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DRILLING INTO MOLTEN ROCK AT KILAUEA IKI

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ABSTRACT

The Sandia Magma Energy Research Project is assessing the scientific feasibility of extracting energy directly from buried circulating magma resources. One of the tasks of the project is the study of geophysical measuring systems to locate and define buried molten rock bodies. To verify the results of a molten rock sensing experiment performed at Kilauea Iki lava lake, it is necessary to drill a series of holes through the solid upper crust and through the molten zone at that location. Thirteen holes have been drilled in Kilauea Iki; eleven by other groups and two by Sandia. The results achieved during the drilling of the two Sandia holes have indicated that the molten zone in Kilauea Iki is not a simple, relatively homogeneous fluid body as expected. The encountering of an unexpected, unknown rigid obstruction 2.5 ft below the crust/melt interface has led to the conceptual development of a drilling system intended to have the capability to drill through a hot, rigid obstruction while the drill stem is immersed in molten rock. The concept will be field tested at Kilauea Iki in the summer of 1978.

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INTRODUCTION

Sandia Laboratories interest in drilling into molten rock stems from the Magma Energy Research Project[1] 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. One of the tasks of that project is the development, demonstration, and verification of exploratory techniques for locating and defining buried molten rock resources. In March 1975, a workshop cosponsored by Sandia and the U.S. Geological Survey of about thirty scientists was convened to assess the present state of knowledge on magma and to recommend critical needs for research.[2] A major recommendation of this group was to evaluate geophysical techniques over a "known" molten rock body. The lava lake in Kilauea Iki crater located in the Hawaii Volcanoes National Park on the island of Hawaii, still molten since the 1959 eruption, was chosen as the site for a Lava Lake Sensing Experiment sponsored by Sandia in early 1976. The evaluation of the abilities of the various geophysical sensing systems used in that experiment to correctly detect and define the buried body of molten rock requires the drilling of a series of holes into and through it.[3] 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. Two holes of this series were drilled through 150 feet of the upper crust and into the molten rock in 1976. The drilling of these holes and the problems encountered are described in this paper.

PREVIOUS KILAUEA IKI DRILLING EXPERIENCE

Thirteen holes have been drilled through the crust of Kilauea Iki lava lake since its filling in 1959. Table I lists the sequence, number and size, and the depth at which melt was reached.

Drilling Agency	Date	Number & Dia. (in.)	Depth to Melt (ft.)
HVO[4]	4-8/60	1-1 3/16	16.0
LRL[5]	7/60	1-2	19.0
HVO[4]	4/61	1-1 3/16	29.7
HVO[4]	10/61	*	35.0
HVO[4]	5-6/62	1-1 3/16	41.6
HVO[4]	12/62	1-1 3/16	43.6
HVO[5]	3/67	1-3	85.0
HVO[5]	5-7/67	1-3	85.0
HVO[5]	10/67	1-3	87.0
HVO[5]	2-3/75	3-3	145.0
SL/HVO	8/76	2-3	149.3

TABLE I

Holes Drilled Into Kilauea Iki

*Deepened hole drilled in 4/61

MASTER

In July 1960, the Lawrence Radiation Laboratory (LRL), now Lawrence Livermore Laboratory, drilled one hole into Kilauea Iki to establish the thickness of the crust, obtain volcanological data, and to test drilling techniques into molten rock. Standard core drilling techniques were used. Compressed air was used as a drilling fluid at rock temperatures up to 850°C. Water and air/water mixtures were used for rock temperatures to 1050°C. The crust-melt boundary was encountered at 19 feet and the drill bit was pushed down an additional foot into the melt. Core recovery was poor.[5]

In the three-year period immediately after the filling of Kilauea Iki, the U.S. Geological Survey core drilled four holes through the crust. The objective of these boreholes was to conduct petrologic and thermometric studies of a semi-enclosed body of slowly cooling basalt.

The first HVO hole penetrated the crust in August 1960. A 1 3/16-inch diameter portable core drill powered by a 2½-hp gasoline engine was used. The specially fabricated drill bits consisted of tungsten carbide cutters set in a high temperature matrix. Core was collected in a conventional thin-wall, 2-foot double-tube core barrel. Manually pumped water was used as a coolant.[4]

The second (4/61 and 10/61) hole drilled by HVO used the same portable drilling equipment previously described. Immediately after the October penetration a stainless steel-ceramic probe containing a thermocouple was forced 4 feet into the melt below the crust.[4]

The third HVO hole (May-June 1962) was drilled using the same drilling equipment. An unsuccessful attempt to push a 10-foot probe into the melt resulted in the freezing and abandonment of the probe and 15 feet of drill rod. The fourth HVO hole (12/62) used more powerful drilling equipment, a 9-hp portable drill and a 3¼ hp water pump.[4] The melt interface was encountered at 43.6 feet.

Three holes were drilled by HVO in 1967. The objectives were to measure the crust thickness and obtain cores for petrologic studies. The equipment used was a commercial diamond drilling rig using A-size drill rod and a 5-foot long NX-size (approximately 3-inch diameter) core barrel. Hole 67-1 was drilled in March and the upper crust-melt interface was reached at a depth of 85 feet. Core recovery was 92%. Hole 67-2, drilled in May to July, reached melt again at 85 feet and core recovery was 83%. Hole 67-3 was drilled in October, reached melt at 87 feet, and 92% of the core was recovered.[6]

The next series of holes were drilled by HVO in February and March of 1975 using the same equipment. Hole 75-1 drilled adjacent to 67-3 reached the upper crust/melt interface at a depth of 144.5 feet. Hole 75-2, adjacent to 67-1, reached the melt interface at 139.5 (?) feet. Hole 75-3 was drilled near the outer edge of the crater at a location expected to be outside of the molten lens. It turned out that the hole location was still over the molten lens and the melt interface was encountered at a depth of 144.7 feet.[6]

CURRENT KILAUEA IKI DRILLING PROGRAM

The first series of geophysical measurements of the Sandia Lava Lake Sensing Experiment were performed in the Spring of 1976. Preliminary analysis of the data indicated that either several of the physical properties of the molten rock were different from those expected or the thickness of the molten lens was about one-third of that obtained from thermal cooling calculations. This result instigated an immediate attempt to drill a diagnostic hole to extend completely through the molten lens near the center of the lake; presumably the thickest part of the melt. Two methods of penetrating through the melt based on the extensive experience on lava lake drilling gained by the USGS/HVO were proposed. They were: (1) drill through the upper crust to the solid/melt interface using adequate cooling water, then shut off the water flow and let the drill string fall or push it to the bottom crust of the molten zone: and (2) drill through the upper crust to the solid/melt interface and then with maximum flow of cooling water chill a solid zone below the bit, drill to the melt, chill a solid zone below, and repeat that sequence until the bottom crust was reached.

Type 316 stainless steel pipe (3½ inches outside diameter, 2 7/8 inches inside diameter, 110 feet long) was obtained and threaded with standard pin and box threads to match NW casing. Two special carbide insert core bits to match the stainless steel pipe were fabricated. These bits used the standard carbide insert matrix since it was planned to water cool this bit while drilling in the upper crust. A Sandia contract was negotiated with a commercial driller to furnish a drill rig, equipment, and drilling crew. R. Helz, USGS Reston, logged the hole as drilled, evaluated the cores obtained, and is performing core analyses at their laboratory.

The drilling of hole KI 76-1 was started on August 18, 1976. It was located 15 feet south of location 17N2 on the lava lake surface. The solid/melt interface was reached on August 24 at a depth of 149.3 feet. Core recovery was 99% of rock drilled. The core barrel dropped 0.7 feet into the melt before it was retrieved. On the following day the stainless steel drill string with the special core bit was assembled and placed down the hole. Drilling was started at 145 feet depth with the volume of cooling water controlled to an amount previously calculated to just boil when it reached the drilling level. Molten rock was encountered at about 149 feet, the cooling water flow was stopped at the surface, and the drill string was pushed by the drill rig feed cylinders a distance of

2.5 feet into the melt where progress was stopped by an unexpected obstruction. At the same time, the drill string was frozen in the melt so that no movement, rotational or vertical, was possible. Everything was left as it was until the next morning to determine if the drill pipe would warm up enough to thaw the lava frozen around it.

On the following morning the depth to the solid that had oozed up inside the drill string was 144 feet and the temperature was 1845°F (1015°C). The drill rig was connected back to the drill string and could rotate and raise it but could not push it deeper. It was assumed that the matrix holding the carbide inserts in the core bit had melted so that no cutting surfaces were available. However, it was thought that the remaining part of the bit might be able to be forced through the obstruction on which it was resting. Accordingly, a 300 pound hammer with a fall-distance of 30 inches was installed on top of the drill string. After 30 minutes of hammering, no progress of the drill string through the obstruction below was observed. It was decided to remove the drill string, replace the bit with a hard steel point and attempt to penetrate the obstruction.

The drill string was removed. It was observed that the lower 1½ inches of the drill bit had broken off at the root of one of the box threads that attached it to the stainless steel pipe. If the broken part of the bit was left at the bottom of the hole, it might prove little or no obstruction to the penetration point.

The following morning the solid material that had oozed up the hole overnight was measured at 145 feet. The downhole temperature was 1760°F (968°C). The drill rig was started to drill out the ooze to a depth of 148 feet, after which the stainless drill string with the steel penetrator point in place would be inserted to hammer into the melt and the underlying obstruction. However, the diamond drill bit encountered an obstruction downhole at 138 feet. After unsuccessfully attempting to grind out the obstruction at the expense of one diamond core bit, it was assumed that the obstruction must be the missing part of the core bit. Apparently the lower end of the bit had been flared out considerably during the previous day's hammering but had remained together as it was retrieved until it reached a portion of the borehole that was cool enough (non-plastic) to wedge it and cause the observed failure at the thread root. After deciding it was not practical to continue drilling, hole KI 76-1 was abandoned and the drill rig was moved about 1½ feet south to start a new hole.

Realizing that there was an unexpected obstruction lying about 2.5 feet below the crust/melt interface that was less plastic (more rigid) than the steel drill stem at the same temperature, it was decided to use the second proposed method for piercing the molten region, namely, chilling the melt ahead of the bit and then drilling through it.

The drilling of hole KI 76-2 was started on August 30, 1976, using the same sequence and equipment down to the solid/melt interface that was used on the first hole. Core recovery was 98% on this hole. The solid/melt interface was reached at 149.9 feet on September 2. At that point the drill bit was raised ten feet and cooling water was pumped downhole for 20-30 minutes before pulling the drill string.

The following morning the drill string was replaced in the hole using a 10 foot NX rigid core barrel with a standard carbide insert NX bit. Bottom hole temperature was measured, before drill string insertion, to be 1718°F (944°C). Drilling started at 141 feet depth. The water pump was running at its maximum flow rate at ~ 100 psi. The drilling crew and observers were alerted to observe the first change in drilling or water flow conditions so that the drill string could be lifted immediately to allow cooling water to chill the molten rock ahead of the bit.

The first observed indication of a change in drilling conditions was a surging and pressure build-up of the cooling water system indicating flow blockage. This occurred at 147.1 feet depth. The drill string was raised a few feet but the flow blockage continued. After a short while the drill string was removed and the drill bit was found to be totally blocked with quenched glass from the molten rock. This material was removed from the bit and core barrel, and the bit was still in good, usable condition. The drill string was replaced downhole and encountered solidified ooze at 143 feet depth. Again, the drilling crew and observers were cautioned to be alert to any surface indications of changes in drilling conditions that would mean molten rock was being encountered. As in the earlier attempt, the first surface indication was a surging and pressure build-up of the cooling water system indicating flow blockage. This occurred at 147.8 feet depth. The drill string was removed and the core bit was found to be blocked with chilled glass from the molten zone. This time the bit was damaged such that it was not reusable.

The depth to the top of the solidified ooze was measured at 136.3 feet. At this time, the decision was made to stop further drilling. The rationale behind this decision was: (1) the carbide bit was damaged and unusable; (2) maximum flow and pressure from the cooling water system available had been demonstrated twice to be inadequate to prevent the molten lava under its geostatic pressure from flowing into and blocking the core bit; (3) an alerted, experienced drilling crew and observers had been unable on two occasions to discern on surface when the molten rock was being encountered; and (4) the planned expenditure of time and money for that year's drilling program had been expended.

CONCLUSIONS

The early (1960-1975) experiences in drilling into Kilauea Iki had been considered successful since they had achieved their objectives, i.e., determining crustal thickness and obtaining core samples for laboratory study. However, none of these drillings had penetrated an appreciable depth into the molten rock.

The Sandia/HVO experience in 1976 had not achieved its objective of drilling through the molten zone. Although the drill did penetrate 2.5 feet of the melt, an unexpected and unknown obstruction prevented a complete transit to the bottom of the molten zone. However, the crustal thickness was determined, very complete core sections of the upper crust were obtained for petrologic studies, and the fact that the molten lens as it existed at the location drilled was not a simple, relatively homogeneous liquid as expected was established.

Future plans include the following: First, the need to verify the geophysical measurements of the Lava Lake Sensing Experiment still remains. Also, it is apparent that much information needs to be gotten to understand the present vertical structure of the molten zone of the lava lake. Finally, a drilling system to achieve the above must have the ability to drill through very hot (~ 1050°C) rock while the drill stem is immersed in molten (~ 1075°C) rock.

Immediately after the completion of the 1976 drilling series, the Lava Lake Drilling Program was initiated at Sandia to develop and build a drilling system that would accomplish the above. The initial concept selected from this program for development employs a double-tube, insulated drill stem and a Mar-M 509 drag bit. High pressure air will be used to cool the inner drill stem and clear the cuttings from the bit when drilling in the molten zone. This concept will be field tested at Kilauea Iki in the summer of 1978.

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