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FY79 Lava Lake Drilling Program - Geoscience Studies; Plans and Results

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Sandia Laboratories

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FY79 LAVA LAKE DRILLING PROGRAM - GEOSCIENCE STUDIES; PLANS AND RESULTS

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ABSTRACT

Fifteen experimental studies were planned for the geoscience studies portion of the FY79 Lava Lake Drilling Program at Kilauea Iki Lava Lake, Hawaii, grouped under headings of petrologic, thermal, strength, liquid/permeability, electrical, and other. This report gives a location, purpose, description, and feasibility analysis for each experiment. A "Results" section for each experiment includes data gathered and analysis to date, where available. Later reports on completed data analyses and conclusions will be published as warranted.

CONTENTS

FY79 LAVA LAKE DRILLING PROGRAM - GEOSCIENCE STUDIES; PLANS AND RESULTS

I. INTRODUCTION

Sandia Laboratories' interest in drilling into molten rock stems from the Magma Energy Research Project (Stoller and Colp, 1978) presently being conducted under the Department of Energy/Division of Basic Energy Sciences sponsorship. The objective of this project is to assess the scientific feasibility of extracting energy directly from buried circulating magma resources. Among the tasks of that project are the development, demonstration, and verification of exploratory techniques for locating and defining buried molten rock resources. In March 1975, a workshop co-sponsored by Sandia and the United States Geological Survey (USGS) of about thirty scientists was convened to assess the present state of knowledge on magma and to recommend critical needs for research (Colp et al., 1975). A major recommendation of this group was to evaluate geophysical techniques over a "known" molten rock body.

The lava lake in Kilauea Iki (K.I.) crater, located in the Hawaii Volcanoes National Park on the Island of Hawaii, believed to have a still-molten lens from the 1959 eruption, was chosen as the site for a Lava Lake Sensing Experiment sponsored by Sandia in early 1976 (Hermance, Forsyth, and Colp, 1979). The evaluation of the abilities of the various geophysical sensing systems used in that experiment to correctly detect and define the buried molten lens required the drilling of a series of holes into and through it. Permission was granted by the National Park Service for Sandia and the USGS Hawaiian Volcano Observatory (HVO) to drill a series of 15 confirmation holes.

Eleven holes had been drilled into the upper crust of Kilauea Iki lava lake by the USGS and others between the years 1960 to 1975 as part of the Survey's continuing scientific study of lava lake characterization. In 1976, Sandia/HVO drilled two holes as part of the Magma Research Project. The drilling of these holes and the results obtained are described by Colp and Okamura (1978). From that experience and the problems encountered, a Lava Lake Drilling Program was planned (Colp and Traeger, 1979) and was conducted from November 1978 through February 1979. Six new holes were drilled and two existing holes were re-entered and deepened (Traeger, Colp, and Neel, 1979).

The FY79 Lava Lake Drilling Program was divided into two complementary parts, Drilling Technology experiments described by Neel, Striker, and Curlee (1979), and Geoscience studies described in this report.

Fifteen experimental studies were planned for the Geoscience studies portion of the FY79 Lava Lake Drilling Program. These individual experiments can be grouped under: (1) petrologic studies, (2) thermal studies, (3) strength studies, (4) liquid/permeability studies, (5) electrical studies, and (6) other studies. The experiments under each group will be presented in the following general format:

Location
Purpose
Description
Feasibility
Results

The "Results" section will include experimental data gathered and analysis to date where available. It is the intent of this publication to be a timely report of the work done and the information obtained. Individual, later reports on completed data analyses and conclusions will be published as warranted.

II. PETROLOGIC STUDIES

Core Collection and Logging

Location

Boreholes K.I. 79-1 through 79-6 and parts of K.I. 75-1 and 76-2 (Figure 1).

Purpose

The object of these operations is to obtain the maximum footage of properly logged, identified, photographed, and stored borehole cores for the following purposes:

1. To obtain a history of the solidified crust over a large area of Kilauea Iki lava lakes.

2. To determine the thickness of the crust over the molten lens to assess the topology of the upper surface of the molten lens.

3. To provide logged core samples of the crust to experimenters within the USGS and others as required for petrological, geochemical, etc., studies.

Background - The USGS HVO has obtained and stores cores from all the previous holes that have been drilled into the Hawaii lava lakes. These valuable cores have been used in many studies of the life-histories of lava lakes and of the solidification of basaltic lavas.

Description

Configuration -- These experiments will utilize the Longyear HC-150 drill rig and the HCQ wireline coring equipment. All equipment will be furnished and operated by the drilling contractor.

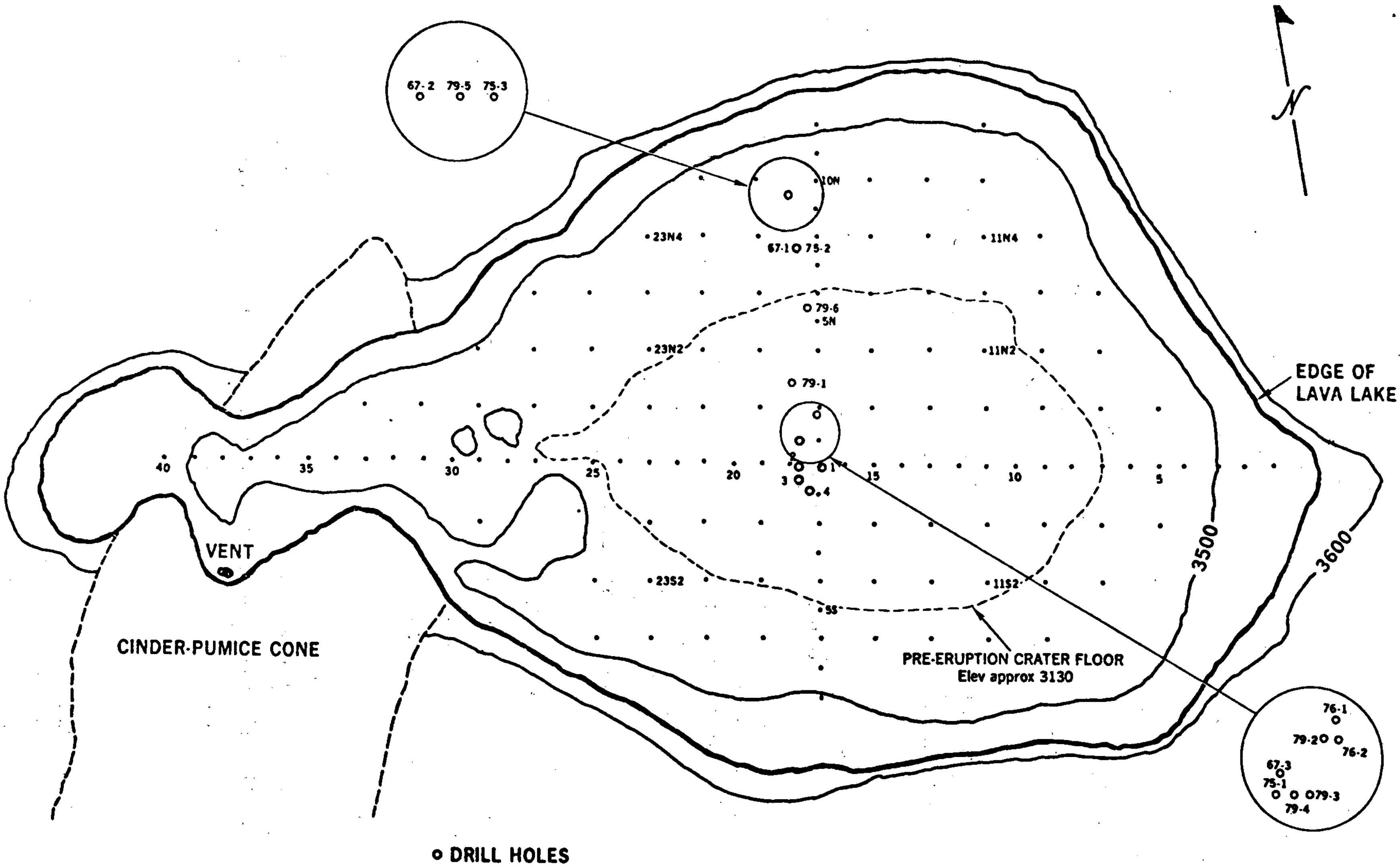

Figure 1. Kilauea Iki Lava Lake Borehole Locations

Operation Plan -- All new boreholes will be located as shown on Figure 1. The actual placement of the borehole may vary a few feet from the location shown due to surface topography. If different, the exact location will be measured and recorded in the experiment log. Each borehole will be drilled and continuously cored to the molten rock surface (1067°C isotherm) or as deep as possible. Each section of retrieved core will be placed in an appropriate core box, labeled as to vertical location, visually examined, and the description noted in the borehole core log book. The filled core boxes will be taken to the USGS HVO, photographed, and stored for future use.

Feasibility

These experiments involve no unusual equipment or techniques, but follow common practice established in previous lava lake borehole experiments. For these reasons, it is concluded that these experiments are feasible.

Results

Approximately 410 m of HCQ core (6.35 cm dia) was collected, logged, photographed, and delivered to the HVO for storage and distribution. Table 1 shows the hole location, drilling dates, core interval, and total length of the cores collected. The preliminary logs of the cores were made by HVO geologists N. Banks, T. Casadevall, and R. Moore and by Prof. Kurt Servos, Menlo College. Copies of these logs are available at the HVO. The cores have been photographed in the core boxes by HVO personnel and copies of these photographs can be obtained from them.

Visual petrologic observation and detailed logging of the collected cores will be made and reported by Drs. Rosalind Tuthill Helz and Tom Wright, USGS National Center, at a later date.

TABLE 1

Sandia/USGS FY79 Kilauea Iki Lava Lake Core Collection Summary
(All Cores HQ, 6.35 cm dia)

Hole No.	Drilling Dates	Core Interval Depth (m)	Total Length (m)
K.I. 75-1 Reentry	12/8-11/78	40.2-52.7	12.5
K.I. 79-1	12/13-21/78	0-61.9	61.9
K.I. 79-1 Redrill	1/25-27/79	50.6-54.3	3.7
K.I. 79-2	12/28/78-1/5/79	0-50.6	2.8
K.I. 79-2 Redrill	1/5/79	46.9-50.0	3.1
K.I. 79-3	1/8-10/79	0-52.7	52.7
K.I. 79-3 Redrill	1/11/79	48.8-51.8	3.0
K.I. 79-4	1/12-16/79	0-52.4	52.4
K.I. 79-5	1/30-2/9/79	0-100.9	100.9
K.I. 79-6	2/10-14/79	0-57.9	57.9
K.I. 79-6 Redrill	2/14/79	48.5-57.3	8.8
			410.3

Sandia personnel have begun preliminary petrologic studies of selected samples of the cores from K.I. 79-1, K.I. 79-2, K.I. 79-5, and K.I. 79-6. Figure 2 shows a suite of polished core sections from K.I. 79-6 illustrating the abundance of olivine crystals at depths just above the melt vein encountered at 190 ft (57.9 m). A preliminary analysis of a core section from K.I. 79-1 at a depth of 202 ft (61.6 m) showed an olivine crystal content of 40% and a glass content of 60%. Figure 3 shows a photograph of this core interval just after it was collected. The corrugated outer surface indicates its plastic (near-molten) condition when suddenly chilled by the drilling water and moved into the core barrel.

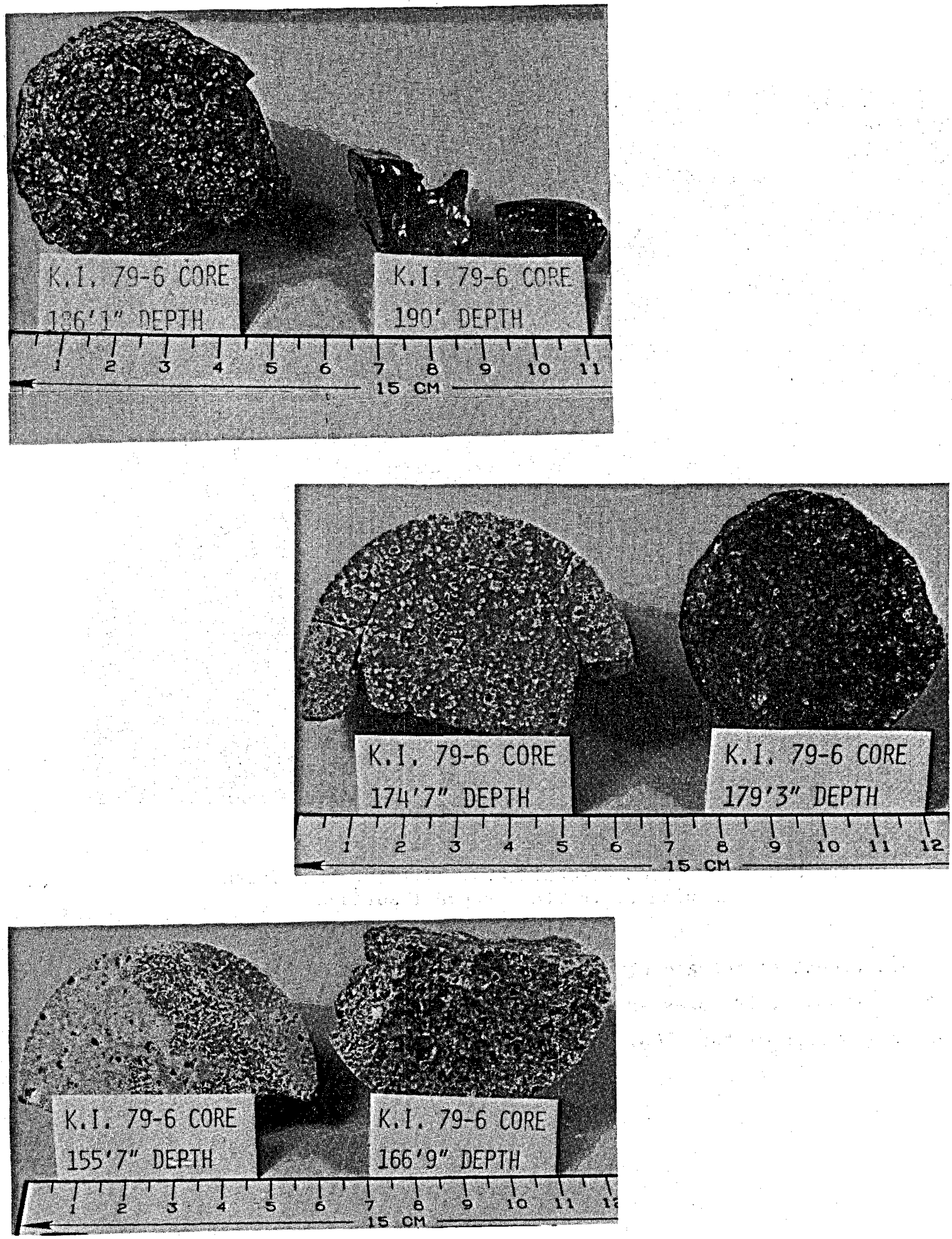

Figure 2. Polished Core Sections, K.I. 79-6

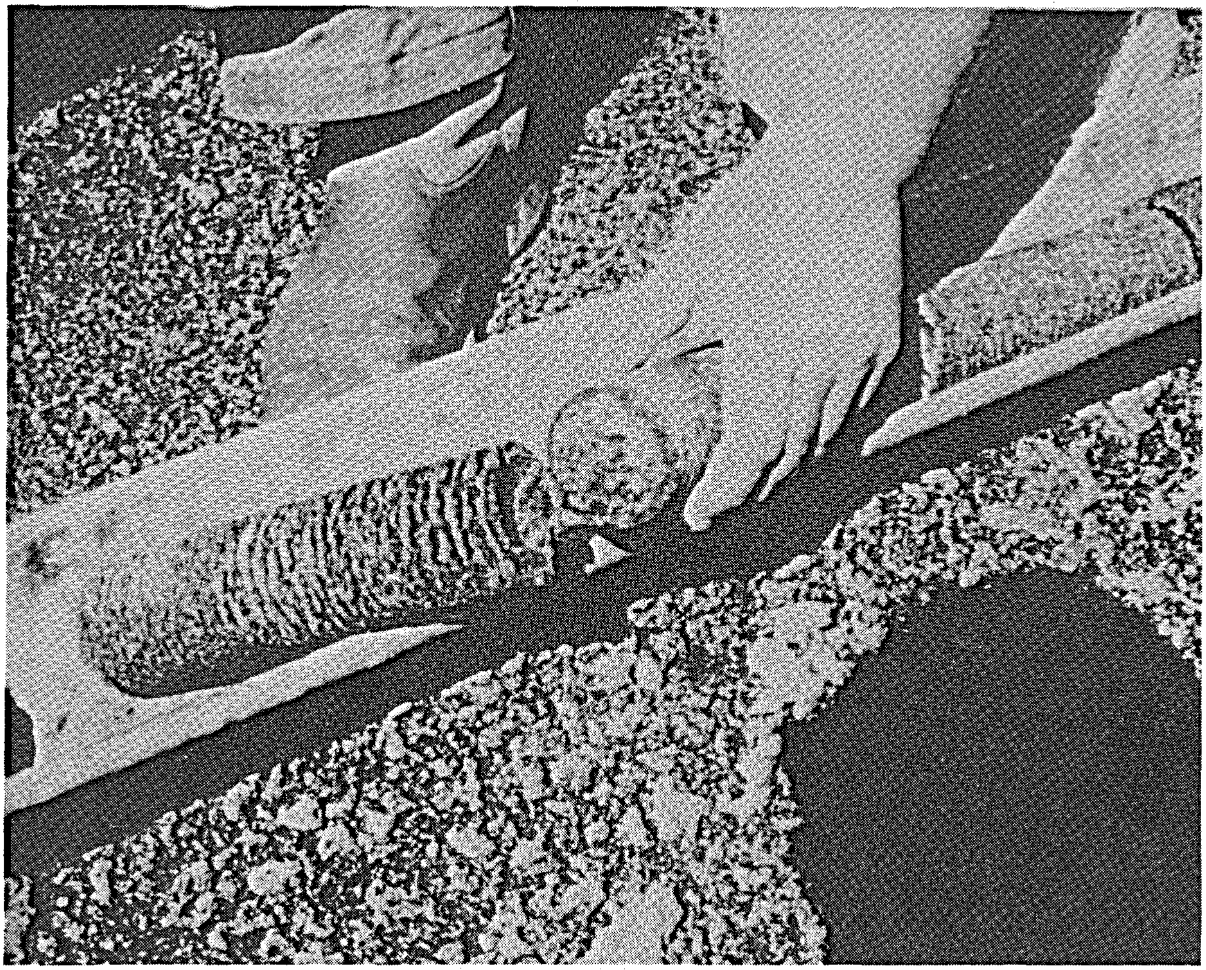

Figure 3. Core From Borehole K.I. 79-1 (~ 61 m depth)
Showing Corrugated External Surface

Additional petrologic studies as well as physical property measurements on the K.I. 79 cores are planned in cooperation with Dr. R. Helz and other scientists of the USGS.

III. THERMAL STUDIES

Cased Hole Temperature Profile Experiment

Location

Borehole 75-1

Purpose

The purposes of this experiment are:

1. To measure the rock temperature profile as deeply as possible through the upper solidified crust of Kilauea Iki lava lake on a continuing basis.

2. To compare the stable temperature profile of the same borehole in an uncased status and after a closed bottom casing is installed in intimate contact with the borehole rock.

Background -- For many years, the USGS HVO has been measuring temperature profiles in existing open boreholes in Kilauea Iki and other Hawaiian lava lakes. The standard technique is to lower a chromel-alumel thermocouple junction down an open, uncased borehole filled with upflowing gas (steam, etc). The thermocouple measures the gas temperature at the various levels selected. One of the objectives above is to determine the correlation of the gas column temperatures with the actual rock temperatures measured in a closed bottom steel pipe that is stemmed into intimate contact with the rock walls of the borehole using vibrated basalt sand.

Description

Configuration -- After the successful completion of the borehole ooze penetration test described elsewhere, a bottom sealed 1-1/4 IPS

Schedule 40S Type 316 stainless steel pipe will be assembled and lowered to the bottom of borehole K.I. 75-1. This casing (pipe) will be suspended from the surface by means of a clamp plate. Using a 3/4-in.-dia galvanized water pipe as a tremie, finely crushed basalt sand will be packed around the full length of the casing to bring it into intimate contact with the borehole rock walls. During the sand installation, a concrete vibrator will be attached to the top of the casing to assist in sand compaction.

After installation, the Type 316 casing will be used in downhole temperature profile measurements. A Sandia-fabricated and calibrated 200-ft-long inconel-sheathed thermocouple assembly with a stainless steel bottom probe similar to the USGS HVO design and a portable Doric Trendicator digital readout instrument will be used to make the temperature measurements.

Operation Plan --

1. The downhole temperature profile of the open, uncased borehole will be periodically measured and manually recorded using the stainless steel probe, the inconel-sheathed thermocouple, and the Doric Trendicator described above until a stable profile is reached.

2. The Type 316 stainless steel, bottom-closed casing is installed and sand-stemmed in place as described above.

3. Step (1) above is repeated inside the closed, stemmed casing until a stable profile is reached.

Feasibility

Analysis of Feasibility -- Temperature measurements in lava lake boreholes using surface-lowered thermocouple probes is a standard technique used for many years. Installation of a steel tube casing and stemming it into intimate contact with the borehole walls uses standard techniques. For these reasons, it is concluded that this experiment is feasible.

Critical Parameter Calculations -- Many years of experience indicates that there are no critical parameters involved in the apparatus used to make borehole temperature profiles. Small diameter (1/8 in.) inconel-sheathed chromel-alumel thermocouple wire which is commercially available has been used successfully.

The selection of the tubing to be used as the borehole casing for this experiment considered two critical parameters, corrosion and high temperature. Although the actual downhole gas environment in a Kilauea Iki borehole at this time has not as far as we know been measured, T. Gerlach, Division 5831, has computed a typical freshly erupted basaltic magma gas composition. (This computed gas environment most probably is much more severe from a corrosion standpoint than the actual current Kilauea Iki borehole environment.) P. J. Modreski, Division 4831, conducted a series of laboratory tests on the corrosion of material samples immersed in molten basalt with the Gerlash-computed gas environment flowing over it. The results of these probably too-conservative tests indicated that Type 316 stainless steel alloy was satisfactory in this high temperature/corrosive environment. Type 316 stainless steel tubing was selected for this application because of its high temperature/corrosion resistance, availability, and price.

Hardware Sizing Calculations -- The minimum diameter of the Type 316 stainless steel casing was dictated by the diameter of the thermocouple probe. It was decided to use the same probe diameter as that currently used by the USGS HVO (3.3 cm). Accordingly, the casing size selection was 1-1/4 IPS Schedule 40S pipe having an inside diameter of 1.38 in. (3.5 cm).

Results

Temperature profile measurements in drill hole 75-1 before and after casing of the hole have shown that the casing has no noticeable effect on temperature measurements in the lower conduction zone of the crust (Figure 4). In the upper two-phase zone of recently drilled holes, however, the temperature measurements in uncased holes are not representative of the true crust temperature. In this instance, the thermocouple in the hole is significantly affected by the flow of superheated steam originating from water used during the drilling operation. True crust temperatures in the two-phase zone can be obtained only by installing a casing or by waiting 1 or 2 months until all the perturbations created by the drilling water are dissipated.

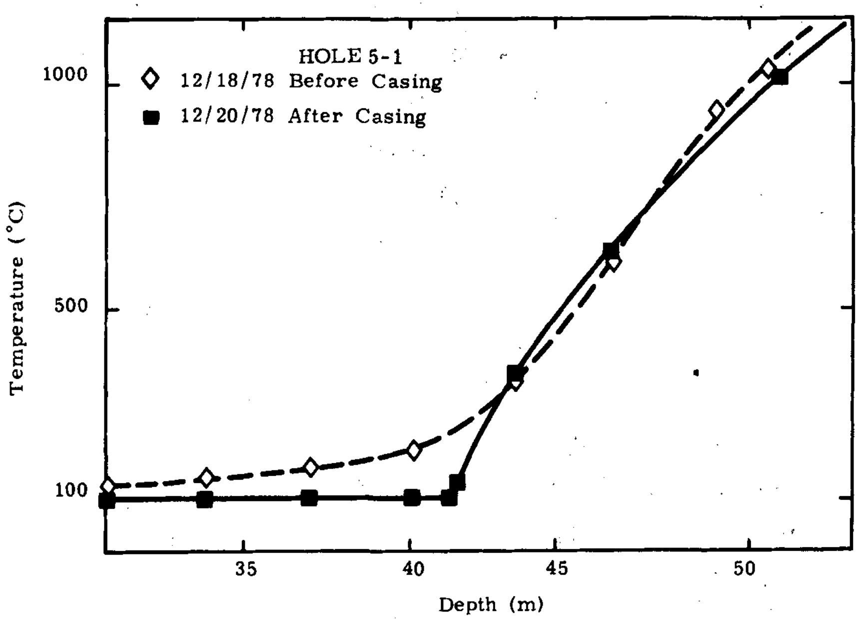

Figure 4. Effect of a Bottom Sealed Casing on the Temperature Profile of Borehole K.I. 75-1

Borehole Temperature/Rainfall Experiment

Location

Borehole K.I. 75-1

Purpose

The purpose of this test is to observe the effect of rainfall at the borehole on the downhole temperature profile.

Background -- Although there have been a large number of borehole temperature profile measurements made in Kilauea Iki since 1960, there are no series which have been made on a regular schedule over an extended time, nor are there any which have been made with a rainfall measurement at the borehole. Some studies of lava lake crust solidification rates have included the amount of rainfall as a factor. This experiment will provide data of value to those studies.

The upper crust of a lava lake such as Kilauea Iki can be considered as an analog model of a hydrogeothermal system in which the location of the heat source is known. It has been suggested that a detailed temperature/rainfall study (this experiment) could provide valuable insight to the thermodynamics/hydrology of an operating hydrogeothermal system.

Description

Configuration -- A standard rainfall gage will be installed immediately adjacent to borehole K.I. 75-1. Downhole temperature profiles will be measured and manually recorded down the stainless steel casing that has been previously installed in borehole K.I. 75-1 and described elsewhere.

Operation Plan -- Measurements of rainfall and downhole temperature profile will be manually recorded daily for the duration of the

Sandia/USGS Lava Lake Drilling Program. Arrangements will be made with the USGS/HVO to continue making the measurements on some regular schedule after that date.

Feasibility

Analysis of Feasibility -- Downhole temperature profiles have been successfully made in Kilauea Iki boreholes for the past 18 years. It is concluded that this experiment is feasible.

Results

A sharp discontinuity in the slope of the temperature profiles occurs at the boundary between the two-phase zone and the conduction zone where the temperature departs from the boiling point. The depth to this boiling departure point was measured over a period of several days (Table 2). Daily variations of as much as 1/2 m were recorded, and over a period of several days (during a period of heavy rainfall) this point shifted downward over 2 m.

The crust of Kilauea Iki lava lake currently consists of an upper, porous two-phase convection zone 41 m thick and a lower conduction zone 12 m thick extending to the melt. The crust has been solidifying at a near-constant rate of 6.7×10^{-8} m/s for the past 12 years. The thickness of the lower conduction zone has been relatively constant during this period (Figure 5). Temperature profiles in the lower conduction zone have a curvature that can be explained in terms of a moving solidification-front conduction solution. Recent temperature profiles (Figure 6) show the predicted reversal of curvature where solidification has ceased.

TABLE 2

Variations in Depth to Boiling Departure Point in Borehole K.I. 76-1

Depth to Boiling Departure Point (m)	Time	
37.5	12/11/78	1:17 p.m.
37.5	12/12/78	9:27 p.m.
38.7	12/12/78	2:18 p.m.
38.1	12/13/78	8:39 a.m.
39.6* (bottom of hole)	12/19/78	10:51 a.m.
39.6	12/19/78	11:30 a.m.

*Depth of two-phase circulation zone increased 2 m during a week of heavy rainfall ($\approx$ 1 inch/day).

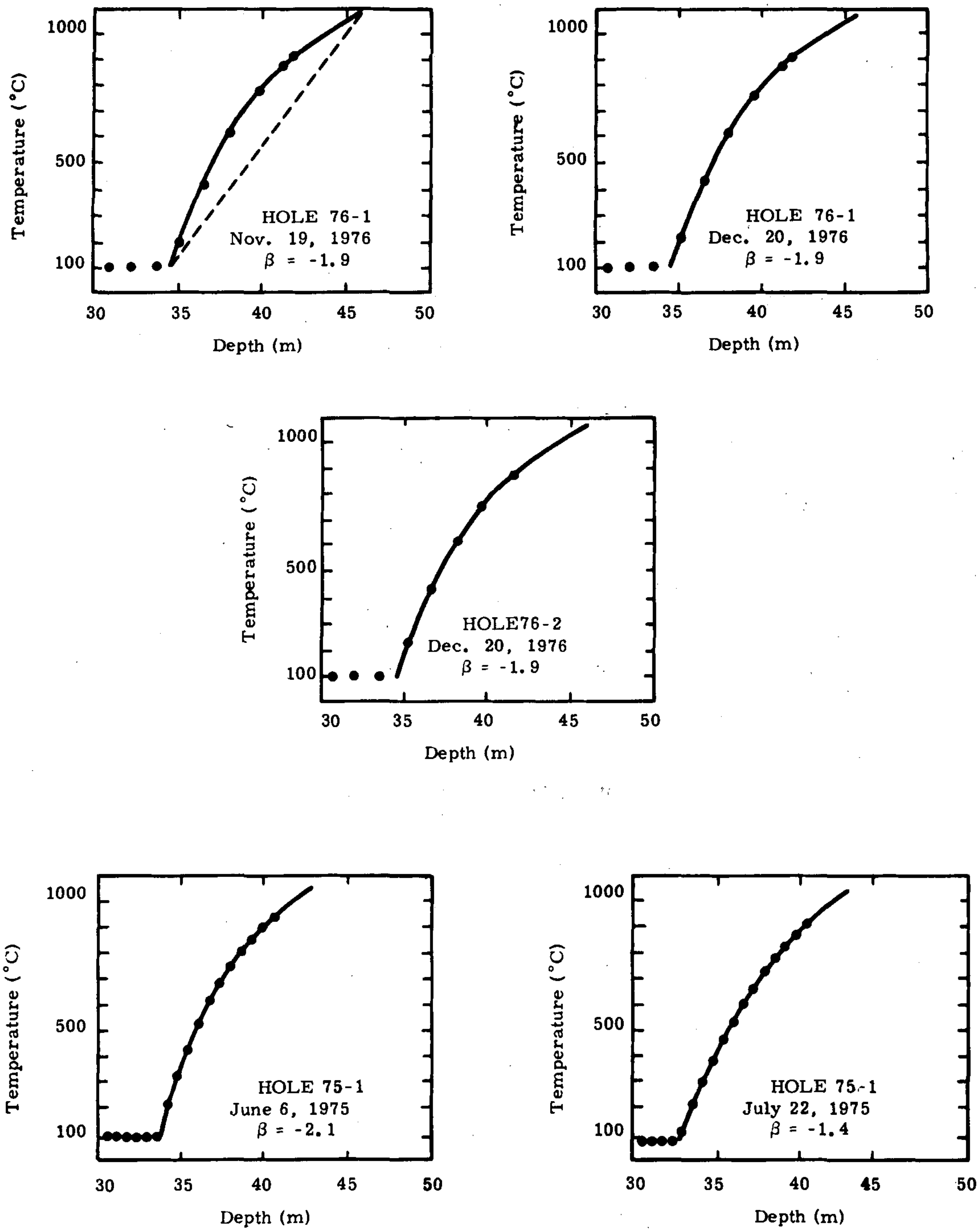

Figure 5. Past Records of Temperature Profiles in Kilauea Iki Boreholes

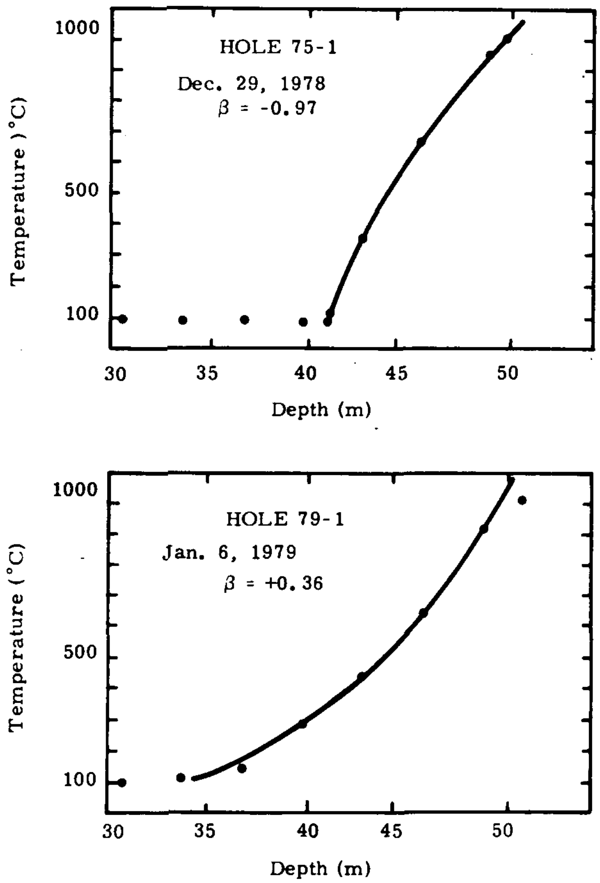

Figure 6. Temperature Profiles of Kilauea Iki Boreholes Showing Curvature Reversal

For further information, discussion and analyses, see topical report SAND78-2059V, Hardee, H. C., Solidification in Kilauea Iki Lava Lake, accepted for publication in Journal of Volcanology and Geothermal Research.

Figures 7 through 13 show records of borehole temperature profiles measured during and after the FY79 Lava Lake Geoscience Experiments.

A total of 58.77 in. (1492.73 mm) of rainfall in Kilauea Iki crater was measured from December 5, 1978 to February 17, 1979 (Table 3).

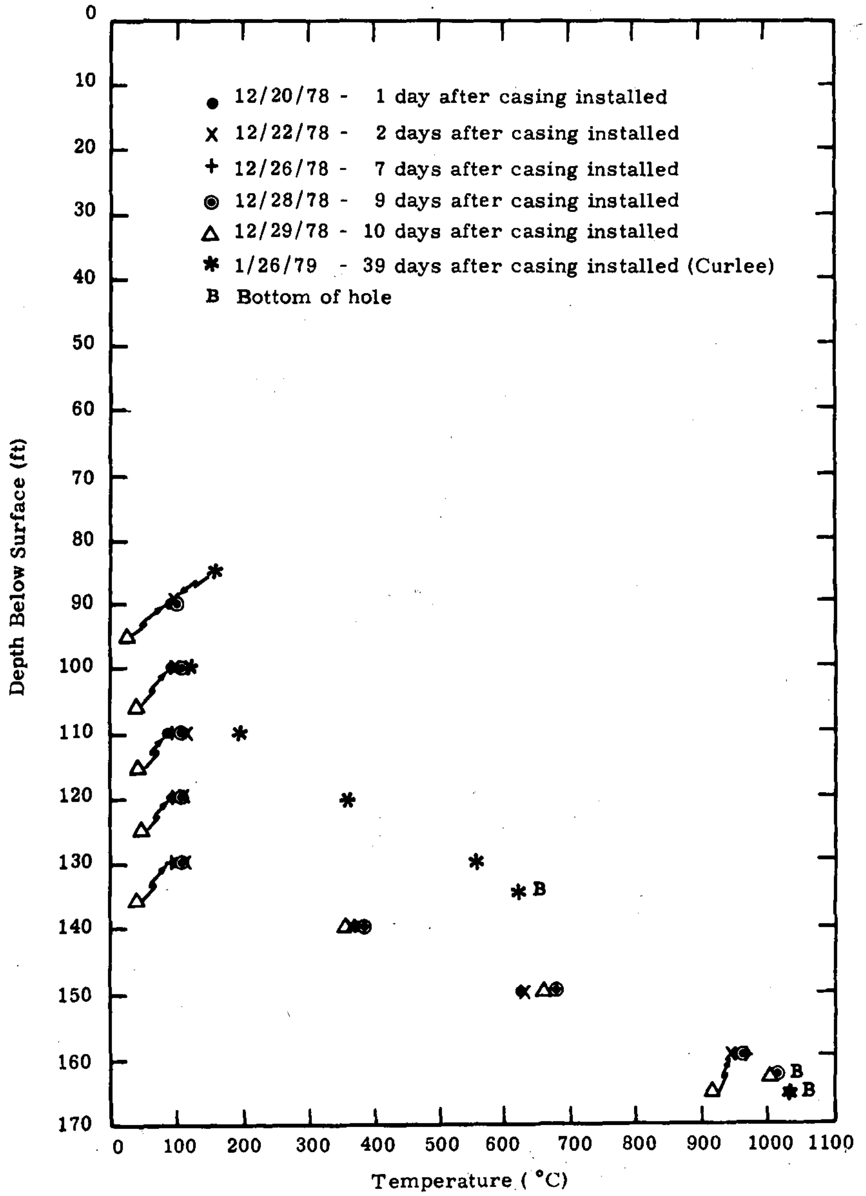

Figure 7. Borehole Temperature Profile K.I. 75-1 (cased)

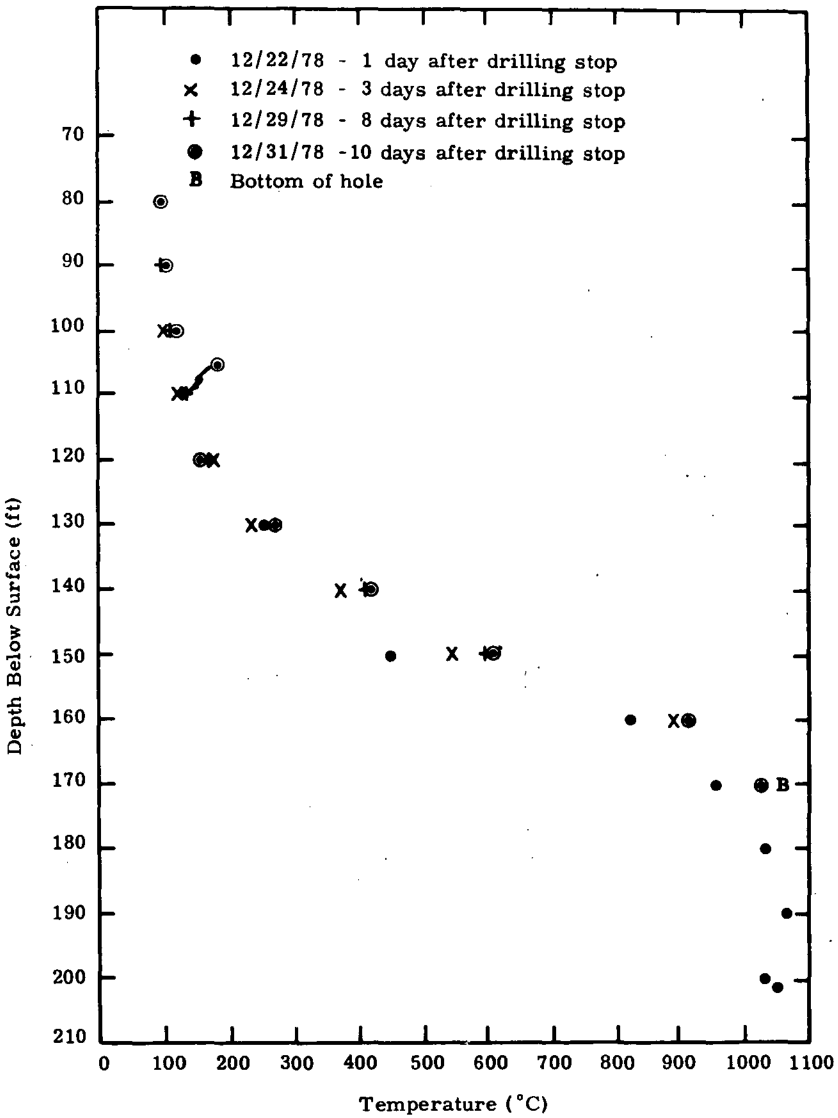

Figure 8. Borehole Temperature Profile K.I. 79-1

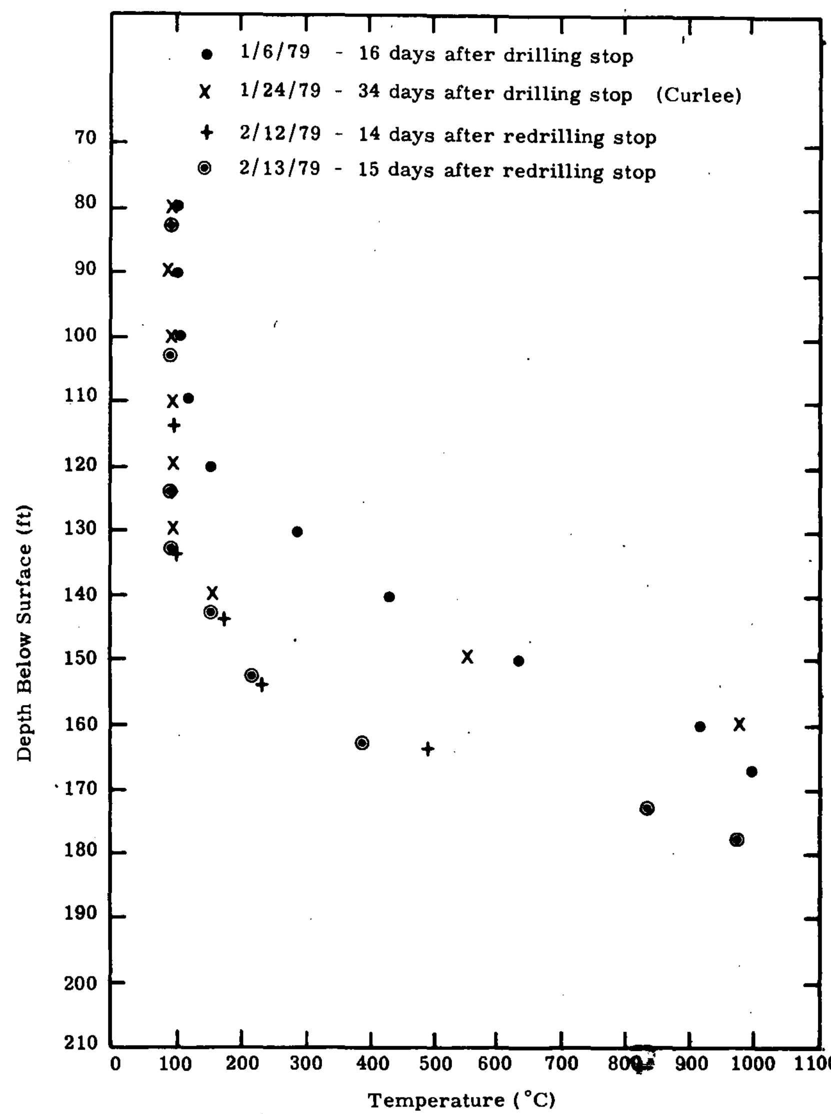

Figure 9. Borehole Temperature Profile K.I. 79-1

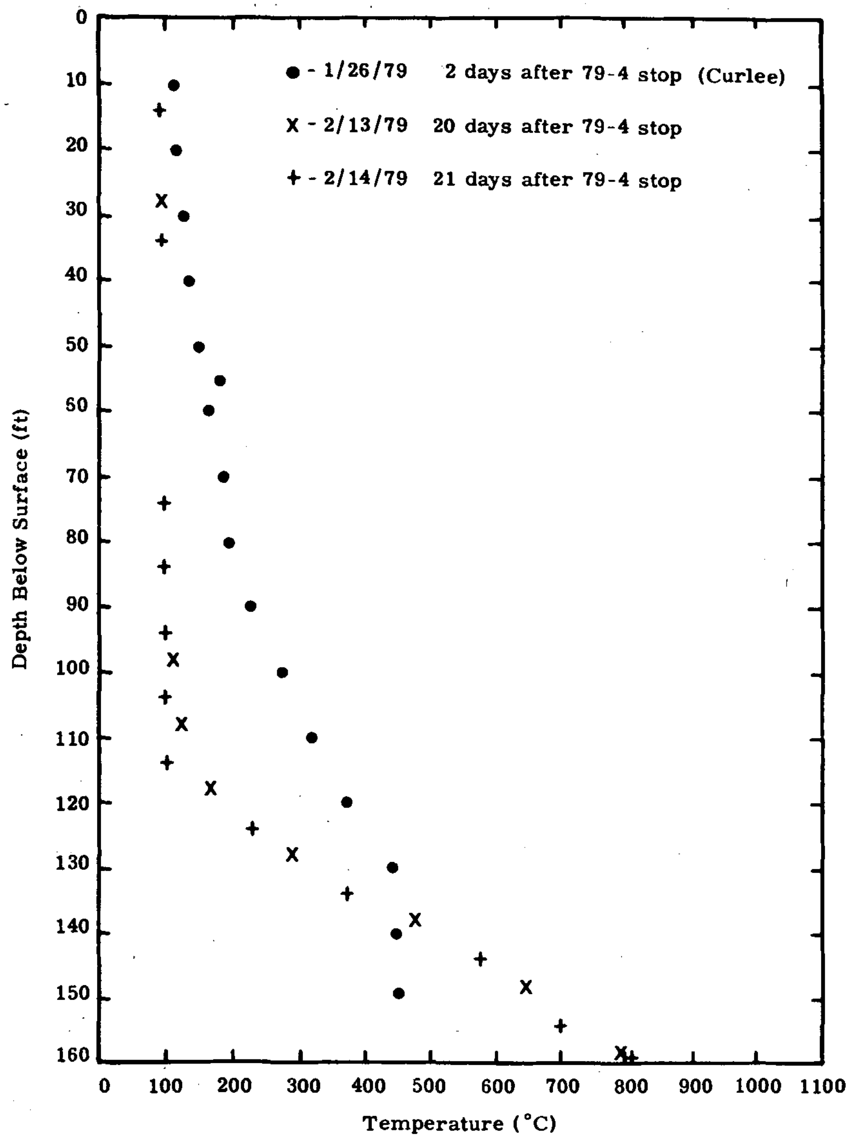

Figure 10. Borehole Temperature Profile K.I. 79-3

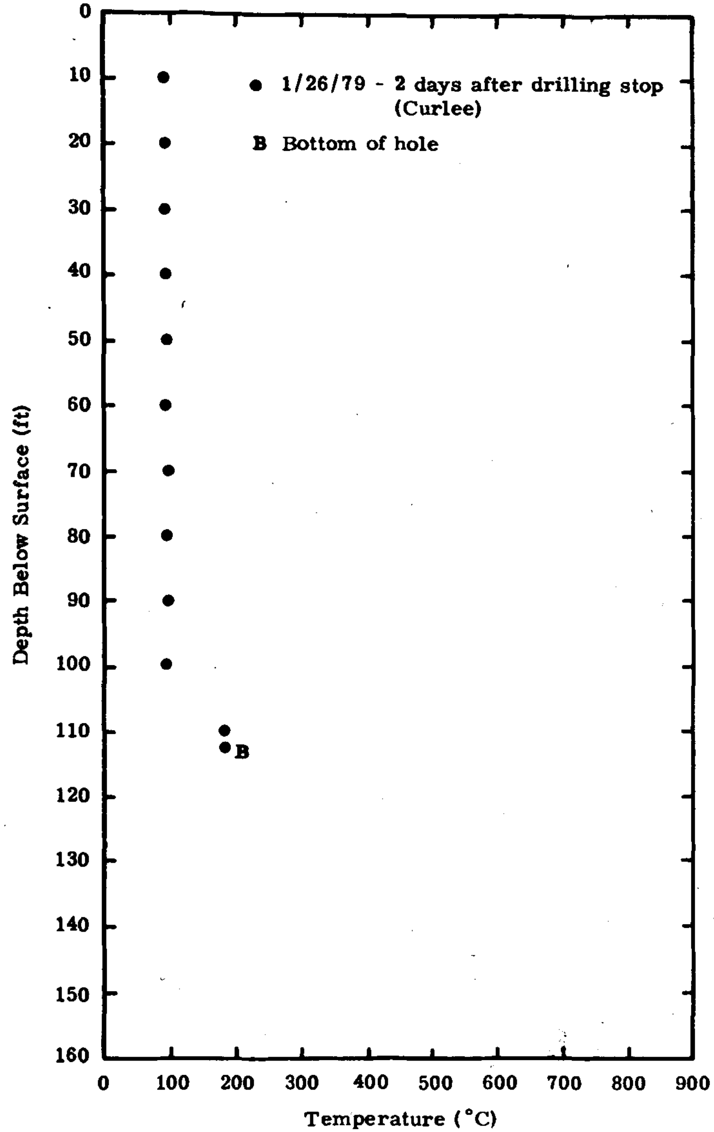

Figure 11. Borehole Temperature Profile K.I. 79-4 (cased)

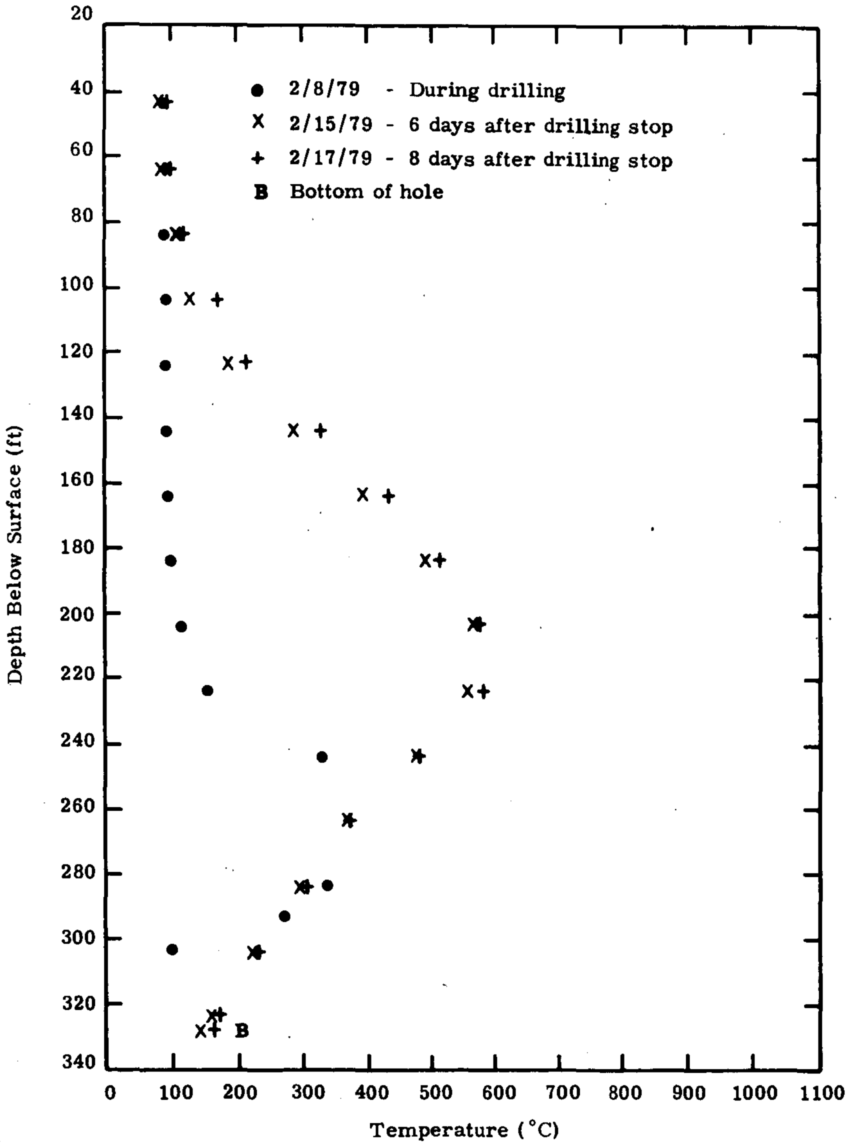

Figure 12. Borehole Temperature Profile K.I. 79-5

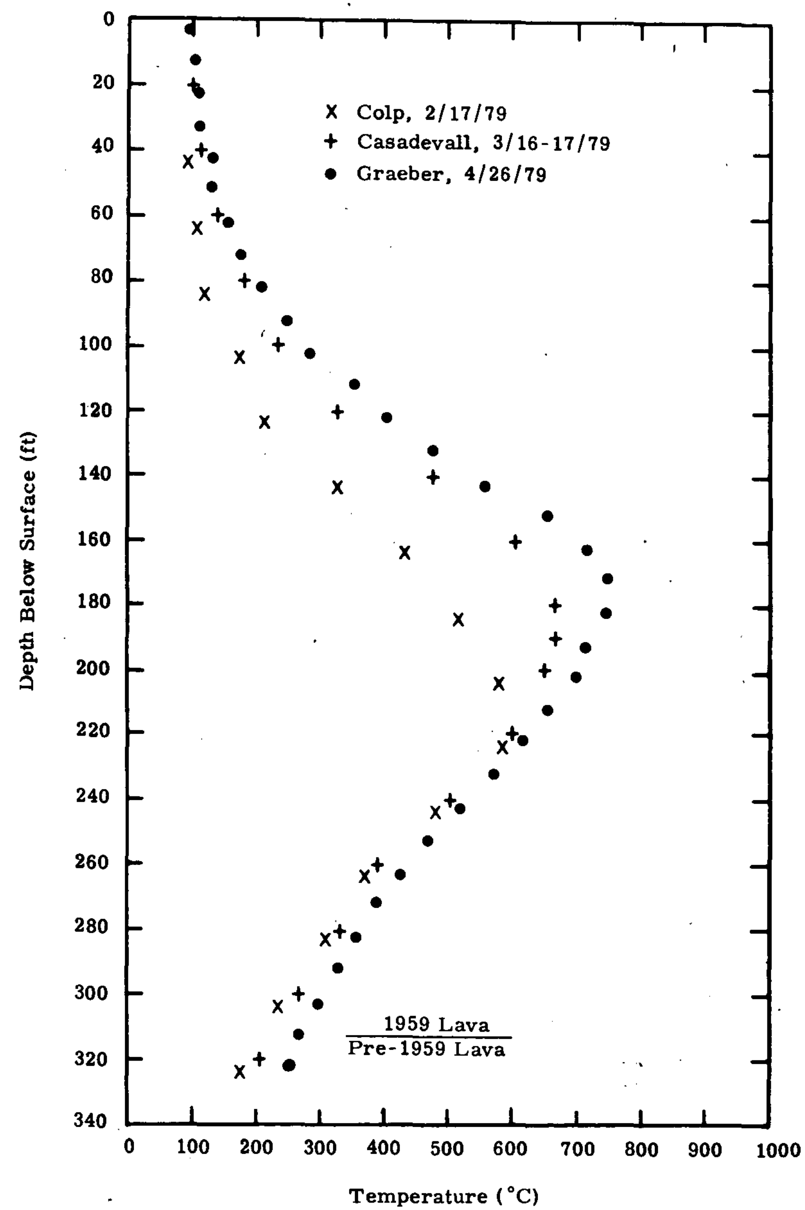

Figure 13. Borehole Temperature Profile K.I. 79-5

TABLE 3

Kilauea Iki Rainfall Data

Date	Rainfall (in.)	Rainfall (mm)	Date	Rainfall (in.)	Rainfall (mm)	Date	Rainfall (in.)	Rainfall (mm)
12/5/78	0.00	0.00	12/22/78	0.00	0.00	1/13/79	5.40	137.16
12/6/78	0.33	8.38	12/24/78	0.03	0.87	1/15/79	4.00	101.60
12/7/78	0.25	6.35	12/26/78	0.00	0.00	1/17/79	4.80	121.92
12/8/78	0.03	0.76	12/27/78	0.01	0.25	1/22/79	0.20	5.08
12/9/78	0.80	20.32	12/28/78	0.00	0.00	1/23/79	6.96	176.78
12/10/78	1.04	26.42	12/29/78	0.00	0.00	1/26/79	1.35	34.29
12/11/78	0.16	4.06	12/31/78	0.00	0.00	2/6/79	22.0	558.80
12/12/78	1.14	28.96	1/1/79	0.00	0.00	2/7/79	0.03	0.86
12/13/78	0.41	10.41	1/2/79	0.00	0.00	2/10/79	0.70	15.24
12/15/78	1.06	26.92	1/3/79	0.00	0.00	2/12/79	1.20	30.48
12/16/78	0.61	15.49	1/5/79	0.00	0.00	2/13/79	0.13	3.30
12/18/78	1.86	47.24	1/6/79	0.00	0.00	2/15/79	0.72	18.29
12/19/78	0.50	12.70	1/8/79	0.04	1.02	2/16/79	0.28	7.11
12/20/78	1.02	25.91	1/10/79	0.00	0.00	2/17/79	0.20	5.08
12/21/78	0.06	1.52	1/11/79	0.09	2.29			
						Total	58.77	1492.73

IV. STRENGTH STUDIES

Minimum Ooze Thickness Experiment

Location

Borehole 75-1 (see Figure 1)

Purpose

The purpose of this experiment is to determine the minimum thickness of solidified ooze in the bottom of a previously drilled borehole that will remain stable, i.e., will not flow or creep upward. This information is required for operational planning of a number of subsequent experiments to be performed during the Sandia/USGS Lava Lake Drilling Program. Some examples are the insulated drill system tests, the jet drill tests, the ooze penetration experiments, the ooze creep tests, and the electrical resistivity probe tests.

The information gained will also be of value to studies of the rheology of cooling basaltic lavas and future studies of access into real magma bodies.

Description

Apparatus Configuration -- The standard HC-150 drill rig and HCQ wireline coring barrel with water cooling will be used on this experiment. That equipment will be furnished by the drilling contractor.

Sandia will furnish a combination sounding weight and sheathed thermocouple 200 ft long with appropriate reel and hole guide roller. Thermocouple measurements will be read with a Doric digital trendicator instrument.

Operation Plan -- The following plan will be followed in the operation of this experiment (Figure 14):

1. Borehole 75-1 will be cleared and cored (HCQ-size) to the melt interface. The core will be collected and logged as described elsewhere. The melt depth will be noted.

2. The wireline apparatus will be removed and the drill string raised to a cooler portion of the hole as soon as possible after intercepting the melt interface.

3. The vertical elevation of the ooze column in the borehole and the adjacent borehole air temperature will be monitored and manually logged at ~15 min intervals until its upper surface has stabilized. The sounding weight and thermocouple can be lowered through the open drill string for this operation.

4. The drill string and coring equipment will be reinserted into the borehole and a 6 in. increment core of the solidified ooze will be removed and logged.

5. Steps (3) and (4) above will be repeated until a depth is reached at which the upper surface of the column of solidified ooze is unstable (i.e., when the ooze is observed moving up the borehole).

6. The depth reached at the last previous drilling increment will be used for definition of the minimum ooze thickness.

Feasibility

Many previous boreholes have been drilled successfully to the melt interface using conventional water-cooled drilling and coring equipment. Solidified borehole ooze was redrilled successfully to the melt interface at least three times previously in boreholes K.I. 76-1 and 76-2 (Figures 15 and 16).

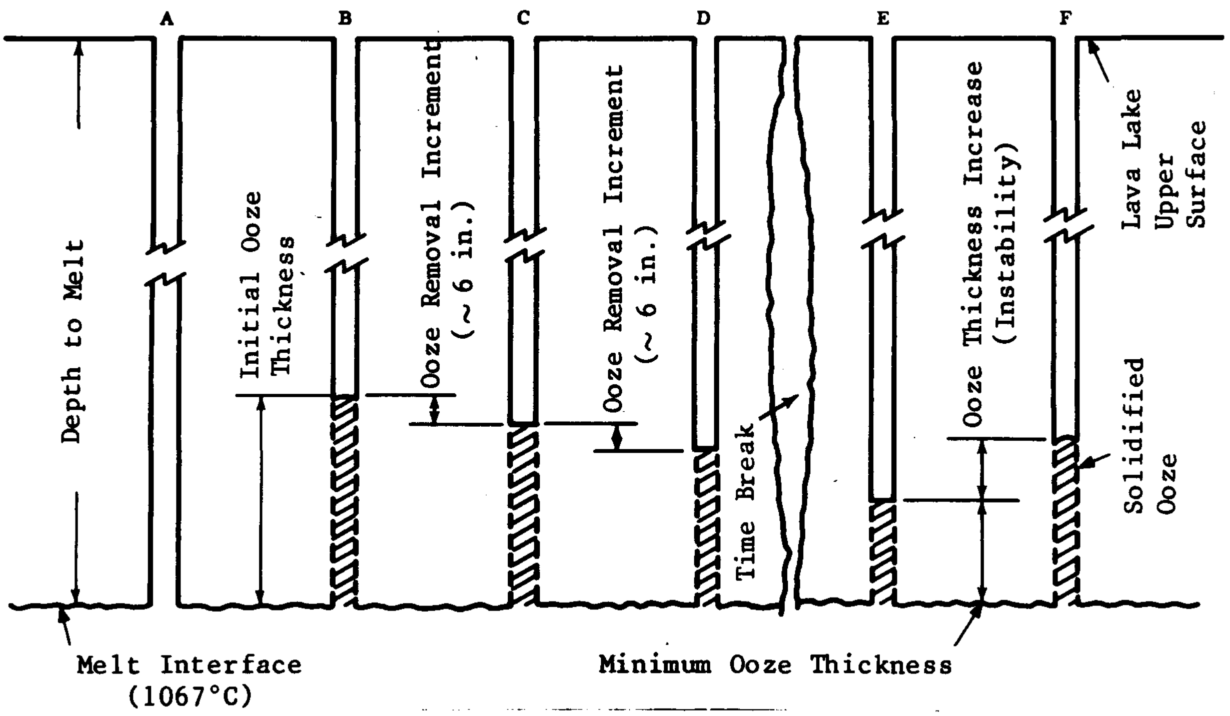

Figure 14. Minimum Ooze Thickness Drilling Sequence

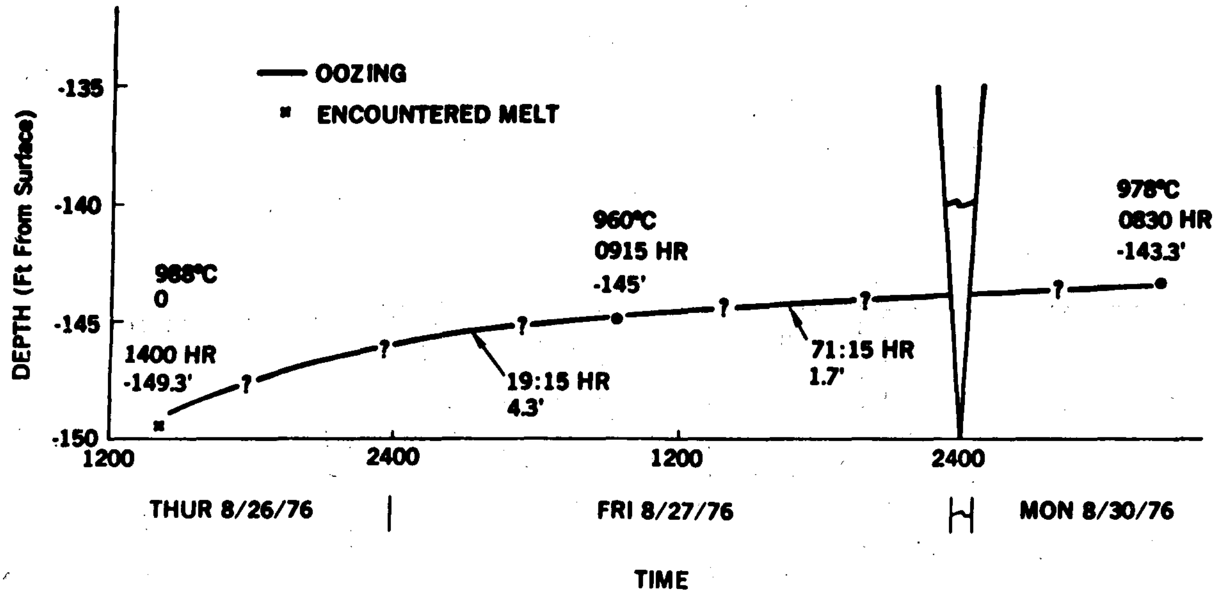

Figure 15. Borehole Kilauea Iki 76-1 Log

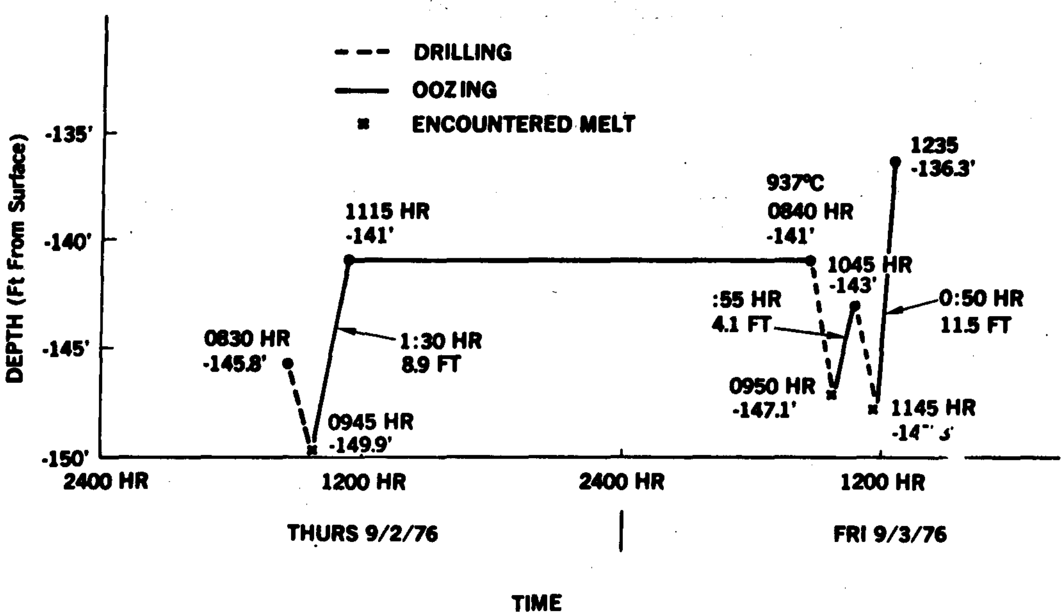

Figure 16. Borehole Kilauea Iki 76-2 Log

Considering the above experience, it is concluded that this experiment is feasible.

Results

Borehole K.I. 75-1 was cleared of debris and drilled to a depth of 172 ft 6 in. (52.6 m) without finding any evidence of molten rock. The hole bottom was stable at this depth for a period of 48 hours. Bottom hole temperature was 1059°C. Drilling was resumed on December 11, 1978, and the initial melt contact with the drill was made at a depth of 173 ft 1 in. (52.8 m). From these measurements it appears that approximately 7 in. (17.8 cm) thickness of undisturbed upper crust is strong enough to contain the liquid (molten) rock below it. (Note: At the time of drilling, this initial melt contact was thought to be with the top surface of a fairly substantial thickness of molten material. Later drilling determined that the melt contacted at this depth was a relatively thin vein--4 to 6 cm--of fluid glass similar to that shown in Figure 17.)

The drill bit coolant openings were plugged at the contact with the molten rock, preventing any cooling water from being pumped down hole to chill the up-flowing ooze (molten rock). The ooze was able to flow back up the borehole for a distance of 9 ft 0 in. (2.7 m) to a depth of 164 ft 1 in. (50 m) below the surface. Measurements over a 20 hour period showed the elevation of the ooze-back to be stable. The temperature was not measured at this time, but previous measurements indicated a formation temperature of 970°C at this elevation.

The operation plan to determine the minimum ooze thickness was initiated at this point. The first incremental drilling was completed to a depth of 168 ft 10 in. (51.5 m). Soundings of the bottom depth determined that this was a stable surface. The second incremental drilling was completed to a depth of 169 ft 5 in. (51.7 m), and the third to a depth of 170 ft 5 in. (52 m). These elevations were also found to be stable.

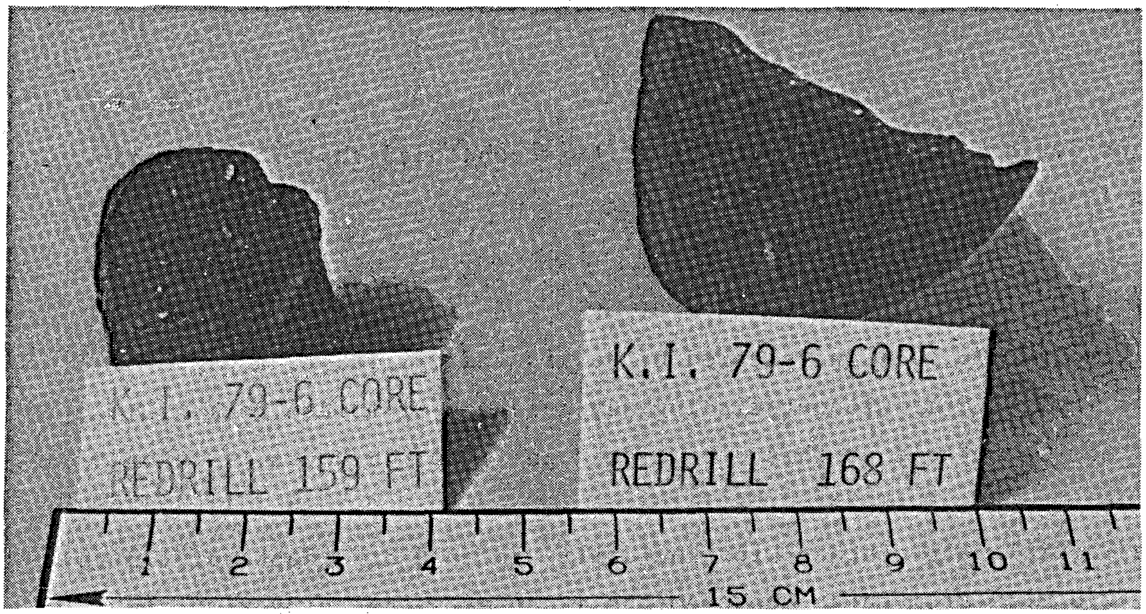

Figure 17. Polished Sections of Core Samples of Ooze-Back Into Kilauea Iki Boreholes

Because of drilling time schedules, it was decided to proceed with the ooze penetration test to be described later. During the preparation for this test, a tempered steel chuck jaw from the drill rig fell into the borehole and could not be recovered, resulting in the hole being abandoned at that time. Table 4 summarizes the foregoing sequence of operations.

Even though this experiment was not fully completed as planned, the following information was gained:

1. Upper crust material 7 in. (17.8 cm) thick at a temperature of $>1059°C$ was sufficiently strong to hold back the fluid pressure of molten rock that later flowed up the borehole for a distance of 9 ft 0 in. (2.7 m).

2. Ooze-back material 2 ft 8 in. (0.8 m) thick at a temperature $> \sim 1040°C$ was sufficiently strong to hold back the fluid pressure from the vein below. (Note: Observations from later drillholes indicate that the solid thickness of this ooze-back column may have been as small as 10 to 18 in. (25 to 46 cm).)

TABLE 4

K.I. 75-1 (Redrill)

Date	Time	Operation	Depth (ft)	Depth (in.)	Condition
12/11/78	12:40	Started drilling	172	6	7 in. undisturbed rock is stable
	12:59	Initial melt contact. Tripped out	173	1	Bit plugged. Depth to initial melt
	13:28	Sounded bottom	164	1	
	14:09	Sounded bottom	164	1	Ooze stable
12/12/78	09:25	Started drilling	164	1	Ooze stable. Ooze-back = 9 ft 0 in. from melt
	10:00	Tripped out	168	10	
	11:30	Sounded bottom	168	6	Ooze stable
	11:38	Tripped out	169	6	
	12:20	Sounded bottom	169	9	Ooze stable
	12:41	Started drilling	169	5	Ooze stable
	12:50	Tripped out	170	5	
	13:07	Started to lower penetrator			Dropped chuck jaw
	14:10	Sounded bottom	170	3	Ooze stable. Thickness = 2 ft 8 in. from melt
	16:30	Tripped out			Abandoned hole
12/14/78	09:00	Sounded bottom	169	10	Ooze stable

Borehole Ooze Penetration Experiment

Location

Borehole 75-1

Purpose

The objective of this experiment is to obtain empirical in situ data on the rate of penetration of a pointed rod into the solidified molten rock that has flowed back up a borehole in order to:

1. Study the rheology of high temperature basalt under high loading rates.

2. Determine if ooze penetration is a viable method for securing entry into a molten rock body overlain by a solidified crust for purposes of making measurements of physical parameters, energy extraction, etc. Some questions that need answers are:

    a. Can the penetrator be pushed through ooze?

    b. Can the penetrator be rotated during pushing?

    c. Can the penetrator be rotated after melt is entered?

    d. Can the penetrator be stopped and restarted during pushing?

    e. Can the penetrator be removed after melt is entered?

    f. Does melt freeze the penetrator after entrance?

3. Study the thermal effects of ooze solidification up the borehole. For example, does the solidified ooze column have a more or less plastic center at some depth?

4. Study the life history of solidifying molten rock bodies. Does age influence ooze penetrability?

Background -- The USGS has successfully pushed through borehole ooze during investigations conducted on young lava lakes, i.e., those with relatively thin crusts and presumably low liquid geostatic pressures. No experiments on ooze penetrability have been made on lakes with thick crusts and presumably higher liquid geostatic pressures.

Some experience was gained on the USGS/Sandia Borehole 76-1 when it was found that a drill stem could be rotated and raised following insertion into the melt after the drill stem was allowed to warm to the environment temperature. No measurements of torque or force were obtained at that time due to the uninstrumented drill rig being used.

Description

Configuration -- A sketch of the apparatus to be used in this experiment is shown in Figure 18. The penetrator will be made from a solid bar of RA 333 high nickel stainless steel alloy 10 ft long and 1-3/4 in. dia. The lower end of the penetrator will have a 2.2 CRH point. Experience on high speed rock penetration studies in the Sandia Terradynamics group has shown that this point shape is the strongest, most efficient one used. (The length and diameter structural analysis calculations were done by S. N. Burchett, Division 5521, and are shown in Appendix A.) The criterion used for this analysis was that the penetrator should be capable of withstanding the maximum downward thrust of the HC-150 drill rig (10,600 lb) without buckling. The 10 ft length of the penetrator was arbitrarily selected as a minimum length required to penetrate through the ooze into the melt.

A threaded connector is welded to the upper end of the penetrator to permit coupling to a string of standard NW (3-1/2 in. OD x 3 in. ID) casing to reach to the surface of the lake. The NW casing will be kept full of water for the purpose of keeping its temperature at approximately 100°C. Under these conditions, and with the restraint of the 3.78 in. dia borehole, Burchett calculates that its buckling is not significant.

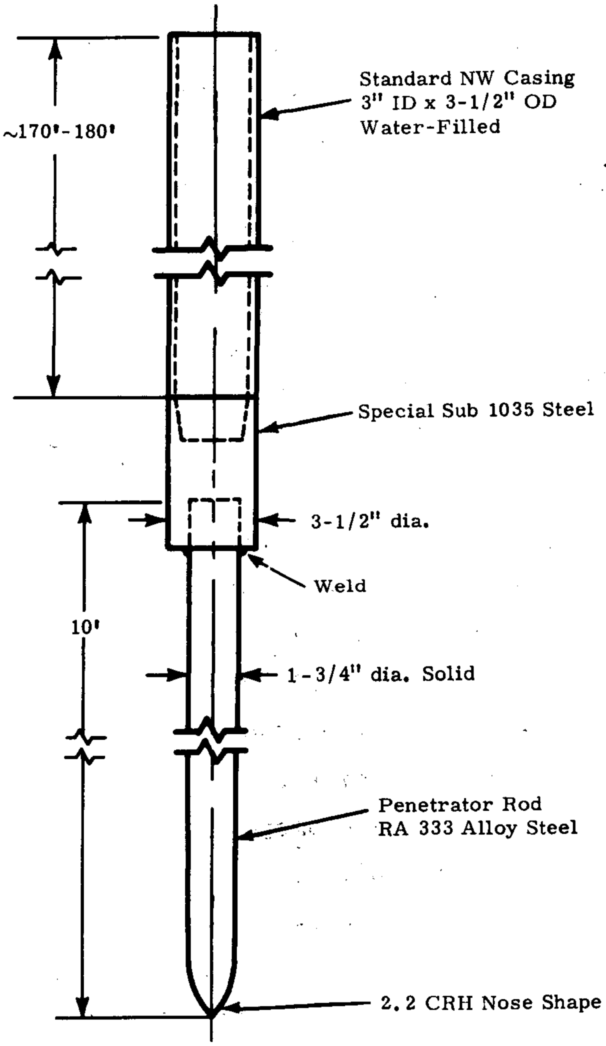

Figure 18. Borehole Ooze Penetration Experiment Apparatus

<u>Operation Plan</u> -- Following the minimum ooze thickness experiment performed in borehole K.I. 75-1, the above described penetrator attached to the NW casing will be lowered down it. As each section of the casing is attached and lowered, it will be filled with water.

When the penetrator touches the top of the solidified ooze, the NW casing will be chucked into the HC-150 drill rig. Hydraulic pressure will be applied to the rig thrust cylinders until penetration occurs. Pressure vs time data will be recorded from the thrust pressure sensor installed on the drill rig during thrust buildup and during the penetrator transit through the ooze. At the end of the 6 ft thrust cylinder travel, the penetrator will be stopped to allow the rig chuck to be raised and reattached to the NW casing. Thrust pressure will then be reapplied to continue penetration for the full length available.

If the ooze is not penetrated by thrusting downward, the casing string will be rotated by the drill rig while it is pushed. Structural analysis calculations by S. N. Burchett, Division 5521, show that the maximum torque expected on the 10 ft length of the penetrator (using molten rock viscosity estimates furnished by Dave Larson, Division 5512) is about 35 ft-lb at 60 rpm of the penetrator. This produces a calculated stress in the penetrator rod of 700 psi. The failure stress in the penetrator in one hour at the environment temperature is on the order of 6000 psi.

After the penetrator is successfully inserted to its full length, it will be removed from the borehole.

Feasibility

Analysis of Feasibility -- USGS researchers have successfully penetrated borehole ooze in previous lava lake studies. However, all of these successful penetrations were early in the histories of the lava lakes, when the crusts were very thin compared with present-day Kilauea Iki. This thinness of crust infers two parameters that are not present now: first, in a shallow hole the drill stem could be removed and the penetrator inserted in a very short time (2 to 3 min); second, the assumed geostatic pressure in the liquid rock was not much above atmospheric ($\sim$11.5 psi for a 10-ft-thick crust). These two parameters appeared to minimize penetration resistance.

Thermal calculations of the cooling profile across a column of molten basalt ooze in a 3-in.-dia borehole made by Dave Larson, Division 5512

(Appendix B), indicate that an essentially isothermal state is reached rather quickly, less than 25 min after emplacement. However, even though the ooze is at wall rock temperature, there is evidence from some dilatometer tests (thermal expansion curves) run by Ed Graeber, Division 5822, on melt samples solidified in the drill bit during the drilling of K.I. 76-2, that part of the basalt may be solidified in a glassy, obsidian state. As shown in Figure 19, this glassy material goes through a transition point at 575°C and a softening point at 670°C, and continues to soften to the terminal temperature of the experiment (750°C). This means that in the temperature environment expected in the borehole 0 to 10 ft above the melt interface (1070°C to 920°C) (Figure 20), any portion of the solidified ooze that was quickly quenched into the glassy state will be softer (weaker) than that which is allowed to slowly cool into a crystalline state. The respective amounts of the ooze that are solidified into these states is unknown. This experiment will give some insight into this question.

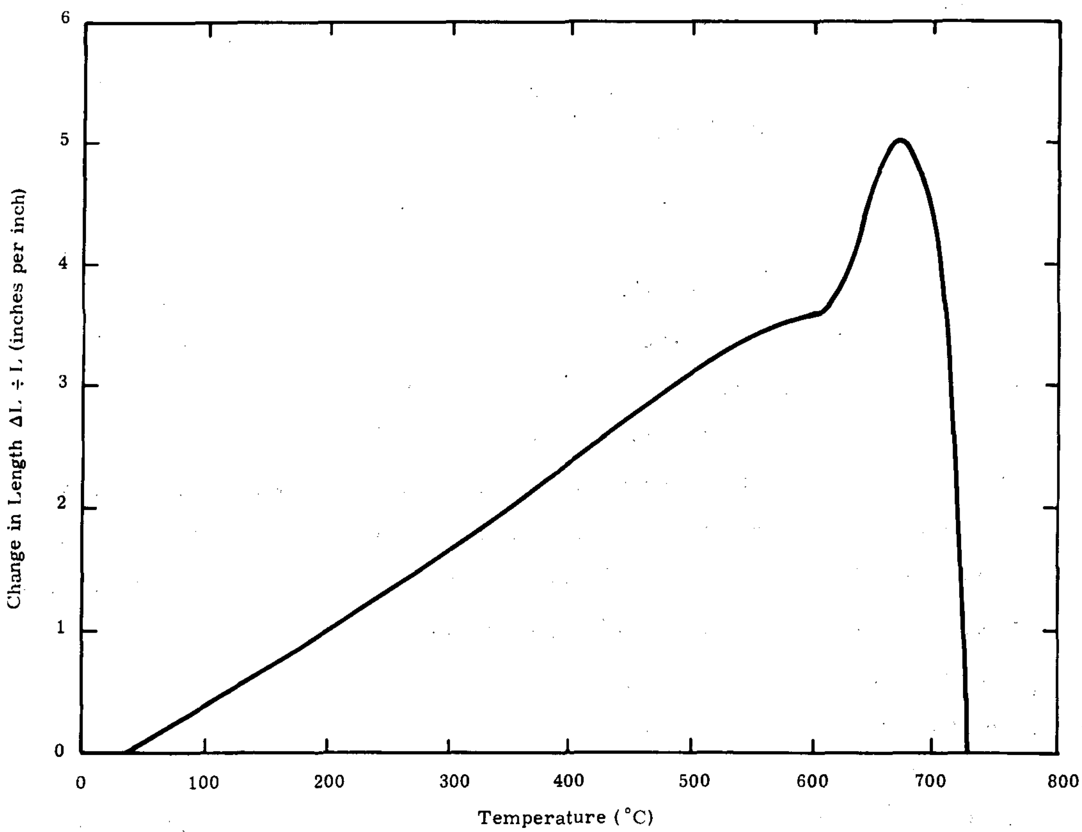

Figure 19. Thermal Expansion of Kilauea Iki Tachylite

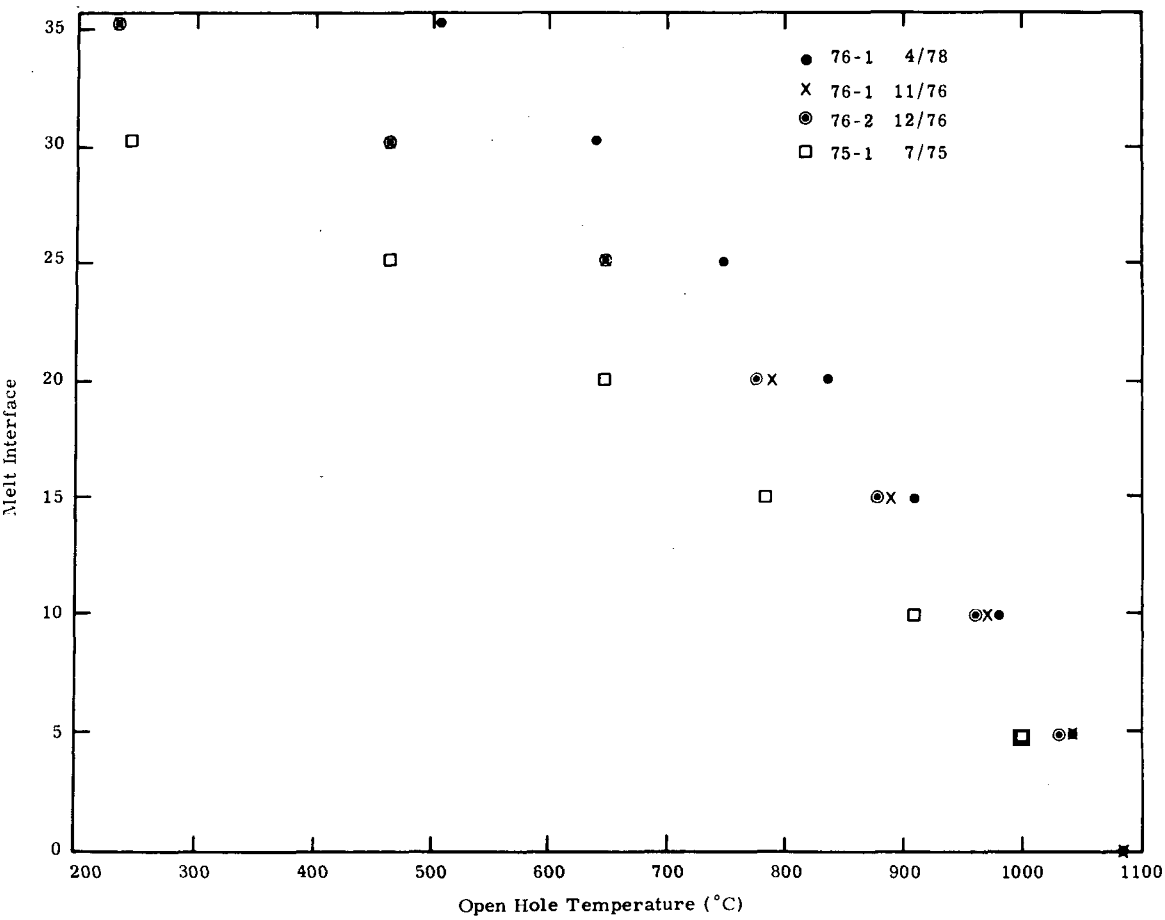

Figure 20. Observed Borehole Temperatures

It can be concluded from the information above and the structural calculations that this experiment is feasible. The probability of successful achievement of full length penetration is not known.

Critical Parameter Calculations -- The following parameters are considered to be critical to the feasibility of the design of the apparatus and the performance of this experiment:

1. Penetrator dimensions - The minimum length is that which is adequate to extend through the "minimum ooze thickness." The maximum length is that which is stable in the buckling

mode considering the minimum diameter, material availability, environment, and maximum thrust available from the drill rig.

Data from borehole K.I. 76-1 (Figure 21) shows that an ooze thickness of 6 ft was measured 90-1/2 hours after drill string removal. (Note: This may not be the "minimum ooze thickness," since the borehole was not continuously cooled during and after drill string removal.) Data from borehole K.I. 76-2 (Figure 22) shows that borehole ooze was stable at an elevation of 8.9 ft at 20-1/2 hours after drill string removal in one instance; at an elevation of 4.1 ft at 55 min after drill string removal in a second instance; and at an elevation of 11.5 ft for several months after removal of the drill string in the third instance. Considering that none of these observed cases were maximized for minimum ooze thicknesses, it was concluded that a 10 ft penetrator length would be a conservative minimum selection.

RA 333 high temperature alloy steel was selected by S. N. Burchett, Division 5521, as a suitable material for a penetrator designed to be loaded in the expected downhole environment.

Based on the above selections and the published downward thrust capability of the HC-150 drill rig of 10,600 lb, Burchett did the structural analysis calculations shown in Appendix A. These calculations resulted in the selection of 1-3/4 in. as the minimum penetrator diameter. (Note: The minimum diameter is desirable since it results in the highest unit loading on the ooze, which should enhance its penetrability.)

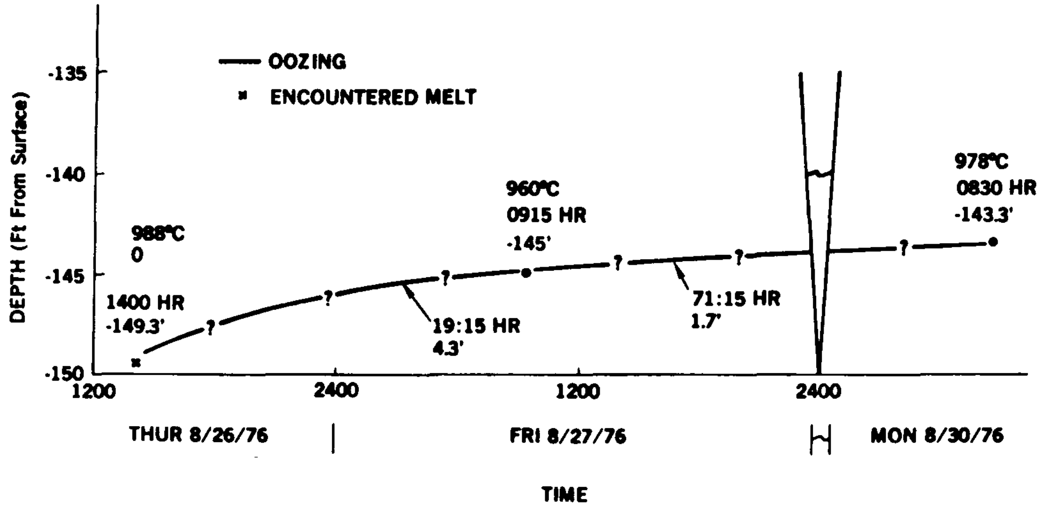

Figure 21. Borehole K.I. 76-1 Log

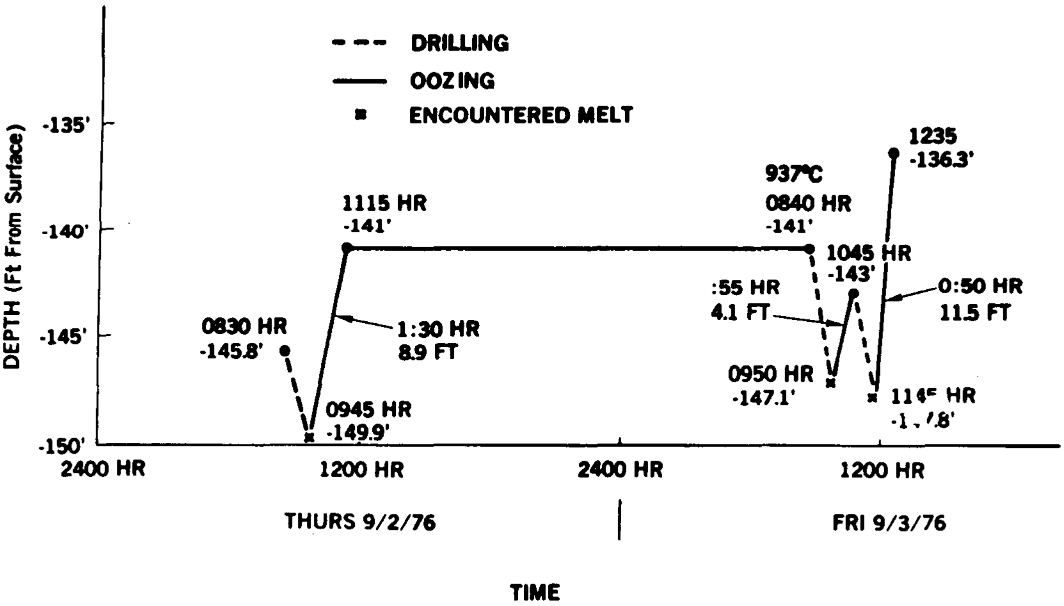

Figure 22. Borehole K.I. 76-2 Log

2. Load application stem dimensions - Standard NW casing (3 in. ID x 3-1/2 in. OD) was selected for the load application stem because it is the largest standard tubular goods that will fit in an HCQ-cored hole (3.78 in. dia), and it has the largest cross-sectional area of standard tubular goods. Water cooling of the inside of the load application stem was selected as a means of acquiring adequate strength without having to use a nonstandard, high temperature-resistant material. The structural analysis of the water-cooled NW casing is included in Appendix A.

Results

As described earlier under "The Minimum Ooze Thickness Experiment," borehole K.I. 75-1 was lost just as the penetrator for this experiment was being emplaced. The hole loss resulted from the accidental dropping of a tempered steel chuck jaw from the drill rig downhole. The chuck jaw could not be recovered. It was decided to abandon K.I. 75-1, to postpone the ooze penetration experiment, and to perform it in combination with the Melt Resistivity Experiment described later in this report.

The ooze penetration experiment was performed in borehole K.I. 79-3 on January 11, 1979. The initial melt contact in this borehole was made at a depth of 172 ft 10 in. (52.7 m). The ooze-back was drilled to a depth of 169 ft 10 in. (51.8 m) for this experiment. The penetrator, made to the same dimensions as shown on Figure 18 but modified to include the melt resistivity experiment, was placed on the bottom of the hole. A total force of 11,000 lb was placed on the point of the penetrator and maintained in a steady state for 3 min with no observable penetration. This was followed by a 3 min sequence of cyclic loading, pulling the drill string up off this borehole bottom and dropping it, and finally, by another steady state load for 10 min. No measurable penetration was observed. The penetrator was removed from the hole and a visual observation of the point revealed no deformation or damage.

In summary, no penetration into an ooze-back surface located 3 ft (0.91 m) above the initial melt contact at an estimated temperature of 1025°C under a sustained and impact load of 11,100 lb for 15 min was observed.

Borehole Ooze Dead Load Creep Experiment

Location

Borehole K.I. 79-1

Purpose

The objective of this experiment is to obtain empirical in situ data on the long term creep rate of a dead-loaded right circular cylinder into the solidified molten rock (ooze) that has flowed back up a borehole, in order to:

1. Study the rheology of high temperature basalt under long term, static loading.
2. Determine if creep penetration of borehole ooze is a viable method for securing entry into a molten rock body overlain by a hot solidified crust for the purposes of measuring physical parameters of the melt, energy extraction, etc.

Description

Configuration -- A sketch of the apparatus to be used in this experiment is shown in Figure 23. The creep penetrator will be made from a solid bar of RA 333 high nickel stainless steel alloy, approximately 10 ft long and 1-3/4 in. dia. The lower end will have a straight cut, resulting in a right circular cylinder shape. A threaded connector is welded to the upper end of the creep penetrator rod to permit coupling to a string of standard NW casing (3-1/2 in. OD x 3 in. ID) to reach to the surface of the lake. The NW casing will be kept full of water to insure its structural integrity. The weight of the penetrator rod, the NW casing, and the water will provide the loading on the ooze.

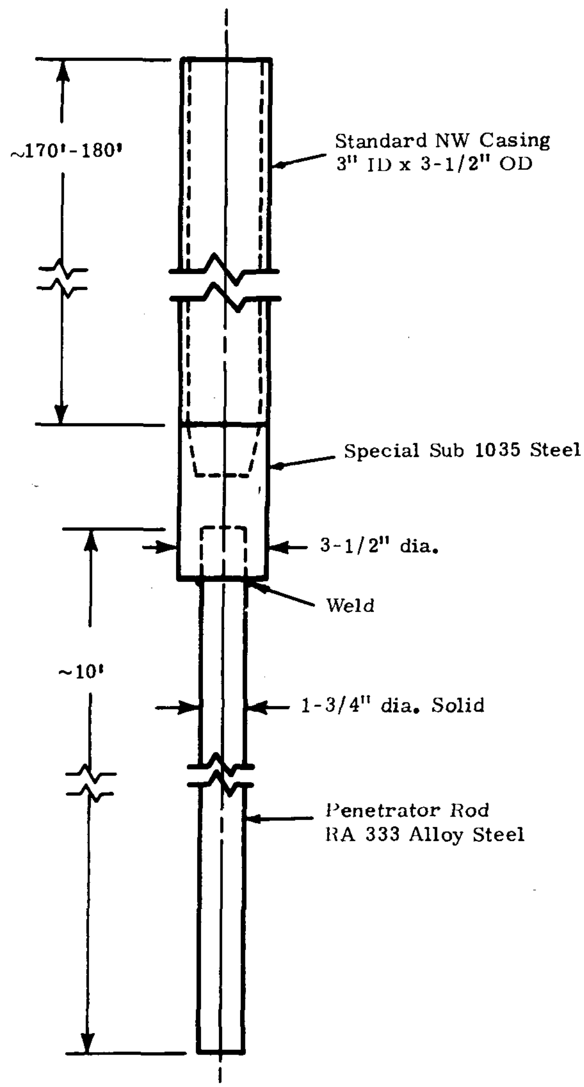

Figure 23. Borehole Ooze Penetration Experiment Apparatus

Operation Plan -- Following the lava lake liquid water sample experiment (described elsewhere) to be performed in borehole 79-1, the ooze creep penetrator rod and NW casing assembly will be lowered to the ooze surface. The NW casing will be filled with water as the assembly is lowered downhole. When insertion is completed and the bottom of the penetrator rod is resting on the ooze, a reference mark will be scribed on the NW casing protruding out of the borehole. A visual observation using a metal ruler 24 in. long, graduated in 1/100 in. increments, of the elevation of the scribed mark above a reference plate grouted to the lake surface will be made and recorded (together with the time) in the experiment log book. The initial elevation reading will be made as soon as the assembly installation is completed. Subsequent elevation readings will be taken at intervals during the next two weeks. At that time an assessment of the requirements for future readings will be made.

Feasibility

Analysis of Feasibility -- *In situ* long term dead load creep strength tests are common field experiments in normal environments. The techniques being used in this experiment are common practice; however, the environment in which this experiment is being run is very uncommon and does not fall in a normal practice category. For that reason a number of critical parameter calculations were required and are described below.

Based on the critical parameter calculations and hardware availability, it is concluded that this experiment is feasible under the constraints established.

Critical Parameter Calculations -- The very high temperature environment at the downhole site of this experiment requires that detailed examination of the long term structural integrity of the test apparatus be made. This examination and analysis is shown in Appendix C. These calculations, based on limited (extrapolated) material data, indicate that the base of the penetrator rod in contact with the ooze may be structurally stable, under the applied load of the water-filled NW casing assembly, for approximately two weeks time. Based on discussions with Burchett and others[1,2] it is believed that the creep/time data observed during the

[1]Personal communication with Dr. M. Friedman, Texas A & M University.

[2]Personal communication with Dr. M. Ryan, Hawaii Institute of Geophysics.

initial two weeks of experiment operation may be adequate to determine if ooze creep failure or penetrator rod failure is occurring. This evidence will be considered when a decision is made at that time whether to continue this experiment.

A second critical parameter considered was whether the water-filled NW casing could be kept full of water during the lifetime of this experiment. Dave Larson, Division 5512, did these calculations (Appendix D). These upper limit (worst case) calculations indicate that it is possible to keep the casing filled. Larson believes it is very likely that this worst case will not occur and that only very small amounts of water will be lost.

Results

The operation plan for this experiment described above was modified, in that Dr. M. P. Ryan, Hawaii Institute of Geophysics, provided the experimental creep measuring and recording equipment and provided the necessary follow-up after experiment installation.

The right circular cylindrical creep penetrator was placed on the surface of the ooze-back in borehole K.I. 79-1 at a depth of 178 ft 2 in. (54.3 m). Just prior to insertion the temperature at this location was measured at 974°C. Insertion of the penetrator proceeded as planned with the NW casing being filled with water as it was lowered. As the penetrator encountered the ooze-back surface and its weight plus that of the water-filled NW casing (approximately 2045 lb total) was released, it was closely observed for any measurable penetration. There was none.

Shortly after the penetrator/casing assembly was installed (4 to 5 min) a violent explusion of the water contained in the casing occurred. The casing was refilled with water and a similar explusion occurred in about the same time. It was decided to leave the downhole assembly without water in it. This reduced the weight on the penetrator contact surface to about 1500 lb.

Dr. Ryan installed and connected the experimental measuring and recording apparatus (a modified tide gage/recorder) he had furnished. Continued examination of the data record for a period of 94 days indicated no measurable movement of the projecting casing.

The observed results of this experiment as planned and performed indicate no creep of the penetrator into the hot ooze at the bottom of the borehole. However, measurements of the depth and temperature of the bottom of the NW casing measured inside of it indicate a temperature of 938°C and a depth of 172 ft 3 in. This observation involves a discrepancy in depths that may show that some movement of the penetrator has occurred. This discrepancy will be investigated to determine its cause and resolution.

V. LIQUID/PERMEABILITY STUDIES

Crust Formation Permeability - Point Source Experiment
(J. Dunn, 5512)

Location

Borehole 79-1

Purpose

This experiment is designed to measure the *in situ* apparent permeability of the upper solidified crust near the center of Kilauea Iki lava lake using a spherical point source injection, radial flow solution.

Background -- *In situ* permeability of the Kilauea Iki basaltic crust has not been previously measured. Based on measured temperature profiles and a heat balance at the single phase-two phase interface in the crust, H. C. Hardee[1] had estimated a permeability of 0.32 Darcy.

Description

Configuration -- The HC-150 drill rig and HCQ wire-line coring equipment will be used to drill into the upper crust in 25-ft increments. An air-inflated isolation balloon packer will be inserted downhole to seal off a small region near the bottom where water will be injected into the formation (Figure 24). A thermocouple will be mounted above the balloon packer to sense the presence of injection water entering the drill hole. Water will be supplied by the positive displacement pump having a capacity of 40 GPM at 500 psi. Water flow rate and injection pressure will be measured at the surface as a function of time.

[1] H. C. Hardee, Solidification in Kilauea Iki Lava Lake, SAND78-2059J, accepted for publication by Journal of Volcanology and Geothermal Research.

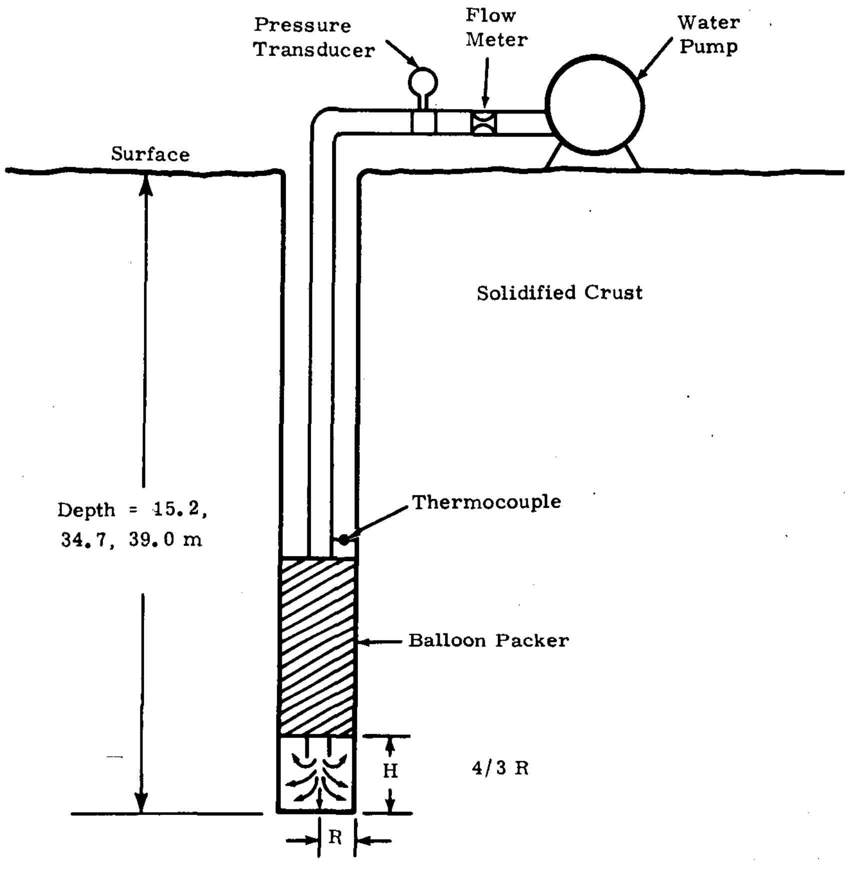

Figure 24. Schematic of Point-Source Permeability Measurement Configuration

Operation -- The sequence of events described below is to be followed:

1. Drill to a depth of 25 ft.
2. Insert balloon packer with water feed line to a depth so that the bottom hole cavity has a height approximately equal to 2/3 of the hole diameter.
3. Using compressed air, inflate the balloon packer to isolate the bottom cavity.
4. Inject water at a constant rate of approximately 20 GPM and measure flow rate and pressure in the surface line as a function of time. (Note: Injection pressure differs from surface pressure by the hydraulic head associated with the injection depth.)

5. If the surface pressure exceeds the pressure of limitation of the pump or is below the resolution capability of the pressure transducer, water flow rate is to be adjusted (see analysis section).

6. If thermocouple reading indicates a large water leak entering the drill hole above the packer, at least one attempt should be made to move the packer up hole. First, move to a position where cavity height is approximately two hole diameters. Should the upper hole continue to receive injection water, this fact should be noted and the test continued.

7. Record surface line pressure at a constant flow rate for a one-hour time period.

8. Remove balloon packer and water feed line.

9. Drill to a depth of 50 ft.

10. Repeat steps 2 through 8.

11. Drill to a depth of 75 ft.

12. Repeat steps 2 through 8.

13. Drill to a depth of 100 ft.

14. Repeat steps 2 through 8.

15. Drill to a depth where temperatures begin to deviate from the 100°C isotherm (about 125 ft). This depth will have been determined in a previous downhole temperature measurement experiment (hole 75-1).

16. Repeat steps 2 through 8.

Feasibility

<u>Analysis</u> -- Determination of <u>in-situ</u> permeability will be based on the analytical solution of one dimensional radial water flow from a spherical source into a dry porous medium. It is estimated[2] that the mass flow rate of water moving down through the lava crust is balanced by a steam mass

[2] H. C. Hardee, private communication, Oct 1978.

flow rate moving upward. This results in the pore volumes being filled almost entirely by steam due to the large difference in specific volume of water and steam at the same pressure. Since steam can move relatively easily through the porous medium when compared to water, the outer boundary condition on the advancing water front is taken as one of constant pressure. This boundary pressure is equal to the initial formation pressure. Note that this flow condition differs from the normal situation in soils or oil or geothermal fields where the formation is usually liquid-saturated. Also, since the formation pressure is estimated at very near one atmosphere, the normal well shut-in, pressure build-up method of determining <u>in situ</u> permeability cannot be used.

The flow geometry analyzed is shown in Figure 25. With the assumptions that

- injection fluid is incompressible
- flow is one-dimensional, radial
- formation is isotropic with constant permeability,

the governing differential equation describing injected water pressure becomes

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dp}{dr}\right) = 0 \tag{1}$$

with boundary conditions

$$\text{at} \quad r = r_w, \quad \frac{dp}{dr} = \frac{-Q\mu}{4\pi k r_w^2} \tag{2}$$

$$\text{at} \quad r = r_e, \quad p = p_i$$

where:

r = radial coordinate

r_w = radius of spherical source

r_e = radius of injected water front

p = injected water pressure

p_i = initial formation pressure

Q = injected water volume flow rate

μ = water viscosity (dynamic)

k = formation permeability.

Solution of Eq. (1) subject to boundary conditions (2) is

$$p - p_i = \frac{Q\mu}{4\pi k}\left[\frac{1}{r} - \frac{1}{r_e}\right] \tag{3}$$

If it is assumed that the injected water advances into the formation in a spherical front, then the front radius can be determined as a function of time as

$$r_e = \left[r_w^3 + \frac{3Qt}{4\pi\phi}\right]^{1/3}$$

where:

t = injection time

ϕ = porosity of formation.

This gives

$$p - p_i = \frac{Q\mu}{4\pi k}\left[\frac{1}{r} - \left(r_w^3 + \frac{3Qt}{4\pi\phi}\right)^{-1/3}\right] \tag{4}$$

or at $r = r_w$

$$p_w - p_i = \frac{Q\mu}{4\pi k}\left[\frac{1}{r_w} - \left(r_w^3 + \frac{3Qt}{4\pi\phi}\right)^{-1/3}\right] \tag{5}$$

Now consider the following representative injection parameters:

Q = 20 GPM = 1262 cm^3/s

μ = 0.003 poise

$k = 0.32\ D = 0.32 \times 10^{-8}\ cm^2$

$\phi = 0.20$

$r_w = 4.80$ cm (HQ hole)

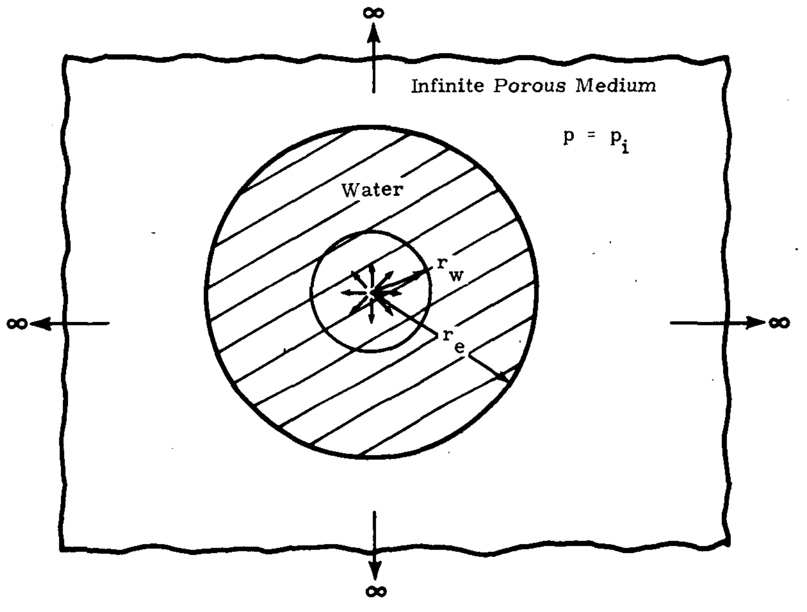

Figure 25. Geometry Used for One-Dimensional Radial Water Flow

For this case, the solution to Eq. (5) is shown as a function of time in Figure 26. Selected values are tabulated below.

t (min)	1	5	10	30	45	60	120	180	∞
$p_w - p_i$ (psi)	254	267	270	275	276	277	278	279	284

It can be seen that the large time solution

$$p_w - p_i = \frac{Q\mu}{4\pi k r_w} \tag{6}$$

is approached rapidly. After one hour, $p_w - p_i$ is within 3% of the infinite time solution. Thus, Eq. (6) can be used in the field to obtain a quick estimate of permeability.

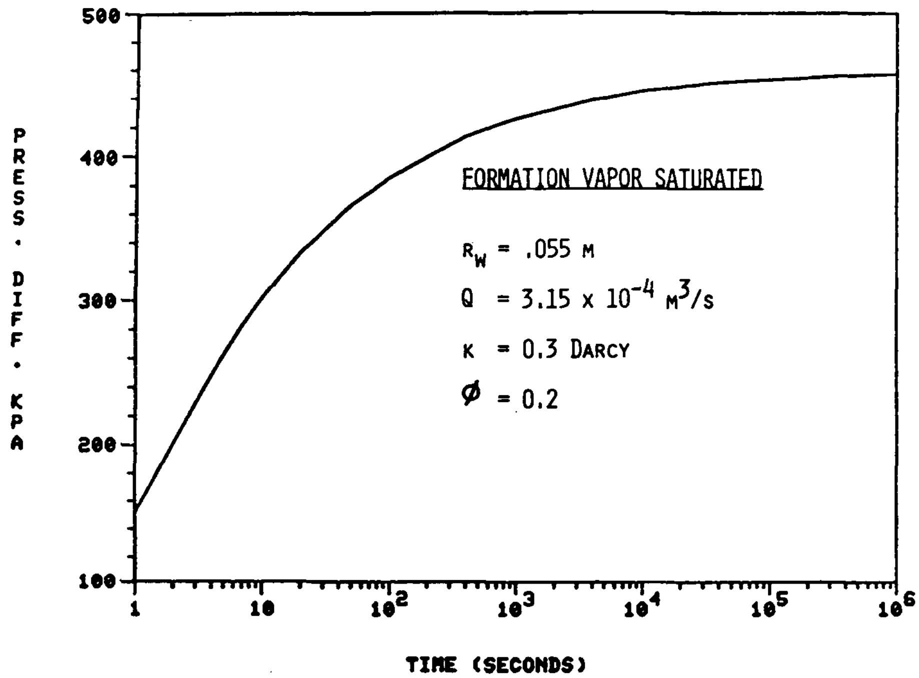

Figure 26. Pressure Build-up--Point Source Solution

The pressure $p_w - p_i$ is approximately proportional to the ratio Q/k. Therefore, if k is found in the field to be significantly different from

0.32 Darcy, Q can be adjusted (within limits) to achieve pressures within the capabilities of the water delivery and measurement systems.

Critical Parameter Calculations -- Not applicable.

Hardware Sizing Calculations -- The four-speed water pump required for other experiments should be entirely adequate if the formation permeability is near the estimated value of 0.32 Darcy. In fact, the 0 to 40 GPM pump should produce reasonable pressures for formation permeability in the range 0.032 to 3.2 Darcies.

The feed water tube should have an inside diameter of at least 0.80 in. in order to accommodate the maximum flow rate of 40 GPM. The following instruments should be capable of measurement in the specified ranges:

water flow meter - 0 to 40 GPM

water pressure - 0 to 500 psi

downhole temperature - 20°C to 150°C

Results (H. C. Hardee, 5512)

The apparent permeability of solidified lava in the upper crust of Kilauea Iki lava lake was measured at several depths during December, 1978. The drill hole used (designated 79-1) was located near the center of the lake.

Permeability was determined by injecting water into the formation at a constant flow rate while measuring downhole pressure rise as a function of time. A balloon packer was used to isolate the region of water injection. Measurements were taken at three depths--15.2, 34.7 and 39.9 m. Inspection of the 79-1 core for regions of fracture indicated the following: (1) solid rock with no fracturing in the vicinity of 15.2 m, (2) a fracture zone running directly through the region of water injection at 34.7 m and (3) a fracture present approximately 1 m above the region of water injection at 39.9 m.

Preliminary analysis of the water injection data indicates an apparent permeability of approximately 0.12 Darcy at 15.2 m and a somewhat lower value of 0.09 Darcy at 39.0 m. Near the fractured zone at 34.7 m, apparent permeability was initially about 0.3 Darcy. Additional fracturing by the injected water then increased permeability to approximately 0.8 Darcy (Table 5).

TABLE 5

Permeability of Kilauea Iki Basalt

Depth (m)	Permeability (Darcy)	Measurement Location	Comments
15.2	0.12	*in situ*	• No apparent fractures
34.7	0.29	*in situ*	• Fracture running through region of water injection • Initial measurement
34.7	0.85	*in situ*	• Measurement after additional fracturing caused by water injection
39.0	0.092	*in situ*	• Fracture present about 1 m above region of water injection
37.8	0.005	Laboratory	• No fractures • Both water and air flow measurement techniques used

The authors are not aware of other in situ permeability measurements in solidified lava. However, comparison can be made with laboratory measurements of permeability using core taken from the Kilauea Iki lava lake. Dunn measured the permeability of a 6.35 cm dia by 11.4 cm core sample taken from drill hole 76-2 at a depth of 37.8 m. Both water and air flow measurement techniques were used. These data show an average permeability of 0.005 Darcy, much lower than the in situ values. Thus, it appears that fracturing plays an important role in the in situ transport of water.

Crust Formation Permeability - Preliminary Cylindrical Source Experiment
(J. C. Dunn, 5512)

Location

Borehole K.I. 79-1

Purpose

This experiment is designed to measure in situ apparent permeability of the upper solidified crust near the center of Kilauea Iki lava lake using a cylindrical injection source.

Background -- In situ permeability of the crust will have been measured in a previous experiment at several depths using a point source injection, radial flow solution. This experiment will repeat permeability measurements at the same depths using a cylindrical source, radial flow solution.

Description

Configuration -- A pair of air-inflatable isolation balloon packers will be inserted downhole to seal off a 4-ft vertical section of crust at selected depths (Figure 27). The drill rig will be used for straddle packer placement. Water will be injected into the formation through the 4-ft vertical section using a 40 GPM positive displacement pump. Water flow rate and injection pressure will be measured at the surface as a function of time. A thermocouple will be mounted above the upper balloon packer to sense the presence of injection water entering the drill hole.

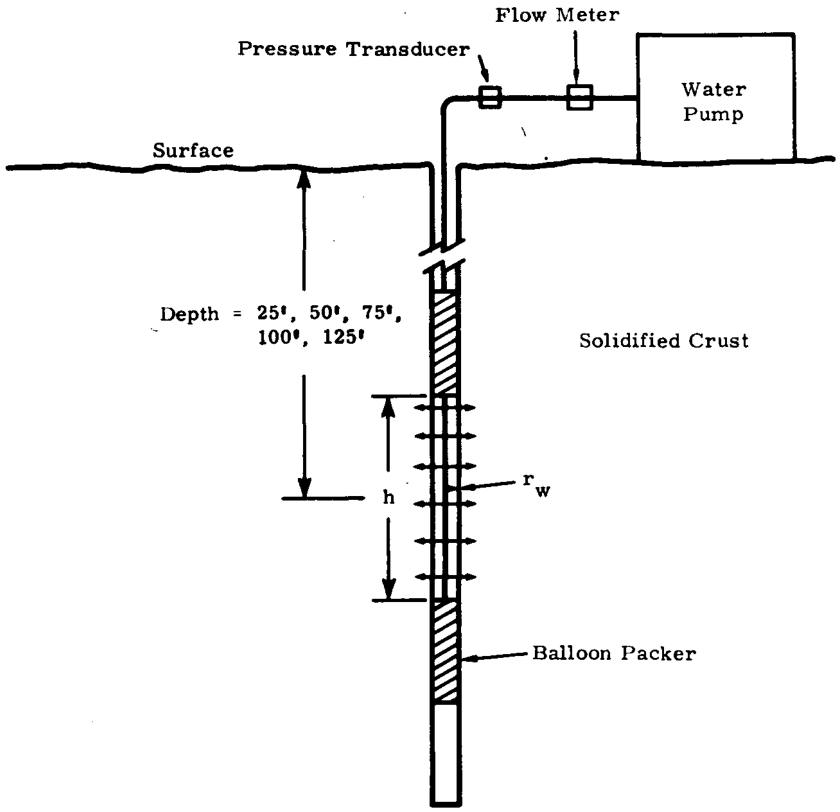

Figure 27. Schematic of Permeability Measurement Configuration-Cylindrical Source

Operation --

1. Insert straddle packer so that midsection is at a depth of 25 ft.
2. Using compressed air, inflate the two balloon packers to seal off a 4-ft section.
3. Inject water at a constant rate of approximately 20 GPM and measure flow rate and pressure in the surface line as a function of time.
4. If surface pressure exceeds the pressure limitation of the pump or is below the resolution capability of

the pressure transducer, water flow rate is to be adjusted. If injection pressure is too low for accurate measurement even at maximum pump capacity (40 GPM), then the length of injection section should be reduced to either three or two ft (see analysis section).

5. If upper thermocouple reading indicates a large water leak entering the drill hole above the packer, at least one attempt should be made to move the packer to a nearby location. If after movement the upper hole continues to receive injection water, this fact should be noted and the test continued. Particular attention should be paid to obtaining a good location at an approximate depth of 50 ft. This is the most desirable depth for conducting the final permeability experiment with instrument holes.

6. Record surface line pressure at a constant flow rate for a one-hour time period.

7. Relocate midsection of straddle packer at a depth of 50 ft.

8. Repeat steps 2 through 6.

9. Relocate midsection of straddle packer at a depth of 75 ft.

10. Repeat steps 2 through 6.

11. Relocate midsection of straddle packer at a depth of 100 ft.

12. Repeat steps 2 through 6.

13. Relocate midsection of straddle packer at the location of deepest point source measurement (about 125 ft).

14. Repeat steps 2 through 6.

Feasibility

Analysis -- Determination of in situ permeability will be based on the analytical solution of one-dimensional, radial water flow from a cylindrical source into a dry porous medium. As in the previous permeability experiment, the outer boundary condition on the advancing water front is taken as one of constant pressure, equal to the initial formation pressure. The flow geometry analyzed is shown in Figure 28, with the following assumptions:

- injected fluid is incompressible
- flow is one-dimensional, radial from a cylindrical source
- formation is isotropic with constant permeability

The governing differential equation describing injected water pressure becomes

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dp}{dr}\right) = 0 \qquad (7)$$

with boundary conditions:

$$\text{at} \quad r = r_w \qquad \frac{dp}{dr} = -\frac{Q\mu}{2\pi khr_w}$$
$$r = r_e \qquad p = p_i \qquad (8)$$

where

r = radius in cylindrical coordinate system

r_w = radius of cylindrical source (wellbore)

r_e = radius of injected water front

p = injected water pressure

p_i = initial formation pressure

Q = injected water volume flow rate

μ = water viscosity (dynamic)

k = formation permeability

h = height of cylindrical source

Solution of Eq. (7) subject to boundary conditions (8) is:

$$p - p_i = \frac{Q}{2\pi kh} \ln\left(\frac{r_e}{r}\right) \tag{9}$$

If it is assumed that the injected water advances into the formation in a cylindrical front, then the front radius can be determined as a function of time as:

$$r_e = \left[r_w^2 + \frac{Qt}{\pi h \phi}\right]^{1/2}$$

where

t = injection time

ϕ = porosity of formation

this gives

$$p - p_i = \frac{Q\mu}{2\pi kh} \ln\left[\frac{\sqrt{r_w^2 + Qt/\pi h\phi}}{r}\right]$$

or at $r = r_w$

$$P_w - P_i = \frac{Q\mu}{2\pi kh} \ln\left[\sqrt{1 + Qt/\pi h\phi r_w^2}\right] \tag{10}$$

Equation (10) shows that, for large times, the wellbore pressure is a linear function of ln t.

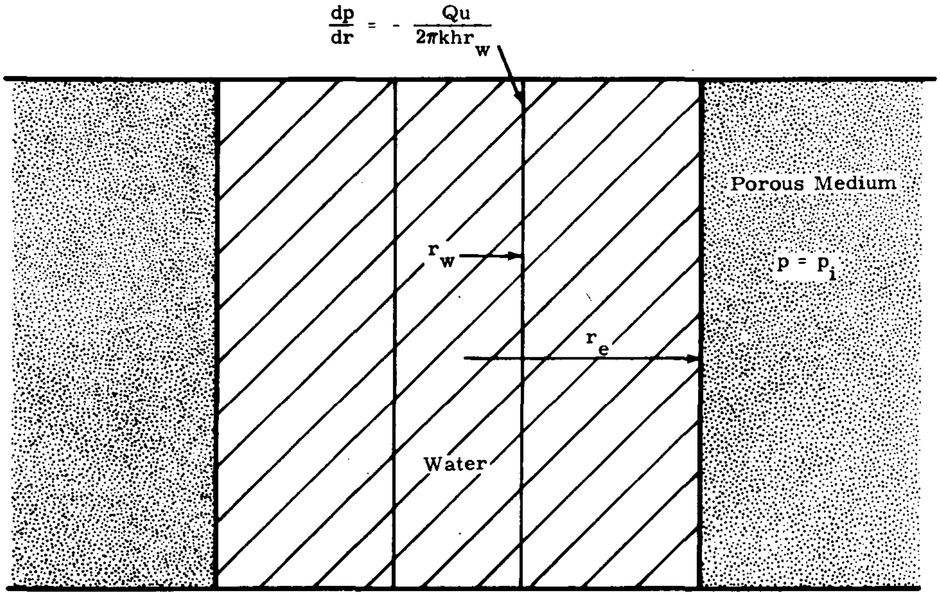

Figure 28. Geometry Used for One-Dimensional Radial Water Flow

Now, consider the following representative injection parameters:

$Q = 20$ GPM - 1262 cm^3/s

$\mu = 0.003$ poise

$k = 0.32$ D $= 0.32 \times 10^{-8}$ cm^2

$\phi = 0.20$

$r_w = 4.80$ cm

$h = 4$ ft $= 121.92$ cm

For this case, the solution to Eq. (10) is plotted as function of time in Figure 29. Also plotted are wellbore pressure solutions for identical injection parameters but for several different values of formation permeability. It can be seen by inspection of Eq. (10) that, for large times, the slope of the wellbore pressure - ln t curve is given by:

$$\text{slope} = Q\mu/4\pi kh \quad .$$

Measurement of this slope, therefore, can be used to determine permeability. Field measurement of injection pressure as a function of time for a one-hour time period should be sufficient to determine this slope. If, within this time period, the increase in wellbore pressure lies outside the range of accurate pressure measurement (either too high or too low), then the injection parameters Q and h can be adjusted in an attempt to bring the pressure build-up within bounds.

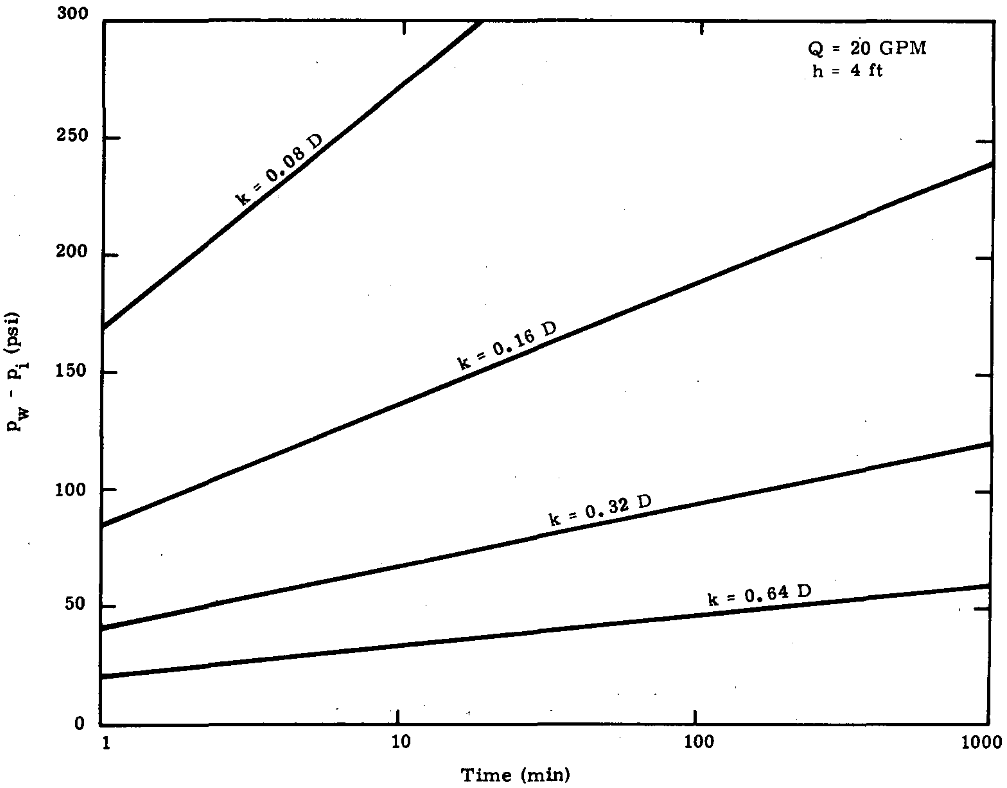

Figure 29. Pressure Build-Up for Water Injection-Cylindrical Source

Critical Parameter Calculations -- Not applicable.

Hardware Sizing Calculations -- The four speed water pump required for other experiments should be adequate if the formation permeability is near the estimated value of 0.32 Darcy. If the formation permeability is 10 times the estimated value, or 3.2 D, then two pumps used in parallel to produce 80 GPM would be sufficient to produce measurable pressure build-up. The feed water tube should have a minimum inside diameter of 0.80 in. for 40 GPM flow rate and 1.13 in. for 80 GPM flow rate. Instruments required for this experiment should be capable of measurement in the following specified ranges:

water flow meter - to 40 GPM

water pressure - 0 to 500 psi

downhole temperature - 20 to 150°C

Results

This experiment was not performed due to tight schedule and lack of time.

Crust Formation Permeability - Cylindrical Source Experiment
(J. C. Dunn, 5512)

Location

Borehole K.I. 79-1

Purpose

This experiment is designed to measure in situ apparent permeability of the upper solidified crust and determine if the crust permeability is strongly anisotropic.

Background -- In situ permeability will have been measured in two previous experiments using the assumption that the crust is isotropic with constant permeability. This experiment will test that assumption by measuring pressures in the formation near the region of water injection from a cylindrical source.

Description

Configuration -- Three pressure transducers will be placed in the formation surrounding borehole 79-1 (Figure 30). The straddle packer will be placed in 79-1 to seal off a vertical section at a depth of approximately 50 ft. A workover rig will be used for straddle packer placement. Water will be injected into the formation through either a 2- or 4-ft vertical section using one or two 40 GPM positive displacement pumps. Water flow rate and injection pressure will be measured at the surface as a function of time. Formation pressure as obtained from the three pressure transducers will also be recorded as a function of time.

Operation --

1. Find depth, "D", near 50 ft where water injection from straddle packer results in a pressure build-up that can be resolved with available instrumentation. Note: The depth may have been determined in the previous preliminary straddle packer measurements.

2. Drill instrument hole #1 (I.H.1), located a distance of 1/2 m from 79-1, to a depth of "D" + 1 m.

3. Drill instrument hole #2 (I.H.2), located a distance of 1 m from 79-1, to a depth of "D".

4. Place the first pressure transducer (P.T.1) in the bottom of I.H.1. Cover with about 2 in. of sand, then grout up to a depth "D".

5. Place P.T.2 in I.H.1 at a depth "D". Cover with about 2 in. of sand, then grout up to the surface.

6. Place P.T.3 in the bottom of I.H.2. Cover with about 2 in. of sand, then grout up to the surface.

7. With midsection of straddle packer at depth "D" in borehole 79-1, seal off a 2-ft vertical section by inflating the balloon packers.

8. Inject water at a constant rate of 40 GPM for about 1 hour.

9. Measure water flow rate and pressure in the surface line as a function of time. Also, record pressure readings from the three pressure transducers as a function of time. Pressures near steady-state conditions should be approached within 1 to 2 hours.

10. If surface pressure exceeds the pressure limitation of the pump, or if formation pressures are below accurate resolution capabilities of the pressure transducers, then the water flow rate and/or the injection length are to be adjusted (see analysis section). Note: It may be necessary to use the second water pump in parallel to achieve high flow rates.

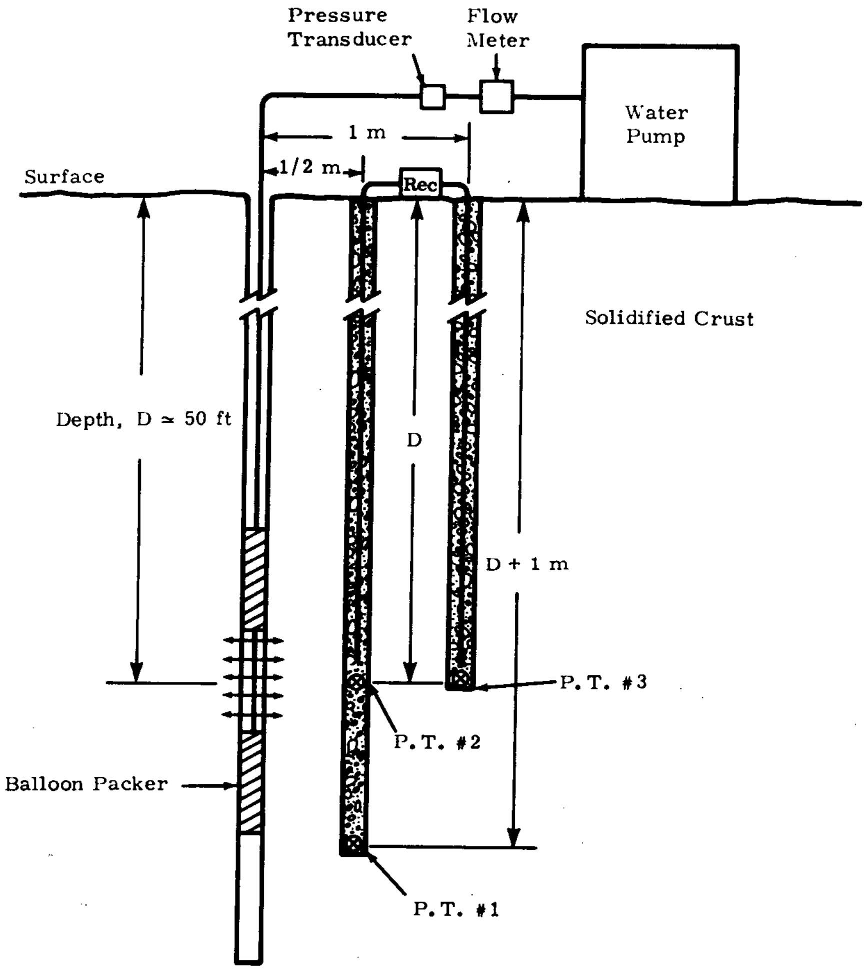

Figure 30. Schematic of Permeability Measurement Configuration-Cylindrical Source With Instrument Holes

Feasibility

Analysis -- Determination of in situ permeability will be based on the solution of two-dimensional water flow from a cylindrical source into a dry, anisotropic porous medium. Pressure distributions due to injection from a line source will be presented here. The heat conduction computer code, CINDA, will be used in final data reduction stages. Flow geometry analyzed is shown in Figure 31, with the following assumptions:

- injected fluid is incompressible
- flow is two-dimensional from a line source
- formation has constant permeability, k_r, in the radial direction and constant permeability, k_z, in the vertical direction

the governing differential equation describing injected water pressure becomes

$$\frac{k_r}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) + k_z\frac{\partial^2 p}{\partial z^2} = 0 \tag{11}$$

Using the following coordinate transformation:

$$\xi = r\sqrt{\frac{K}{k_r}} \quad \text{and} \quad \eta = z\sqrt{\frac{K}{k_z}}$$

where K is a constant, Eq. (11) becomes:

$$\frac{1}{\xi}\frac{\partial}{\partial \xi}\left(\xi\frac{\partial p}{\partial \xi}\right) + \frac{\partial^2 p}{\partial \eta^2} = 0 \tag{12}$$

This is the normal two-dimensional heat conduction equation for an isotropic medium. The pressure solution of Eq. (12) is obtained by analogy from a corresponding temperature solution in an infinite medium due to a line heat source.[1] In the original r, z cylindrical coordinate system, this solution is

$$p - p_{\infty} = \frac{Q_L \mu}{4 \pi \sqrt{k_r k_z}} \ln \left[\frac{\dfrac{z + L/2}{\sqrt{k_z}} + \left\{ \dfrac{(z + L/2)^2}{k_z} + \dfrac{r^2}{k_r} \right\}^{1/2}}{\dfrac{z - L/2}{\sqrt{k_z}} + \left\{ \dfrac{(z - L/2)^2}{k_z} + \dfrac{r^2}{k_r} \right\}^{1/2}} \right] \quad (13)$$

where:

p = injected water pressure

p = injected water pressure at large radius (initial formation pressure)

r = radius in cylindrical coordinate system

z = vertical distance in cylindrical coordinate system

Q_L = line source strength (injected water volume flow per unit length)

μ = water viscosity

k_r = formation permeability in radial direction

k_z = formation permeability in vertical direction

L = length of line source

Equation (13) can be used to evaluate the influence of different permeabilities in the radial and vertical directions. Two representative examples have been solved and are shown in Figures 32 and 33. In the first, the following injection parameters were used:

Q_L = 40 GPM/2 ft = 41.40 $cm^3/cm\ s$

μ = 0.003 poise

[1]Charles E. Hickox, Jr, Steady Thermal Convection at Low Rayleigh Number from Concentrated Sources in Porous Media, SAND77-1529, December 1977.

$L = 2$ ft $= 60.96$ cm

Solutions are obtained for the isotropic case

$k_r = k_z = 0.32$ Darcy

and shown as solid lines. The dashed line solutions are for the condition of much lower permeability in the radial direction.

$k_z = 0.32$ Darcy

and

$k_r = 0.032$ Darcy

Figure 32 can be used to demonstrate that a large difference between the radial and vertical permeabilities can be detected by pressure measurements in the formation. For example, consider two pressure measurements at $z = 0$, $r = 50$ cm and $z = 100$ cm, $r = 50$ cm. For an isotropic medium with a permeability of 0.32 Darcy, the pressure difference between these locations is approximately 30 psi (55 psi - 25 psi). On the other hand, with $k_r = 0.032$ Darcy and $k_z = 0.32$ Darcy, the pressure difference is only 8 psi (54 psi - 46 psi).

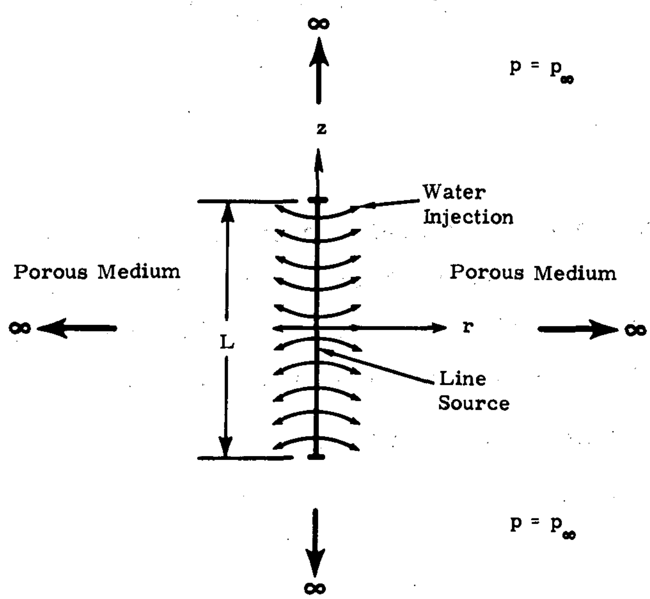

Figure 31. Geometry Used for Two-Dimensional Water Flow From a Line Source

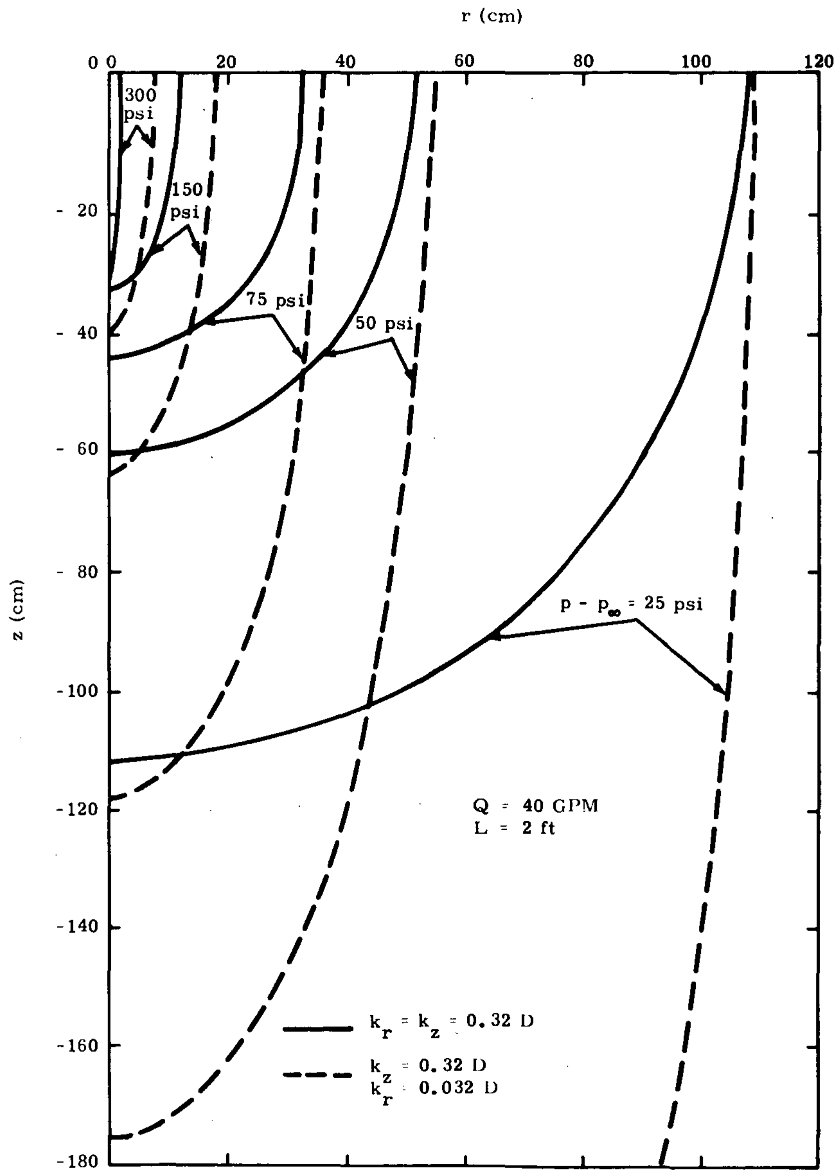

Figure 32. Isobars for Water Injection-Line Source

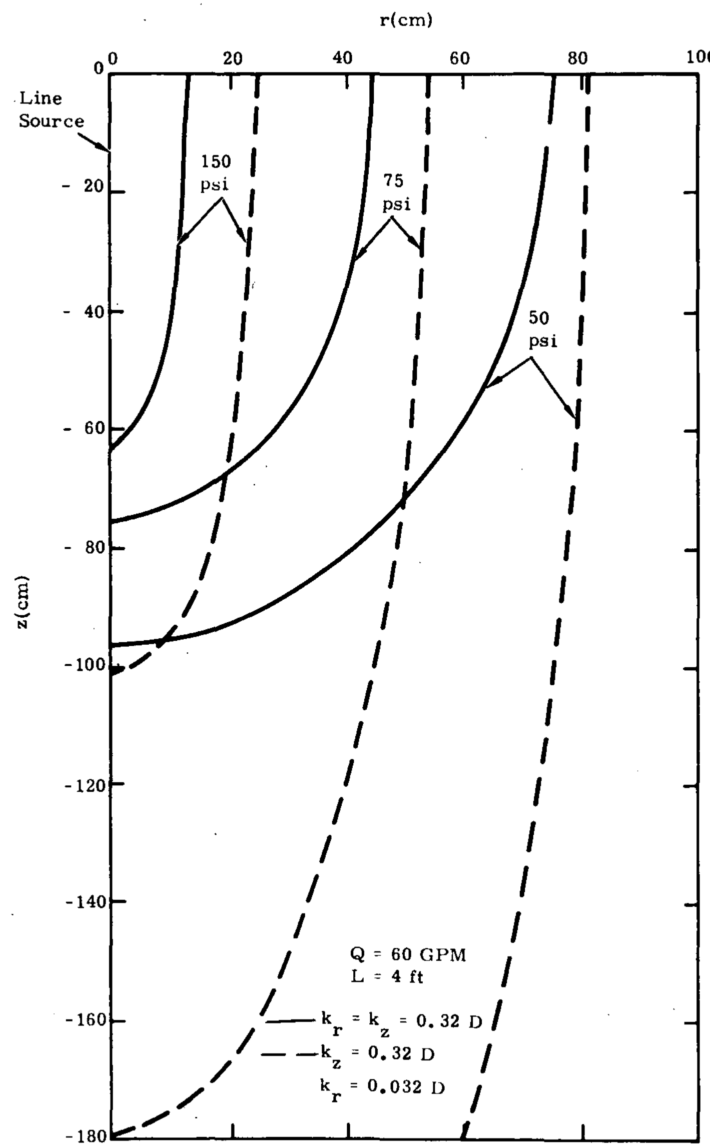

Figure 33. Isobars for Water Injection-Line Source

For this permeability experiment, pressures in the formation will be measured at three points:

$z = 0$, $r = 50$ cm

$z = 0$, $r = 100$ cm

$z = 100$ cm, $r = 0$

Strong anisotropic behavior, if present, should therefore be immediately evident from these data. Final data analysis to determine radial and vertical permeabilities will include use of the heat conduction code, CINDA.

Critical Parameter Calculations -- Not applicable.

Hardware Sizing Calculations -- The four speed water pump having a maximum flow rate of 40 GPM, required for other experiments, should be adequate if the formation permeability is near the estimated value 0.32 Darcy. If pressure differences between the formation transducers are too small to accurately record, the water flow rate should be increased above 40 GPM. This would require a second pump in parallel with the first. At higher flow rates, the vertical length of the injection section can also be increased. Isobars obtained with a 4-ft vertical injection section are shown in Figure 33. The feed water pipe should have a minimum inside diameter of 0.80 in. for 40 GPM flow rate and 1.13 in. for 80 GPM flow rate. Instruments required for this experiment should be capable of measurement in the following specified ranges:

Water flow meter - 0 to 40 GPM
Water line pressure - 0 to 500 psi
Formation pressure - 0 to 500 psi

Results

This experiment was not performed due to tight schedule and lack of time.

Crust Liquid Water Sampling Experiment

Location

Borehole K.I. 79-1

Purpose

The objective of this experiment is to obtain samples of in situ liquid water from several locations in the solidified upper crust of Kilauea Iki lava lake in order to:

1. Determine the lowest levels (and corresponding temperatures) in the upper crust at which liquid water exists.

2. Analyze collected in situ liquid water samples to determine the water/rock mass transport interactions.

3. Measure the salinity of collected in situ liquid water samples to aid in the construction and/or understanding of geoelectric models of the upper crust of the lava lake.

Background -- Cooling lava lakes may be considered to be dynamic models of hydrogeothermal (both liquid- and vapor-dominated) resources.[1,2] The collection and analysis of in situ liquid water samples from several levels in the upper crust of a cooling lava lake could be a valuable aid in further understanding the hydrothermal regime of these resources.

Geoelectric models of the vertical section through the upper crust of Kilauea Iki lava lake have been postulated based on the results obtained

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[1]Prof. R. W. Decker (Dartmouth College), personal communication, July 1978.

[2]D. E. White (USGS), personal communication, July 1978.

in the 1976 Sandia/USGS Lava Lake sensing experiment. Little is known about the variations of electrical conductivity at various depths in the upper crust. Locations (depths and temperatures) where in situ liquid water exists and its salinity would be valuable in such studies.

Description

Configuration -- A selected uncased borehole into the upper crust of the lava lake will be used for this experiment. A pair of air-inflated isolation balloon packers will be inserted downhole to seal off a selected 4-ft high interval of crust. A clean glass beaker will be fastened to the packer tube at the bottom of the sealed-off interval and a sample of the in situ formation water will be collected and retrieved when the packer is raised to the surface.

Operation Plan -- The following sequences of operations will be conducted in this experiment:

1. A pair of isolation balloon packers will be inserted downhole to a selected depth and inflated with compressed air.
2. Formation water samples will be collected by waiting for a period of at least 24 hours for a container to fill and be retrieved by raising the packer.
3. The above described sequences will be repeated at increasing depths until no samples of liquid water are retrieved.
4. Collected formation water samples will be sealed in sterile bottles and sent to Sandia Laboratories, Albuquerque or USGS, Menlo Park, for analysis.

Feasibility

Analysis of Feasibility -- Sampling of formation water in saturated mediums using isolation balloon packers in uncased boreholes is a common operation using commercially available equipment. The packer equipment selected for this experiment uses inflatable glands suitable for use in temperature environments up to 350°F, and should be adequate for this equipment.

Based on the above information, it is concluded that this experiment is feasible.

Since the formations to be sampled are not saturated due to the thermal flux present, the presence of liquid formation water is not known and the ability to retrieve samples is also unknown. For these reasons, the probability of success of this experiment cannot be predicted.

Results

This experiment was not performed due to tight schedule and lack of time.

VI. ELECTRICAL STUDIES

Mise-a-la Masse Melt Boundary Experiment

Location

Borehole K.I. 75-1

Purpose

The purposes of this experiment are to evaluate the definition of the lateral boundaries of the molten lava lens in Kilauea Iki using a method not tried in the 1976 Sandia/USGS Lava Lake sensing experiment and to obtain more definitive data to test the geoelectric model of the molten lava lens edge than has been developed by the USGS using the 1976 data.

Background[1] -- USGS results from the Turam and VLF measurements, designed to map the surface projection of the melt edges of Kilauea Iki lava lake, made as part of the 1976 Sandia/USGS Lava Lake sensing experiment, indicated that the boundaries are not simple. The higher lateral resolution of the VLF technique suggested that a high resistivity exists between the melt edge and outer, narrow, conductive wet zone. A geoelectric model developed by the USGS postulates that the high resistivity zone probably represents the area where the lava temperatures are between approximately 800° and 150°C and the outer conductive zone may include precipitant-enriched liquid-phase water.

Description

Configuration -- The stainless steel casing installed in borehole K.I. 75-1 as part of a previous experiment described earlier in this

[1] C. V. Zablocki (USGS, Denver), letter to J. L. Colp, Sandia, dated June 5, 1978.

report will be used as the lava lake electrode. A low-frequency current transmitter (5 to 20 Hz) will be used to energize the casing electrode and some distant grounded electrode placed outside the lava lake.

Operation Plan -- The low frequency current transmitted into the casing electrode in borehole K.I. 75-1 would cause the whole melt lens in the lake to appear as an electrode because the currents would tend to be collimated in the highly conductive melt. The current leaving this massive "electrode" would encounter the bounding high resistivity zone and would result in a large voltage gradient at the lake surface. The potential distribution would be mapped on the surface with a band-pass high impedance volt meter. Because of the present limitation of analytical interpretive techniques to simple and restrictive models, the USGS will make physical tank model studies to aid in the interpretations.

Feasibility

The mise-a-la masse technique is a standard method that has been used successfully to map the edges of buried conductive electrodes (ore bodies). Because of this experience, it is concluded that this experiment is feasible.

Results

The experimental measurements were made successfully as planned. The initial examination of the data acquired showed it to be coherent. Computer modeling studies to analyze the experimental data are underway but are not complete yet. A final report on this experiment will be prepared by C. J. Zablocki, USGS.

Melt Resistivity Experiment (T. L. Dobecki, 4733)

Location

Borehole 79-2

Purpose

The objective of this experiment is to penetrate the minimal crust thickness of Kilauea Iki Lava Lake with a combination penetrometer/resistivity probe, enter the melt, and determine the electrical resistivity of the melt. The results of the penetration portion of the experiment will augment those measurements made in borehole 75-1 (see Borehole Ooze Penetration Experiment). The purpose of the electrical resistivity measurement is primarily to provide an accurate value of the melt resistivity to enable more accurate modeling of the lava lake for inversion schemes utilized by surface electrical and electromagnetic surveys. This single value will also increase the current available knowledge on the general question of the *in situ* electrical characteristics of molten rock bodies.

Background -- Earlier electrical and electromagnetic surveys on the Kilauea Iki lava lake to determine the size and geometry of the molten mass have used a melt resistivity of 2.3 ohm/m in the inversion schemes. Observed interpretational errors have been blamed on fresh water recharge areas and the possibility of an incorrect model. A single *in situ* melt resistivity determination has been made at this site by Frishcknecht in 1962. The results of this experiment should provide information on the aging effects of lava lakes.

Description

Configuration -- A sketch of the apparatus to be used is shown in Figure 34. The penetrator tip experiment section and extension rod section are of 2 in. dia RA 333 high nickel stainless steel alloy. The tip, as with the ooze penetrator, is a 2.2 CRH point. Similar calculations relating length and diameter (Appendix A) were performed to verify the tool integrity under proposed applied static loads. The experiment section has a slotted section into which an insulating material (transite), equipped with four 1/8 in. dia 316 stainless steel pins which serve as contact electrodes, fits. The pins are equally spaced, in line, at 1-in. intervals. The outer pins will be current (I) injection points, while the inner two will measure resulting potential difference (ΔV). The measured resistivity, ρ_m, is related to these values by:

$$\rho_m = K \frac{\Delta V}{I}$$

where K is a geometric factor depending on tool design. K will be determined by calibration in fluids of known resistivity. In addition, present plan designs call for installation of thermocouples in at least the outer two electrodes to simultaneously measure temperature gradient while in the melt.

Uphole instrumentation is not yet firmly defined, but the desired system includes a constant current source ($I \sim 50$ mamp; variable frequency sine wave) and a recording system to provide permanent records of current and measured potential difference waveforms.

Operation Plan -- The penetration aspect of this experiment will be tailored exactly as the successful operation of the preceding ooze penetration experiment. Note that rotation of the stem will not be allowed in this test. Upon penetration, current input and measured potential drop will be recorded as a function of time and temperature (from thermocouple). Measurement will continue until probe failure or a time period not to exceed one hour (on a continuous basis). If probe failure does not occur in this time, measurements will continue at five-minute intervals.

Feasibility

Penetration -- The analysis of feasibility as presented in the description of the Ooze Penetration Test is certainly applicable here. The main differences which decrease our feasibility relative to that test are that the resistivity tool is of slightly greater diameter, and the resistivity device may not be rotated. Our ability to also withstand the full static push of the drill rig leads us to believe that this experiment is feasible.

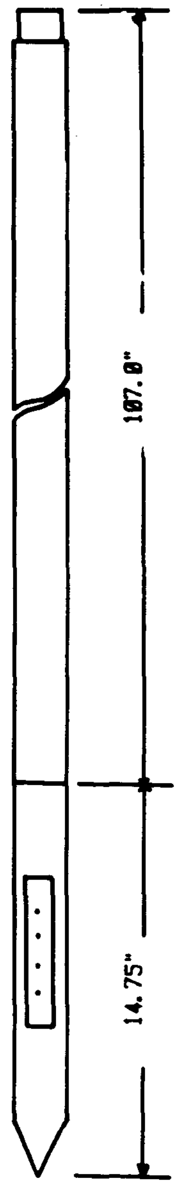


Figure 34. Apparatus Melt Resistivity Experiment

Resistivity Measurement -- Prior tests of a similar transite probe in a small furnace melt at Sandia Labs were entirely successful. Measurements were made over a five-minute insertion into the melt. After retrieval, neither the probe nor the electrodes/wires showed any thermal degradation.

On the basis of these tests, we feel that if penetration is achieved with little strain on the measuring section, reliable resistivity measurements can be made.

Results

The melt resistivity experiment was attempted on January 11, 1979, in borehole 79-3, located near previously drilled 75-1. Melt was encountered in 79-3 at a depth of 172 ft 10 in. Subsequent soundings showed an ooze rise of some 18 ft. This plug was redrilled to a depth of 169 ft 9 in., at which depth the level of plug stabilized. At this point, the penetrator-restivity probe was lowered to the bottom of the hole. The borehole was producing steam, but this did not complicate the lowering of the probe. The lowering operation required approximately 1.5 hours.

Upon reaching hole bottom, temperature measurements were attempted; however, both thermocouples read open. It is felt that these may have been severed in the process of eliminating a short between two electrodes the day before. All resistivity leads and electronics were connected and turned on. Full rig push was begun at 1550 hours. Input voltage of 22.5 V was sufficient to set up a current of ± 680 to 730 mA, implying low contact resistance even though the probe had not passed through rock. It is felt that the probe was not centralized, and the observed conduction path was through the sidewall, against which the measuring section of the probe was pushed. In any case, a conducting path with finite resistance existed; the electrodes were not shorted, nor were they open as would be expected. If steam existed at the hole bottom, perhaps this could set up a conduction path, but steam should not exist at bottom hole temperatures.

The full rig push was maintained for approximately 15 min. In this time, the probe had not advanced. It was decided that successful penetration could not be achieved under the given set of circumstances. Options were few: (1) retrieve probe and wiring intact, and re-try in the next boring (drilled to a few inches above melt); (2) abandon the resistivity probe but attempt penetration with the 1-3/4 in. penetrator in the next hole; or (3) abandon all resistivity and penetration experiments and proceed to advanced drilling experiments. After discussion, the third course was chosen. The resistivity probe was recovered, at the expense of the 300 ft of lead wires which had to be cut as pipe sections were removed. Upon probe recovery, the following was observed:

1. A small, hairline crack had been formed in the transite block. However, the block was whole and functional;

2. The transite resistance had dropped from infinite to approximately 200 K ohms;

3. The electrodes were shorted--this due to cut lead wires laying in a water-filled pipe.

In all, the probe had survived both the temperature and the applied static load.

The observed lowered resistance of the transite is felt to have been caused by absorption of water in the steam section of the borehole. It was also felt, prior to insertion, that any steam absorbed on the trip in would be driven off by the elevated temperatures at the bottom of the hole.

Conclusions

Due to substantial strength in chilled ooze, insignificant penetration could be obtained using full rig push. Although penetration was not realized, apparent resistivity measures of 2.3 to 2.6 ohm/m were obtained, perhaps implying contact of electrodes with the sidewall. It is interesting to note that 2.3 ohm/m is the value of melt resistivity used by earlier experimenters. The probe was recovered intact and usable. Further analysis of full current/potential waveforms from tape recorded data as well as a complete dissection and evaluation of the probe may provide insight as to what was being measured at hole bottom. The failure of this experiment, then, was in its inability to gain penetration and, of less importance, measure temperature. The resistivity system proved functional both downhole (probe) and uphole (instrumentation).

Formation Resistivity Experiment

(A Multiple Purpose Instrumentation Probe for In Situ Measurements of Crustal Material at Kilauea Iki Lava Lake (P. C. Lysne, 2355))

Location and Tactics

The instrumentation package described herein is designed to in situ measurements of the resistivity, the Eh and Ph, and the temperature and pressure at selected points in Kilauea Iki crustal material. Two or three 2-m-long probes will be buried in an existing drill hole in the area of the 100°C isotherm (depths 5 to 40 m) (Figure 35). Hopefully, the probes will return data for several weeks thereafter.

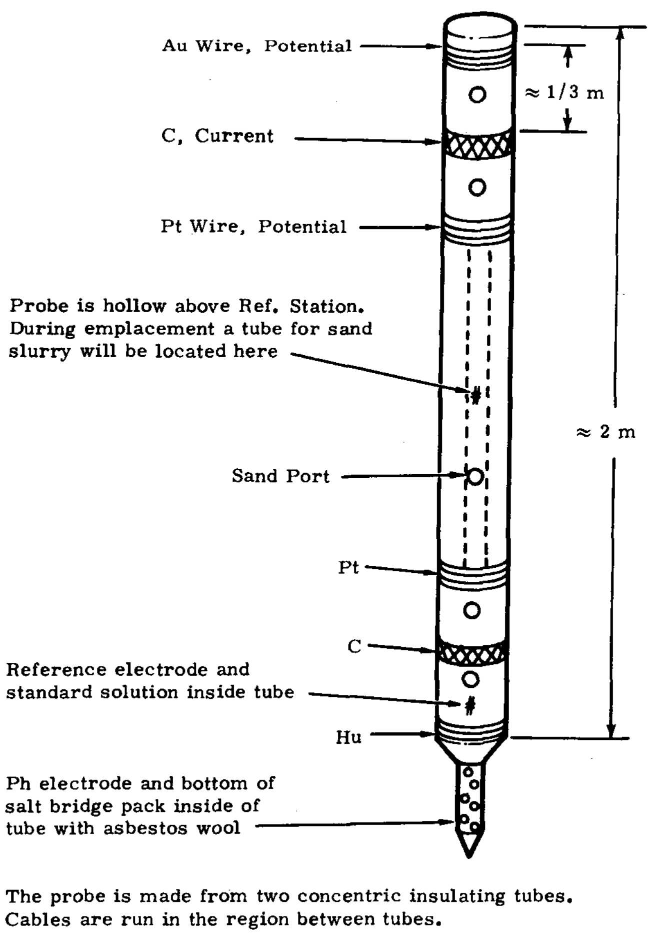


Figure 35. Instrumentation Probe

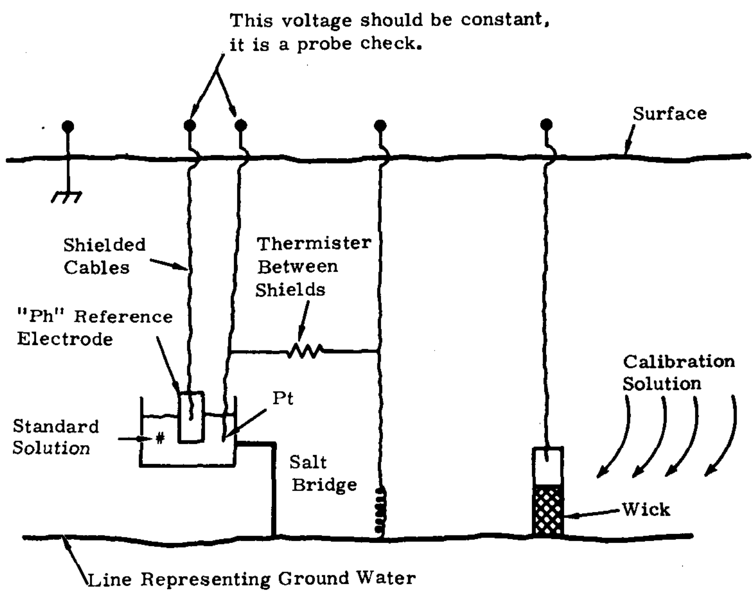
Purposes

Formation Resistivity -- Other experiments are being performed to determine the size of the molten zone and its conductance using surface and downhole electrical arrays, and the resistivity of the crustal material is required to correctly interpret the data obtained from them. Furthermore, the resistivity, as well as the Eh and Ph discussed in the Melt Resistivity Experiment, are dependent upon the amount and ionic content of the liquid-phase pore water. The spatial as well as temporal variation of the resistivity, Eh, and Ph provide some information on fluid flow patterns which evolve due to rainfall variations as well as instabilities in convective flow systems.

The resistivity measurements will be made using a standard electrical array. The electrodes will make contact to the formation through the surrounding damp sand. Current will flow between two massive electrodes, and potentials will be measured at four other locations on each probe. Such multiple measurements allow a correction for the resistivity of the damp sand. The resistivity electrodes are made of inert materials (C, Pt, Au) so that they may also function as Eh electrodes.

Formation Eh and Ph -- The Ph is a measure of the acidity of a solution whereas the Eh is a measure of its oxidizing capability. Together they yield complete information concerning the formation chemistry. These quantities provide constraints on possible mineralization, and they are a measure of corrosivity. Some aspects of this experiment are developmental.

Commonly, Eh and Ph measurements are made by obtaining voltage differences between their respective electrodes and a reference electrode, all electrodes being submerged in the solution of interest (Figure 36). Eh electrodes are made of inert materials, and the elements C, Au, and Pt are all candidates. Should one or two of these elements be attacked by groundwater, a backup element will remain. Special Ph electrodes are commercially available that operate in damp environments. These electrodes, when connected to the formation through a suitable wick, should work reasonably well. The reference electrode is more troublesome since commercial devices cannot take the downhole environment. In the probe, a reference system will be made from a second Ph electrode immersed in a buffer solution of known Ph. This solution is joined to the formation waters through a commercial salt bridge.



Note: The voltage between all Eh electrodes should be zero. If it is not, the difference may be due to:

a. electrode corrosion (erratic voltages)

b. gradients in groundwater chemistry (systematic voltages)

Figure 36. Eh/Ph Schematic

Obviously, there is some uncertainty in this experiment. However, so little is known concerning the groundwater chemistry that uncertainties of ±0.5 Ph and ±0.1 V Eh are acceptable.

Temperature -- Temperature measurements are required in the calibration of the Ph electrodes and the buffer solution as well as in the reduction of the data. They will be accomplished in a straightforward way using thermocouples or thermistors.

Calibration, Pressure, and Whatever -- To remove some of the uncertainty from the Ph measurement, a tube will be run from the vicinity of this electrode to the surface. This will allow the introduction of reference solutions at appropriate times during the course of the experiment. It also allows pressure determinations (the borehole will be sealed between probes with epoxy grout), and some downhole chemistry experiments may be performed.

Experiment Requirements

With the exception of the Ph electrodes and the salt bridge, all of the materials required for the construction of the probes are readily available. There are no critical areas in the design or fabrication of the probes and they should go together quickly. The uphole requirements include weather-tight connections, a switch box, portable high impedance voltmeters or electrometers and a power supply that may be as simple as a battery pack. It is anticipated that the probe and uphole instrumentation can be gathered in a month.

To be used most effectively, data should be obtained from the probes regularly, e.g., daily for the first week and weekly thereafter. It is expected that personnel from the HVO will participate in this experiment.

Results

This experiment was not attempted nor was the equipment fabricated due to time limitation.

VII. OTHER STUDIES

Recovery of 1975 Heat Flux Experiment Remains

Location

Borehole K.I. 75-3

Purpose

The objective of this operation is to recover, if possible, the hardware used for the 1975 heat flux experiment that was left at the bottom of borehole K.I. 75-3 in order to:

1. Study the effect of 45 months' exposure to the near-molten rock environment on the variety of engineering materials used to build the heat flux gage.

2. Deduce the mechanism responsible for the observed downhole sinking of the 1975 experiment remains.

Background -- In March 1975, a joint USGS HVO/Sandia experiment to measure the heat flux from molten rock was attempted in a borehole (K.I. 75-3) freshly drilled into the molten rock of Kilauea Iki by the USGS. The experimental apparatus was designed and built by Sandia in a very accelerated time frame. The apparatus (Figure 37) was very similar to equipment previously used in another program.[1] A variety of materials, including stainless steel, copper, high carbon steel, and tungsten carbide were used in fabricating the test apparatus. It was suspended and rotated downhole by approximately 135 ft of 1-1/2 in. dia schedule 40S Type 316 stainless steel ASA pipe with 316 stainless steel couplings.

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[1]H. C. Hardee and A. B. Donaldson, A High Intensity Direct Reading Heat Flux Gage, SCDR71-0194, Sandia Laboratories, Albuquerque, NM, May 1971.

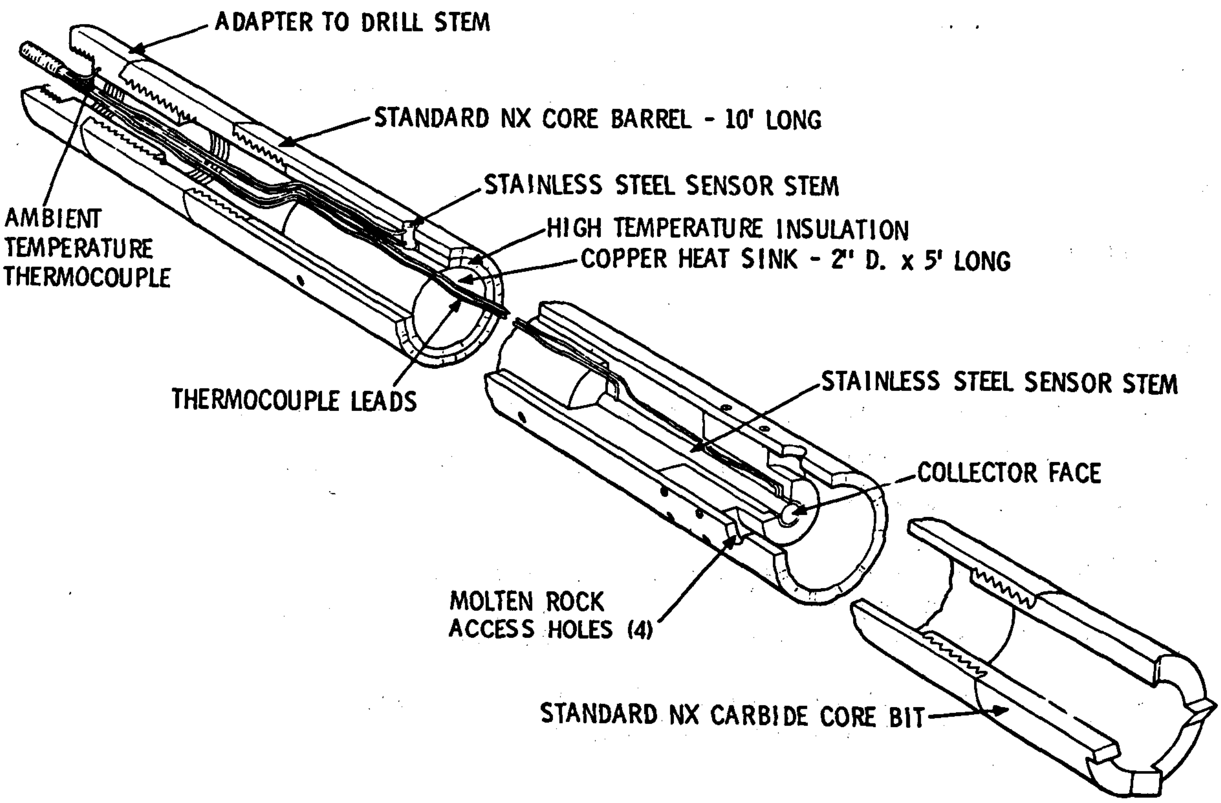

Figure 37. Molten Rock Heat Flux Sensor

The experiment was not successful. The test section could not be inserted into the molten rock as planned for unknown reasons. The test section was stuck at the bottom of the borehole (-145 ft) and was left with the stainless steel drive pipe intact to the surface of the lake, where it was sawed off flush.

In February 1976, C. Zablocki, USGS, observed that the top end of the stainless steel pipe was about 15 in. below the lake surface. The reason for this sinking is not known, although it should be noted that a + 7 magnitude earthquate had occurred on November 29, 1975, about 10 to 15 miles from the borehole site.

In March 1977, D. Moritz and J. L. Colp, Sandia, observed that the top of the pipe was then about 30 ft below the lake surface. Using very crude fishing tools, they succeeded in removing three sections (~30 ft) of the stainless steel pipe from the borehole; however, no couplings were removed.

The obvious hypotheses for the observed sinking of the pipe are (1) destruction of its lower end by corrosion due to the hot, adverse environment near the molten rock interface (Note: The pipe sections removed in 1977 showed very little corrosion at their elevation) and (2) slow creeping of the entire pipe column through the plastic rock into the molten rock presumed to lie below. The second purpose of this experiment is to gain information to aid in explaining the observed downward pipe movement.

Description

Configuration -- This experiment will utilize the Longyear HC-150 drill rig, standard fishing tools, and overbore coring tools. All equipment will be furnished and operated by the drilling contractor.

Operation Plan -- Borehole K.I. 75-3 will be cleaned of debris to the top of the existing stainless steel pipe (~-60 ft). As much as possible of the pipe will be fished, examined, labeled as to location, photographed, and moved to HVO. Material remaining in borehole will be overbored, brought to surface, and treated as above. The hole will be left open, with a suitable locked cover to meet NPS approval.

Feasibility

This experiment involves no unusual equipment or techniques. It has been discussed with the drilling contractor who says it can be done using normal commercial tools and techniques. For these reasons, this experiment is concluded to be feasible.

Results

This experiment was not performed due to tight schedule and lack of time.

Crust Bacterial Activity Experiment

Determination of Bacterial Activity in Near Surface Crustal Material of Kilauea Iki Lava Lake Experiment (P. C. Lysne, 2355)

Location and Tactics

Core and grab specimens of crustal material will be taken in the interval between the surface and the 100°C isotherm (depth $\approx$ 5 m). The specimens will be cut into $\approx$ 0.2 m lengths, marked and placed in sterile packages prior to air lift to Albuquerque and Socorro (NMIMT). Once in the laboratory, a quick look for bacterial activity as a function of depth, and, hence, temperature and other life-determining constraints, will be made. If these results appear to be significant, a detailed bacteriological/mineralogical study will be undertaken.

Purpose

Certain bacterial such as Thiobacillus ferroxidans and Thiobacillus thiooxidans have the capability of oxidizing iron and sulfur. In the oxidized state, these elements serve as oxidizing agents for other elements, thereby causing a "weathering" of rocks and an alteration of the groundwater chemistry. This bacterially "catalyzed" oxidation can proceed at rates appreciably faster ($\approx 10^3$) than more conventional processes. This rapidity has proven useful in some solution mining operations.

While the above Thiobacteriacea are common, and, hence, possibly active in the Kilauea Iki crust, their niche is small, and in situ it is most likely governed by their narrow temperature span for activity ($\approx$ 25 to 40°C). Other oxidizing bacteria have adapted to more extreme environments, such as hot springs approaching 100°C. The question addressed by this experiment is: Has there been sufficient time since the formation of the lava lake in 1959 (an obviously sterile environment) to the present to establish a varied and active population of oxidizing bacteria? One implication of a positive answer is that such a population could become quickly established in geothermal wells, thereby shortening the life-time of corrosion-susceptible hardware placed downhole. Another implication is that bacteria may significantly alter the groundwaters in the vicinity of thermal warm, spent nuclear fuel casks.

Experiment Requirements

Ideally, the core specimens would be obtained by air drilling. Since this does not presently seem possible, water-drilled core will be used. To avoid contamination of the center portions of the core, it should be taken quickly, and, if necessary, in short lengths. Immediately upon recovery, the core will be cut into ≈ 0.2 m lengths and packaged for shipment. It may be advisable to take a bacterial specimen immediately upon cutting the core and place them in an appropriate growth media. Ancillary measurements include the temperature and Ph profiles of the crust to about 5 m. This should not be difficult; litmus paper and a simple thermocouple apparatus are sufficient, although care must be taken to insure that the measurements are reasonably representative of in situ conditions.

Grab specimens may be obtained from old drill holes, fissures, and other representative locations. They may be in the form of crustal material or swab or wash inoculants.

The on-site expenditure for this experiment is estimated to be two man-days, largely to be spent in the supervision of the coring operation to insure protection of the bacterial data. The laboratory work will be conducted in the microbiological laboratory at NMIMT, where personnel are familar with the types of bacteria possibly present in the crustal material. The expenditure for the examination is minimal.

The expenditure is undetermined should the program grow beyond this phase.

Results

Five grab samples from the surface of the 1959 eruption were gathered by R. R. Neel, Division 4731. The locations and descriptions by Neel follow:

1. Sample 1 - Taken from a reddish-brown hole in the crust in the NE quadrant of the crater. Sample was quite moist. There was a white feathery deposit in the shady area.

2. Sample 2 - Collected near the top of a gas pressure mound near the base of the tram in the NW quadrant of the crater. There was a reddish-brown deposit all over the surface.

3. Sample 3 - Taken near the SW edge of the main eruption vent in the SW quadrant. Discoloration was not so pronounced.

4. Sample 4 - Collected in the SE quadrant in the area of nail 11S2.

5. Sample 5 - Collected in center area of crater near nail 19N2.

Ten core samples were collected from the core of borehole K.I. 79-3 by R. R. Neel, Division 4731. The depths at which the core samples were collected were:

No.	ft	in.
1	0	0
2	0	11
3	1	10
4	2	10
5	3	6
6	4	7
7	5	1
8	6	3
9	6	9
10	8	0

All samples were sealed in plastic bags and air-shipped to Albuquerque. The samples were then taken to the microbiological laboratory at NMIMT. Examination there revealed no presence of bacterial activity.

APPENDIX A

Structural Design Calculations - Borehole Ooze Penetration Test

This appendix summarizes the structural design calculations that were done to size the penetrator for the borehole ooze penetration test to be conducted in borehole 75-1. The criterion used for this analysis was that the penetrator and casing be capable of withstanding the maximum downward thrust of the HC-150 drill rig (P_{max} = 10,600 lb) without buckling or yielding. The length of the penetrator section was selected arbitrarily. A sketch of the ooze penetrator is shown in Figure 1.

Due to the close fit of the NW casing in the 3.75 in. dia borehole, buckling of the casing due to a compression load is prevented. The maximum axial stress in the NW casing due to an axial compression of P_{max} = 10,600 lb is

$$\sigma_A = 10{,}600 \text{ lb} \div \frac{\pi}{4(Do^2 - Di^2)}$$

$$= 10{,}600 \text{ lb} \div \frac{\pi}{4(3.5^2 - 3.0^2)}$$

$$\sigma_A = 4152 \text{ psi}$$

Since the NW casing is water-cooled to a temperature of T = 100°C, the yield strength of the 1035 carbon steel NW casing is approximately σ_y = 40,000 - 55,000 psi.[A1] The stresses in the NW casing are therefore at least an order of magnitude below yield.

For the solid round bar penetrator, RA 333 high temperature alloy steel was selected as a prime contender based primarily on availability. Two design criteria were considered. First, the bar should not buckle under the maximum thrust of the drill rig (P_{max} = 10,600 lb); the critical buckling load for a prismatic bar with one end fixed and one end hinged is [A2]

$$P' = 2.046 \frac{\pi^2 EI}{\ell^2}$$

For RA 333 at a temperature of T = 2000°F, the modulus of elasticity is approximately E(RA 333) = 16.5 x 10^6 psi.[A3] The moment of inertia of a solid round bar is

$$I = \pi/4 \, r^4$$

Since the length of the bar was assumed to be ℓ = 10 ft = 120 in., the critical buckling load is

$$P' = \frac{2.046 \, \pi^2 (16.5 \times 10^6) \left(\frac{\pi}{4}\right)(r^4)}{120^2}$$

or

$$P' - 18,172 \, r^4 \quad .$$

Since we would like P' ≥ 10,600 lb, the critical radius for buckling is

$$\gamma_{crit} = 0.874 \text{ in.}$$

Also, the axial stress should be below the yield strength. The axial stress in a round bar is

$$\sigma_A = R/\pi r^2 \quad .$$

For P = 10,600 lb and r = 0.875 in. (1-3/4 in. dia), the axial stress is σ_y = 4400 psi. The "short" time yield strength of RA 333 at 2000°F is approximately σ_y = 9000 psi, and the 10-hour tensile creep rupture strength is approximately 4500 psi; therefore, the 1-3/4 in. dia RA 333 bar should be adequate.

Based upon these design calculations, a 1-3/4 in. dia RA 333 bar is adquate for the 10 ft long penetrator.

<ins>Rotating Penetrator</ins> -- Another consideration in the design of the penetrator is the possibility of rotating the penetrator after it has

penetrated into the magma. Using molten rock viscosity estimates furnished by Dave Larson, Division 5512, the maximum torque on a 1-3/4 ft dia bar is 3.5 ft-lb/ft at 60 rpm or for a 10 ft long section, the maximum torque is T_{max} = 35 ft-lb at 60 rpm. At 60 rpm, the maximum shear stress in the bar is

$$eff = \sqrt{3\, T^{2}_{max}} = 690 \text{ psi/60 rpm} \quad .$$

The tensile creep rupture strength of RA 333 at T = 2000°F for 1 hour is approximately 6000 psi, therefore, the 1-3/4 in. bar is structurally adequate to rotate at 60 rpm in the magma.

References

[A1] Personal communication with R. G. Henning, Division 5833.

[A2] Handbook of Structural Stability, edited by C. R. C. Japan, Corona Publishing Co., Ltd, Tokyo, Japan.

[A3] Rolled Alloys, Inc., Technical Data Sheet.

APPENDIX B

Temperature Profile Data

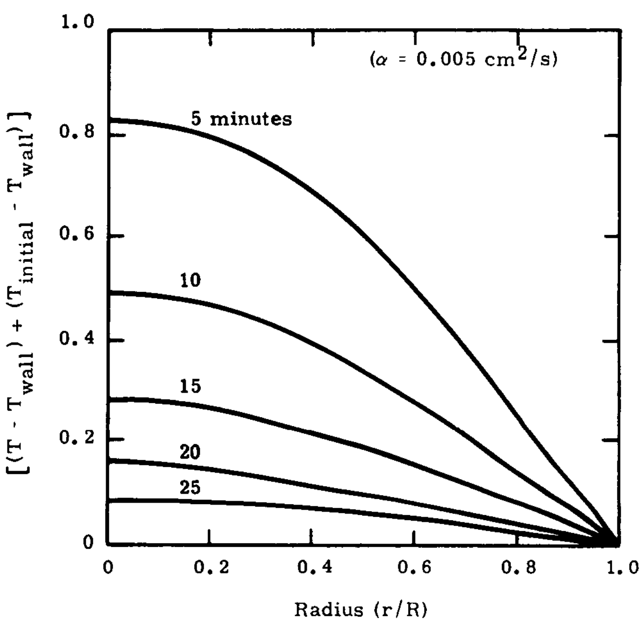

Figure B-1. Temperature Profile Across 3 in. dia Conduit of Magma With Constant Wall Temperature

Temperature (°C)*

Time	Distance (ft) \ r/R	0.0	0.2	0.4	0.6	0.8	1.0
5 min	3	1046	1045	1043	1038	1032	1026
	6	1039	1037	1029	1016	999	982
	9	1033	1030	1019	999	973	947
	12	1028	1024	1009	982	947	913
	15	1022	1018	999	965	930	874
10 min	3	1038	1037	1036	1033	1029	1026
	6	1016	1014	1011	1001	991	982
	9	999	996	988	976	962	947
	12	982	978	968	951	932	913
	15	965	961	947	927	903	879
15 min	3	1033	1032	1031	1030	1028	1026
	6	1001	1000	997	993	987	982
	9	977	975	970	964	956	947
	12	952	950	943	935	925	913
	15	929	925	917	906	893	879
20 min	3	1030	1030	1029	1028	1027	1026
	6	993	992	990	987	984	982
	9	965	963	960	956	952	947
	12	936	934	930	924	919	913
	15	908	905	900	893	886	879
25 min	3	1028	1028	1028	1027	1027	1026
	6	988	987	986	985	983	982
	9	957	956	955	952	950	947
	12	926	924	923	920	916	913
	15	894	893	891	887	883	879

*Assume linear profile along conduit from 1050° to 875°C at 15 ft.

APPENDIX C

Structural Design Calculations - Borehole Long Term Ooze Creep Test - Lava Lake Drilling Program (S. N. Burchett, 5521)

Ref: 1) Rolled Alloys, Inc., Technical Data Sheet

This memo summarizes the structural design calculations that were done to size the penetrator rod for the long term ooze creep test. In this test, the molten rock ooze is to be loaded with a fixed load and the displacement of the load rod monitored as a function of time. It is necessary, therefore, that the load rod be as stable as possible. This information should aid in the understanding of molten rock ooze. A sketch of the test setup is shown in Figure 23. The test hardware is the same as was selected for the borehole ooze penetration test and consists of a 10 ft long, 1.75 in., solid, RA 333 high temperature alloy steel bar coupled to a water-filled (for cooling) standard NW casing. The total weight of this hardware including water is approximately 1895 lb. The major question to be answered is, therefore, how long will this test hardware withstand the severe high temperature environment?

Due to the applied load, the maximum stress in the RA 333 bar is $\sigma_A \cong$ 790 psi. The RA 333 bar will be near molten rock temperature: $T \cong 2000°F$. Extrapolating tensile data for RA 333 (from Ref 1) to 2000°F, it is found that this stress level will cause 2% total creep in approximately 300 hours (12.5 days). If this strain were evenly distributed over the 10 ft section, the load rod would shorten 0.2 ft (2.4 in.). The critical buckling load for a 10 ft long 1.75 in. round RA 333 bar with fixed/pinned end conditions is approximately 10,600 lb, based upon the elastic modulus of

RA 333 at 2000°F. At these strain levels, however, the tangent modulus approaches zero and creep buckling may be a problem even at these relatively low loads.

Since this NW casing is water cooled, the maximum stresses in the casing due to the weight of casing (σ_A = 600 psi) and due to the water head ($\sigma\theta$ = pr/t = 1125 psi) are minimal compared to the yield strength of 1035 carbon steel at T = 100°C ($\sigma_y \cong$ 40,000 - 55,000 psi). Flexural buckling of the NW casing is also not a problem due to the relatively close fit of the casing in the borehole.

In summary, based upon those simple calculations and with the limited (extrapolation) material data, the load rod appears to be unstable under its own weight (including water) for more than two weeks.

APPENDIX D

Boiling Water Losses From Water-Filled Pipe Above Ooze Creep Penetrator
(D. W. Larson, 5512)

The potential loss of water due to boiling was determined for a three-inch schedule 40 pipe filled with water and inserted in a 160 ft deep well-bore in Kilauea Iki lava lake. The thermal profile in the well-bore was assumed to be a constant 100°C for the first 120 ft and to increase linearly to 1100°C over the next 40 ft.

The water was assumed to be at saturation temperature (which maximizes water loss, since energy required to heat water to saturation conditions is ignored), and the energy transfer from the well-bore to the pipe was assumed to be by black-body radiation (which maximizes energy transfer). The energy is delivered early to the pipe and water at an average rate of 22 kW/m^2 over the lower 40 ft of the pipe. This is sufficient energy to boil away 32 gal/hour of water (total pipe capacity is 61 gal). Due to a cooling effect on the walls and conduction-limited heat transfer rate in the rock, the energy transfer rate will gradually decline over a period of 48 hours to a steady value of about 1.0 kW/m^2, which is sufficient to boil away approximately 1.5 gal/hour of water.

The above water loss rates due to boiling are upper limits, since the water vapor generated in the lower 40 ft of the pipe must traverse 100 ft of 100°C water before being released to the atmosphere. The water vapor will very likely condense before reaching the surface, and the resulting energy increase in the upper 100 ft of pipe will be transferred to saturated media surrounding the well-bore.

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