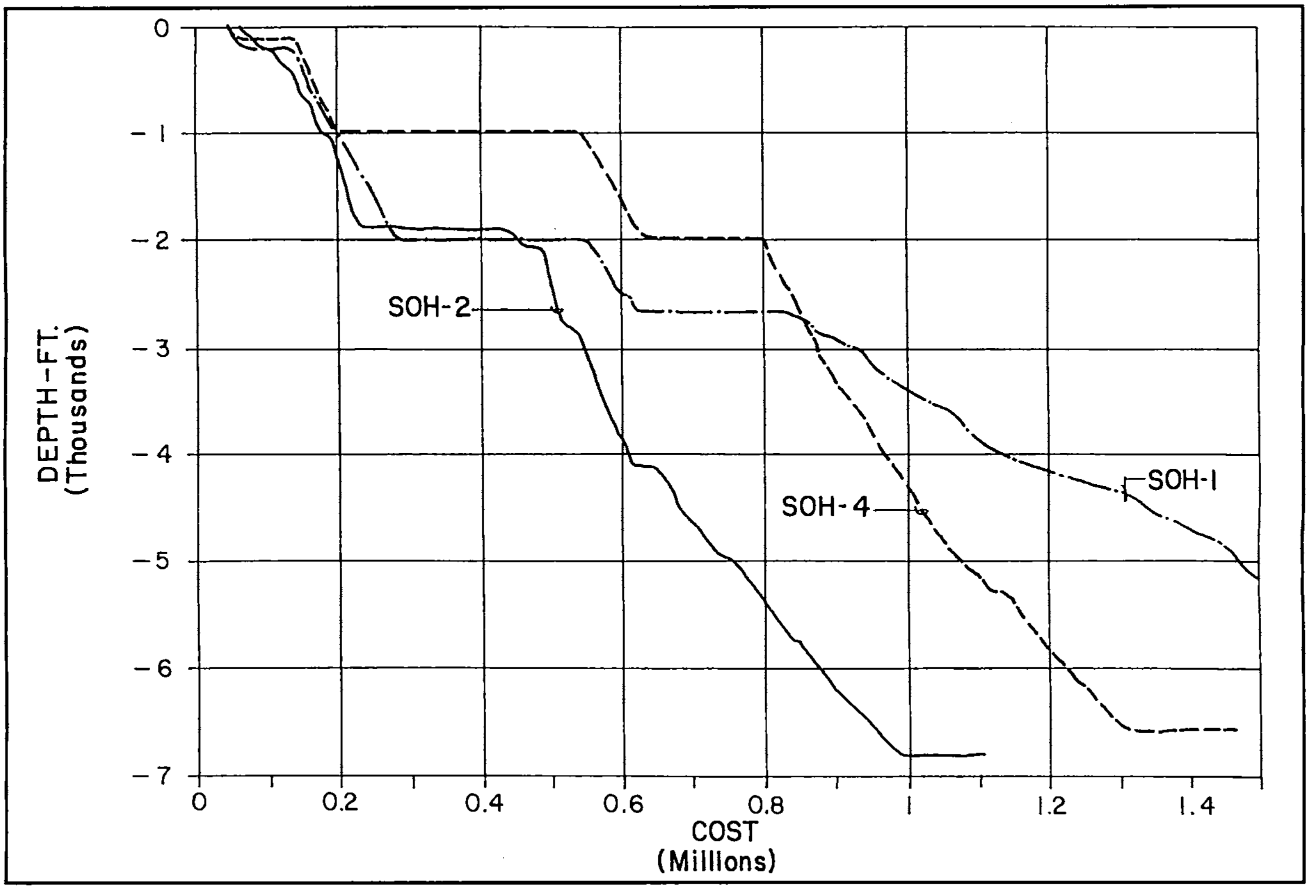

Figure 5. SOH drilling performance, depth versus cost.

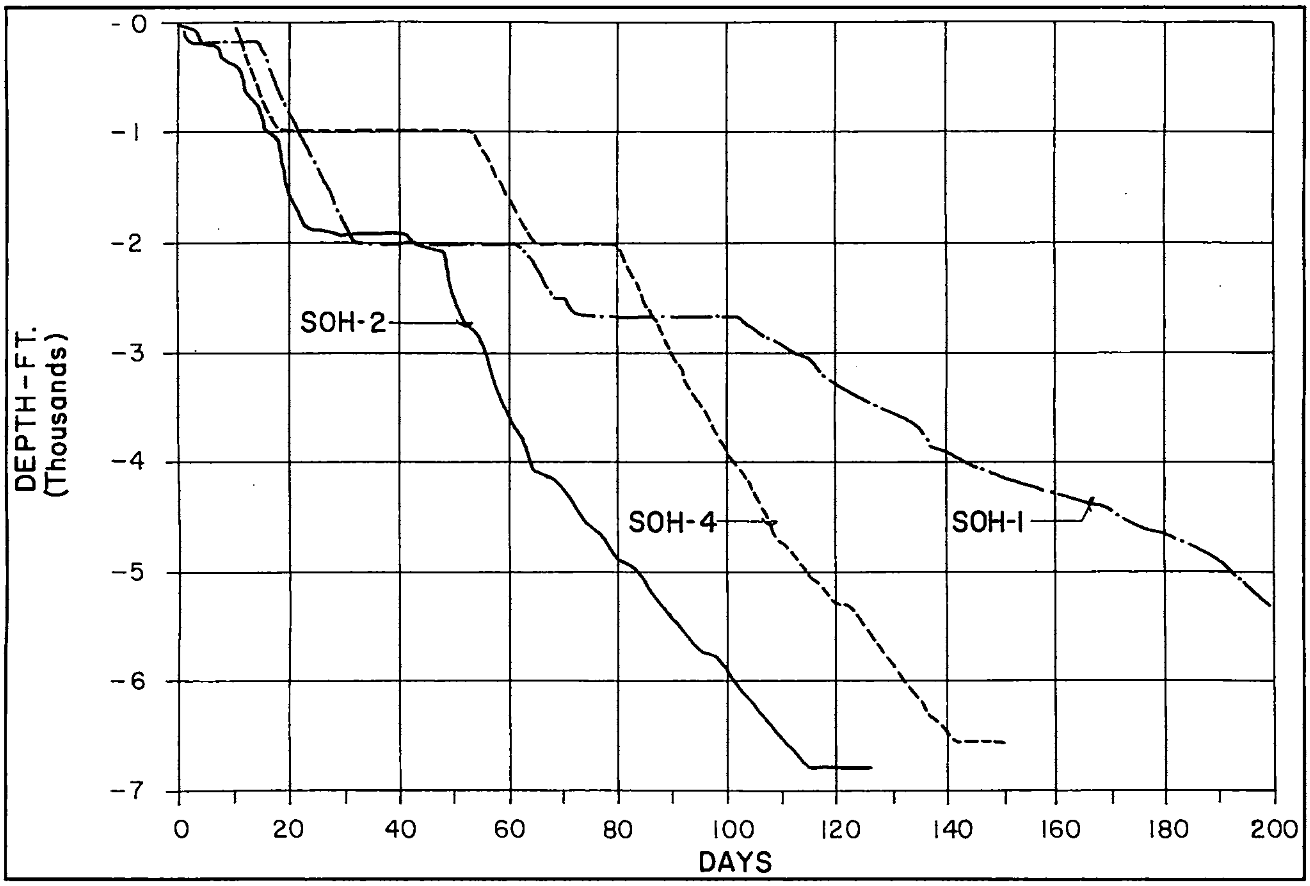

Figure 6. SOH drilling performance, depth versus time.

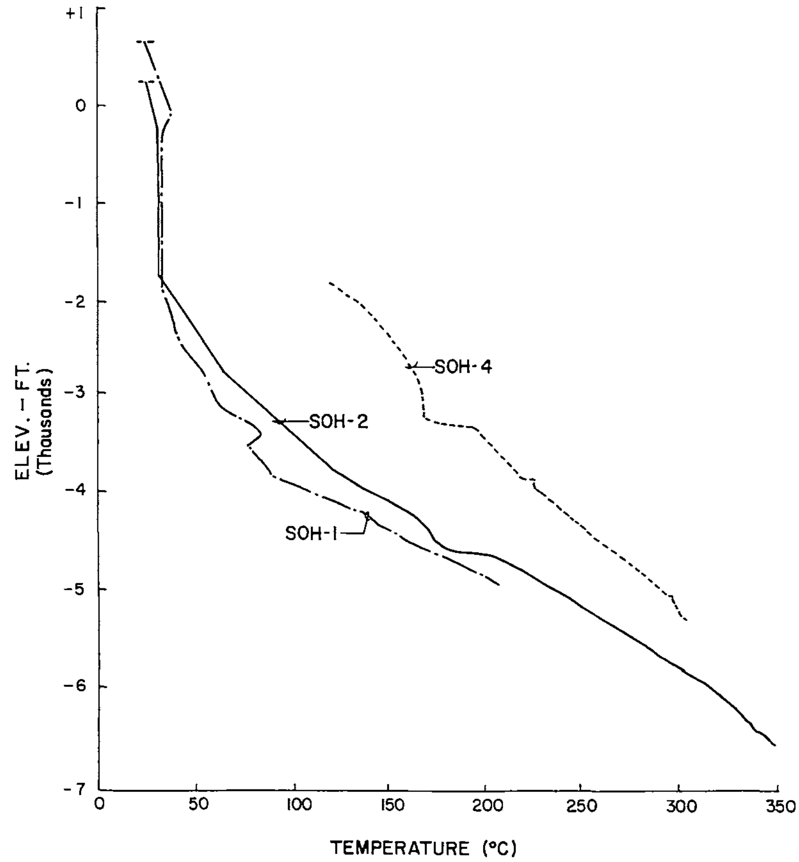

Figure 7. SOH temperature versus elevation.

SOH-2

The third hole, SOH-2, was drilled to a total depth of 2,073.2 m (6,802 ft) and recorded a bottom hole temperature of 350.5°C (663°F). The drilling plan was again modified to incorporate the lessons learned in the drilling of the first two holes. To reduce drilling costs, the upper 580 m (1,900 ft) of the SOH was rotary drilled with no coring. Casing was set approximately 30 m (100 ft) higher in SOH-2 than in the other two SOHs because of a sudden 4° deviation in the hole in an 8.2 m (27 ft) interval between a depth of 567 to 575 m (1,860 to 1,887 ft), which resulted in several drill collar twist-offs and fishing jobs. After the casing was set, coring encountered difficult, time consuming, and expensive drilling conditions similar to those encountered in SOH-1.

At that time a decision was made not to attempt to fight the hole down by coring, and the hole, subsequently, was rotary drilled to approximately 1,250 m (4,100 ft). As circulation was lost at the surface, only a few scattered rock samples were collected in the upper rotary portion of the hole. However, the dogleg caused by the sudden hole deviation, persisted through the casing and drilling continued to be plagued by repeated twist-offs to the bottom of the hole. Luckily all the twist offs occurred inside the casing and fishing, although time consuming and costly, did not result in major delays or loss of the hole. Temperature at a depth of 1,250 m (4,100 ft) was 132.7°C (270.9°F) which was sufficient to bond the fractured submarine basalts (or the section previously had been subjected to higher temperatures with the same results), and coring proceeded rapidly and smoothly to the bottom of the hole. Subsequent injection testing indicated that a permeable interval between 1,488.3 and 1,505.7 m (4,883 to 4,940 ft) with a temperature of 210.3°C (410.5°F) can be designated as a possible "discovery". Additional drilling in the vicinity of SOH-2 should intersect fracture permeability below a depth of 1,825 m (6,000 ft) with fluid temperatures in excess of 300°C (572°F).

Total drilling costs for SOH-2 are US$1,106,684 or US$533.80 per meter (US$162.70 per foot), which represents a savings of greater than US$300,000 while drilling 73 m (240 ft) deeper than SOH-4, and greater than US$460,000 while drilling 389 m (1,276 ft) deeper than SOH-1.

Table 1. SOH Drilling Activity Cost Summary.

SOH-4 Activity	Cost (US$)
Site construction, MOB & Setup	42,297
Core 101mm (0-112 ft) in Type II	13,703
Open hole to 17½" (0-112 ft)	53,847
Casing (13⅜" 0-112 ft) cmt/rig BOPE	31,886
Core 101mm (112-1,008 ft) in Type II	65,930
Open hole to 12¼" (112-992 ft)	283,609
Casing (9⅝" 0-992 ft) cmt/rig BOPE	53,617
Core 101mm (1,008-2,000 ft) in Type II	89,452
Open hole to 8½" (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
	$223.54/ft
SOH-1 Activity	**Cost (US$)**
Site construction, MOB & Setup	42,916
Core, open to 12¼" (0-202 ft)	35,129
Casing (9⅝" 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 8½" (0-1,996 ft)	175,593
Casing (7" 0-1,996 ft) cmt & rig BOPE	93,149
Core 101mm (1,996-2,671 ft) in Type II	84,463
Fish, ream over stuck drl rods & open hole to 5⅝" (1,996-2,671 ft)	201,709
Core 134mm (2,671-3,022 ft) in Type I	73,047
Casing (4½" 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
	$297.42/ft
SOH-2 Activity	**Cost (US$)**
Site construction, MOB & Setup	66,170
Drl 12¼" hole (0-202 ft)	35,192
Casing (9⅝" 0-202 ft) cmt/rig BOPE	18,548
Drl 8½" 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 5⅞" hole (2,044-2,785 ft)	51,062
Core HQ (2,785-2,830 ft) in Type I Rx	18,261
Rotary 5⅞" hole (2,830-4,103 ft)	89,978
Casing (4½" 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
	$162.70/ft

PRELIMINARY SOH PROGRAM RESULTS

Very preliminary results from SOH program indicate that:

- Core (slim) holes can be successfully drilled to depths in excess of 2,070 m (6,800 ft) and can be used to assess geothermal resource potential at substantial savings in drilling and permitting costs and environmental impact. Initial drilling results indicate that SOHs in Hawaii can be most efficiently drilled by a combination of rotary and core drilling techniques.
- Analysis of the drilling results indicates that the key to reducing costs involves more than drilling faster. Over the long run, staying out of trouble usually results in faster penetration rates and lower drilling costs. Consequently, after the experience with the twist-offs in SOH-2, a decision was made to core-drill future, cool, unmetamorphosed, subaerial basalts, and then to open the hole by rotary drilling, which will probably result in a straight hole and more data, rather than to attempt to reduce costs by not coring and running the risk of twist-offs and possible loss of the hole.
- It was not possible to collect uncontaminated groundwater or reservoir fluids in the SOHs in a cost effective manner by bailing. To obtain reliable fluid samples the holes must either be pumped or flowed. As groundwater and reservoir fluid chemistry is vital to the assessment of the geothermal potential of an area, future SOHs will be permitted to allow the sampling of downhole fluids by pumping or flowing. Wellhead abatement equipment will probably be required to reduce possible noise and H_2S emissions.
- The geothermal potential of the Kilauea East Rift Zone has not been proven, and additional production and assessment drilling must be completed before a reasonable estimate of the size and characteristics of the resource can be made.
- Although high temperatures probably are continuous along the KERZ, a single large geothermal reservoir (or several relatively large reservoirs) probably does not exist within the KERZ. The geology of the geothermal reservoirs that do exist probably will be highly complex and the reservoirs may be relatively small and discontinuous.
- SOH-1 essentially defines the northern boundary of the HGP-A/PGV reservoir, which has produced between 2 and 3 megawatts of electrical power with a plant factor of greater than 90% for over 7½ years. Utilizing published

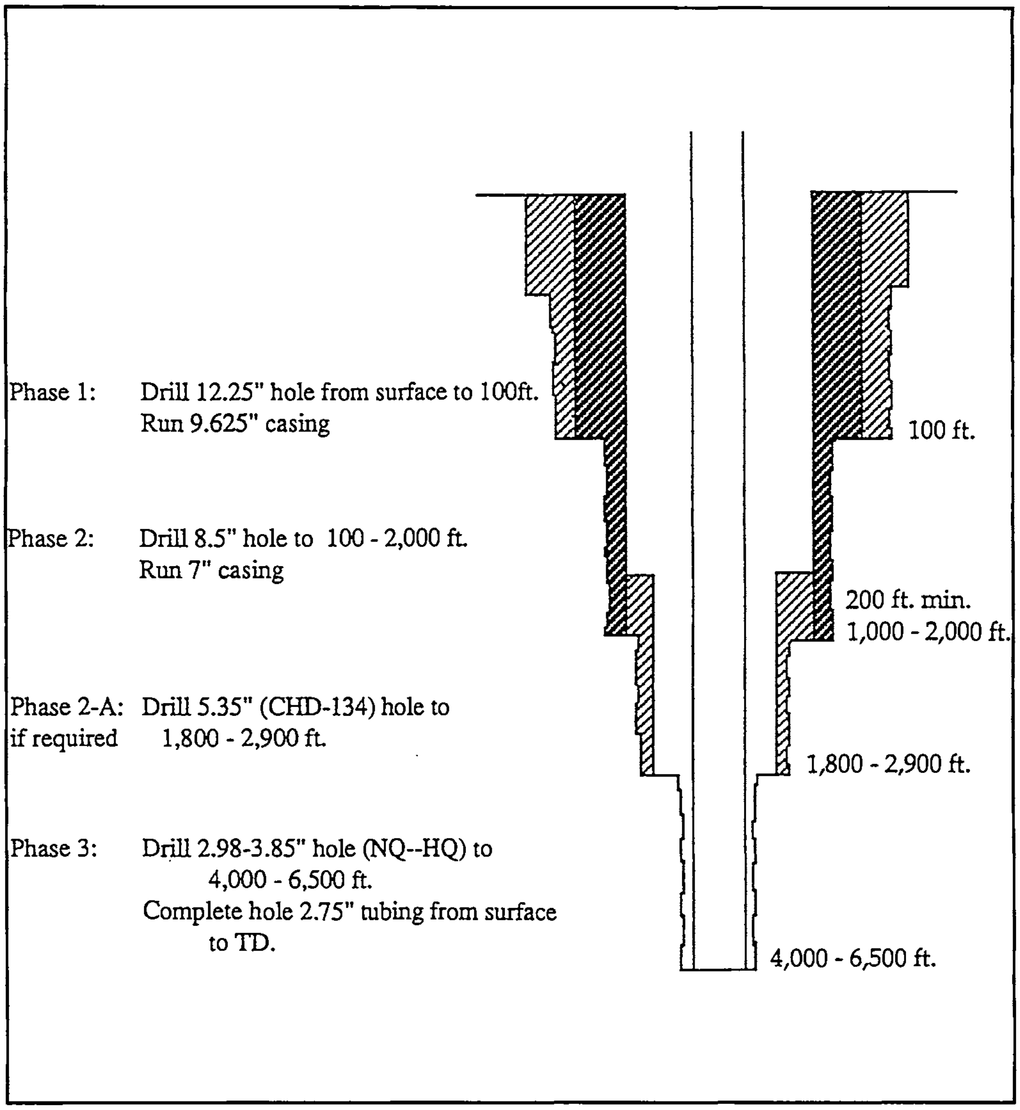

Figure 8. SOH-1 and SOH-2 revised casing plan.

data from HGP-A, the KS wells drilled by Thermal Power in the early 1980s, and SOH-1, reservoir conditions at a depth of 1,250 m (4,100 ft) and a cutoff boundary of 200°C (392°F) indicate a narrow, easterly dipping resource approximately 800 m (2,600 ft) wide that is open to the west, as shown in Figure 9. GeothermEx (1991) projected subsurface temperatures along the KERZ using data from SOH-2 and SOH-4. This isotherm map does not reflect the shallow reservoir intersected by PGV's KS-7, KS-8, and KS-9 wells. Sufficient published data are not available to predict the vertical size and extent of the PGV reservoir.

ACKNOWLEDGEMENTS

This is the School of Ocean and Earth Sciences and Technology contribution number 3161.

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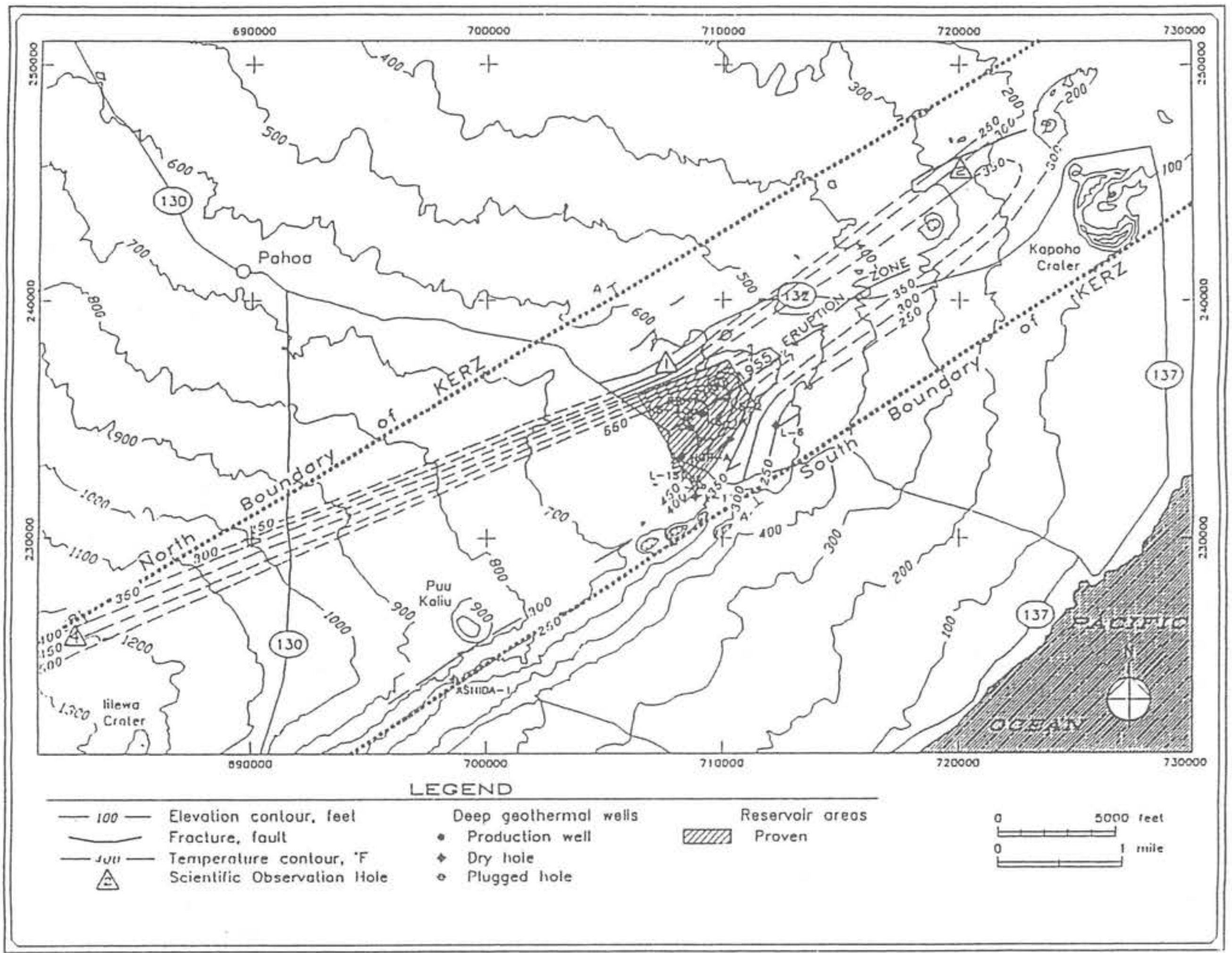

Figure 9. Outline of the HGP-A/PGV geothermal reservoir and subsurface temperatures along the Kilauea East Rift Zone. Temperature distribution at -1,220 m (-4,000 ft) mean seal level. After GeothermEx, 1991.

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Manuscript received 5 March 1993