UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

DRILLING REPORT AND CORE LOGS FOR THE 1988 DRILLING OF KILAUEA IKI LAVA LAKE, KILAUEA VOLCANO, HAWAII, WITH SUMMARY DESCRIPTIONS OF THE OCCURRENCE OF FOUNDERED CRUST AND FRACTURES IN THE DRILL CORE

by

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Open-file report 93-15

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INTRODUCTION

The main purpose of this open-file report is to describe the 1988 drilling of Kilauea Iki lava lake, and to present the recovery logs and petrographic descriptive logs for the drill core recovered during the 1988 drilling. In addition, the report reviews the evidence accumulated to date that the lava lake is deeper than pre-eruptive topography would have suggested, and summarizes what has been learned about the distribution of foundered crust in the lake from study of the drill core recovered from 1967 to 1988. Lastly this report summarizes observations on the occurrence of certain kinds of fractures in the drill core, namely the pre-drilling vertical fractures, and fractures induced by shrinkage of the core during drilling.

Kilauea Iki lava lake, which formed during the 1959 summit eruption of Kilauea Volcano, lies just to the east of Kilauea's modern caldera (Figure 1). The 1959 eruption was very extensively studied at the time, and has been the object of recurring interest. A detailed description of the eruption can be found in Richter and others (1970); more recent work includes reports by Helz (1987a) and Eaton, Richter and Krivoy (1987).

The 1959 lava lake, because it has not been covered up by more recent eruptive activity, has been the object of an extensive series of drilling operations and other studies. The earliest drill core, recovered in 1960-1962, was described by Richter and Moore (1966). Since then the lake has been drilled in 1967, 1975, 1976, 1979, 1981 and most recently in 1988. Previous drilling reports include Helz and Wright (1983) and Helz and others (1984). A summary of the literature on Kilauea Iki lava lake, which has included chemical and petrographic study, determination of physical properties of core, and a number of geophysical studies is given in Helz (1987b).

THE 1988 DRILLING PROJECT

Kilauea Iki lava lake was redrilled most recently in late 1988. The project used HVO's own drill rig, with supplemental equipment supplied by an outside contractor. The crew were driller Charles Robinson and his assistant Mark Boykin, both from Exploration Supply and Equipment, Inc., based in Anchorage, Alaska.

The plans called for two holes to be drilled. Their locations are shown in plan view in Figure 2 and in cross-section in Figure 3; the precise, final locations are given in Table 1. The first (KI88-1) was to be near the north edge of the lake, about 25 feet south of a site last occupied in 1975. The intent was to extend the available section in this crucial part of the lake, which lies above the edge of the floor of the old pit crater (see Figure 3). We assumed that the lake would be completely solid at this location, and we hoped to drill all the way through the 1959 lava, into the underlying

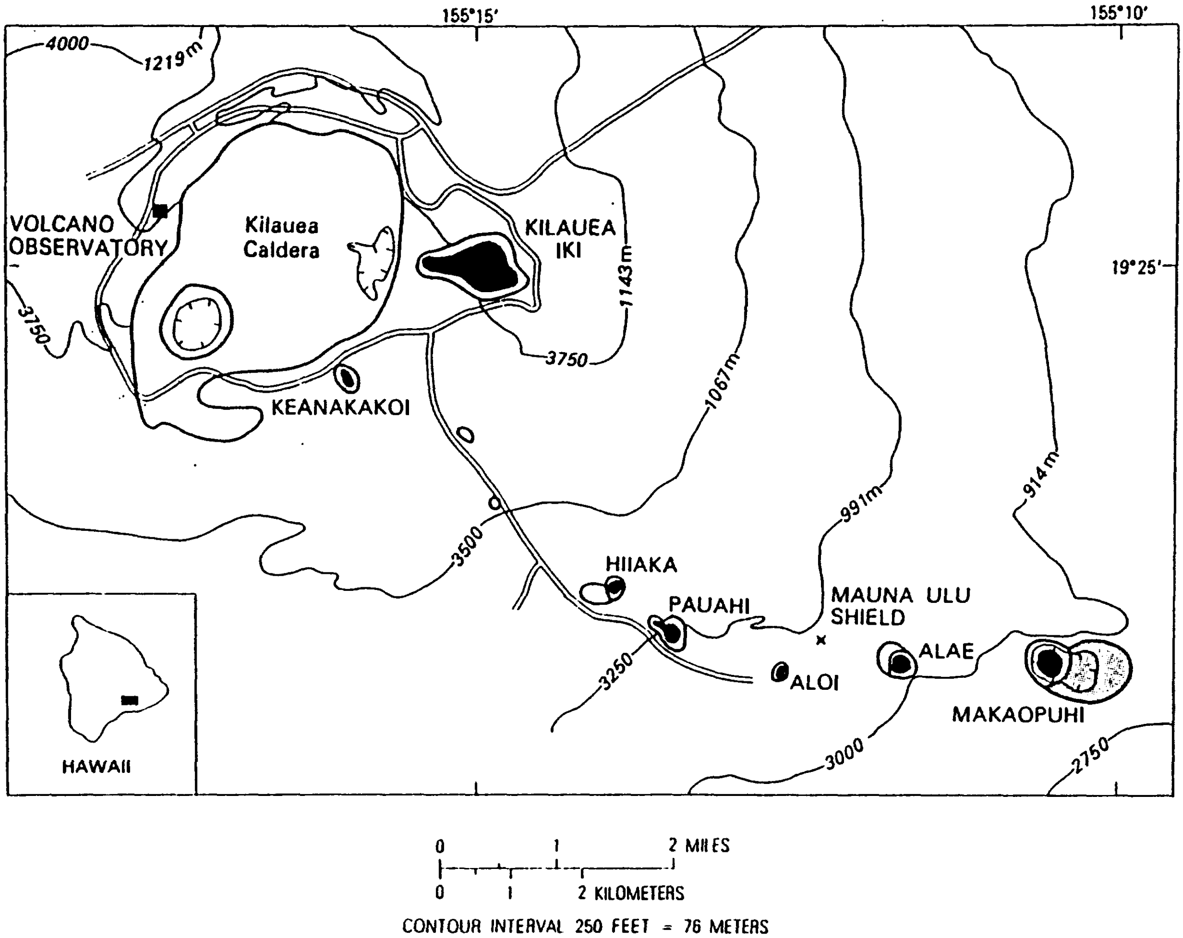

Figure 1. Index map of the summit area of Kilauea Volcano. All historic lava lakes formed to date (1992) are shown in black. The prehistoric Makaopuhi lava lake is shown in the stippled pattern. The historic lava lakes in Aloi, Alae, and Makaopuhi pit craters are now covered by lavas from the Mauna Ulu satellite shield, the summit of which is indicated by the "X".

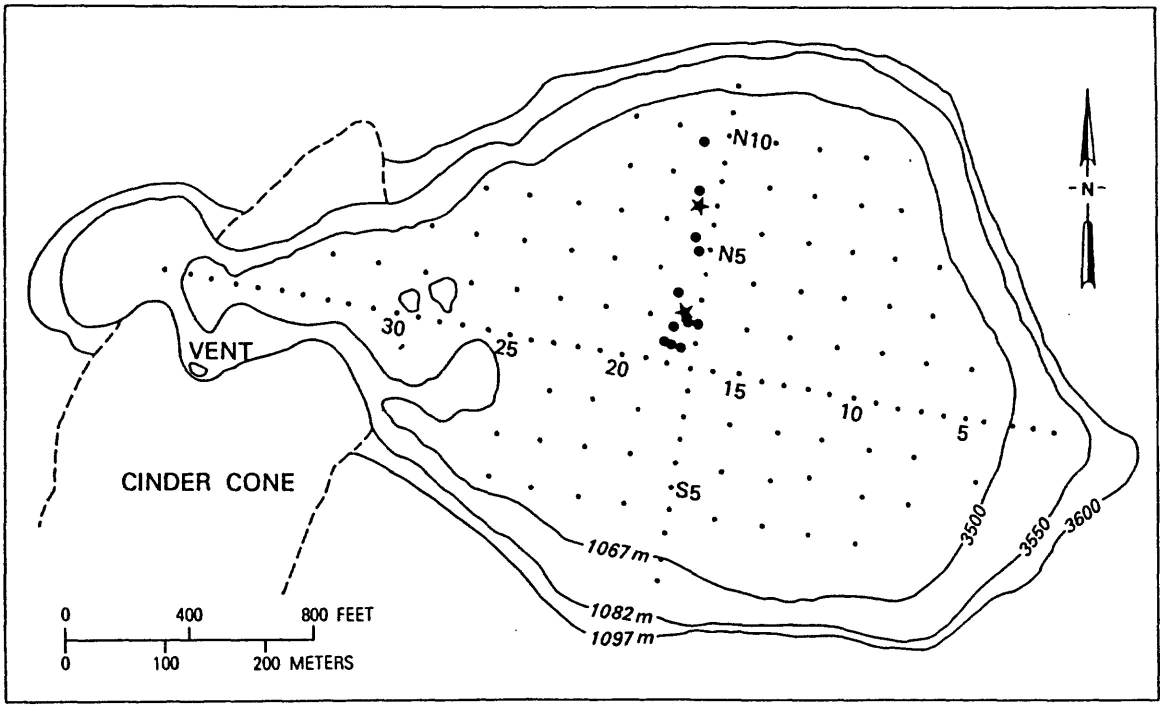

Figure 2. Plan view of the post-1959 surface of Kilauea Iki. The network of levelling stations is shown by the small dots. Their labelling is read as follows: the point labelled N5 is levelling station 17N5, that is, it is 1700 feet west of the easternmost station on the principal east-west axis, and 500 feet north of that axis. The locations of drill holes in Table 1 are given in terms of this network. The larger dots indicate the locations of holes drilled from 1967 to 1981; the stars mark the location of the two holes drilled in 1988.

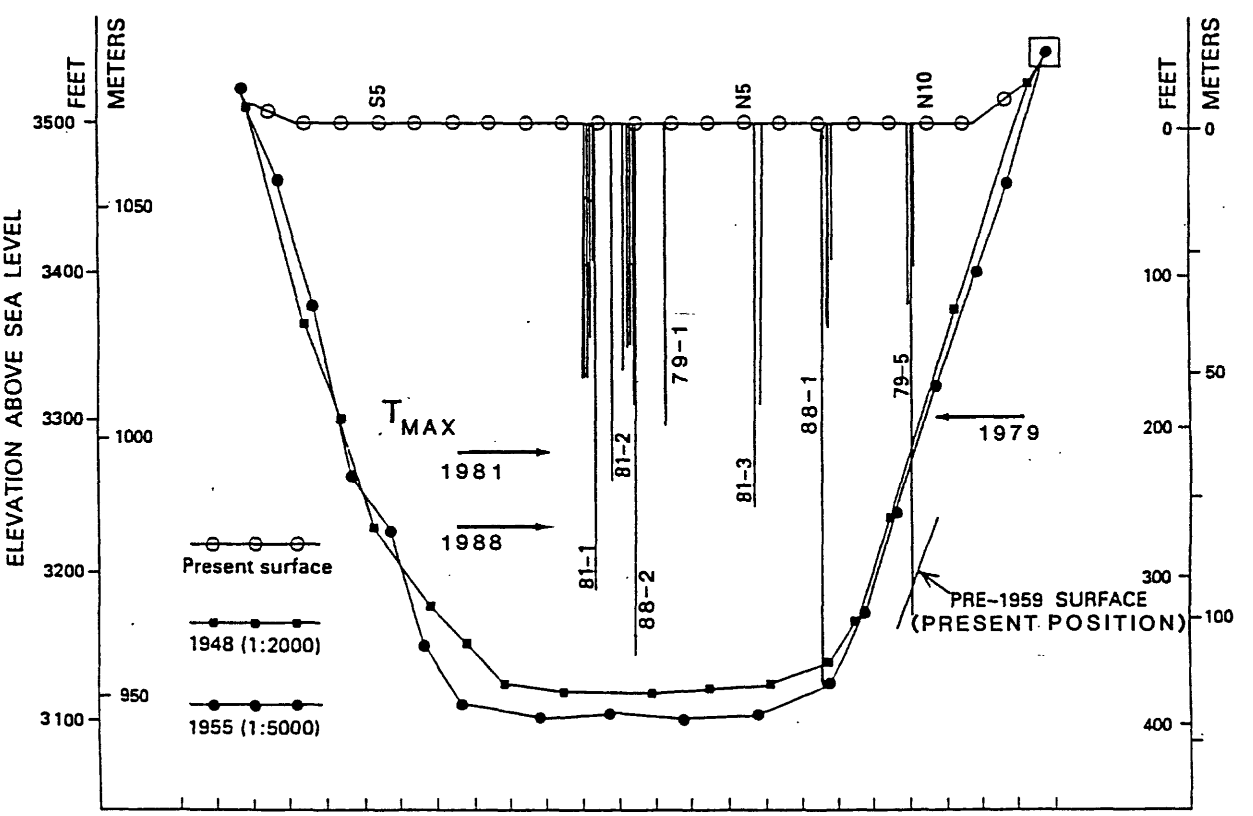

Figure 3. Cross-section of Kilauea Iki lava lake, taken along the N-S line of closely-spaced levelling stations shown in Figure 2. The present surface of the lava lake and two pre-eruption profiles are shown. The pre-eruption profiles are taken from two different topographic maps: one (at 1:2000) is based on air photos taken in 1948; the other (at 1:5000) is based on air photos taken in 1955. Both maps were prepared by R. Jordan, U.S.G.S., Flagstaff. The present position of the lake bottom is shown only where it intersects drill hole KI79-5. The vertical exaggeration is 4:1.

The drill holes, which mostly lie along a line 100 feet to the west of this section, are shown as vertical lines projected onto this cross section. Several of the drill hole locations have been reoccupied more than once, in order to sample the same section of the crust in several stages of development. Spacing between these holes is not to scale in this figure. Only the deepest hole in each cluster has been labelled, for clarity. The arrows mark the position of the thermal maximum, as found by analyzing glass in quenched, partially molten drill core, in 1979, 1981, and 1988.

older basalt. The second hole, in the middle of the lake, was located at a site previously occupied in 1976, 1979, and 1981. This location was the hottest known part of the lake (Helz and Thornber, 1987). It was thought that a new drill hole at this position would give us our best chance of recovering the last, thin, partially molten zone, which we assumed would still exist in the center of the lake.

KI88-1 was started on 10/31/88 and finally abandoned on 11/21/88, at a depth of 375.9 feet (114.6 m) below the surface of the lake. Hole KI88-2 was collared on 11/23/88 and abandoned on 12/15/88 at a depth of 356.8 feet (108.7 m), as shown in Table 1. Core recovery was virtually 100% in both holes, so that, in terms of core recovery, the operation was highly successful. However, one of the main objects of the project was to drill completely through the lava lake, and in this we were not successful. A more detailed description of the operation, and the problems encountered, may help to make the next drilling (if any) more successful in this respect.

Details of the 1988 Drilling Operation

The drilling operation began on October 26, with a helicopter airlifting the heavy equipment from the helipad near Kilauea Marine Camp (KMC) and/or the Pu'u Pu'ai parking lot, to the floor of Kilauea Iki pit crater. The bulk of the equipment was moved down to the crater floor in 4 hours, thanks to massive support from HVO personnel, who helped load and unload the slings. The drill crew set up the rig at the KI88-1 site on October 27-28, and set the anchor bolts, so that drilling could begin the following Monday (10/31).

As in most previous drilling operations, we used diamond bits, and aimed for continuous core recovery. BQ drill rod was used, resulting in a core diameter of 3.5 cm, as noted in Table 1. It would not have been possible to use larger-diameter drill rod with the HVO drill rig, to the depths we intended to drill. Water was used to cool the bit and string, and to quench the core, throughout the operation. The lava is so permeable that there is no problem with backflow, and no possibility of recovering and recycling water, either. One serious limit on our ability to drill was thus water supply. The local supply on the crater floor was held in one or two "frog ponds", large, canvas pools lent by the Park Service for the purpose.

Hole KI88-1 was collared on 10/31/88, and drilling proceeded uneventfully until November 8, when we recovered partially molten core from the 251.8-261.7 interval. From extrapolation of previous results, I had thought that the KI88-1 site would have a maximum temperature of no more than 1000°C, essentially the solidus temperature of the rock. However this interval and the next 10 feet of core contained substantial (5-15%) amounts of black glass. In view of the high wallrock temperatures in the lower part of the hole, we tripped out 80 feet of drill string, leaving the bit at a depth of 191 feet overnight.

TABLE 1: Data on holes drilled in 1988 in Kilauea Iki

Hole No.	Location	Date collared	Date finished	Depth of hole (feet)	Core diameter (cm)	Comments
KI88-1	1795N688	10/31/88	11/21/88	375.9	3.5	Hole was stopped when rig could no longer turn drill string.
KI88-2	1723N193	11/23/88	12/15/88	356.8	3.5	Hole reamed out with oversized bit, to reduce friction along length of string, from 0-354.9 ft. Hole stopped at 356.8 ft because we could not maintain water supply to the drill bit.

We lowered the string the next day to 271.7 feet without incident. No necking-down of the hole had occurred between 191 and 271.7 feet; nevertheless, we were unable to drill. The string was stuck in the hole. We hauled the string out by double-lining the hauling cable with an extra pulley; this was a very slow process, and one which taxed the mast on the HVO rig to its utmost. The lowermost three pieces of drill rod and the core barrel were severely warped, apparently damaged by heat. It was not clear at that time whether the heat damage had been incurred the previous day, or during the lowering of the string on the morning of 11/9. It was thought unlikely to have occurred overnight, as the temperature of the wallrock where the string had been left overnight should have been <200°C. Furthermore, we had left the bit at that depth (191 feet) over the November 6-7 weekend, without mishap. The damaged pieces were replaced, and the string lowered into the hole for the night, this time to a depth of only 150 feet, to be certain it would not be subject to heat damage.

The next day we lowered the drill string into the hole, stopping for 5-10 minutes at a depth of 230 feet, to run cooling water down the hole. Upon reaching 271.8 feet and turning on the drill, we found the string unmovable, as on the previous day. We double-lined the string out of the hole, and found the lowermost two pieces of pipe and the core barrel hopelessly warped, as on the previous day. After consultation, it was decided that we needed to increase the flow of water down the hole, first by increasing the pumping rate of water down inside the drill string, and second, by having a second pump (and a second "frog pond") to run water down the outside of the string during drilling. This second stream of water would then be available to run down inside the string during lowering of the string into the hole in the morning, and during wire-lining of the core, in order to limit heating-up of the drill rod during those operations. (These were precautions I was familiar with from previous drillings in Kilauea Iki; but the driller could not be persuaded that they were needed, until after November 9. His previous experience in geothermal drilling involved maximum temperatures of 300°C, so he was not entirely ready for wallrock temperatures of 1000-1100°C, and how quickly they can warp drill steel.)

Drilling resumed on November 15, with the new arrangements in place, and the hole was extended to 300.9 feet. Progress was steady for the next three days, though water consumption was so high that there were times when we had to stop drilling, to let the "frog ponds" fill up again. (Inflow was limited by the diameter of the hose that carried water from the tap at Magma House.) However even with our additional precautions, some more pieces of pipe warped and had to be removed from the string. Also, bit consumption was high: at the end of November 18, with the hole at 372.9 feet, we put on the sixth new bit since the beginning of drilling. This was a hard-matrix bit, intended normally for drilling in clastic sediments, and was put on because we had run out of others. It proved to be much better for drilling in Kilauea Iki than the soft-matrix bits conventionally used in hard-rock drilling. I speculate that this bit was satisfactory because the rock in Kilauea Iki is in fact relatively friable,having more the drilling character of a well-cemented sandstone (albeit a very high-temperature one) than a granite. We drilled the last three feet of KI88-1 and all of the second hole to a depth of 292.7 feet, using this one bit. This contrasts with an average bit life of 75 feet for the first five bits used in KI88-1.

However, beginning at 360.8 feet on November 18, and continuing on November 21, the core was so heavily fractured that it jammed in the bit frequently. We had to wire-line every 0.5-1.5 feet, which was time-consuming and also was hard on the engine of the HVO drill rig. Finally at a depth of 375.9 feet, after a final core run of 0.4 feet, the HVO rig could no longer turn the string in the hole: there was too much friction along the pipe, whether because of necking-down in the hottest part of the hole, or thermal expansion of the drill string. The string was withdrawn from the hole, and broken down for the move to the second drill site.

Hole KI88-2 was collared on November 23, a few feet northwest of drill hole KI81-4. In view of the difficulty in keeping the drillstring turning in the lowest part of KI88-1, it was decided to drill KI88-2 with an oversized bit, so that the hole diameter would be 0.25 inches greater than the diameter of the drill string. An oversized bit was not on site, so we began drilling with the hard-matrix bit, as mentioned above. In fact the oversized bit did not arrive until December 8, when the hole was 292.7 feet deep. The second hole was hotter than the first, as could be seen from the amount of melt present in the core below 240 feet, but previous experience and a larger water pump kept us free of major problems with warped drill rod. Water consumption was 6000-8000 gallons per day, however, and drilling was frequently halted to let the water supply catch up. A larger input hose would not have helped much, because the bottleneck would still be the size of the pipe at Magma House.

On December 8, 9, 12 and 13 the driller enlarged the hole using the oversized bit. Coring began again on 12/13, at 292.7 feet, and the hole was extended to 327.9 feet. When we re-entered the hole the next day, the hole was partially blocked at 270-275 feet, and again at 290-295 feet, and was reamed out on re-entering. The hole was extremely hot, so we ran water down it for 15 minutes before trying to drill. The first vertical fractures below the thermal maximum were encountered at 349 feet, and shortly thereafter fragments of core began jamming in the bit, as they had in the lowest part of KI88-1. By 352 feet, the drill string could be turned only with great difficulty, as if some part of it was warped, so we pulled it all, to rotate the pieces and replace the bit. The new bit was standard BQ, rather than oversized, to minimize the amount of reaming-out that might be necessary the following morning.

On December 15, the hole was entered by stages, with cooling water run down it for 10-15 minutes at two different depths. Despite all feasible precautions, we were again having to wireline every few inches, and the engine of the HVO rig was seriously overheating during the process. Steam backpressure in the core barrel may have prevented the inner barrel from seating properly as well. We made four attempts to drill, with a maximum run of 1.2 feet, before giving up the hole. The depth reached was 356.8 feet. The oversized hole did prevent the string from siezing up in the hole, as it had in KI88-1, but the higher temperatures and the extremely fractured nature of the core stopped the hole just as effectively.

Results of the 1988 Drilling

Two deep holes were drilled during the project, and continuous core recovered from them. Of the 732+ feet of core recovered, 334 feet (46%) comes from parts of the lake not sampled in any previous drilling. The upper part of both cores of necessity duplicates material recovered in earlier drilling.

The most important features of Kilauea Iki as defined by the 1988 drilling are shown in Figure 4. Note that KI88-1 fills a major gap in our coverage of the deeper parts of the lake between the northernmost cluster of holes (the group including KI79-5) and the extensively analyzed sections in the center of the lake (from the group including KI81-1 to hole KI79-1). A zone containing residual partial melt was encountered in both holes; its extent is shown by the stippled area in Figure 4. The amount of melt present is <20% by volume everywhere, so this region posed no obstacle to drilling, once adequate cooling water was delivered downhole; thus we were able to obtain complete sections through the partially molten zone in both holes. The upper contact of this zone is nearly horizontal, at 240 feet (73.1 m) while the lower contact is deeper in the center of the lake, as shown. This zone was 60 feet (18.3 m) thick in KI88-1 and about 90 feet (27.4 m) thick in KI88-2. These cores afford a unique look at the final stages of crystallization of a sizeable magma body.

Core from the molten region of the lake contains no fractures, other than those created by the cooling water, or by breakage that occurred during subsequent handling of the fragile quenched core. Surrounding the partially molten zone, there is a sheath of apparently subsolidus hot rock 18-21 feet (5.5-6.4 m) thick which also contains no pre-drilling fractures. This unfractured zone was found in both holes, both above and below the partially molten region. Outside this sheath, the core contains steeply dipping fractures that clearly predate drilling; these are interpreted as being the leading edge of the upper and lower columnar joint sets, propagating slowly into the lake's interior. The positions of the leading edges of these two fracture sets is indicated in Figure 4 by the fine vertical lines above and below the stippled area. Hole KI88-1 penetrated this lower fractured zone for 54 feet (between 322 and 376 feet).

By contrast, hole KI88-2 reached the top of the lower colonnade at 349 feet, only eight feet (2.4 m) above the bottom of the hole. All of the core recovered from below about 225 feet, whether it contained visible glass or not, was quenched from high temperature, and was still quite warm when brought to the surface.

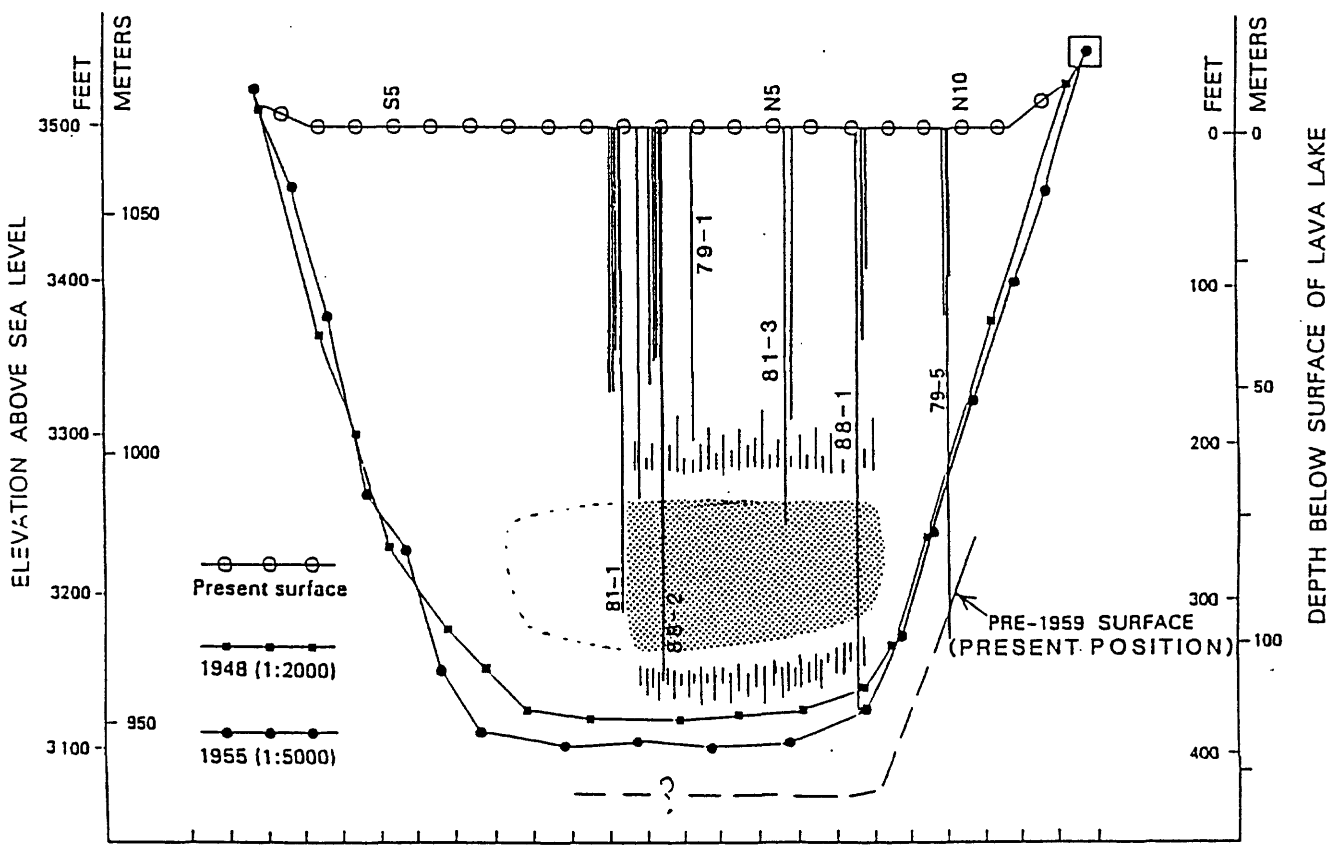

Figure 4. Cross-section of Kilauea Iki lava lake, as shown in Figure 3, with vertical exaggeration of 4:1. The stippled area corresponds to the region of the lake that still contained minor (trace to 15%) melt in 1988, with the inferred extent of this region indicated by the light dashed line. The short vertical lines above and below the partially molten zone indicate the leading edges of the vertical fractures of the upper and lower columnar joint sets. The dashed line below the two topographic profiles shows the present position of the base of the lake, as determined by drilling of hole KI79-5 and inferred from the 1988 drilling.

To summarize: the most important result of the 1988 drilling is the recovery of continuous core sections from previously unsampled depths, in two locations. The core is especially valuable because so much of it was quenched while the rock was still very hot and fresh. The intervals of greatest interest are the partially molten zones and the very hot, fresh, unfractured rock surrounding those zones (223-323 feet in KI88-1 and 222-349 feet in KI88-2). The core from the lower fractured zone (323-376 feet in KI88-1 and 349-357 feet in KI88-2), though somewhat altered by exposure to air in the open fractures, is also of great importance simply because it is the only material available from these depths in the lake. Its composition will tell us whether either of the 1988 drill holes reached the stagnant, undifferentiated chill zone that should exist near the bottom of the lake.

Recommendations for future drilling

From the scientific viewpoint, the study of Kilauea Iki cannot be considered complete until we obtain and analyze at least one complete section through the center of the lake. The one existing core that is complete (KI79-5) lies so close to the edge of the lake that it is not representative of the main body of the lake (Helz and others, 1989; Helz, unpublished data). We still do not know (1) how thick the lake really is, (2) what the lowermost parts of the lake are like, and (3) what effects the 1959 magma has had on the underlying basalt from the 1868 eruption. Much progress has been made in defining and quantifying the differentiation processes active in the lake, but until we have a complete section, our quantitative understanding of the movement of crystals and melt in the lake remains incomplete.

From our experience in 1988 it is clear that, in order to drill through the lava lake, we must use a larger, more powerful drill rig than the HVO rig. A double set of water pumps will be necessary, as it was in 1988. Lastly, the core size should be increased, to NX (6.35 cm in diameter). It may also be desirable to drill an oversized hole, as was done in KI88-2.

I make these recommendations because the principal obstacles to drilling through the lake were and will be (1) the need to move a sufficient amount of cooling water past the central hot zone to the bit, and (2) the need to be able to drill very hot (600-1000°C), heavily fractured core. Water consumption will be very high, up to 10,000 gallons a day. Because the drill string is subject to heat damage (in a matter of minutes) as it passes through the hottest zone, flow of water both inside the string and outside, must be continous, and the drilling contractor must be persuaded of this from the beginning.

The larger core diameter is recommended for the following reason: once the lower fracture zone is reached, water tends to disappear down the vertical fractures, leading to jamming of the bit as it overheats. Now, the amount of water that can be delivered to the bit is a function of the diameter of the drill string, and a larger string lets the amount of water go up as the square of the diameter, while exposed crack length increases linearly. This is apparently important: the successful drilling of KI79-5, in which NX fittings were used, was accomplished with less water consumption and much less heat damage than the 1988 drilling. Temperatures encountered in drilling KI79-5 were as high as 1000°C (Helz, unpublished data), and the temperature at the lower contact was at least 400°C (Ryan, unpublished data). These are the temperatures that would be expected to obtain in Kilauea Iki throughout the 1990's, so the example of KI79-5 is relevant to any new drilling of the lava lake.

DEPTH OF KILAUEA IKI LAVA LAKE

Prior to the 1959 eruption, Kilauea Iki was a wide, largely empty collapse crater, floored in its central region by the 1868 lava. This latter eruption was very brief, and the volume of lava erupted small, so the 1868 material can have formed only a relatively thin flow across the older rubble (Klein, 1982). Two different sets of air photos are available for the pit crater, one taken in 1948 and another in 1955. The topographic profiles of the pit crater, as defined by these two sets of photos, are shown in both Figures 3 and 4. Early publications on the lake show the lake as being 360-365 feet thick, based on this topography (Richter and Moore, 1966).

When KI79-5 was drilled, we found that the lava lake was 313 feet (95.4 m) deep at that location, considerably deeper than the 220-230 feet that was anticipated, based on the pre-eruptive topography. The difference cannot be explained by appealing to uncertainties in the topography or in the position of KI79-5 relative to the crater wall: some movement of the wall/floor of the crater must have taken place, such that at the position of KI79-5 the lake is 80-90 feet (24-27 m) deeper than expected, based on the pre-1959 topography (Helz, 1980).

None of the holes drilled in 1981 was intended to go through the lake, or came close to doing so. However, one of the chief aims of the 1988 drilling was to do exactly that, at the location of KI88-1, where the pre-eruptive topography suggested the lake would be 360-375 feet thick. Unfortunately, neither of the new holes penetrated the base of the 1959 lava lake, as far as could be determined by examination of the recovered drill core.

In hole KI79-5, the only drill hole which has passed completely through the lake, the bottom of the lake was marked by the following features: First, we encountered a zone 10-15 feet (3.0-4.6 m) thick where the amount and average size of the olivine phenocrysts decreased quite conspicuously, followed by a thin interval (< 1 m thick) containing vesicles partially filled with differentiated liquid, which in turn was underlain by about 10 cm of moderately vesicular rock, with open vesicles. This was the chilled margin: it was underlain directly by a baked, weathered horizon, <1 cm thick. Below that we recovered 30 feet (9.1 m) of highly vesicular, oxidized basalt, before abandoning the hole (see descriptive logs for KI79-5, Helz and others, 1984).

None of the features that marked the lowermost part of the lake in KI79-5 is present in the lowermost part of the KI88-1 core. From their absence it can be inferred that the bottom of the lake lies at least 15 feet deeper than 375.9 feet, at the location drilled. Hole KI88-2 was drilled in a part of the lake known to be hotter, and suspected of being deeper than at the first drilling site. We had less hope of drilling through the lake at that site, and in fact were stopped short of the depth reached in KI88-1, and presumably far short of the bottom of the 1959 lake.

Although the thickness of the lake is not yet known at the KI88-1 location, it can be estimated from the position of the thermal maximum in the recovered drill core. That position was at roughly 265 feet, determined by inspection of drill core in the field, and confirmed by subsequent analysis of glass in the core, using the glass geothermometry method previously developed for Kilauea Iki (Helz and Thornber, 1987). The thermal modelling of Jaeger (1961) predicts that the final position of the thermal maximum, during the crystallization of a sill-like body, will be 62% of the distance down through the body, assuming that heat loss is dominantly by conduction. The relevant data for KI79-5 and KI88-1 (in feet) are:

	KI79-5	KI88-1
Depth to T_{max}	193	265
Depth of lake	313	427 (estimated)
Pre-1959 depth from photos	230	360-375
Increase in depth in lake	83	52-67

Note that the observed position of T_{max} in KI79-5 is exactly 62% of the way through the lake, suggesting that the conductive-cooling models of Jaeger (1961) are applicable to the lava lake. If similar conditions obtain in KI88-1, then the bottom of the lake is at 427 feet (130 m). This assumes that the position of T_{max} observed in 1988 is essentially its final position before the melt disappears. Given that T_{max} is 1070-1080°C, and that the partially molten zone is only 60 feet thick in KI88-1, this assumption cannot be far off. If this is the correct thickness of the lake, then there remain 50 feet of section to sample at this locality. The drilling results by themselves suggest the hole is at least 20-30 feet deeper than had been thought.

The estimated position of the lake bottom is shown in Figure 4 by a dashed line. Its position is known near KI79-5, and can be inferred with some confidence below KI88-1. The floor of the central part of the lake is inferred to be flat, as indicated. The next question to be considered is, when did the subsidence of the crater floor take place?

Subsidence on the scale of 50-90 feet did not occur prior to the 1959 eruption. Such large movements would have been noticed immediately, even at a pit crater more remote than Kilauea Iki. We can also state with confidence that the subsidence has not occurred since December 24, 1959. That is the date on which the upper crust of the lava lake ceased overturning, and stabilized. Within a few months thereafter the initial set of levelling stations was installed on the new lake surface, and monitoring of its position was begun. Since that time, the surface of the lake has subsided steadily, but always very slowly. At no time has there been a 50-90 foot drop of the lake surface. Again, such subsidence would have been very conspicuous, even in a remoter location.

One can only conclude that the subsidence took place during the 1959 eruption, and was not noticed because of the alternate filling and drainback of the lake, which understandably preoccupied observers at the time (Richter and others, 1970; Eaton and others, 1987). However, when I explored this possibility in conversations with J.P. Eaton, he replied that there is nothing in the seismic record of the 1959 eruption that could clearly be attributed to subsidence on this scale occurring during the eruption.

It is clear from the KI79-5 results that substantial subsidence has occurred near the north edge, and the KI88-1 results suggest that at least some subsidence (20-30 feet at a minimum) has taken place at that location. How could such an event be aseismic? A recent tomographic study of Kilauea's east rift zone (Ho-Liu, 1988) picked up a small body of magma directly under Kilauea Iki lava lake, at an approximate depth of 1 km. Given that this part of the volcano has not been active since 1959, and that the next most recent activity prior to 1959 was the very brief 1868 eruption, it seems likely that the magma body seen in the tomographic experiment is what remains of the subterranean chamber that fed the 1959 eruption. There was extensive cycling of magma from this chamber to the surface during fountaining episodes, followed by extensive drainback after fountaining ceased (Murata and Richter, 1966; Richter and others, 1970). One possible explanation for the relatively aseismic subsidence of the floor of the pit crater would be that the cylinder of rock that separated the surface lake from the underlying sill simply floated down, in effect a magma-lubricated piston, as magma moved from the deeper site to the surface, over the course of the eruption.

DISTRIBUTION OF FOUNDERED CRUST IN KILAUEA IKI

Crustal foundering is a process that has been observed in all historic lava lakes, including Kilauea Iki (Richter and others, 1970) and the 1965 Makaopuhi lava lake (Wright and others, 1968). The process entailed formation of a thin, rapidly quenched, rigid layer of lava, which was too thin to remain intact, so would break readily into plates, usually 10-20 feet across, as the underlying molten material shifted around. Meanwhile, the melt below the plates of thin crust continued to degas rapidly, so that a very frothy layer would build up underneath it, at which point the plates of crust would tip, and be overrun by the incandescent, highly frothy material. Often, once this kind of instability started locally, it propagated rapidly all over the whole surface of the lava lake, so that the surface went from mostly black, with glowing cracks, to entirely incandescent in a few minutes. This process was observed to occur many times in Kilauea Iki, both during the eruption, and for most of a week after the eruption ceased.

Observers on the crater rim (Richter and others, 1970) did not have any means of knowing how deep the foundered crust went, during these roll-over events, but tended to assume (T.L. Wright, oral communication) that it sank to the bottom of the lakes, as the earliest drill core recovered from both Kilauea Iki and the 1965 Makaopuhi lava lake did not have discernable foundered crust in it. In fact, material identifiable as foundered crust has since been recognized in drill core at several levels in Kilauea Iki. The purpose of this section is to describe these occurrences, but first it is necessary to review the characteristics of foundered crust.

The essential feature of foundered crust is its high vesicle content. All material recognizeable as foundered crust includes layers a few centimeters thick containing abundant large (5 mm and up) vesicles. Detailed study of vesicles in Kilauea Iki core has shown that such large vesicles are common in the olivine-phyric core from the uppermost 30-35 feet of the lake (Mangan and Helz, 1986); below that depth they are much scarcer, and are almost always associated with segregation-vein material. Hence it is reasonable to assume that any coarsely vesicular olivine-phyric basalt found at greater depths has moved down from the surface of the lake. In foundered crust, the coarsely vesicular layers alternate with layers where the vesicles are smaller, or alternate with finegrained dense layers that appear to have been largely vesicle-free. The denser-looking layers are similar in thickness to the coarsely vesicular layers, and both types of layers are planar, in that they extend all the way across the drill core. They may occur as a single couplet but more typically are found in larger packets, making up intervals of 10 to 20 feet in the drill core.

As a matter of observation, most foundered crust is quite olivine-rich, so in many parts of the lake it can be recognized not only by the alternating coarsely vesicular/denser layering, but by its high olivine content, and by the relative coarse grainsize of its olivine phenocrysts. In the zone of maximum olivine enrichment this is not useful, but that region of the lake appears to be largely clear of foundered crust, by any criterion.

The last essential feature of foundered crust is that the vesicles in it were filled with air at the time it was overrun and moved down into the lava lake. Most of the variation in appearence of foundered crust is produced because of (1) differences in the extent to which the original trapped air has been displaced by differentiated liquid seeping into the spongy crust, and (2) the extent of interaction between any remaining air and the enclosing crust. If the air was not displaced, the crust could not and did not founder very far. For crust to founder deep within the lake, it seems that almost all of the air in the vesicles had to be displaced by differentiated liquid: at least there is a very good correlation between degree of infilling of vesicles and the depth reached by the block of foundered crust. There is also a good correlation between the intensity of oxidation and the extent of infilling of vesicles.

In the shallower parts of the lake, or in places where coring occurred while the core was still extensively molten, the recognition of foundered crust has been relatively straightforward. In 1988, however, we recovered core from deep within the lake, which had reached near-solidus or subsolidus temperatures prior to being sampled. The conspicuous glassy pools (melt-filled vesicles) that had made even melt-saturated foundered crust easy to recognize had finished crystallizing, obscuring the contrast between original host and vesicle. The crystals that grow in the melt pools achieve a slightly coarser grainsize than crystals in the matrix: this phenomenon had been observed in the more molten core recovered in previous years. Holocrystalline foundered crust therefore has a mottled-looking groundmass, with irregular coarser-grained patches in finer matrix. It also tends to be somewhat vuggier than the normal matrix rock in the lake.

Presence of vesicles and/or anomalously large melt pools is not automatically an indicator of foundered crust, however. The segregation veins and the various diapiric tracks produced as part of the segregation-vein-forming process (see discussions in Helz, 1980; Helz, 1987b; Helz and others, 1989) are also more vesicular and more melt-rich than typical matrix. Correct identification of foundered crust requires that we be able to distinguish foundered crust in all its metamorphoses from all of the segregation-vein-related phenomena.

The segregation veins themselves pose no difficulty: they are ferrodiabasic in composition, containing little or no olivine, and crystals in them are 2-3 orders of magnitude larger than the same phases in the rest of the lake. The veins are generally more vesicular or vuggy than their immediate host rock, but the contrast in grainsize and bulk composition is so great as to make it virtually impossible to confuse the veins with foundered crust.

There are three distinct types of vertical diapir-like bodies observed in drill core that appear to be produced by the upward transport of segregation-vein liquids in the lake. The first are the "vorbs", described in Helz (1987b) and in Helz and others (1989). These bodies run vertically up the side of the core; they contain more, and coarser, olivine than the adjacent host; lastly, the material between the olivine phenocrysts and/or clumps of early-formed crystals consists of continuous channels of melt, or (in holocrystalline vorbs) of coarser-grained, vuggier groundmass. The second class of related structures are melt chimneys, found at 257-260 feet and below. These are, as the name implies, larger vertical channels of melt. They differ from the vorbs in that the channel is largely free of coarser olivine phenocrysts, and there is no excess of olivine in or near the channel, relative to the adjacent rock.

These were first encountered in 1981, in drill holes KI81-1 and KI81-5, but their significance was not recognized until the 1988 core was examined (see discussion below). The 1988 core contains, in addition to examples of the melt chimneys more crystalline than those in the 1981 core, a third class of vertical structure: these are arrays of melt blebs or (often) tiny speckles of melt, which extend up the side of the core in the same way the vorbs do (see section on Description of the 1988 Core Logs, below). Similar melt blebs were produced in the partially molten mush that oozed up into drill hole KI79-1. It is quite certain that these blebby textures developed during flow of crystal-liquid mush up the open borehole, because such textures were completely lacking in the original KI79-1 core (see description in Helz and others, 1984). (Detailed descriptive logs of the KI79-1 ooze are presented in this report, for the first time, in order to have all of the descriptive material on these anomalous textures in one place.) All of these relatively melt-rich regions either have crystallized or will crystallize to produce areas of coarser, vuggier groundmass.

The underlying distinctions between foundered crust and the three structures involved in transport of segregation-vein liquids are:

(1) The vorbs, melt chimneys, and regions of speckled rock are always nearly vertical, running up the side of the core, and only rarely extending across the entire cross-section of the core.

(2) There is no binary association of melt-rich and melt-depleted layers, where the anomalous rock is one of these diapiric bodies. There is no depletion of melt in the adjacent matrix. Only the vertical, cross-cutting melt-rich region and the normal host rock are present.

(3) There is no oxidation associated with any of these diapiric bodies.

In most circumstances, these differences allow us to assign an interval of mottled-looking, anomalous core as being either former "leopard rock" or former "speckled rock", without ambiguity, even though individual pieces of core, or thin sections, might be ambiguous.

The distribution of known blocks of foundered crust is shown in Figure 5. This figure shows only the 2/3 of the lake where drill holes exist, and emphasizes the following features: First is the rapidly cooled marginal zone of the lake (hachured area), which is about 30 feet thick along the lake's free surface (Helz and others, 1989, based in part on data from Mangan and Helz, 1986) and about 25 feet thick (true thickness) in the lowermost part of hole KI79-5 (Helz, unpublished data). The second region of the lake illustrated is the olivine-depleted zone: the part of the lake where bulk MgO is less than 11% by weight, and olivine phenocrysts, though present, are mostly small (<2 mm). This region is free of foundered crust, but is directly overlain by foundered crust along the north edge of the lake. Lastly, the dark blocks mark the position of significant bodies of foundered crust that lie inside the chilled marginal zone of the lake.

The largest known repository of foundered crust in Kilauea Iki is in the upper 30-40 feet of the lake. Examination of drill core from the 23 deep holes drilled

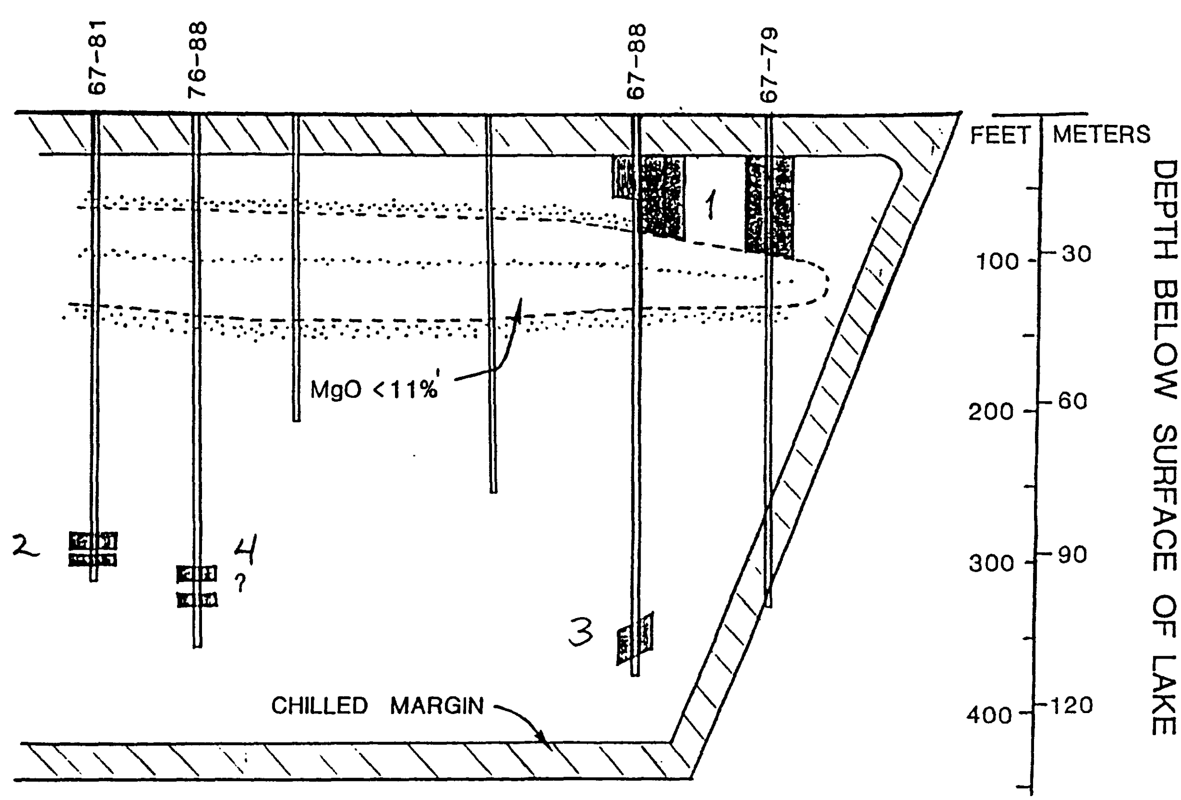

Figure 5. Distribution of foundered crust in Kilauea Iki as determined by drilling. The hachured zone around the edge of the lava lake represents the rapidly cooled margin of the lake, and is 25-30 feet thick, where sampled. The dark gray blocks represent the known intervals of foundered crust that lie within the body of the lake. The area outlined by the dashed line and stipples is the olivine-depleted zone: the central line of stipples represents a layer containing slightly more olivine, within this zone. The olivine-depleted zone is shown here because the wedge of foundered crust that exists along the north edge of the lake forms its roof along that edge of the lake. The numbered blocks of foundered crust are discussed individually in the text. Drilling locations are shown as a single vertical line labelled with the years over which that location has been occupied. Vertical exaggeration in this figure is 2:1.

between 1967 and 1988 shows a consistent stratigraphy within the uppermost crust, including (1) thin dense zones that recur at the same depth for hundreds of feet laterally, (2) highly vesicular, olivine-rich material, with or without filled vesicles, between 20 and 30 feet, and (3) a consistent zone of rock with stretched, flattened, often steeply dipping vesicles, which typically occurs between 27 and 38 feet (see descriptive logs for drill core in Helz and others, 1984; Helz and Wright, 1983; and the present report).

This upper-crust complex contains the inverted stratigraphy of the initial crusts formed during the 17 active phases of the 1959 eruption. Some of the material in this complex spread out directly from the vent onto the (barely stable) lake surface as thin flows, some is shallow foundered crust, and some is frothy material that overrode the initial thin crusts from below. Often the more vesicular, olivine-rich slabs are separated by thin segregation veins or olivine-poor denser layers; the denser layers are interpreted as chilled rinds that formed on the downgoing slabs. It is striking that not one of the 23 hole drilled has encountered any kind of window in this layer. If there are large expanses of the lake that were stripped of this complex, in the course of crustal foundering, we have not yet encountered them. The area to the southwest of the center of the lake, nearer the Pu'u Pua'i vent, might be such an area.

Deeper foundered crust was first encountered in the two 1967 holes drilled toward the north edge of the lake (occurrence #1 in Figure 5). The section recovered in KI67-1 includes the most striking examples of oxidized, blackened olivines found so far. These are produced when air trapped in the foundered block interacts with the iron in the abundant olivine phenocrysts to produce magnetite and a very magnesian olivine, plus some pyroxene. The magnetite is dispersed as tiny inclusions in the colorless olivine, so that the olivines appear black in hand specimen, and look dirty or cloudy in thin section. The foundered crust recovered in KI67-2 (nearest the edge of the lake) includes spectacular intervals of "leopard rock", a name given by Richard Fiske to melt-soaked, formerly vesicular core, because of the large black glossy patches of melt visible on the surface of the core. These packets of foundered crust extend essentially continuously down from below the chilled margin to 89 feet and 98 feet, respectively (see descriptions in Helz and others, 1984). Both localities were redrilled in 1975, at which time the foundered crust intervals were holocrystalline. This double-drilling of unequivocal foundered crust has provided us with the means of identifying similar material elsewhere in the lake. Layering in both packages of foundered crust was steeply dipping, but the absolute orientation of the dips is unknown.

No new occurrences of foundered crust were discovered in 1976 or 1979, though hole KI79-5 did resample the package of foundered crust found in KI67-2 and KI75-3. However in 1981 we encountered occurrence #2, in the center of the lake. The upper block of foundered crust at this locality includes almost ten feet of alternating, horizontal layers of leopard rock and denser, finer-grained layers, all very olivine-rich. This material lies between 277 and 287 feet in core from hole KI81-1,

TABLE 2. Data on layers of filled vesicles ("leopard rock") and other kinds of melt-spotted rock in core from KI81-1

Interval of core (in feet)	Observations
254.0-254.2	Patch of rock with melt blebs on side of core
259.0-259.2	Patch of melt-rich rock, lowest part of which contains small round glass-lined vesicles, on side of core
277.4-278.1	Six layers of leopard rock, mostly 1 cm thick. The lowest is 0.3 ft thick.
280-281.9	Five layers of leopard rock, one 0.25 ft thick
281.9-282.5	One layer of leopard rock, 0.6 ft thick.
282.5-283.3	Three layers of leopard rock.
283.3--284.6	Three layers of leopard rock, plus one continuous from above interval.
284.6-284.8	One layer of leopard rock.
284.8-287.0	One layer (?) 1 cm thick at 285.7 ft, plus some glassy partings (?)
287.0-289.9	No obvious leopard rock. Appears to be a septum of normal, very olivine-rich matrix rock. Some smears of glass = sheared spots?
289.9-293.6	One layer of leopard rock at 290.5 ft.
293.6-296.1	Three layers, one of which does not extend through the core (?)
296.1-299.3	One layer at 296.2 is vesicular with black olivines. Glass blebs between 298.2 and 299.0 ft are sheared at the top, round at the bottom of the interval. Sheared leopard rock?
299.3-303.0	One layer of leopard rock at 299.9 ft.
303.0-307.0	Thin layer at 304.0? Melt-rich shear at 303.3 ft. Otherwise massive.

and was encountered again at 278-286 feet in hole KI81-5, which lies about 20 feet to the west of KI81-1 (see Helz and Wright, 1983). From this second hole we know that the block of foundered crust is truly flat-lying, and also that it is fairly extensive, being at least twice as large in the horizontal plane as it is in the vertical. It was particularly valuable to be able to confirm that the apparent dip seen in the drill core is representative of the true dip of the larger block.

All occurrences of melt-spotted rock in hole KI81-1 are described in Table 2. This table, which is much more detailed than the logs in Helz and Wright (1983), is based on my detailed re-examination of the deepest part of the KI81-1 core, done on 1/2/85. Initially I had thought that essentially all core below about 275 feet was foundered crust, but a closer look suggests that we are dealing with two packages of foundered crust, separated by a septum of more "normal" material. The upper block (between 277 and 287 feet) is the more obvious, and contains a total of 20 individual layers of "leopard rock" in the 10-foot interval. There is a two-foot septum of clear, "normal" core, one layer of ambiguous melt spots, and then another 3 feet or so of massive core completing the interval between the foundered crust packets. Between 293.6 and 299.9, there are 5-6 distinct layers of "leopard rock", alternating with finer-grained, denser material. There is one layer with open vesicles, which (not surprisingly) also contains blackened, oxidized olivines. Clearly there is another, thinner packet of foundered crust here, but it has been somewhat disrupted by shearing, whether during emplacement of the blocks or later. KI81-5 did not extend to this depth, so we have only the KI81-1 core to work with below 288.3 feet.

Table 2 also describes two occurrences of the other kind of melt-spotted rock in KI81-1. These occur as patches on the side of the core; from that, plus their depth, their small size, and their isolation, I have interpreted these as being examples of the "speckled rock" diapirs, which are so common in the 1988 core. The 1981 examples differ only in having been quenched from higher temperatures.

The depth is significant, because two of the three types of diapiric structures associated with the transport of segregation-vein liquid first appear between 254 and 260 feet, in every drill core that extends to those depths. In KI81-1, we have these two patches of "speckled" rock. In KI81-5, there are melt chimney structures present at 256.6-256.8 and 259.3-260.8 feet. Hole KI81-3 was stopped abruptly at 258.8 feet, when the drill string dropped into a pool of something very liquid. The drillers were able to retrieve the string without getting stuck, but the lowermost 4 feet of core fell out of the barrel and could not be recovered. At the time (see discussion in Helz and Wright, 1983) it was not clear what this melt-rich body could be, but from the 1988 core, and re-examination of the deepest 1981 core (especially KI81-5) is seems reasonable to suggest that the drillers encountered a melt chimney in KI81-3. Similar anomalous, cross-cutting features are found on both 1988 cores, beginning in this same depth range (see logs, this report).

In 1988 we also encountered more blocks of foundered crust. The first of these is occurrence #3 in Figure 5, found between 334 and 362 feet in KI88-1. This is a package of alternating fine-grained, denser rock and coarser, more olivine-rich mottled rock, with local occurrences of blackened olivines. The layers dip at 50-60° through the core, and are particularly continuous in the center of the interval. This is fairly obviously foundered crust, even though small pieces of the mottled layers (former "leopard rock") can look much like holocrystalline "speckled" rock (see queries in the descriptive log for KI88-1). The thick series of layers and the presence of blackened olivines are the decisive features here.

The last occurrences of foundered crust to be described (#4 in Figure 5) are in KI88-2. These have been the most complicated to decipher, because some of the foundered crust layers have been extensively disrupted, and because there may be diapirs of speckled rock within foundered crust locally. (There is no reason in principal why vorbs, melt chimneys, and speckled-rock diapirs, which develop later, could not cut through thin layers of foundered crust.) However, the layer of coarse amoeboid melt spots at 301.7-302.5 ft, and its associated denser cap appear to be the top of a zone of (very messy) foundered crust that extends to 312.5 ft. Between 321.3 and 326.2 the core contains alternating layers of denser rock and coarser, mottled rock as in KI88-1; this is clearly foundered crust. The interval between 312.5 and 321.3 feet is fine-grained, relatively olivine-poor rock that looks like the chilled rind that occurs locally around some of the other blocks of foundered crust (occurrences #1 and #2, Figure 5); this chilled septum contains blackened olivines, which is not the usual pattern, but is still presumably an indicator of trapped air in this whole interval. It is obvious from the descriptive log for KI88-2 that this section is sufficiently complex that further work (bulk chemistry, petrography) will be necessary to resolve the tentative interpretations made here.

Even allowing for some uncertainty in the interpretation of the KI88-2 core, however, there are some striking features of the pattern of occurrence of the deeper blocks of foundered crust. First, the foundered crust tends to occur in packages roughly 20 feet thick, or (as in KI81-1 and in KI88-2), in pairs of 10-foot intervals. One possible indication of this is the interval of shallow foundered crust resampled in the upper part of KI88-1. The two earlier cores from this locality (KI67-1 and KI75-2) had foundered crust to 89 feet. In the 1988 hole, which lies 30 feet to the south, foundered crust extends to 61.4 feet only. One could say that the base of the foundered crust was dipping at 45°, but the base of the foundered crust drops only 9 feet from KI67-1 to KI67-2, a distance of 250 feet. An alternative explanation (illustrated in Figure 5) is that the wedge of foundered crust at KI88-1 contains one less 20-foot thick packet than is present just to the north. This interpretation is supported by the chemical composition of the core from holes KI67-1 and KI75-2 (Helz, unpublished data), which shows two repetitions of the same chemical signature between 40 and 89 feet.

This crude 20-foot thickness for packets of foundered crust is curious. It is somewhat thinner than the present upper crust, which is 30-40 feet thick at present.

The crust presumably thickened gradually during the eruption, however and in any case its present thickness is itself partly shallow foundered crust. The 20-foot packets would thus correspond roughly to the entire thickness of crust available through much of the middle part of the eruption. It seems that either (1) only large packets of crust could sink to appreciable depths in the lake or (2) the only foundered crust we can recognize is the largest packets, with smaller lenses of foundered crust having been digested too completely for us to discern their presence.

It seems evident from Figure 5 that there is a wedge of imbricate slabs of foundered crust, underplating the chilled margin (or upper-crust complex) along the north edge of the lake. This side of the lake is opposite the vent, so would be a logical place for foundered crust to pile up, after having been swept along by magma currents from the vent. This wedge forms the roof of the olivine-depleted zone in this part of the lake, as shown, and is presumably responsible for the slope of that roof (which one might otherwise expect to be horizontal).

Last but not least, there are significant blocks of foundered crust in all three deep holes out in the center of the lake. In each instance we see approximately 20 feet of foundered crust, but with relatively massive olivine-phyric basalt below. The depth to these deep blocks varies from 277 to 334 feet, but so far, no drill hole lacks this material. What underlies these blocks? It is clear from the available drill core that there is not a self-supporting pile of foundered crust all the way to the bottom of the lake, so why did they stop where they did? Further work on the existing 1988 core may help resolve this, but final resolution will probably depend on the availability of core that passes completely through the lava lake.

DISTRIBUTION OF FRACTURES IN DRILL CORE FROM KILAUEA IKI

Fractures observed in drill core from Kilauea Iki fall into two categories: those that predate drilling, and those produced by drilling. They occur in all of the drill core recovered, so that observations of fractures in the core are scattered through all of the descriptive logs, made over the past 20 years. This is the first attempt at a systematic review of this data.

Pre-existing Fractures

Fractures that fall unambiguously in the first category are those where the fracture surface is coated with some mineral or alteration product, or (rarely) glass. In the upper part of the lake, fracture coatings include whitish or yellowish sulfates (gypsum, anhydrite, thenardite, possible some iron sulfates) or reddish films (hematite) or black feathery films (manganese oxides). These are found in the two-phase part of the geothermal system in the lake, that is, where liquid water and steam coexist,

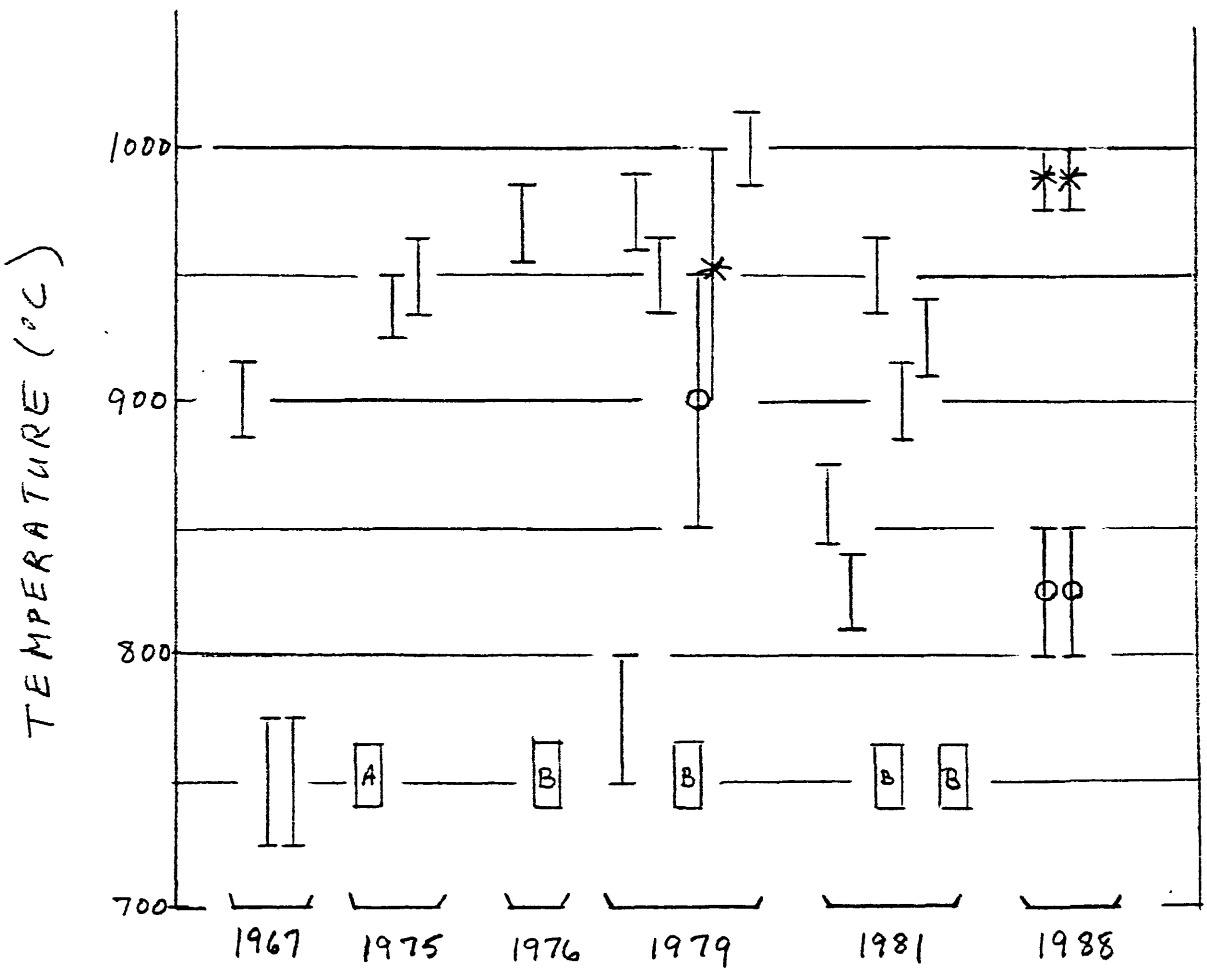

Figure 6. Maximum temperature to which vertical fractures extend, as observed in core from the upper and lower crusts of Kilauea Iki lava lake, in drill core from 1967 to 1988. In most holes, only the upper crust was sampled; these are shown by the plain brackets. For the three holes that passed through the thermal maximum in the lake, the limiting fracture in the upper crust is the bracket with the open circle on it, while that in the lower crust is the bracket with the asterisk. The length of the bracket indicates the uncertainty in the individual temperature measurement/estimate. The block labelled "A" indicates a drill hole (KI75-1) where core recovery was poor, and the core so broken and ground up, that observations on fracturing were not possible. The blocks labelled "B" mark holes where we have no direct temperature information on that core, because the hole effectively duplicates another, nearby hole, as discussed in text.

and T<115°C. The fractures usually cut the core at high angles (some 45°, but most nearly vertical). Such fractures are also found in higher-temperature regions, but there the fracture surfaces are either reddish or completely fresh.

Between the partially molten zone and the lower contact of the lake, where the temperature is always 500°C or higher (see, e.g., the calculations of Jaeger, 1961), pre-existing fracture surfaces are strongly oxidized, with the effects of oxidation extending several mm into the adjacent rock. The fractures are all very steep, and may extend for several feet along the core. They extend up into the base of the partially molten zone, as in KI88-2, where the surfaces of the uppermost vertical fracture encountered (at 349 feet) are coated by rhyolitic glass (see logs below).

Data on the farthest extent of the vertical fractures into the core of the lake is summarized in Figure 6, which shows the temperature of the deepest vertical fracture above the partially molten zone, or the highest vertical fracture below that zone. Location of the fracture is determined by observation of the core, of course. The temperatures come from (1) downhole measurement of temperatures, using thermocouples, (2) oxide geothermometry and (3) observations on the occurrence of glass in the core and use of glass compositions as geothermometers. Results from these various methods are combined, as described in Helz and Thornber (1987) to construct a continuous temperature profile, which then gives us an estimated temperature at the location of the deepest/shallowest fracture. The uncertainty in those estimates is indicated by the brackets in Figure 6. To the extent that a bias exists, these temperatures will be too low, because they are all based in part on post-drilling thermocouple profiles, which are always cooler than pre-drilling temperatures (see discussion in Helz and Thornber, 1987).

For four drill holes, we have no direct temperature data; such holes are indicated by "B" in Figure 6. These are in all cases one of a pair of holes, which has not been studied in detail because the core from the second hole is too similar to the first core to be worth separate study. The pairs are:

Studied core	Unstudied matching core
KI76-1	KI76-2
KI79-3	KI79-4
KI81-1	KI81-5, KI81-7

The fractures in the second set of cores extend to the same depth, and presumably at the same temperature, as in the twin hole. In one hole (KI75-1) the core is so badly broken up and the surfaces of individual pieces so abraded, that I have been unable to get a reasonable "deepest fracture" location. The very low temperatures shown for fractures in two of the three 1967 cores may also reflect poor core recovery.

These limitations aside, the results in Figure 6 show that the vertical fractures commonly extend to the 900-1000°C range in Kilauea Iki. The maximum observed temperature of fracturing appears to rise systematically from 1967 to 1979. This could be real: the olivine content of the core in this temperature range increased steadily over this period, the solidus temperature increased slightly, and hence the amount of residual glass left in the core near the solidus must have decreased. The decrease in maximum temperatures for fracturing seen in the 1981 and 1988 core is not consistent with this, however.

Another possible interpretation of the observed variation in maximum fracture temperature is that we are looking at the effects of variations in core diameter and recovery rate. The earliest two sets of core produced core 5 cm in diameter, with less than 100% recovery rates. The 1976-1979 core was 6+ cm in diameter, while the 1981 and 1988 core was mostly 3+ cm in diameter. In this case, the high-temperature fractures seen in the 1976 and 1979 holes would mean that the 6-cm core diameter is wide enough to catch the true limiting fracture, while the 3-cm core recovered in 1981 and 1988 often missed the limiting fracture. Note that all of the 1981 and 1988 fractures extend to T>800°C. Only the two 1967 holes and hole KI79-1 show lower temperature limits for observed vertical fractures, and in two of these three cases we are hampered by relatively poor core recovery.

A few of these steepest fractures will widen to become the bounding surfaces of the columnar joints that are presumably (see, e.g. Ryan and Sammis, 1981) developing in Kilauea Iki. However, the fractures are present in every core recovered, and so must be much more closely spaced than the final columns will be. As discussed above, the pattern in Figure 6 suggests that the fractures are spaced every 5-10 cm or so, so that 6-cm core intersects the leading edge of the fracture in almost all cases, whereas 3-cm core often misses. These observations imply that the fractures that widen to form the bounding surface of columns in thick basalts are only a small fraction of the vertical fractures forming as the rocks cool.

Fractures Produced by Drilling

Fractures induced by drilling, or by quenching of the core, are usually radial or concentric with respect to the core's outside surface. Most of these occur in characteristic temperature ranges (or melt percent ranges). One kind is produced in a certain zone of the lake, and presumably is somehow controlled by bulk composition.

Very high-temperature core, including the hottest core recovered in 1988, has closely spaced, "onion-skin" fractures around all individual pieces of core. These occur parallel to all surfaces, including any produced by breaking of the core as it moves through the core-catcher and up into the core barrel. This kind of fracture is observed where enough melt is present for it to be obvious by casual inspection of the surface of the core. Pre-quenching temperature is generally greater than 1000°C.

Beyond the obviously partially molten zone is a temperature range where the core breaks with a radial, hackly fracture. This lower-temperature type of induced

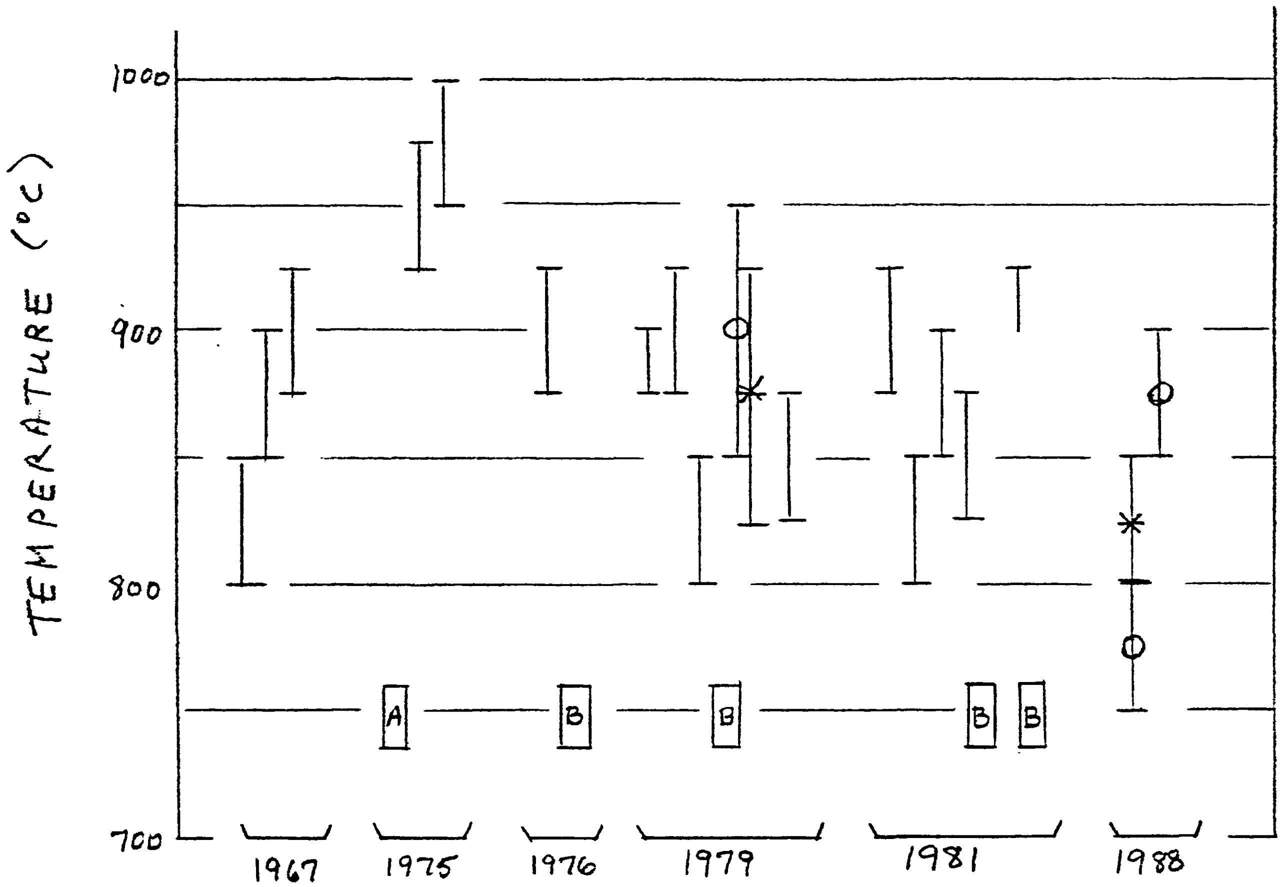

Figure 7. Minimum temperature at which the recovered core shows radial, hackly fracture, in drill core from Kilauea Iki lava lake, recovered from 1967 to 1988. Various brackets, plus"A" and "B" labels as in Figure 6.

fracture contributed to the stopping of the 1988 drill holes, especially KI88-2, as the resulting angular bits of core very easily become jammed in the bit, instead of passing through the core-catcher. These fractures have been observed in all cores recovered from 1967 to 1988; Figure 7 shows the lower temperature limit of their occurrence, in each core for which we have temperature data. The temperature estimates in Figure 7 are obtained from the same profiles used in getting the temperature data shown in Figure 6.

The most striking feature of the data in Figure 7 is that the hackly fractures generally extend to the 800-900°C range in most cores. In one hole (KI88-1) they appear to extend to slightly lower temperatures in the upper crust, while in two of the 1975 holes they appear to be restricted to much hotter core. In the latter two cases, we are handicapped by relatively poor recovery in the critical temperature interval: the actual temperature limit could be lower, but the core has been so abraded in the core barrel that we cannot tell exactly where the hackly fractures cease to occur.

This result is peculiar, because the solidus of the rock is 970-1000°C, and cooling of the lava lake has been so slow that in general, glass crystallizes completely at that solidus temperature, in the olivine-phyric basalt. That is, there is no glass detectable by optical examination of the thin sections or with the electron microprobe. The only rock types in which readily detectable metastable glass persists below the solidus are the diabasic segregation veins and the more differentiated late segregations (as described in Helz, 1987b). For rocks in which trace amounts of melt are clearly present, it is easy to understand the origin of the hackly fractures: they form by shrinkage of the core, which shrinks because the melt shrinks when it is quenched by the cooling water used during drilling. The question is, why do the hackly fractures extend out into the high-subsolidus core, as they do in every single core examined? Alternatively, why do they stop where they do, at about 800°C, and are not found in core quenched from the 500-800°C range, for example, which is also still hot?

I suggest that there is a vanishingly thin film of glass still on the surface of most crystals in the aggregate, which has failed to crystallize because it is too thin for nucleation of the necessary phases (SiO_2 polymorph and feldspar) to occur. It still has the properties of melt, down to the glass transition temperature, and shrinks when chilled. For core below the glass transition temperature, the core does not shrink because this film no longer has the properties of melt. If this explanation is correct, it may imply that the glass transition temperature in this material is 800-900°C, somewhat higher than the 700-750°C estimated by Ryan and Sammis (1981) in their studies. It should be emphasized that, as in Figure 6, if the temperatures in Figure 7 are biassed, they are biassed low, not high, so the difference between the two temperature estimates can only increase, if one tries to correct back more rigorously to pre-drilling conditions.

Another possible explanation for the difference in temperature between Figure 7 and the Ryan and Sammis (1981) estimate is that what counts is not the pre-drilling temperature of the core, but the actual temperature of the rock as the bit reached it and began to sample it. Because the rock had already been exposed to some cooling water at that point, it is conceivable that its temperature was lower than predrilling temperatures farther ahead of the bit. In this case, the apparent, predrilling temperatures of 800-900°C might have been actual moment-of-sectioning temperatures of 700-750°C. In any case, it is quite clear from the drilling record in 1988 that these fractures form at the moment of cutting of the rock, before the core has moved past the core-catcher. If they formed in the core barrel, they would not have blocked the drilling so effectively.

The presence of these hackly fractures in the core, and the difficulty experienced in drilling and recovering the (badly broken) core explains why, in earlier drillings, core recovery was frequently worst in the high-temperature part of the subsolidus region. This was true not only in the 1967 and 1975 drillings of Kilauea Iki, but also in the earliest (1960-62) drilling, and in the various drilling ventures in the 1965 Makaopuhi and 1963 Alae lava lakes (Wright and Okamura, 1977; Wright and Peck, 1978). Much of the lower part of Kilauea Iki will be in this temperature range for several years to come, and so will pose a major obstacle to complete sectioning of the lake.

The third type of induced fracture that is persistently observed in Kilauea Iki core is the curving, conchoidal fracture seen in core from the olivine-depleted zone in the lake (outlined in Figure 5). These fractures occur in every core that passes through this layer, regardless of the temperature from which it was quenched. They are not observed in more olivine-rich, or in more vesicular core.

The conchoidal fractures must form after the core has passed through the core catcher. Core recovery is typically 100% in this depth range, but as the core slides out of the core barrel into the tray, for examination and boxing, it can be seen to consist of a three-dimensional puzzle of sharp, interlocking shards. These fit together perfectly, as they emerge from the barrel, but fall apart in the tray, and are virtually impossible to reassemble afterward. I infer that they form as the core moves into the barrel, and previous confining stresses on the core are released. If these fractures existed in the lake prior to drilling, it would be extremely difficult to pass through this horizon. Why they are restricted to the olivine-poor core is not clear at present.

DESCRIPTION OF THE 1988 CORE LOGS

For each hole there are two logs. The first is a recovery log, which gives the dates on which particular depth intervals were drilled and the amount of core recovered. Core recovery was 100% in almost all cases. The second log for each hole is a brief petrographic description of the core. The lake consists mostly of olivine-phyric basalt, with 5-10% coarser-grained, ferrodiabasic segregation veins, so the logs describe variations within a fairly narrow range of rock types. Features noted include:

(1) Freshness. Presence and extent of oxidation or other alteration.

(2) Vesicularity. Shape, size, distribution of vesicles. Presence of denser layers in between more vesicular material. Such layers are an indicator of foundered crust, as discussed above.

(3) Presence, size and relative abundance of olivine phenocrysts. The quantity terms used indicate the following approximate modal proportions:

olivine-rich	>25% olivine phenocrysts by volume
olivine common	10-25% olivine phenocrysts
olivine present	5-10% olivine phenocrysts
olivine sparse	<5% olivine phenocrysts

(4) Presence of glass. Glass first appears in the core as black, vitreous specks. the matrix of the rock darkens from greenish-gray to dark gray to black as the percentage of glass increases.

(5) Presence of vesicle fillings; presence of mineral coatings on joint surfaces. Presence of whitish bloom (of thenardite, Na_2SO_4) on core collected just above the steam-water interface.

(6) Presence, thickness and orientatation of segregation veins and other pockets of differentiated material.

(7) Presence and character of regions of anomalous appearence, such as vorbs, melt chimneys, patches of speckled rock, and possible foundered crust.

(8) Presence and character of fractures in the core.

The core was logged from top to bottom, so comparative terms (such as, "more olivine-rich" etc.) refer to the immediately preceding interval of core unless otherwise specified.

Most petrographic terminology is standard. However several non-standard field terms have evolved, to describe some of the diapiric structures in Kilauea Iki, and to describe foundered crust. The glossary developed for foundered crust is:

leopard rock. This refers to vesicular foundered crust where the vesicles are partly or completely filled by melt, to create dark, irregular spots conspicuous on the surface of the core. The term was first used by R.S. Fiske in describing core from KI67-2 (Helz and others, 1984).

spotted rock. This is holocrystalline leopard rock from shallow blocks of foundered crust, where the crystallized melt in the vesicles has a very sharp edge with the enclosing matrix. Term originally used for 1975 core (Helz and others, 1984).

mottled rock. This is holocrystalline rock, either former leopard rock or former coarsely speckled rock. Found in deeper parts of the lake, where slower cooling has blurred the edges of formerly sharp melt blebs. Most examples appear to be former leopard rock. Term first used in this report, for the 1988 core.

blackened/black olivine. This describes olivines that have interacted with air trapped in foundered crust, to produce swarms of tiny magnetite inclusions in formerly iron-bearing olivine phenocrysts. This feature iss distinctive for foundered crust because the level of oxidation is not sufficiently intense to produce hematite, the reddish alteration that is characteristic of interaction between hot rock and air in cracks or voids connected directly with the atmosphere. Term first used by Fiske for 1967 core.

The terms that have been developed to describe the various cross-cutting, apparently diapiric, bodies associated with the upward transport of differentiated liquids in the lake include:

vorb. A "vertical, olivine-rich body," the track left by passage of a vesicle- and melt-rich plume. Described in Helz (1987b) and Helz and others (1989). The vorbs are found above 200 feet in the lake, are best developed between 130 and 200 feet.

melt chimney. These are vertical melt-rich bodies (or more crystalline equivalents) found in 1981 and 1988 core, below 256 feet. Less olivine-rich than vorbs. Term first used in this report.

ogb or **olivine-glass body.** These are sub-horizontal areas rich in vesicles plus crystallite-free glass, found in the olivine cumulate zone between 200 and 250 feet. They were first seen in 1981 and are characterized by extreme depletion in groundmass phases (olivine, augite, plag) relative to olivine phenocrysts and glass. Often highly vesicular in 1981 core, but holocrystalline equivalents in 1988 core are much less vesicular. Origin presently unknown. Term first used in Helz and Wright (1983).

speckled rock. This describes regions of core containing round to oval blebs of glass, which are much too small to have been filled vesicles. These are usually very evenly distributed within the region, which normally appears to be a steep, diapiric structure, running up the side of the core. Seen in 1981 and 1988 core. Term used in this report for the first time.

In addition, the core descriptions contain a number of terms used to describe the fractures that occur in the core. The fractures, and the terms used to describe them were discussed in the preceding section.

The 1988 core is currently (12/92) in storage at the Hawaiian Volano Observatory. Requests to sample and use the core should be routed through R.T. Helz (U.S.G.S., Reston) to facilitate coordination with other, ongoing studies of Kilauea Iki lava lake. The core was drilled using a 5-foot core barrel, so the drillers' blocks occur at non-metric intervals. Accordingly, the core boxes are labelled in feet rather than meters. All depth and most length measurements in the logs are in feet or tenths of feet, to make it easier to work with the core as labelled. The exception is grainsizes and the size of other small features, which are given in centimeters or millimeters.

DESCRIPTIVE LOGS OF REDRILLED OOZE FROM KI79-1

In the original report (Helz and others, 1984), the redrilled ooze from various holes re-entered during the 1979 drilling was described only very sketchily. The oozing behavior itself was reviewed in detail in Helz and Wright (1983), but the recovered ooze was not logged in detail until 12/31/84.

Most of the ooze recovered was fairly massive black glass from segregation veins at the base of the drillable crust. The ooze from holes KI75-1R, KI79-2, KI79-3 and KI79-6 is of this sort, and is adequately described by the initial logs. The ooze from KI79-1 was known to be olivine-rich mush, but until the relogging I did not appreciated how peculiar the first run of ooze was. These detailed logs are presented as part of this report because of the blebby, spotty textures found in the ooze from the first re-entry. These are remarkable because such material, either with these compositions or with these textures, was completely absent from the original core from KI79-1 (see logs in Helz and others, 1984). The textures documented in these logs demonstrate that it is possible to produce segregated blebs of melt in mush as it rises diapirically into a borehole. This was the first clear indication that more than one kind of spotty, blebby core might be recovered in Kilauea Iki. Thus when the 1988 core was recovered, this ooze provided a vital part of the background for the interpretation of the many occurrences of spotty, blebby or speckled rock in those cores.

The second and third runs of ooze recovered much more massive, uniform material. Evidently the extensive internal differentiation seen in the first run of ooze was produced during slow creep, rather than the more rapid surges seen in the later re-entries (see discussion in Helz and Wright, 1983, for information on the timing of oozing).

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Core Recovery Log for KI88-1

Date	Interval drilled (in feet)	Core recovered (in feet)	Percent recovery
10/31/88	0.0- 3.8*	0	0%
	3.8- 7.1	3.3	100
	7.1- 11.0	3.9	100
	11.0- 16.0	5.0	100
	16.0- 21.2	5.2	100
	21.2- 26.4	5.2	100
	26.4- 31.5	5.1	100
11/1/88	31.5- 36.5	5.0	100
	36.5- 41.6	5.1	100
	41.6- 46.6	5.0	100
	46.6- 51.4	4.8	100
	51.4- 56.7	5.3	100
	56.7- 61.7	5.0	100
	61.7- 65.1	3.4	100
	65.1- 66.9	1.8	100
	66.9- 71.6	4.7	100
	71.6- 76.5	4.9	100
11/2/88	76.5- 81.6	5.1	100
	81.6- 86.6	5.0	100
	86.6- 91.6	5.0	100
	91.6- 96.6	5.0	100
	96.6-101.6	5.0	100
	101.6-106.5	4.9	100
	106.5-111.6	5.1	100
	111.6-116.7	5.1	100
	116.7-120.6	3.9	100
	120.6-121.7	1.1	100
	121.7-125.7	4.0	100
	125.7-126.7	1.0	100
11/3/88	126.7-131.1	4.4	100
	131.1-136.1	5.0	100
	136.1-139.3	3.2	100
	139.3-141.2	1.9	100
	141.2-144.2	3.0	100
	144.2-146.1	1.9	100
	146.1-149.4	3.3	100
	149.4-151.2	1.8	100
	151.2-152.0	0.8	100
	152.0-156.4	4.4	100
	156.4-161.3	4.9	100
	161.3-166.1	4.8	100

Core Recovery Log for KI88-1 (con't)

Date	Interval drilled (in feet)	Core recovered (in feet)	Percent recovery
11/4/88	166.1-171.2	5.1	100
	171.2-176.4	5.2	100
	176.4-181.4	5.0	100
	181.4-186.2	4.8	100
	186.2-191.2	5.0	100
11/7/88	191.2-196.0	4.8	100
	196.0-201.3	5.3	100
	201.3-206.2	4.9	100
	206.2-211.2	5.0	100
	211.2-216.2	5.0	100
	216.2-221.2	5.0	100
	221.2-226.2	5.0	100
	226.2-231.4	5.2	100
	231.4-236.4	5.0	100
	236.4-241.5	5.1	100
11/8/88	241.5-251.5	10.0	100
	251.5-251.8	0.3	100
	251.8-261.7	9.9	100
	261.7-271.5	9.8	100
11/15/88	271.5-276.2	4.7	100
	276.2-281.3	5.1	100
	281.3-286.2	4.9	100
	286.2-290.9	4.7	100
	290.9-296.1	5.2	100
	296.1-300.9	4.8	100
11/16/88	300.9-305.8	4.9	100
	305.8-311.0	5.2	100
	311.0-314.6	3.6	100
	314.6-316.7	2.1	100
	316.7-321.7	5.0	100
	321.7-325.4	3.7	100
11/17/88	325.4-326.7	1.3	100
	326.7-330.1	3.4	100
	330.1-332.9	2.8	100
	332.9-336.7	3.8	100
	336.7-340.7	4.0	100
	340.7-345.7	5.0	100
	345.7-350.7	5.1	100
	350.7-355.8	5.0	100

Core Recovery Log for KI88-1 (con't)

Date	Interval drilled (in feet)	Core recovered (in feet)	Percent recovery
11/18/88	355.8-360.8	5.0	100
	360.8-362.0	1.2	100
	362.0-366.0	4.0	100
	366.0-368.7	2.7	100
	368.7-369.4	0.7	100
	369.4-369.5	0.1	100
	369.5-372.6	3.1	100
	372.6-372.9	0.3	100
11/21/88	372.9-374.1	1.2	100
	374.1-374.8	0.7	100
	374.8-375.5	0.7	100
	375.5-375.9	0.4	100

End of hole.

*Rock bit used between 0.0-3.8. No core recovered.

Petrographic Log for KI88-1

Box	Interval	Description
1	0 - 11.2	No core 0-3.8 feet. Core is fresh, highly vesicular, olivine-rich. Minor anhydrite/ gypsum from 3.8-6.0 feet, lining vesicles. Dense layer 0.1' thick at 10.5 feet.
2	11.2- 20.6	Upper 1.5 foot interval relatively dense, fresh. Rest is highly vesicular, oxidized, olivine-rich. One small (1 inch) segregation at 16.3.
3	20.6- 29.7	Highly vesicular, oxidized. Olivine-poor to (locally) olivine-rich. Segregation vein layer at 23.3-24.1 feet. Fresher rock with stretched, dipping vesicles present locally from 27.5 to 29.7. Material lining vesicles is locally oxidized (28± feet).
4	29.7- 38.7	Relatively dense rock with steeply dipping vesicles locally (29.7-31.5). Segregation from 30.1-30.7 ft. Vesicular, olivine-rich, oxidized rock from 31.5-36.5 feet, especially at 33-34. Fresher, less vesicular below (36.5-38.7), but olivine content still high.
5	38.7- 48.0	Dense fresh rock with moderate to low olivine content at 38.7-41.6 and again at 42.8-43.1 ft. Core from 41.6-48.0 contains scattered large vesicles, undeformed, with a moderate to high olivine content. Thin (0.1 ft.) segregation at 46.7 ft.
6	48.0- 56.9	Top of interval (48.0-49.0) again dense, fresh, with moderate to low olivine. Upper contact (at 47.9-48.0) is sharp, lower is gradational. From 49.5-52.0 the core is oxidized and fairly olivine-rich. Vesicle content moderate. There is a thin (0.2 ft.) segregation at 52.2 ft. Below the vein, the rock is very olivine-rich and fresh, with alternating more- and less-vesicular layers (52.2-56.9). The vesicles in this zone are commonly frosted with segregation-like material. This is probably foundered crust.

Box	Interval	Description
7	56.9- 66.0	Top part (56.9-61.4) is a continuation of the block of foundered crust in the above interval. Underlain by a segregation vein (61.4-61.7). Core below that (61.7-66.0) is dense to sparsely vesicular, fresh, with little phenocrystic olivine.
8	66.0- 74.7	This interval fresh, generally dense (<u>not</u> diktytaxitic). Olivine content low in the upper 4 feet. Olivine content and grain size higher below (70.0-74.7). As usual, the more olivine-rich rock is somewhat more vesicular.
9	74.7- 84.0	The matrix rock for most of this interval (74.7-83.1) consists of dense fresh rock with sparse olivine. There are irregular vesicle-rich and/or olivine-rich regions (especially between 74.7 and 76.5 ft.) that may be olivine-poor vorb. This interval is conspicuous for containing a series of thin segregations at 78.0, 78.2, 79.3, 80.1, 80.9, 81.8 and 83.0. These are -0.1 ft. thick and have sharp but irregular contacts. From 83.1-84.0 the rock is diktytaxitic with sparse olivine (<u>ie</u>, it looks like "normal" core from the olivine-depleted zone). The anomalously dense rock seen from 61.7-83.1 ft. may be a chill zone surrounding the foundered crust seen in this same depth range in holes KI67-1 and KI75-2.
10	84.0- 93.2	Most of this interval (84.0-91.6) is fairly dense rock, with a series of minor segregations (at 84.7, 85.0, 86.8, 88.3). Vesicles and olivine are associated with each other and patchily distributed. The olivine content is locally high (<u>eg</u>, at 86.8-87.0). Are these olivine-poor vorbs? The lowest part of the interval (91.6-93.2) is spongy fresh rock with moderate olivine (all small grains).

Box	Interval	Description
11	93.2-102.0	Spongy, diktytaxitic core with moderate to sparse olivine. No coarse olivine. Segregation at 93.6-94.1. Lower contact horizontal, upper irregular. Large empty vesicles at 95.3 and 96.7.
12	102.0-111.2	Core as in above interval, but slightly less spongy. Segregation at 105.2-105.4. Large vesicles at 104.1 and 110.8.
13	111.2-120.4	Olivine-poor rock, finely diktytaxitic. Large segregation present at 115.3-116.9. Large empty vesicle at 114.2.
14	120.4-128.9	Core as in above interval. Segregation at 126.7-127.4, underlain by network of small (feeder?) veins (127.4-127.7).
15	128.9-138.0	Olivine-poor rock, denser than in above interval. Segregation vein from 131.0-132.3. Spongier interval with minor veining from 132.3-133.0. Steep fractures common, but not as conchoidal, as they were in earlier core.
16	138.0-146.1	Upper part (138.0-144.1) dense, olivine-poor rock with several segregations, at: 139.1-139.3, 139.9-141.9 (lower contact almost gradational-??) and 142.8-143.5. Lowermost part (144.1-146.1) contains much more olivine, all quite fine-grained. Transition is fairly sharp.
17	146.1-155.1	Upper interval (146.1-149.8) is dense with moderately abundant small olivines. Swirls of vorb present, especially at 147.4 and 149.1, but the olivines are fairly small in these, as well as in the matrix. Below 149.8, coarse olivines are present and the amount of olivine increases downward. Irregular segregations at 151.2, 152.2-152.4, 152.5, 153.2-153.5 and 153.6-153.7.

Petrographic Log for KI88-1 (con't)

Box	Interval	Description
18	155.1-163.8	Core moderately olivine-rich, with scattered coarse olivines (155.1-157.6). Segregation vein at 157.6-158.9 is underlain directly by vorb, which continues to 163.8 feet. This vorb contains abundant, very coarse olivine. The size of the olivine in the vorb decreases slightly downward, from 159.0 to 163.8.
19	163.8-172.2	Continuation of vorb to 164.1. Dense rock with moderate olivine content from 164.0-165.5. Contact between matrix and the next vorb, at 165.5, is extremely sharp. Vorb extends from 165.5 to 171.0. Coarsest olivine is again at the top, as in the vorb in the above interval. Both of these vorbs are moderately vuggy. From 171.0 to 172.2 is mostly matrix rock (moderate olivine) with small patches of vorb.
20	172.2-181.4	Olivine content moderate to high in dense fresh rock. Streaks of vorb running up the side of the core common. Coarse segregation vein at 173.6-174.0, has slightly wavy contacts.
21	181.4-190.4	Fresh olivine-rich rock. Olivines coarse. Some vorb at 188.0-189.4. Steep fractures coated with white mineral (anhydrite?) at 185.5-187.5. Small segregation at 185.0 ft.
22	190.4-199.7	Olivine-rich core, olivines locally tarnished (slight oxidation?). Olivines up to 1 cm long, uniformly distributed.
23	199.7-209.2	Fresh core. Olivine size, distribution as in above interval. Exception: two patches rich in fine-grained olivines, at ~200 feet and at 206.6. Looks like former ogb, now holocrystalline.

Petrographic Log for KI88-1 (con't)

Box	Interval	Description
24	209.7-218.4	Fresh olivine-rich core. Olivines coarse. Small irregular vuggy areas at 214.9 and 216.2. Still a few steep fractures in this interval (at 210 and 212). Patch of ogb(?) at 218.0. Mineral bloom at 209.6-210.0 = Na_2SO_4?.
25	218.4-227.2	Core olivine-rich throughout. Patches of possible ogb at 222 and 222.3. Hackly radial fractures well-developed at and below 225 feet. Some steep fractures at 223 ft.
26	227.2-236.4	Very olivine-rich core. Some ogb at 230.4-231.4, locally very vuggy. Strong radial hackly fracture throughout.
27	236.4-244.2	Very olivine-rich core, olivine content increasing downward. Fractures as in above interval.
28	244.2-253.8	Very olivine-rich, with olivine content uniform. Some very coarse olivines present. Circumferential fractures (= onion-skin fractures) begin at -247 feet.
29	253.8-263.3	Core fresh, olivine-rich. Onion-skin fractures, as in above interval. First flecks of glass seen in the field at 259.5 ft. Slightly vuggy patches (= former ogb?) present, especially between 262-263 ft.
30	263.3-271.7	Core as in above interval. Two extensive zones of olivine-rich rock, with coarser groundmass crystals, and containing glass-lined vesicles are present at 264.3-264.8 and 267.5-268.8 ft. Contacts with the normal matrix vary from irregular, mostly dipping steeply (upper zone) to subhorizontal, relatively planar (lower zone) and are sharp in both cases. These may be lower-crust vorb or ogb equivalents or (less possibly) leopard rock. This is the glassiest interval in hole KI88-1.

Petrographic Log for KI88-1 (con't)

Box	Interval	Description
31	271.7-280.5	Olivine somewhat less abundant than in the above interval. Some vertical glassy/vuggy patches present at 274.8-275.2 = lower crust expression of vorbs? Matrix still dark. Concentric fracture still present.
32	280.5-290.0	Core still has a dark matrix. Olivine content moderate to high. Irregular large vesicles present at 283.4 and 284.6. Chain (??) of olivines present at 283.8,dipping 45° across core.
33	290.0-299.2	Core mostly as in above interval. Olivine content decreases downward. The matrix gets lighter and concentric fractures are only weakly developed by 299.2 ft. Rare large vesicles present (e.g., at 295 and 297.4).
34	299.2-308.4	Olivine content moderate in this interval, passing through a minimum at 302.8-303.7 feet, and increasing both above and below. The change is gradational. Matrix is greenish-gray, very flinty-looking.
35	308.4-317.7	Olivine content moderate, with coarse olivines scattered throughout. Olivines tarnished at 315.0-316.3. Core is very dense, flinty.
36	317.7-326.2	Core matrix lighter than in preceding intervals. Hackly fractures very well-developed. First steep (80°) fracture encountered at 322.6. These are presumably the fractures of the lower colonnade propagating upward. Olivine content moderate, but slightly variable.
37	326.2-334.5	Light gray core, very dense, with moderate olivine. Both steep (60°-80°) fractures and radial hackly fractures present.

Box	Interval	Description
38	334.5-342.2	Core as in above interval to approximately 337 ft. Black olivines are present at 334.5-336.0. Below, the core is riddled with areas of somewhat coarser-grained rock, which is locally more olivine-rich than the matrix. The coarser areas are slightly more porous than the matrix. Contacts are locally sharp, but very irregular overall. The coarse-groundmass material looks like the holocrystalline equivalent of the layers present at 264-268 feet. That is, the coarser matrix tends to occur in spots, giving the rock a mottled appearance. Holocrystalline leopard rock?
39	342.2-350.8	Core as in the 337-342 interval. Intervals with more and/or coarser olivine, and a coarser and more porous groundmass occur within a finer-grained, flinty matrix. Contacts locally irregular, but sometimes planar and parallel, even though steeply dipping. Olivines locally tarnished/ blackened. Foundered crust, almost certainly.
40	350.8-360.3	Core as in above interval, except that the olivine content is higher and the groundmass in the anomalous areas is even coarser-grained. Contacts steep to vertical, and less planar than in above interval. Olivines locally tarnished. Hackly fracture still present, but more weakly developed than above.
41	360.3-368.9	Core to 362 as in above intervals. Below -362, the core is dense, flinty rock, with moderate olivine content. Steep fractures have red, oxidized surfaces throughout this interval. Hackly fracture still present, but less well developed than in above interval.

Petrographic Log for KI88-1 (con't)

Box	Interval	Description
42	368.9-375.9	Core as in above interval. Radial hackly fracture gone by 369-369.5. Deepest core is dense, flinty, oxidized, with moderately abundant coarse olivines. There is no sign we are near the lower contact of the lake.

Core Recovery Log for KI88-2

Date	Interval drilled (in feet)	Core recovered (in feet)	Percent recovery
11/23/88	0.0- 4.9	0*	0%
	4.9- 9.7	4.8	100
	9.7-14.9	5.2	100
	14.9-17.3	2.4	100
	17.3-22.1	4.8	100
	22.1-27.0	4.9	100
	27.0-28.3	1.3	100
	28.3-31.9	3.6	100
	31.9-35.7	3.8	100
	35.7-40.9	5.2	100
	40.9-42.7	1.8	100
11/24/88	42.7-47.2	4.5	100
	47.2-52.4	5.2	100
	52.4-57.4	5.0	100
	57.4-62.8	5.4	100
	62.8-67.8	5.0	100
	67.8-70.5	2.7	100
	70.5-75.0	4.5	100
	75.0-77.9	2.9	100
	77.9-83.0	5.1	100
11/25/88	83.0-87.9	4.9	100
	87.9- 93.0	5.1	100
	93.0-97.9	4.9	100
	97.9-102.9	5.0	100
	102.9-107.6	4.7	100
	107.6-112.9	5.3	100
	112.9-117.2	4.3	100
	117.2-120.7	3.5	100
	121.7-122.5	1.8	100
11/28/88	122.5-125.5	3.0	100
	125.5-127.5	2.0	100
	127.5-130.6	3.1	100
	130.6-132.4	1.8	100
	132.4-137.4	5.0	100
	137.4-141.8	4.4	100
	141.8-144.5	2.7	100
	144.5-147.2	2.7	100
	147.2-152.2	5.0	100
	152.2-157.2	5.0	100
	157.2-162.5	5.3	100
	162.5-165.8	3.3	100

Core Recovery Log for KI88-2

Date	Interval drilled (in feet)	Core recovered (in feet)	Percent recovery
12/1/88	165.8-167.5	1.7	100
	167.5-167.8	0.3	100
	167.8-172.8	5.0	100
	172.8-177.5	4.7	100
	177.5-181.1	3.6	100
	181.1-183.3	1.6 (0.6 gap)	73
	183.3-187.0	3.7	100
	187.0-192.0	5.0	100
12/2/88	192.0-197.0	5.0	100
	197.0-202.2	5.2	100
	202.2-207.4	5.2	100
	207.4-212.4	5.0	100
	212.4-217.5	5.1	100
	217.5-222.5	5.0	100
	222.5-226.2	3.7	100
12/6/88	226.2-227.5	1.3	100
	227.5-232.9	5.2	100
	232.7-237.4	4.7	100
	237.4-242.6	5.2	100
12/7/88	242.6-247.6	5.0	100
	247.6-252.8	5.2	100
	252.8-257.7	4.9	100
	257.7-263.0	5.3	100
	263.0-267.8	4.8	100
	267.8-272.8	5.0	100
	272.8-277.8	5.0	100
	277.8-282.8	5.0	100
12/8/88	282.8-287.6	4.8	100
	287.6-292.7	5.1	100
12/8 12/9 12/12 12/13	Reamed out hole KI88-2 with an oversized BQ bit to 292.7 feet		

Core Recovery Log for KI88-2 (con't)

Date	Interval drilled (in feet)	Core recovered (in feet)	Percent recovery
12/13/88	292.7-297.7	5.0	100
	297.7-302.7	5.0	100
	302.7-307.6	4.9	100
	307.6-312.8	5.2	100
	312.8-317.7	4.9	100
	317.7-322.6	4.9	100
	322.6-327.9	5.3	100
12/14/88	327.9-332.6	4.9	100
	332.6-337.3	4.8	100
	337.3-342.2	4.9	100
	342.2-347.4	5.2	100
	347.4-352.4	5.0	100
	352.4-354.9	2.5	100
12/15/88	354.9-355.1	0.2	100
	355.1-356.6	1.5	100
	356.6-356.8	0.2	100

End of hole

*Rock bit used between 0 and 4.9 feet. No core recovered.

Petrographic Log for KI88-2

Box	Interval	Description
1	0.0- 14.6	No core 0.0-4.9 feet. Core is oxidized, highly vesicular throughout, except for a somewhat denser layer at 8.4-8.7 feet. Olivine content moderate to high. Small segregations at 9.5 and 9.6 ft.
2	14.6- 23.8	Core oxidized to 15.3 ft., fresher below. Dense layers at 15.3 and 17.0-17.2. Spotted rock locally present between 16 and 17 feet. Minor segregations at 17.4 and 23.3-23.7. Core in between these two segregations is vesicular with moderate to high olivine content; it is all quite vesicular, but the size of the vesicles varies.
3	23.8- 33.3	Fresh, vesicular core with moderate to high olivine content. Some very coarse olivine present (at 27.7 ft.). Segregation at 26.3-26.7 ft. Vesicles somewhat flattened below 31 feet.
4	33.3- 42.4	Core is fresh, vesicular, olivine-rich. Minor segregations at 36.0, 37.0, 37.4, 38.0, 38.1, 38.8, 39.1-39.9, 41.9. Their contact geometry is very variable. Vesicles locally flattened (33-38 ft.). In lower part of interval (40-42) the vesicles are frosted with vuggy segregation material.
5	42.4- 51.7	Upper 0.1 ft. of interval continues as above. At 42.5 ft the rock changes abruptly to denser, fresh rock with moderate to sparse olivine. Coarse olivine sporadically present. Flattened vesicles locally present (42-49 feet). Segregations at 42.7-42.9 and 45.4. Vesicle plume, quite vuggy, at 49.1-49.7 ft.
6	51.7- 60.9	Core is fresh, finely vesicular with sparse olivine phenocrysts. Rare segregation veinlets present. Vuggy vesicle plume at 60.1-60.9 ft.

Box	Interval	Description
7	60.9- 70.5	Core as in above interval. The vesicle plume present at 60.1-60.9 ft. extends to 62.4 ft., and locally includes coarse olivines. It appears to be equivalent to a vorb. Segregations present at 63.2-63.3, 69.0-69.7 ft.
8	70.5- 79.9	Fresh, gray, finely vesicular core, with sparse, small olivines. Segregations present at 75.7-77.8 and 79.5-79.7 feet.
9	79.9- 89.0	Core as in above interval. Segregation vein (internally differentiated) at 86.2-88.2 ft. Vesicles ± segregation material rising off this vein (?) present at 85.4-86.2. Large empty vesicles at 84.3 (one) and 85.0 (a cluster). These larger vesicles may be derived from the large segregation as well.
10	89.0- 98.0	Core is fresh, gray, with sparse small olivines, and is finely vesicular throughout this interval. Segregations at 91.8-92.0, 95.9, 96.2-96.3 ft.
11	98.0-107.6	Matrix rock is fresh, gray with sparse, small olivines. Vesicle size decreases to diktytaxitic by 105 feet. Segregations present at 99.3-100.0 and 106.9-107.6, both exceptionally vuggy. There is a large empty vesicle at 104.9 ft.
12	107.6-117.2	Matrix rock diktytaxitic, with olivine rare. Segregation veins dominate this interval, being present at: 107.6-110.0, 111.9 (60°), 112.3 (30°), and 114.2-117.2 ft.
13	117.2-125.2	Matrix denser than in above interval. Olivine rare. Core broken by extensive steep fractures. Segregation at 121.0-123.4 ft., plus minor segregation stringers.
14	125.2-134.2	Core as in above interval: dense, much-fractured, olivine-poor. Segregations at: 126.6-128.0, 131.9-132.2 and 133.6-134.2. The vein at 132.2 has some very coarse (1 cm long) black lathy mineral (mqanganese oxide?) present either in the vein or on the fracture surface.

Petrographic Log for KI88-2 (con't)

Box	Interval	Description
15	134.2-143.0	Core as in above interval to 140.4 ft. Below 140.4, the olivine content increases, though the olivines are all small. Segregations at: 134.2-135.6 (continued from above) and at 139.4-140.4. Fracture in segregation at 140.3 has same coarse black, bladed mineral seen at 132.2
16	143.0-152.2	Fresh gray rock, with abundant small olivines. Many vorb patches, most having small olivines only. Segregations at 143.0, 148.7-151.0. Upper contact of the big vein is very irregular. It is directly underlain by vorb.
17	152.2-161.2	Olivine content, grain size somewhat higher than in above interval. Vorb material more abundant. The size of olivines in vorb and in adjacent matrix continues to be correlated closely, as in the above interval. One segregation at 156.5-158.1. This has an extremely irregular upper contact, with segregation stringers present from 153.4-156.5; these are probably derived from the main vein.
18	161.2-170.2	Olivine content, grain size continue to increase gradually. Vorbs present, though less abundant than in overlying interval. No segregation veins.
19	170.2-179.4	Olivine conspicuously coarser than in overlying intervals, in matrix and vorbs alike. Vorb present only locally (especially at 170.5-171.0 and 178.0-179.4). Segregations at 173.5-173.6, 175.0, and 177.5-178.0.
20	179.4-189.0	Core very fresh, with coarse olivines. Vorb present, especially at 179.4-180.5. This was partially molten in 1981. The lower part of this interval (182-189.0) contains abundant Na_2SO_4, evident as a whitish bloom on the core. One minor segregation at 187.0
21	189.0-197.7	Core fresh, olivine-rich. Mineral (Na_2SO_4) bloom extends to 191 feet. Core dry, bloom-free below that. Little vorb, no segregation material.

Petrographic Log for KI88-2 (con't)

Box	Interval	Description
22	197.7-206.9	Fresh gray olivine-rich core. Conspicuous patches of formerly melt-rich vorb (that failed to unmix) extend from 202.6 to 206.3. Was this vorb prematurely quenched by the heat-extraction experiment carried out in 1981 in adjacent hole KI81-4?
23	206.9-215.8	Fresh, olivine-rich core. Local patches of vorb/ogb at 207.4, 208.1, 213.4. Minor segregation at 217.6. Steep to vertical fracture present from 210-211.7, coated with whitish mineral (not water-soluble Na_2SO_4). Core immediately below (211.7-212.4) has Na_2SO_4 bloom.
24	215.8-224.4	Very olivine-rich rock. Olivine distribution uniform. Crystallized ogb patch with unusually coarse olivine (0.5 x 1.0 cm) at 219.5. One steep fracture at 222 ft.
25	224.4-233.6	Very olivine-rich core. Minor ogb (crystallized) at 230.7, 232.8. Olivine uniformly distributed otherwise. Hackly fractures well-developed by 230.9 feet.
26	233.6-243.0	Friable, olivine-rich core. Olivine content somewhat variable, with less olivine at 238.8-239.4 and 240.8-241.4. Onion-skin (circumferential) fracture well-developed by 240 feet. Matrix dark gray = interstitial melt is present.
27	243.0-252.5	Extremely olivine-rich core with dark gray matrix, onion-skin fracture. Patches of ogb at 245.4-245.6 and at 248.7-248.9 on the side of the core. Rock otherwise uniform in this interval.
28	252.5-261.9	Core as in above interval. Very coarse olivine locally present. One interval of slightly coarser-grained, more olivine-rich, vuggier, "speckled" rock at 257.6-259.7. Melt blebs are small, sharp-edged; upper contact flat, lower dips 30°. Top of drilling interval at 258.0 is dark, flinty, devitrified, as in hot-zone core recovered in 1981.

Petrographic Log for KI88-2 (con't)

Box	Interval	Description
29	261.9-271.1	Olivine-rich core, with black glassy matrix. Onion-skin fracture present throughout. Minor "speckled" rock at 265.0, 269.9 (with larger pools of glass) and 271.1. Some very coarse olivines present.
30	271.1-280.3	Olivine-rich core, with black glassy matrix. Olivine content somewhat lower than in the overlying intervals (Boxes 27-29). Extensive "speckled" rock present, at: 271.1-272.8 (in patches running up the side of the core), 274.8 (small patch on side), 275.3 (ditto), 276.7-277.1 (dipping 70°), 277.5-277.7 (on side), and 279.0-280.0 (pervasively present, with irregular, near-vertical contacts). Contact relations strongly reminiscent of vorbs. Glass "blebs" all small (≤ 1 mm) and sharp-edged. "Speckled" rock is generally more olivine-rich than the adjacent matrix. Top of drilling intervals is dark gray, flinty, devitrified as in overlying intervals.
31	280.3-289.4	Core matrix black, changing to dark gray by 289.4 feet. Onion-skin fracture present throughout. Matrix rock olivine-rich (slightly more so than in Box 30). "Speckled" rock present at: 281.0, 281.8 (dipping 45°-60°), 284.1-284.5 (dipping 30°-70°, upper contact complex) and 285.3-286.3 (lower contact flat, upper steep). In the two deeper intervals, near their upper contacts, there appear to be <u>two</u> different generations of "speckled" rock, one almost crystalline, the other with larger, fresher melt blebs. The sharper (= newer?) the melt blebs, the finer-grained the groundmass. Where they are fuzzier, the groundmass is coarser. Does invasion of glass blebs coarsen the groundmass? Open gas cavities present at 282.0 feet.

Petrographic Log for KI88-2 (con't)

Box	Interval	Description
32	289.4-298.7	Core matrix dark gray, with well-developed onion-skin fracture. Olivine content starts high, decreases to 297.7 and then increases slightly to 298.7. Exterior of core smooth, light-colored. Some olivines, especially for 296.5-298.7, are very pale, so the decrease in olivine is not as marked as it looks at first glance. There is no "speckled" rock in this interval, nor are there any patches of coarser groundmass.
33	298.7-307.6	Upper part of this interval (298.7-301.6) mostly similar to core at 296-298.7: smooth, light surface, olivine content moderate, with a few coarse olivines present. Below that the olivine content increases again. The onion-skin fractures, still well-developed at 298.7-301.4 are only weakly developed by 307.6 feet. "Speckled" rock present at 299.0-300.0 (very small, sharp blebs in broken-up core). There is a layer at 301.7-302.5 which contains large (0.5-1 cm) ameboid pools of glass. These are slightly fuzzy-edged (= incipient crystallization) but occur within a generally fine-grained groundmass. Recent invaders? Leopard rock? Similar ameboid spots occur at 303.2-303.9, but are more crystallized, and in a coarser groundmass. Other "speckled" glass patches are pervasive from 305.5 to 307.6, some very olivine-rich matrix. In general, the less melt left, the coarser the groundmass.
34	307.6-317.5	Upper section (307.6-312.5) as in above interval: very coarse, very olivine-rich, with local smears of vuggy, segregation-vein-like material. Contacts with matrix (where evident) steep to vertical and always irregular. Below 312.5, olivine content, frequency of coarse patches decreases steadily. Lowermost section (315.5-317.5) is dense, flinty rock with sparse olivine phenocrysts. Some blackened olivines present. Core at 317.5 contains steep contact between flinty matrix and rock that looks like olivine-poor vorb(?) Onion-skin fracture is gone.

Petrographic Log for KI88-2 (con't)

Box	Interval	Description
35	317.5-326.2	Core initially olivine-poor, very dense and flinty, with a dark greenish-gray matrix. Olivine content increases downward. At 321.3-322.1 there is a layer of mottled rock that looks like the holocrystalline equivalent of the ameboid-spotted rock present between 301.7 and 302.5 ft. From 322.1-326.2 the core alternates between denser, finer-grained rock and coarser, more olivine-rich mottled rock. Minor glass still present, especially conspicuous in the mottled rock. Foundered crust? Nearly-crystalline leopard rock?
36	326.2-335.2	Top of interval still glassy, but rock is holocrystalline by 335.2 ft. Olivine content moderate. Minor vuggy segregation vein atchesat 328.2 and 328.7, associated with "mottled rock" layer. More segregation stringers between 333.7 and 335.2, overlain by several large empty vesicles (from 330.2-333.7). Hackly fracture present throughout.
37	335.2-344.4	Dense flinty core, olivine content moderate, increasing slightly downward. Vuggy segregation present at 335.6-335.9 (irregular form). Coarse layer of mottled rock, present at 340.1-341.6, is much more olivine-rich than matrix.
38	344.4-353.7	Dense flinty core, with olivine content higher than in preceding intervals (Boxes 35-37). Former "speckled" rock at 345.6-346.9, associated with minor segregations (345.5 and 346.5). First vertical fracture encountered at 348.8 feet. Fracture coated with glass. Core extremely broken-up from that depth on. Extreme hackly fracture.
39	353.7-356.8	Dense, flinty core, in sharply angular fragments. Olivine content moderate throughout. Strong hackly fracture prevented drilling beyond this point.

Petrographic Notes on Ooze Recovered During Redrilling of KI79-1

Depth of recovery (feet)	Description of core
First re-entry	
166.8-167.0	Greasy mess. Core is vesicular, has olivine phenocrysts.
167.0-168.4	Olivine-poor layer, partially devitrified. Lower contact is sharp.
168.4-170.0	Coherent core, olivine moderately abundant. Some glass-rich blebs present, in more crystalline matrix.
170.0-170.1	Olivine-poor septum, with plagioclase microphenocrysts.
170.1-170.25±	Thin septum of core with moderate olivine content.
170.25-171.8	Glassy core, olivine-poor. Exterior surface is finely corrugated. No plag microphenocrysts or other large crystals visible. Has sharp lower contact which dips at 45°.
171.8-172.7	Coherent interval of core with moderate olivine content. Contains irregular blebs of nearly 100% glass in more crystalline matrix.
172.7-172.8	Glassy, olivine-poor interval (like 170.25-171.8).
172.8-175.0	Glassy olivine-rich core. Contains irregular glass blebs in more crystal-rich matrix. Continuous glassy partings at 173.3 and 173.7.
175.0-175.4	Less glassy (?) core, with smooth exterior surface. Contains some large (0.5-1.0 cm) olivines. Discrete glass blebs still present.
175.4-176.0	As above, but with more olivine. The olivines appear to be aligned vertically in places. Glass blebs are small to absent.
176.0-176.8	Coherent, olivine-rich core. Surface is slightly corrugated, in contrast to all of the above core, which has a smooth surface (except for the glassiest layers).

Second re-entry

172.9-173.0 Olivine-rich core with a smooth gray surface.

173.9-176.4 Uniformly more olivine-rich than above interval. Surface of core is finely corrugated.

176.4-178.0 Olivine-rich, as in above interval. The core surface has coarse corrugations, and the core has concentric (onion skin) fractures. There are places where the core appears to have been pulled apart as it moved up into the core barrel. In places the core contains a large, rough-surfaced interior void. (Significance uncertain).

Third re-entry

172.9-178.4 Core is very olivine-rich, more so than at the top of re-entry #2. It becomes slightly less olivine-rich with increasing depth in this interval. The core right at 173.8 is exceptionally rich in coarse olivines.

178.4-181.0 Alternating bands of relatively smooth-surfaced and heavily corrugated core. All extremely olivine-rich.

181.0-181.4 (?) There is 1.8 feet of core, though the recorded depth of the drill bit was 181.4. (Field notes suggest core was oozing up inside the core barrel). Mostly very rough-surfaced, with stretched, twisted appearance. Glass filaments on surface.

Fourth re-entry

This core was recovered at a later date. Dates and depth of recovery unknown. The core is all olivine-rich, in a flinty, devitrified matrix. Ooze redrilled to emplace M.P. Ryan's penetrometer experiment?