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Kilauea Iki Lava Lake Experiment Plans

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ABSTRACT

Twelve experimental studies are proposed to complete Sandia's field laboratory work at Kilauea Iki lava lake. Of these twelve experiments, eleven do not require the presence of melt. Some studies are designed to use proven techniques in order to expand our existing knowledge, while others are designed to test new concepts. Experiments are grouped into three main categories: geophysics, energy extraction, and drilling technology. Each experiment is described in terms of its location, purpose, background, configuration, operation, and feasibility.

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F-81 KILAUEA IKI LAVA LAKE EXPERIMENT PLANS

1.0 INTRODUCTION

The objective of the DOE-funded Sandia Magma Energy Research Project is to investigate the scientific feasibility of extracting energy directly from buried magma sources. The project is divided into five discrete tasks: (1) Source Location and Definition, (2) Source Tapping, (3) Magma Characterization, (4) Material Compatibility, and (5) Energy Extraction.

As part of these tasks, the Magma Energy Research Project has been studying and performing field laboratory experiments on the shallow molten basalt body at Kilauea Iki lava lake. At present Kilauea Iki provides the only opportunity to directly test and measure in-situ property data for the various geophysical techniques that can be used to locate and define magma bodies deep in the crust. Kilauea Iki also provides a rare opportunity to study the dynamics of a cooling magma body. In addition, Kilauea Iki lava lake is the best location in the United States to conduct energy extraction experiments relevant to Magma Energy Research. Nowhere else in the United States does there exist an accessible large body of high temperature magmatic material at shallow depth. The purposes of the proposed experiments described in this report are to complete the geophysical study of a cooling magma body, to measure in-situ magma properties, to gain insight into the later stages of the cooling dynamics of magma bodies, and to study the scientific feasibility of extracting energy from magma bodies on a scale greater than can be achieved in conventional laboratory experiments.

The planned experiments have been divided into three general headings and are listed below.

1. Geophysics

- . Chemical and petrological analyses of recovered drillhole core.
- . Two-dimensional temperature profile.
- . Downhole steam flow measurement.
- . In-situ electrical conductivity measurements.
- . In-situ seismic measurements.

2. Energy Extraction

- . Energy extraction in magma using an open system.
- . Energy extraction in a permeable medium above a magma body.
- . Heat transfer rate measurements in magma.
- . Heat transfer rates using a downhole calorimeter.

3. Drilling Technology

- . Drill and core to pre-1959 surface near center of the lake.
- . Water-jet augmented core bit drilling in magma.
- . Evaluation of conventional core bit design in upper crust.

The proposed geophysical experiments are designed to complement but not duplicate the previous geophysical experiments in such a way as to form a comprehensive study of the life history of a buried magma body from not only a petrological, chemical and thermal point of view, but also from a geophysical sensing point of view. Knowledge gained from this study is necessary in order to locate and define magma bodies in the earth's crust. Two experiments are designed to measure in-situ magma electrical and seismic properties. Information on these properties,

which is not presently available, is necessary in order to accurately locate and define magma bodies. Two experiments are proposed to study the later stages (also applies to the mid-stages) of the cooling dynamics of a buried magma body. In contrast to earlier work, these experiments will study not only the region over the center of the body, but also the regions on the margin and beneath the body. Such a study is necessary in order to understand how a magma body cools and how the thermal signature of the body, which can be seen from the earth's surface and from boreholes, relates to the energy content, exact location, and configuration of the body. A chemical and petrological experiment is planned and involves analysis of the core samples that are obtained during the drilling required for the other experiments. In order to obtain a complete mass balance model of the crystallization and differentiation of Kilauea Iki lava lake, coring through the center of the lake to the pre 1959 surface must be done. The resulting data, when used in combination with previous core analyses, will be used to test thermodynamic equilibrium models of crystallization and provide a capability for predicting magmatic evolution and energy content that will be applicable to basaltic chambers other than Kilauea Iki.

The present test plan proposes both open and closed systems to measure energy extraction rates in magma. Neither of these measurements have ever been made in-situ. For the open system experiment, the magma will be water cooled in an attempt to thermally induce fractures in order to create a large surface area for heat transfer. This should result in energy extraction rates that are much greater than rates obtained with closed heat exchanger systems. The basic idea of thermally inducing fractures in a magma has never been tried. The success of such a scheme,

however, could be of major importance when assessing the feasibility of the project's Task 5, energy extraction. One experiment is designed to measure in-situ thermal properties and heat transfer rates to a closed system. Measurements will be obtained by heating, rather than cooling, the magma, thereby allowing data collection at temperatures higher than the in-situ state. These measurements will complement data obtained in the laboratory at Sandia where geometry restrictions are limiting. In addition to the measurements in magma, one experiment is planned to measure energy extraction rates in the high temperature margin above a magma. This measurement is important to assess the potential for energy extraction above a magma body without direct entry into the magma chamber.

Although development of drilling technology is not part of the Magma Energy Research Project, drilling in the lava lake is necessary to conduct the proposed geophysical and energy extraction experiments. During this drilling, the Magma Energy Research Project would be remiss if it did not evaluate drilling performance, especially in high temperature regions of the lake.

In light of the recent data of Hardee (1980) and Gerlach and Luth (1980), there may not be sufficient melt present in Kilauea Iki lava lake to justify the downhole calorimeter experiment. However, the other experiments do not require a molten lens; they are just as relevant whether melt is present or not, as long as a high temperature, plastic region does exist. The in-situ property experiments should still be run to establish how very hot rock ($> 800^{\circ}\text{C}$) differs in geophysical appearance from magma. The cooling dynamic experiments (temperature, steam flow) are still appropriate, since a hot impermeable body surrounded by a wet permeable medium, which is

characteristic of many magma bodies, will still exist at Kilauea Iki. The energy extraction experiments are all meaningful experiments with or without the presence of melt in the Kilauea Iki lava lake. The open system (3.1) only requires a large region of plastic material that can be thermally fractured (temperatures greater than about 725°C). The margin experiment (3.2) is conducted in the crust at relatively low temperatures (below about 700°C), and the heat transfer rate experiment (3.3) uses a downhole heater to create melt around the heater. The calorimeter experiment (3.4) can still be used to measure heat transfer rates in the drillhole, but this particular experiment would be more meaningful with the presence of melt. Therefore, the calorimeter experiment would probably be canceled if melt does not exist.

The experiments described in this test plan directly relate to the investigation of the scientific feasibility of energy extraction from magma bodies. However, the knowledge gained from these experiments can have important applications in other areas of research. For example, the geophysics of magma body location and definition are also applicable to the magma bodies located under geothermal fields. Evaluation of the final locations for Continental Scientific Drilling Program (CSDP) boreholes can benefit from the geophysical techniques associated with magma body location and definition. The study of the hydrothermal circulation around magma bodies will help to understand not only the thermal signatures observed over magma bodies at the earth's surface, but also those observed from boreholes (CSDP). The study of hydrothermal circulation around magma bodies in a permeable medium will also be applicable to the study of mineral deposition. Energy extraction using open systems in hot, plastic

rock may have application below present geothermal fields. Investigating energy extraction rates in the margins near a magma body can provide important information for intermediate systems in the temperature range between Magma and "Hot Dry Rock." Finally, data obtained from the heater experiment may show that this method can be used effectively to measure in-situ thermal conductivity at high temperature.

Individual experiment plans are described in the following sections. Time estimates shown are based on: 1) a set-up time of 1/2 day for each new hole, 2) a drilling rate of 25 m/day, and 3) a time of 1/2 day for casing. The equipment list for each experiment includes some items that are required as a part of the drilling operation, or are required to support several different experiments. These items of general use are identified by an asterisk (*).

2.0 GEOPHYSICS

2.1 Chemical and Petrological Analysis of Recovered Drillhole Core from Kilauea Iki Lava Lake

Location

Five new holes located along a north radial line from the center of the lake. Distances from the E-W centerline are 0, 90, 180, 270 and 360 m (0, 300, 600, 900 and 1200 ft). Holes will be BQ size.

Purpose

Provide basic data for a mass balance model of the crystallization and differentiation of Kilauea Iki lava lake. This can yield a current estimate of the amount and distribution of residual liquid in the lake. Also, these data in combination with previous core analyses will be used to test thermodynamic equilibrium models of crystallization and provide a capability for predicting magmatic evolution that will be applicable to basaltic chambers other than Kilauea Iki.

Background

Similar chemical and mineralogical analyses have been completed for core obtained from 3 holes (KI 79-1, KI 79-2, KI 79-6) during the FY 79 drilling program [Gerlach and Luth (1980)]. This provides background data at one point in time. Only one hole (KI 79-5) has been drilled to the pre-1959 surface and this hole was located near the edge of the lake where no molten basalt was encountered. To properly model the lake, several holes to the pre-1959 surface are required with at least two located to pass through the molten lava lens.

Description

Configuration--The first hole to be drilled will be located along the north radial line of previous drilling at a distance of 180 m (600 ft.) from the center of the lake. Recovered core will be examined during the drilling and real-time measurements of glass refraction index and glass fraction will be made. In this manner, crustal, transitional, and molten regions will be identified. Coring will be completed when the pre-1959 surface is reached. The second hole to be drilled will be located at the center of the lake. The location of the next three holes will depend somewhat on the results obtained from the first two holes but are to be located such that at least two of the five holes penetrate the molten lens, and at least two holes penetrate the pre-1959 side slope.

Operation--Core samples will be analyzed using conventional techniques. Early preliminary analysis will be attempted during the drilling operation by air shipment of selected samples to Sandia.

Feasibility--Coring the upper crust of Kilauea Iki has been done many times and presents no problems. Drilling through the molten lens, however, has never been attempted and problems are to be expected. Previous drilling with conventional coring equipment in the lava lake has been stopped several times by liquid lava flow into the drill hole. Limited drilling success was achieved during the FY 79 drilling program, but depth into the molten material was only on the order of 10 m. If they are required, both conventional and water-jet augmented core bits will be used in the attempt to drill through the molten lens to the pre-1959 surface.

Experiment Requirements

1. Material and hardware (exclusive of drill rig)

- A. Conventional BQ-3 wireline coring equipment*
- B. Water-jet augmented coring equipment *
- C. Standard core boxes*
- D. Microscope for refraction measurements

2. Personnel (exclusive of drillers)

One petrologist will be required to log core and measure refraction index of glasses on site. He will also identify crustal, transitional and molten regions and evaluate entry into the pre-1959 eruption surface. Another person will be required to supervise the drilling.

3. Time estimate

- A. Drilling to the pre-1959 surface will take about 6 days.
- B. Total time estimate for the 5 holes is 30 days.

2.2 Two-Dimensional Temperature Profile

Location

Five cased boreholes spaced radially outward from the center of the Kilauea Iki molten lava lens.

Purpose

The purpose of this experiment is to evaluate the temperature distribution in a vertical plane extending from the center to a point past the

*equipment items of general use

margin of the molten lava lens. The temperature profiles provide the best means of observing the cooling dynamics of a lava body. Specific questions that the temperature measurements can answer are:

- A. Does the heat source that is causing an unusual increase in bottomhole temperature in KI 79-5 exist at other radial locations?
- B. Is natural convection more important at the lateral margins of the molten lens than over and under the center of the lens? A comparison of the observed temperature profiles with theoretical conduction models for the lava lake [see Ryan (1979)] will show the relative importance of natural convection at various locations throughout the lake.
- C. Can temperature measurements (above 725°C) taken in several boreholes off the edge of the molten lens lead to predictions for the thickness of the lens that agree with other geophysical techniques? Ryan (1979) suggests that very little thermally induced cracking takes place above 725°C. Thus, the region of the lake above 725°C may be void of hydrothermal convection and conduction theory could be used to define the thickness of the lens.
- D. Is the 100°C isotherm actually closer to the surface near the margin of the lens than over the center, or are the KI 79-5 measurements a demonstration of steam contamination created by the uncased hole?
- E. How does a buried molten rock body cool with time?

Background

No temperature measurements in cased boreholes along the margins of the Kilauea Iki molten lava lens exist. A problem that can exist with uncased boreholes is thermal contamination due to steam flowing up the hole. Uphole steam flow is observable in all the present Kilauea Iki boreholes. Numerical experiments indicate that steam rising at 0.6 m/s for a period of 11 months in a hole similar to KI 79-5 will cause the wall temperature to rise as much as 100°C above the formation temperature. The steam temperature, which is what a downhole thermocouple in an uncased hole actually measures, can be up to 120°C above the corresponding true formation temperature after 11 months. The time rate of change of the borehole temperature can also be higher in a steam contaminated borehole than in the surrounding formation. For example, modeling a hole similar to KI 79-5 with the steam flowing up the hole at 0.6 m/s gives a time rate of change of borehole steam temperature that is five times that expected due to a conduction induced change. The KI 79-5 borehole is, in fact, changing temperature at five times the rate expected due to pure conduction at 30 m depth. Based on visual observation in March 1980, a steam flow rate of 0.6 m/s up KI 79-5 is reasonable. This indicates that the current temperature profiles in KI 79-5 are more a reflection of thermal contamination than formation temperature. The difference in measured temperature and formation temperature at 30 m can be as much as 120°C.

The effect of steam contamination in uncased boreholes over the center of the molten lens is probably much less due to the lack of a significant quantity of steam in the dryout zone of the formation [see Hardee (1980)]. However, casing the holes over the center and out at the margins of the

lens has the advantage of reducing the time necessary to eliminate the drilling water cooling effects [see Colp (1979)] from several months to a few weeks. Casing in holes through the center of the lens is also required, to maintain hole stability.

Description

Configuration--The experiment is to consist of five cased boreholes extending from the center of the lava lens to a point past KI 79-5. The holes outside the bounds of the molten lens must extend below the pre-1959 surface. If the holes that are drilled over the molten lens can be drilled through the lens, much valuable information can be gained. However, only holes drilled to the upper melt boundary are necessary for the successful completion of the experiment.

The holes are to be cased with conventional stainless steel 310 small diameter tubing. The hole is to be stemmed with multiple grain size volcanic sand by tremieing the sand in place. The casing is to be sealed at the bottom and capped at the top with a removable but "tourist-proof" cap. The temperature sonde is to be a slender version of the stainless steel sonde used successfully in previous experiments.

Operation--The procedure for the experiment is:

1. Drill each hole 10 meters below the pre-59 flow or as deep as possible into the melt.
2. Case the hole by lowering the casing in place. The casing should be capped at the bottom and "tourist-proofed" at the top. The casing should then be stemmed by lowering a tremie tube into the hole along the side of the casing, and air-blowing sand into place.

3. Take preliminary temperature measurements by lowering the sonde in 3 m increments and allowing the sonde to equilibrate. The temperature can then be hand recorded from a trendicator.
4. Repeat steps 1 through 3 for the other 5 boreholes.
5. Repeat the temperature measurements after a three day period and at subsequent intervals (weekly) until the effect of the drilling water has disappeared.

Feasibility--Numerical experiments indicate that the difference between true formation temperature and measured temperature in the cased boreholes will be less than 3°C , assuming a hydrostatic pressure gradient and 25 darcy sand. Twenty-five darcy sand is readily available. The main problem expected in installing a casing is creating an effective stem around the casing. However, tremieing concrete in place has been proven to be an effective technique for placing concrete in the building industry. Sandblasting is also a well established technique. By tremieing the sand in place through a modified form of sandblasting, a successful stemming should be obtained.

A problem encountered with a previous casing in Kilauea Iki is corrosion due to the magmatic gases. However, as lab tests indicate [Traeger et al. (1979)], stainless steel 310 is much more resistant to corrosion than is the stainless steel 316 used for the previous casing.

Experiment Requirements

A. Material and hardware (exclusive of drill rig)

1. Temperature sonde on reel (150 m of cable)*
2. Trendicator*
3. Casing and caps, 650 m stainless steel 310
4. Tremie tube, 130 m, steel pipe
5. Sand
6. Sandblaster
7. Generator*
8. Tent*
9. BQ-3 wireline coring equipment*

B. Personnel (exclusive of drillers)

One person will be required to measure borehole temperatures.

C. Time Estimates

Total drilling and casing time will be 6 days for each hole.

If drilling through the melt proves not feasible, drilling to the melt will take 3 days.

The temperature measurements will take 1/2 day per hole.

2.3 Downhole Steam Flow Measurements

Location

One new uncased borehole over the center of the molten lens and the existing KI 79-5 borehole on the margin of the lens.

*equipment items of general use.

Purpose

The purpose of this experiment is to evaluate the mass flow rate of the superheated steam that flows up uncased Kilauea Iki boreholes. A knowledge of the mass flow rate as a function of depth in a hole over the molten lens and in a hole off the margin will answer the following questions:

1. Is the mass flow rate of steam up a hole in the dry-out zone of a significant quantity to indicate convection exists in the dry-out zone?
2. Is there a significant mass flux into a hole at depths corresponding to temperatures greater than 725°C? Ryan (1979) suggests that very little thermally induced cracking occurs above 725°C. If the quantity of thermal cracking isn't significant, little convection will be present in the super 725°C region of the lake.
3. Is the mass flow rate into the hole introduced through a few large cracks, or through a large number of small cracks? How important is the contribution of flow through the unfractured material?

Background

While downhole flow measurements are common in low temperature applications, the high temperature corrosive environment encountered in the Kilauea Iki lava lake precludes the use of conventional techniques. The most promising device to measure the superheated steam flow is the hot wire anemometer. Uncooled platinum hot wires are capable of operating in highly corrosive environments at temperatures up to 800°C.

Description

Configuration--The experiment is to consist of 2 uncased holes; KI 79-5 and a new hole over the center of the molten lens. A hot wire anemometer will be lowered by a 310 stainless steel sheathed coaxial cable to various depths. A separate temperature sonde such as the one described in the experiment plan 2.2 will be used to determine in situ temperatures so that the output of the anemometer can be corrected for temperature. The electronics associated with the anemometer will be attached to the hot wire by a coaxial cable and housed in a tent for protection from the elements. A generator will be necessary to power the hot wire anemometer and its associated equipment.

Operation--The procedure for the experiment is:

1. Drill a hole into the dry-out zone over the center of the molten lens.
2. Wait two months to allow the residue cooling water to dissipate from the hole.
3. Lower the unpowered hot wire into the hole to depths in increments of 3 m, power-up, and record the output.
4. Remove the hot wire from the hole and lower a temperature sonde to the same depths and record the corresponding temperatures. Allow 2 minutes for the sonde to equilibrate.
5. Repeat steps 3 through 5 for the KI 79-5 hole.

Feasibility--Possible causes of failure are:

1. Corrosion of the hot wire at high temperatures.
2. Breakage of the hot wire due to mechanical shock imparted to the wire supports or hot wire directly,
3. Corrosion or failure of the coaxial cable,
4. Inability of hot wire to sense very low velocities.

The chemical characteristics of magmatic gases are such that in terms of metal incompatibility, O_2 and S_2 are of critical importance [Traeger, et al. (1979)]. Tests indicate that platinum, when exposed to O_2 and S_2 at magmatic temperatures, displays no corrosion. A hot wire constructed of platinum operating in the downhole conditions expected at Kilauea Iki will probably survive the corrosive environment. Platinum hot wires that can survive $800^\circ C$ temperatures are commercially available.

The problem of breakage of the hot wires can be minimized by enclosing the wire probe in a stainless steel 310 wire cage such as the one used successfully on the existing temperature sondes. Caution in constructing the cage is necessary in order to prevent the cage from modifying the flow patterns seen by the probe.

The corrosive or thermally induced failure of the coaxial cable depends on the materials used in the cable. While high temperature corrosive resistant coaxial cable is commercially available, it is expensive. An alternative to a high temperature cable is a low temperature cable encased in a water or air cooled stainless steel 310 jacket.

Since hot wires operate at temperatures above ambient conditions, the lower limit for an accurate velocity measurement is that velocity for which

the contribution to the flow due to thermally induced convection by the hot wire is insignificant. Thermo-Systems Inc. state that their sensors are capable of measuring velocities down to 6 cm/s in air and 0.6 cm/s in water. By reducing the overheat ratio, lower velocities can be measured. The accuracy of the measurement will decrease, however, with a reduction in overheat ratio. Future work is required to determine the minimum measurable steam velocity and the effect of this velocity on the success of the experiment.

Experiment Requirements

A. Material and hardware (exclusive of drill rig)

1. Hot wire probe and 5 spares (\$340 each)
2. 150 meters of coaxial support cable and probe receptable reel
3. Anemometer system (can get one on loan)
4. 150 meters of external calibration cable
5. Generator*
6. Tent to protect equipment*
7. Temperature sonde on wheel*
8. Trendicator*

B. Personnel (exclusive of drillers)

Two people will be required to measure temperatures and velocities.

C. Time Estimate

The drilling of the borehole over the center of the lens to the melt will require 3 days. The velocity and temperature measurements will require 1 day per hole.

*equipment items of general use

2.4 In-Situ Electrical Conductivity Measurements

Location

Several boreholes in the Kilauea Iki lava lake.

Purpose

The purpose of this experiment is to evaluate the electrical conductivity as a function of depth, and therefore temperature, of a magma body in its later stages of cooling.

Background

The United States Geological Survey has proposed a value of 6 to 8 Mhos for the depth-conductivity product of the melt in the Kilauea Iki lava lake whereas the University of Texas at Austin group has suggested an "effective" product of 1-2 Mhos. The Geological Survey estimates are based on surface loop-loop electromagnetic measurements, whereas the UTA group's estimates are based on telluric measurements. The UTA group suggest that the discrepancy is due to a resistive steam sheath surrounding the lava lens.

At the present time, there is no direct evidence that can be used to test the validity of the steam sheath model. The existence of a steam sheath will be a critical parameter in the selection of electromagnetic methods used in the exploration of magma bodies. In-situ measurements will help resolve this question.

FY80 measurements indicate that a highly conductive zone exists throughout a depth range much larger than the depth range indicated by 1979 core analysis for the melt zone. This contradiction suggests that the hot rock surrounding the melt zone contributes, through some unresolved mechanism,

to the highly conductive image seen in Kilauea Iki. In-situ measurements are needed to evaluate the extent of this contribution.

Description

Configuration--The experiment is to consist of logging freshly drilled uncased boreholes by standard induction logging techniques. The transmitter-receiver spacing will be chosen to "see" past the solidified region of the magma surrounding the borehole which is caused by the drilling water cooling effect.

After the experiment is run, the hole should be cased to allow for accurate temperature measurements.

Operation--The procedure to be used for each hole logged is:

1. Immediately after the drilling of a hole, lower the induction sonde in place and log at different depths.
2. If hole stability in the high temperature region is a problem, run cooling water in the hole between measurements.
3. Case the hole and measure the temperature profile by the procedure discussed in the Two-Dimensional Temperature Profile experiment (2.2).

Feasibility--Borehole induction logging is a well established technique (Telford, et al. (1976)). The only difficulty expected is designing a probe that can fit downhole and withstand a high temperature environment for a short period of time. This precaution is suggested in case the water cooling of the high temperature borehole is not sufficient. Conventional techniques such as encapsulating the probe in a silvered quartz dewar should suffice.

Experiment Requirements

A. Material and hardware (exclusive of drill rig)

1. Induction probe, cables, and supporting electronic equipment
2. Power supply for probe
3. 130 m of steel downcomer if cooling required
4. Water pumps and filters if cooling required*
5. Holding tank if cooling required*
6. Temperature sonde on a reel (150 m of cable)*
7. Trendicator*
8. Casing and caps, 130 m stainless steel 310
9. Tremie tube, 130 m, steel pipe
10. Sand
11. Sandblaster
12. Generator*
13. Tent*

B. Personnel (exclusive of drillers)

Two people will be required to handle the induction logging equipment.

One additional person is required for the borehole cooling equipment.

C. Time estimate

Total drilling and casing time for each hole is 6 days. Logging will require one day per hole.

2.5 In-Situ Seismic Measurements

Location

One borehole drilled through the center of the lake to the pre-59 surface.

*equipment items of general use

Purpose

To determine in-situ seismic properties of the high temperature regions of the lake.

Background

Although surface and downhole seismic studies have been done at the lake, the highly fractured surface layers of the lake make interpretation difficult. The previous experiments had both sources and receivers at or near the 100°C isotherm. Thus a seismic signal had to travel down to the molten lens and back up to the receiver. In the present experiment, the source is to be located at various depths below, in, and above the high temperature zone and the receivers are to be located on the surface near the borehole and positioned to allow stacking of the signal to reduce the interference of the highly fractured surface layers.

Description

Configuration--The experiment is to consist of a source, such as a sparker, placed at various depths in an uncased borehole at the center of the lake. A series of geophones are to be placed at the surface near the borehole to allow stacking of the seismic signal. All other instrumentation is to be housed in a tent.

Operation--The following sequence of events comprise the experiment:

1. Place all surface geophones.
2. Drill borehole through melt (or high temperature region).
3. Keep hole open with circulating water.
4. Stop water pumps and remove downcomer pipe.
5. Place seismic source into hole at an appropriate depth.

6. Run seismic experiment.
7. Resume cooling of hole.
8. Repeat steps 4 through 7 for each source depth.

Feasibility--The experiment is feasible if a hole can be drilled through the molten lens (or high temperature zone) and held open with water.

Experiment Requirements

A. Material and hardware (exclusive of drill rig)

1. 130 m of steel downcomer
2. Water pump and fittings*
3. Holding tank*
4. Generator*
5. Seismic source such as a sparker
6. Seismic equipment
7. Tent*

B. Personnel (exclusive of drillers)

Three people will be required to conduct the seismic experiment. Two seismic experts are required for the data acquisition, and one additional person is required for the operation of the cooling apparatus.

C. Time estimate

1. The drilling time for an uncased hole through the molten lens is about 6 days.
2. The seismic experiment can be completed in one day for each hole measured.

*equipment items of general use

3.0 ENERGY EXTRACTION

3.1 Energy Extraction in Magma Using An Open System

Location

New hole approximately 5 m into molten lens, NQ size, cased with BW casing.

Purpose

Measure energy extraction rates in molten basalt that has been thermally altered. Determine if a closed region can be created that will contain water and steam.

Background

For closed heat exchanger systems placed in a basaltic magma chamber, estimates of steady-state energy extraction rates are from about 1 to 30 kW per square meter of heat exchanger surface. Open heat exchangers offer the potential of significantly increasing the heat transfer area in a drill hole thereby providing larger energy extraction rates per hole.

Description

Configuration--The open heat exchanger concept is illustrated in Figure 3.1. An NQ size hole will be drilled close to the molten lens. BW casing with carbide cutters will then be drilled approximately 2 m into the molten material establishing a sealed system. The BQ water-jet augmented coring system will then be used to core out material in the casing and then approximately 3 m deeper into the lens. During drilling, and during the downhole experiment, molten basalt near the drill hole will be solidified and thermally fractured. The extent of fracturing in terms of heat transfer area will be estimated by measuring the rate of energy

Figure 3.1 Schematic Illustration of Open Heat Exchanger System

production from the hole. A double tube arrangement will be used to pump water into the hole and receive steam flow up through the casing. A valve in the steam return line will be used to control steam flow and downhole pressure. Either continuous or "huff-and-puff" operation can be accommodated. Rates of energy extraction will be measured with a condensing calorimeter that has previously been used for steam systems. A comparison between return steam mass flow rate and downhole water mass flow rate will provide information concerning the extent to which the fractured cavity is sealed.

Operation--The sequence of events is:

1. Core an NQ-3 hole to a stable location (approximately 0.25 m) above the molten lens.
2. Drill BW casing about 2 m into lens.
3. Using water-jet augmented system, core about 3 m past the end of the casing.
4. Install insulated downcomer with attached thermocouples, casing seal, and condensing calorimeter.
5. Operate counterflow heat exchanger with continuous flow. Control inlet water flow rate to produce steam at the outlet.
6. Operate heat exchanger in "huff-and-puff" mode. Control downhole pressure with the outlet steam valve. Lithostatic pressure is not to be exceeded.
7. Data recording requirements are: two downhole thermocouples, two calorimeter thermocouples, calorimeter load cell, and inlet water flow rate meter.

Feasibility--An attempt to establish an open heat exchanger based on similar concepts (the porous plug experiment) was made during the FY79 drilling program. In that experiment, a closed system was established several times using casing and liquid lava flow-back. However, the closed system was not maintained and could not be reestablished at the end of drilling. This was caused by several factors. At one time, the casing-basaltic glass seal was broken when retrieving the N-size water-jet augmented drilling system which had become stuck in the casing. A second time the casing seal was destroyed when the casing was fixed at the top. Cooling water caused thermal contraction of the casing in the longitudinal direction and this led to separation. Finally, downhole pressures of about 3.5 MPa caused fracturing of the formation and established communication with an adjacent drill hole.

Experience with heat exchanger probes in the foundry has shown that a good glass-to-stainless steel seal is produced when cooling liquid basalt with a heat exchanger. Estimates of the thermal profile surrounding the BQ drill hole can be obtained by considering a constant temperature cylindrical cavity in an infinite medium that is initially at 1100°C. With a hole temperature of 25°C for 8 hours, the 1050°C isotherm occurs at a radial location of 0.25 m from the wall of the BQ hole. Of course fracturing will provide sites for further cooling away from the hole, but it is unlikely that large fractures (on the order of 2 m) will be generated. Downhole pressures will be maintained at a value less than the lithostatic pressure to prevent hydraulic fracturing. To prevent separation of the magma/casing seal, the casing must not be rigidly supported at the top of the borehole.

Experiment Requirements

A. Material and Hardware (exclusive of drill rig)

1. NQ wireline coring equipment*
2. BW casing
3. BQ water-jet augmented coring equipment*
4. Insulated downcomer .025 m (1 inch) diameter (includes two thermocouples located on outside surface)
5. Steam piping, .05 m (2 inch) diameter
6. Steam throttling valve for .05 m (2 inch) line
7. Water shut-off valve*
8. Casing seal for BW casing to .025 m (1 inch) downcomer
9. Condensing calorimeter (includes 1 load cell and 2 thermocouples)
10. Three SOLTEC recorders.*

B. Personnel (exclusive of drillers)

Two people will be required to direct the experiment, control water and steam flow rates and take data.

C. Time Estimate

1. Approximately 3 days will be required to set up, drill, and core the NQ hole to a stable depth above the molten lens.
2. One additional day will be necessary for coring to the molten lens, installing BW casing, and drilling the casing into the lens.

*equipment items of general use

3. A final day will be necessary for coring 5 m into the molten lens, final installation of experiment hardware, and data collection.

Note: these last steps require continuous operation to maintain stability of the heat exchanger cavity.

4. Total time estimate: 5 days.

3.2 Energy Extraction in a Permeable Medium Above a Magma Body

Location

New hole into transition region above molten lens.

Purpose

Measure energy extraction rates in porous material above a source of high temperature basalt. Rates are to be measured both with and without water stimulation.

Background

During the FY79 drilling operation, overall energy extraction rates using a counterflow heat exchanger were measured for a period of 1-1/2 hours [Dunn (1979)]. This vertical-pipe configuration was located in the upper crust from the surface to a depth of 52 m. Measured heat transfer rates were considerably higher than rates calculated assuming heat transfer in the formation by conduction alone. Thus, it appears that heat transfer by convective movement in the upper crust was significant. This raises the possibility of using porous regions above a magma body for energy extraction. More detailed data are required to determine a heat transfer rate profile with depth and the effects of water stimulation on heat transfer to the heat exchanger.

Description

Configuration--Figure 3.2 shows the upper crust heat exchanger configuration. NQ coring equipment will be used to core into the crustal/molten lens transition region. The hole will be terminated above the molten lens at a depth that will remain stable for a period of several weeks. BW casing with the bottom 6 m made of 310 stainless steel will be placed in the hole and held a few centimeters off bottom with a foot clamp at the surface. The lower end of the casing will be capped with a removable .025 m (1 inch) plug. A .025 m (1 inch) insulated downcomer will then be installed inside the casing and sealed at the top with a casing seal. This arrangement gives a vertical pipe, counterflow heat exchanger. The downcomer is supplied by a water pump and the outer annulus is connected to a .025 m (1 inch) outlet pipe. Water flow rates in the heat exchanger will be controlled so that only hot water (no steam) leaves the heat exchanger. Thermocouples will be placed on the outside surfaces of the casing and downcomer at approximate heights of 0, 5, 30 and 50 m above the bottom of the downcomer. Measurements will be taken at three separate times: 1) immediately after installation, 2) 5 days after installation, and 3) after water stimulation. A controlled amount of water will be injected into the formation by removing the bottom casing plug and then pumping water through the downcomer. The plug will be replaced and heat transfer rates measured.

Operation--The sequence of events is:

1. Core an NQ-3 hole to a depth about 0.5 m above the molten lens.
2. Case hole with special BW casing which includes attached thermocouples and a closed end with a removable plug.

Figure 3.2 Schematic Illustration of Crustal Heat Exchanger

3. Insulated downcomer, casing seal, and outlet flow pipe.
4. Operate counterflow heat exchanger for a period of 5 hours.
5. Wait 5 days, then operate heat exchanger again for a period of 5 hours.
6. Remove casing end plug.
7. Force 18 m³ of water into formation through bottom of casing.
8. Replace casing end plug.
9. Operate heat exchanger for 5 hours.
10. Data recording requirements are: 8 downhole thermocouples, one outlet flow thermocouple, and inlet water flow rate meter.

Feasibility--Based on the experience obtained during the FY79 energy extraction measurements, this experiment should not have any major difficulties. The more carefully instrumented system described herein will be used to obtain more complete data for this energy extraction concept.

Experiment Requirements

A. Material and Hardware (exclusive of drill rig)

1. NQ wireline coring equipment.*
2. BW casing with 4 thermocouples located on outer surface.
(lower 6 m made of 310 stainless).
3. Bottom casing seal with removable plug.
4. Insulated .025 m (1 inch) downcomer with 4 thermocouples.
located on outer surface.
5. Water flow meter.*
6. Water throttling valve.*

*equipment items of general use

7. Outlet flow thermocouple.
8. Foot clamp for casing.*
9. Casing seal for .025 m (1 inch) downcomer.
10. Recording capability for 10 low level data channels.*

B. Personnel (exclusive of drillers)

Drilling personnel can be used to aid in the installation of the heat exchanger. After installation, one person will be required to run the experiment and collect data.

C. Time Estimate

1. Approximately 3 days will be required to drill the hole.
2. One day will be required to install heat exchanger equipment.
3. Measurements will be taken at three separate times. The first two will require 1/2 day each and the third will require a full day.
4. Total time is 6 days.

3.3 Heat Transfer Rate Measurements in Magma

Location

New hole, BQ size, uncased.

Purpose

The objective of this experiment is to determine if convective movement, significant to the heat transfer process, can be established in a magma at subliquidus temperatures. Heat transfer rates will be measured in molten basalt as a function of temperature. Also, in-situ thermal conductivity and viscosity will be measured.

*equipment items of general use

Background

A physically realizable heat transfer rate in magma is one of the most important parameters needed to determine the economic feasibility of using a heat exchanger to extract energy directly from magma bodies in the crust. Laboratory tests conducted in the Sandia Foundry have provided heat transfer rate measurements for Cuerbio basalt [Hardee (1979), Larson (1979), Pelletette (1980)]. At 1290°C molten basalt convection appears to be important in the heat transfer process and a convective heat flux as high as 34 kW/m^2 was determined from the data. Foundry tests are restricted to small volumes of $.0125 \text{ m}^3$, where cooling of the liquid body is difficult to prevent, and geometry effects alone can limit convection. Kilauea Iki Lava Lake offers the opportunity to conduct heat transfer measurements in a molten basalt of significant volume. In-situ thermal property measurements are extremely difficult at magma temperatures and have not previously been attempted at Kilauea Iki.

Description

Configuration--A schematic illustration of equipment required for this experiment is shown in Figure 3.3. BQ-3 wireline coring equipment will be used to drill into the highest temperature region near the center of the lake. This region should be approximately 1050°C at about 60 m. The cylindrical heat source will be lowered into the borehole while feeding high temperature electrical wires through 310 stainless steel tubing sections. The tubing will be secured at the surface in such a manner that thermal expansion can be accommodated. The hole will be allowed to close around the heater, then hole depth will be measured. A generator will be used to supply a constant power of 1 kW to the heater. The heater surface temperature response will be recorded as a function of time.

Figure 3.3 Schematic Illustration of Downhole Heater Experiment

Operation--The sequence of events is:

1. Core a BQ-3 hole to a depth that is approximately 3.5 m into the molten lens.
2. Install cylindrical heater and 5 kW generator.
3. Wait until hole closes around heater.
4. Operate heater for a continuous period of 40 hours.
5. Data recording requirements are: six downhole thermocouples, and heater current and voltage.

Feasibility--The experiment operating mode is similar to the line source probe technique for measuring thermal properties in that the surface temperature history of the heater is used to define the response and properties of the medium into which it is placed. Initially, the temperature of basalt surrounding the heater will be about 1050°C. The viscosity at this temperature will be sufficiently high so that convection will not be present initially. Thus, the early time response of the heater surface temperature is governed by thermal conduction in the basalt. This portion of the experiment lasts for about three hours and will be used to determine the in-situ thermal conductivity. At later times, the heater surface temperature will begin to fall below the temperature for pure conduction. This signals the onset of convection. The time and rate of convection onset can be related to the Bingham yield stress. As the material temperature increases beyond this point, convection dominates and the heater surface temperature response can be used to determine the viscosity of the basalt.

Experiment Requirements

A. Material and Hardware

1. Cylindrical heating element .051 m diameter by 0.51 m long -
Operating temperature is 1300°C with maximum power dissipation
of 5 kW
2. Six type K thermocouples with high temperature sheath - 70 m long
signal leads
3. Heater support pipe
4. 5 kW generator, 120 volt with voltmeter and ammeter*
5. Four SOLTEC recorders*
6. Cable-weight assembly to measure hole depth*

B. Personnel (exclusive of drillers)

Two people will be required to place the heater-tube assembly downhole. Thereafter, one person will be required to periodically check generator operation and the SOLTEC recording.

Note: Overnight operation will be necessary for one evening and this will require two people due to safety considerations.

C. Time Estimate

1. Three days will be required to drill the hole into the melt.
2. Heater placement and operation will require 40 continuous hours.

3.4 Heat Transfer Rates Using a Downhole Calorimeter

Location

Placed in the melt in the Kilauea Iki lava lake.

*equipment items of general use

Purpose

The purpose of this experiment is to place a steady-flow heat exchanger calorimeter into the molten lava lens at Kilauea Iki and to measure the resulting heat flux to the calorimeter.

Background

A previous attempt was made to place a calorimeter into the in-situ melt, but the experiment was canceled due to the termination of the insulated drill stem experiment. The smaller diameter of the holes to be drilled in FY81 precludes the use of the existing insulated drill stem calorimeter. A new calorimeter is to be designed.

Description

Configuration--Shown in Figure 3.4 is a preliminary sketch of the proposed calorimeter. By specifying the size of each of the three orifices, and by controlling the flow rate in the vertical pipes, the bleed rate of the water into the heat exchanger section can be controlled. A bleed rate of only $4.5 \text{ cm}^3/\text{s}$ is required to maintain a 10°C temperature rise across a 1 meter heat exchanger section when placed in the melt. The higher flow rate in the vertical tubes is necessary to keep the cooling water from boiling during its long trip down from the surface of the lake.

The calorimeter is designed to be lowered down the drill stem after the drilling is completed. The thermocouples will be attached to a SOLTEC recorder. A variable output pumping system will be used to supply the cooling water.

Figure 3.4 Schematic Illustration of Calorimeter

Operation--

1. Drill borehole into melt.
2. Lower calorimeter down drill stem.
3. Pump the cooling water at a rate that will give about a 10°C rise across the heat exchanger.
4. Record pump flow rate and the temperatures of the two thermocouples over a period of time.
5. Recover calorimeter.

Feasibility--The calorimeter is a relatively simple device that can be constructed entirely of 310 stainless steel. The supporting water tubes will maintain their strength during the short time period required to run the experiment, due to the cooling water. No major engineering problems are foreseen.

Experiment Requirements

A. Material and hardware (exclusive of drill rig)

1. Calorimeter including 120 meters of SS-310 tubing and thermocouples.
2. Water pump and holding tank.*
3. Water flow meter.*
4. 1 SOLTEC recorder.*

B. Personnel (exclusive of drillers)

Two people will be required to conduct the calorimeter measurements.

C. Time estimate

The drilling will require 3 days. The calorimeter experiment should take 1 day.

*equipment items of general use

4.0 DRILLING TECHNOLOGY

4.1 Drill and Core to Pre-1959 Surface Near Center of Lava Lake

Location

New hole near center of lake, BQ size, uncased.

Purpose

Obtain core and provide a drillhole from the surface to the pre-1959 surface of Kilauea Iki lava lake.

Background

A hole has not been drilled through the center of Kilauea Iki lava lake to the pre-1959 eruption surface. The benefits to be derived from such a drill hole are numerous. First, core obtained through the entire lake profile would be invaluable for petrological and geochemical studies of the historical and present state of the lava lake. Second, geophysical measurements (temperature, resistivity, seismic) obtained with a deep hole through the lake could lead to much better interpretation of geophysical measurements related to the location of shallow magma bodies in the crust and to a better understanding of the cooling dynamics of magma bodies. Third, a core through the lake would provide information concerning the present lake structure that would be valuable in the final planning of energy extraction and heat transfer measurements in the lake.

Description

Configuration and Operation--The first attempt to core through the lake will be with conventional BQ-3 wireline coring equipment. Two types of conventional bits will be available for use: the first, a surface set diamond bit having 25 stones per carat, the second, an impregnated diamond

bit with waterways. Both of these bits will be operated in the high temperature region with a relatively high water flow rate of about $1.9 \times 10^{-3} \text{ m}^3/\text{s}$. If core recovery becomes a problem, a special inner-tube assembly that incorporates a basket-type core catcher will be used. Water flow down the drill rod is to be maintained during wireline operation. If conventional drilling is stopped by molten lava flow into the drill hole, reentry will not be attempted with conventional equipment. Under this circumstance, the same hole will be reentered with a BQ-3 water-jet augmented bit described in the "Water-Jet Augmented Core Bit" experiment plan, 4.2. Drilling procedures given in that plan will be followed. Drilling will stop when the pre-1959 eruption surface has been penetrated [estimated depth of 120 m (390 ft.)].

Feasibility--With one exception, conventional drilling in Kilauea Iki lava lake has been unsuccessful in regions where molten lava was present. Liquid lava flowing into the drill hole has entered or surrounded the bit causing blocked water passages or seizure. The 1979 drilling of KI 79-1 is the exception. A depth of 61.9 m (202.5 ft.) was successfully cored with conventional HQ wireline equipment and the core showed high glass content below about 53 m (172 ft.). Drilling was halted at 61.9 m (202.5 ft.) due to time schedule constraints and not due to lava flow back. However, filter-press material soon entered the hole and later reentry attempts to deepen the hole with conventional equipment were unsuccessful. Reentry with an N-size water-jet augmented core bit did successfully advance the hole, but core was not recovered. This experience in KI 79-1 lends a measure of hope to the feasibility of coring through the lake with conventional equipment. The Icelanders have successfully drilled in molten basaltic lava flows using conventional diamond and tricone bits [Bjornsson and Sigurgeirsson (1979)]. The key to success here appears to be high

water flow rates ($1 \text{ to } 2 \times 10^{-3} \text{ m}^3/\text{s}$) during drilling. Core recovery in this case was not attempted. The water-jet augmented core bit probably has a higher probability for success in molten material due to the cooling characteristics of its high momentum forward-directed jets. Also, jet stagnation pressure at the nozzles will be greater than the maximum expected lava pressure. The core recovery problem experienced in FY79 should be eliminated by the inclusion of a basket-type core catcher.

There is probably a set of circumstances under which neither the conventional coring equipment nor the water-jet augmented bits will function. This situation could occur if a large amount of highly mobile melt exists under substantial pressure, say lithostatic pressure at 61 m which would be approximately 1.4 MPa. Since the drill hole pressure is approximately atmospheric, there is a large potential for flowing liquid lava into the hole. If a large flow area is developed between the lava and drill hole, molten lava could be forced rapidly into the hole. In this case, bit water flow probably would not be able to solidify the lava rapidly enough to prevent bit seizure. More importantly, however, is that there is a real hazard associated with this set of circumstances. Rapid mixing of molten lava with water in the bottom of the drill hole could produce a violent steam explosion. At this time, the drilling in Kilauea Iki will probably not encounter large bodies of highly mobile fluid lava under high pressure. Calculations by Hardee (1980) show that the lake is in a late stage of solidification. Analyses of core samples from KI 79-1, KI 79-2, and KI 79-6 show a glass volume percent of only slightly above 30% in high temperature (molten) regions of the lake [Gerlach and Luth (1980)]. Such a high proportion of crystals (70%) in a magma results in a very high effective viscosity. Therefore, the potential for rapid flow through fractures is much less than it would be for more fluid magmas.

In addition, there is the successful experience of drilling to 61.9 m with conventional equipment in hole KI 79-1. Analysis of the core from this hole shows transition from crustal material to molten lens complete by 54 m [Gerlach and Luth (1980)]. Thus, approximately 8 m of molten material was successfully drilled.

Experimental Requirements

A. Material and Hardware (exclusive of drill rig)

1. BQ-3 wire line coring equipment.*
2. BQ-3 water-jet augmented coring equipment.*
3. Modified core barrel that includes basket-type core catcher.*
4. Meter to measure water flow rate.*
5. Plastic bags for fragmented core.*
6. Microscope.*

B. Personnel (exclusive of drillers)

One geologist will be required to log core and measure refraction index of glasses from recovered core on site. He will identify crustal, transitional, and molten lens regions of the lake and evaluate entry into the pre-1959 eruption surface. Another person will be required to supervise the drilling and make decisions concerning bit selection, advance rate, and water flow rate.

C. Time Estimate

1. Coring with conventional equipment to the pre-1959 eruption surface will require 6 days.
2. If the water-jet augmented bit is necessary, the total coring operation will also take about 6 days.

*equipment items of general use

4.2 Water-Jet Augmented Core Bit Drilling in Magma

Location

Any new hole in molten lava, BQ size.

Purpose

Drill into molten basalt and recover core.

Background

At the present time, experience in Kilauea Iki lava lake indicates that water-jet augmented drill bits offer the highest probability of success when drilling in molten basalt. Two types of water-jet augmented bits were successfully tested in Kilauea Iki during the FY79 drilling program. One was a modified 3-wing drag bit; the other, a modified face discharge, pilot-type, diamond core bit. The core bit was used to reenter filter-press material in hole KI 79-1 where reentry with conventional coring equipment was unsuccessful. Problems experienced with the jet augmented core bit were no core recovery and rapid wear of the pilot-type bit caused by insufficient cooling.

Description

Configuration and Operation--Two water-jet augmented bit designs in BQ-3 size will be tested. The first will use a standard surface-set diamond bit with jet nozzle shapes incorporated into the matrix material at the time of manufacture. The second design will use an impregnated diamond bit with the same manufacturing technique of including nozzle shapes in the matrix material.

A special core recovery system will be used with the jet augmented core bits. This includes a modified inner tube that will accommodate a basket-type core catcher in series with a standard core lifter.

Jet nozzles and the water flow delivery system will be designed to produce a nozzle stagnation pressure of 1.7 MPa which is above the maximum expected pressure in the lake. When drilling in regions of high percentage melt, a water flow rate of $1.9 \times 10^{-3} \text{ m}^3/\text{s}$ will be used. Advance rate will be controlled to prevent molten lava flow into the borehole. An initial rate of 3 m/hr will be used. During water-jet augmented drilling, water flow rate will be recorded along with the following drill functions: RPM, bit load, and advance rate.

Feasibility--The drilling success in FY79 proves that the water-jet augmented concept can work in molten basalt. The jet augmented core bit was used to drill 4.5 m in molten material but core was not recovered. A new core recovery system has been designed for the water-jet bit to solve this problem. A basket-type core catcher will be used in series with a standard core lifter in a modified core barrel. Bit crown shape, waterways, and water flow rate will be designed to provide better bit cooling than was possible with the pilot-type bit.

Experiment Requirements

A. Material and Hardware (exclusive of drill rig)

1. Water-jet augmented core bits (two designs).
2. Two modified BQ-3 core barrels with basket-type core catcher and standard core lifter.
3. Water flow rate meter.*

*equipment items of general use

4. Two SOLTEC recorders.*

5. Plastic bags for fragmented core.*

B. Personnel (exclusive of drillers)--

One person will be required to supervise the drilling, evaluate bit performance, and make decisions concerning bit selection, water flow rate and advance rate.

C. Time Estimates

1. Drilling the upper crust to the molten lens using conventional BQ-3 wireline coring equipment will take about 3 days.
2. The drilling rate of the water-jet augmented core bit should be about 3 m/hr.

4.3 Evaluation of Conventional Core Bit Design in Upper Crust

Location

New holes required for other experiments, size BQ-3.

Purpose

Select most desirable core bit characteristics for drilling solidified basalt.

Background

The most significant expense associated with conducting an experimental program in Kilauea Iki lava lake can be attributed to simply drilling holes. Much of this drilling (approximately 50 m depth) can be considered conventional drilling in that the formation is solidified basalt at about 100°C. This situation is not unique at Kilauea Iki. Experimental measurements of

*equipment items of general use

interest to the Magma Energy Research Project (temperature, velocity, resistivity, energy extraction, etc.) will require drill holes irrespective of location. Areas involving shallow basaltic bodies in the crust will probably also be characterized by cooled basaltic flows which must be drilled to reach the higher temperature regions of interest. This is certainly true in Hawaii, Iceland and the Cascades. Therefore, improving drilling rates in solidified basalt by proper core bit design can have an important long term benefit to the Magma Energy Project.

Description

Configuration--A total of 12 coring bits whose characteristics are given in Table 4.1 will be evaluated. Six new holes in the upper crust will be required. These holes can be located anywhere in the lake. The site will be selected on the basis of other experiments that require BQ-3 drill holes. Each bit will be used in one of two depth intervals: 1) 0 - 12.5 m and 37.5 - 50 m, or 2) 12.5 - 37.5 m. Nominal penetration rate is 3 m/hr. Bits that perform significantly below this value will be discontinued before their assigned depth interval is reached. The following drill functions are the minimum required for proper bit evaluation: RPM, bit load, and advance rate. These data are to be recorded as a function of time. A postmortem evaluation of bit wear will be made.

Operation--

1. Use bit #1 to core from the surface to a depth of 12.5 m.
2. Remove bit #1 and visually evaluate wear. Photograph.
3. Install bit #2 and core from 12.5 m to 37.5 m.
4. Remove bit #2 and visually evaluate wear. Photograph.
5. Install bit #1 and core from 37.5 m to 50 m.

6. Remove bit #1 and visually evaluate wear. Photograph.
7. Repeat steps 1 through 6 for the remaining bits.
8. Data recording requirements are: RPM, bit load, advance rate, visual wear evaluation, and photography.

Feasibility--All bits listed in Table 4.1, except bit #12, are available directly from drill bit companies and require no major development work. Bit #12 does require application of technology developed by Sandia, Organization 4741. This Division will provide bit #12. The newer Longyear drill rigs include instruments that measure RPM and bit load. Advance rate can be timed with a watch.

Experiment Requirements

A. Material and Hardware (exclusive of drill rig)

1. Twelve coring bits described in Table 4.1.*
2. Instruments to measure RPM and bit load.*
3. One SOLTEC recorder.*

B. Personnel (exclusive of drillers)

One person will be required to make decisions about drill bit selection, to properly log drill bit history, and to collect data.

C. Time Estimate

Bit evaluation should not significantly affect normal time required for coring holes in the upper crust. Expected nominal penetration rate is 3 m/hr. Thus, six new holes to 50 m would require 100 hrs of actual drilling time exclusive of set-up time.

*equipment items of general use

Table 4.1: BQ-3 Core Bit Characteristics

1. Diamond Bits - The following bits all have a hard matrix and waterway reinforcement where applicable.

Bit #	Diamond Set	Diamond Size	Diamond Quality	Waterways	Crown Design	Probable Supplier
1	surface	25 s/c	medium	yes	semi-round	Christensen
2	surface	25 s/c	medium	no	semi-round	Christensen
3	surface	25 s/c	medium	no	round	Christensen
4	surface	10 s/c	medium	no	semi-round	Acker
5	surface	40 s/c	medium	yes	semi-round	Christensen
6	surface	25 s/c	high (carbonado)	yes	semi-round	Christensen
7	impregnated	25/35 mesh	synthetic	yes	flat	Christensen or Longyear
8	impregnated	150 s/c	medium	yes	circle-set	Acker

2. Tungsten Carbide Bits

Bit #	Description	Probable Supplier
9	Standard SRTC core bit	Christensen
10	Standard insert type core bit	Acker

3. STRATAPAX* Bits

Bit #	Description	Probable Supplier
11	New CHRISDRIL** core bit	Christensen
12	in-house development	Sandia, Division 4741

* STRATAPAX is a trademark of General Electric

** CHRISDRIL is a trademark of Christensen, Inc.

5.0 Drillhole Requirements

Table 5.1 describes the drillholes that are necessary to support the proposed experiments. Holes are listed in the preferred drilling order with experiment utilization of each hole keyed to the section numbers (sections 2 through 4). Although, as shown in Table 5.1, considerable joint usage is possible, a total of nine new holes are required. These holes are shown in plan view in Figure 5.1. Seven holes require casing and five of these are to be drilled to a depth of about 130 m. Two holes require N-size (.0757 m (2.98 in.) dia.) coring equipment and all others require B-size (.0600 m (2.36 in.) dia.). The drilling time shown in Table 5.1 includes set-up time and time for casing the hole. A total of about 42 working days will be necessary to complete the drilling program.

Table 5.1. Drillholes Required for Experiments

Drill Hole	Size	Location	Approx. Depth (m)	Cased Hole	Approx. Drilling Time (days)	Experiment Utilization											
						2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	3.4	4.1	4.2	4.3
81-1	BQ	180 m N of center	130	yes	6	X	X		X							X	X
81-2	BQ	near center	130	yes	6	X	X		X	X					X	X	X
81-3	BQ	90 m N of center	130	yes	6	X	X		X						X	X	X
81-4	BQ	270 m N of center	130	yes	6	X	X		X								X
81-5	BQ	360 m N of center	130	yes	6	X	X		X								X
81-6	NQ	45 m N of center	65	yes	3						X					X	X
81-7	NQ	45 m S of center	55	yes	3			X				X					X
81-8	BQ	45 m E of center	65	no	3								X			X	X
81-9	BQ	45 m W of center	65	no	3									X		X	X

Figure 5.1 Map Showing New Boreholes

6.0 Summary

The successful completion of the twelve experiments described in this plan would significantly add to our understanding of the scientific feasibility of extracting energy from magma bodies in the crust. Important new information would be obtained in four of the five project tasks:

- (1) source location and definition (experiments 2.1, 2.2., 2.3, 2.4, 2.5);
- (2) source tapping (experiments 4.1, 4.2, 4.3); (3) magma characterization (experiments 2.1, 2.2, 2.4); and (5) energy extraction (experiments, 3.1, 3.2, 3.3, 3.4).

Our plans are to complete several of these experiments during the spring of 1981. However, the project's budget for FY81 will not support the entire set of experiments outlined in this report. Since the twelve experiments described in this plan form a comprehensive set, the authors feel that the remaining experiments should be completed at a later date.

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