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Shipboard Report For Hawaii GLORIA Ground-Truth Cruise F2-88-HW, 25 Feb.-9 March, 1988

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SCIENTIFIC SUMMARY

Principal results of Hawaii Ground-Truth Cruise F2-88-HW include:

Kilauea East Rift Flows: Highly reflective large flows in the Hawaiian Trough, first imaged by GLORIA, were confirmed as lava flows by sea floor photography and dredging. The flows commonly have pillowed margins and flat or wrinkled axial surfaces. Sampled flows include aphyric and picritic basalt. One flow having no visible palagonite is probably historic.

Hawaiian Arch Lava Field: An apparently young lava field 100 nm south of Hawaii Island, first identified on GLORIA images, was sampled and photographed. Much of this field, which may represent precursory leakage of melt from the Hawaiian hotspot, is a large and remarkably flat flow of ponded sparsely plagioclase-phyric basalt.

Sediment Penetration by GLORIA: Photography, dredging, and coring indicate that GLORIA sonograms can yield high backscatter on both bare basalt and flows covered by a meter or more of sandy and silty sediment.

Submerged Reefs: Dredging confirmed the occurrence of deeply submerged coral terraces imaged by GLORIA on the Kohala platform and the east rift of Haleakala volcano. Isotopic ages of coral samples from as deep as 2100 m will constrain the timing of submergence and volcanism.

Deep Samples, Hawaiian Rift Zones: Samples dredged from as deep as 3500 m from rift zones of Hualalai, Mahukona, and Haleakala will constrain the poorly known petrologic evolution and ages of early tholeiitic shield-building stages for these volcanoes.

Turbidites in the Hawaiian Trough: Coring demonstrates that graded basaltic sands and silts are widespread in the Hawaiian Trough and correlate with broad changes on GLORIA and 3.5 kHz records. The turbidite deposits probably record gravitational failure of shallow-water eruptive deposits and deep-water landslides off the steep island flanks.

Introduction

This cruise was the first Hawaii ground-truth cruise following two GLORIA imaging cruises in October and November 1986 (F5-86-HW and F6-86-HW), and it is to be followed by four additional imaging cruises around the leeward islands of the Hawaiian chain in March-June 1988. This cruise circumnavigated the Island of Hawaii in a clockwise direction, using the town of Hilo as its port of call (Fig. 1). Forty-five stations were occupied during the cruise including 37 dredge stations, 5 box core stations, and 3 camera stations (Table 1). The GLORIA mosaics provide a regional base map, analogous to high-altitude air photos for on-land studies, which we used to focus on key areas for detailed study.

The cruise was intended to focus primarily on recent volcanic features; later work was planned for the sediments and Cretaceous sea floor and seamounts farther offshore. Major targets included : (1) the large lava flows imaged by GLORIA adjacent to the lower east rift zone (Puna Ridge) of Kilauea Volcano, that are inferred to record rapid draining and caldera collapse at the summit of the volcano; (2) an apparently youthful lava field that blankets Cretaceous seafloor along the Hawaiian Arch 100 nm south of Hawaii Island that might record unusual petrologic processes; (3) the physical character of sediments of contrasting acoustical transparency on 3.5 kHz records and backscatter brightness on GLORIA images in relation to possible turbidite aprons associated with large debris slides from the Hawaiian Ridge; (4) petrologic variations of the under-water Mahukona volcano, west of Kohala; (5) petrologic variations among basalts from low on the rifts of Hualalai and Haleakala volcanoes; and (6) verification of deeply submerged coral reefs imaged by GLORIA on the Kohala platform and Haleakala east rift, and sampling for age determinations. The final section of this report outlines some remaining problems and recommendations for future work.

Operations and Equipment

R/V FARNELLA departed Hilo at 1900Z on February 25 (Table 2) and proceeded ENE, toward the northwest end of the large lava flows from the Puna Ridge in the Hawaiian Trough. Progress was slowed when the 3.5 kHz towfish failed on launch and had to be replaced by the backup. At the same time the main winch-wire had to be respooled, and some problems were found with the level-wind; about 8 hours were lost to deploying the towfish, repair, and respooling. The backup 3.5 kHz fish failed during routine survey on the fourth day of the cruise, and was inoperative for 3 days during repair.

The GPS system worked well and provided about 12 hours per day of navigation. The rho-rho LORAN also worked well, except close to the baseline between the master and station X and north of the islands, which shadowed the master station. These difficulties caused two semi-aborted dredge attempts and periods of confusion. Another navigational problem was communicating with the bridge, especially when we wanted to go to an endpoint from our present position rather than from some predetermined location in the computer. Also, if we drifted away from the endpoint of a

Figure 1. Index map showing ship track and stations

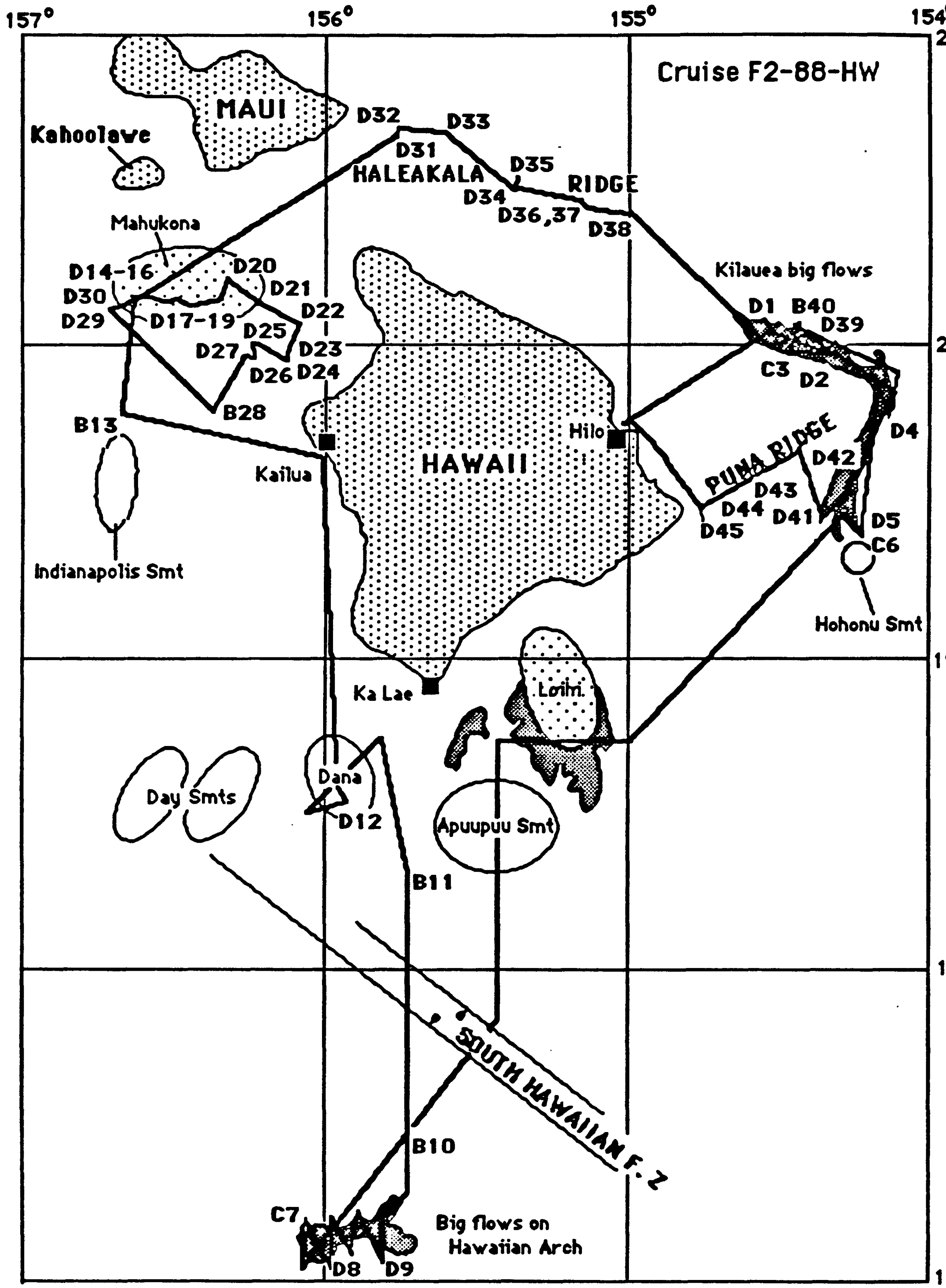


Table 1: DREDGE, CAMERA, AND BOX CORE STATIONS

HAWAII FARNELLA CRUISE (F2-88-HW), FEB. 25-MAR. 9, 1988

Sta.	Loc.	Depth, m	N. Lat.	W. Long	Type	Description
D1	ERZ Kil	S 5550 E 5535	20°04.1 20°03.5'	154°36.1' 154°37.6'	Dredge 0 kg	0.5 kg buff mud in sock, dents in dredge.
D2	ERZ Kil	S 5475 E 5480	19°58.7' 20°00.5'	154°19.2' 154°18.9'	Dredge 0 kg	0.1 kg buff mud in sock; glassy fine sand.
C3	ERZ Kil	S 5480 E 5503	19°56.4' 20°00.9'	154°26.1' 154°25.9'	Camera	Mainly sed on "flow"; pillow frag. on slope.
D4	ERZ Kil	S 5460 E 5475	19°48.2' 19°51.0'	154°08.6' 154°07.9'	Dredge 150 kg	Ol-rich, glassy lava; lobate &sheet flows; some palagonite.
D5	ERZ Kil	S 5485 E 5500	19°26.2' 19°27.7'	154°16.0' 154°16.7'	Dredge 50 kg	Pillow and sheet flow frag. some palagonite.
C6	ERZ Kil	S 5505 E 5515	19°26.2' 19°29.3'	154°16.0' 154°17.3'	Camera	Cross lava flow with pillow & wrinkled sheet flows.- 10-30 cm sed.
C7	Arch Lava	S 4945 E 4970	17°10.1' 17°14.1'	156°00.1' 156°00.2'	Camera	Ponded lava with pillow & wrinkled sheet flows, 5-15 cm sed.
D8	Arch Lava	S 4945 E 4940	17°09.3' 17°11.0'	156°00.3' 156°00.2'	Dredge 100 kg	pillow frag. of aphyric basalt with thick palagonite
D9	Arch Lava	S 4910 E 4920	17°12.2' 17°13.2'	155°51.8' 155°52.4'	Dredge 75 kg	Wrinkled sheet flow aphyric basalt; 40 microns palag. ?
B10	Haw Arch	4881	17°27.4'	155°49.2'	Box core	Full box, light brown soupy mud.
B11	H. Trough	4938	18°16.7'	155°48.9'	Box core	Full box, brown mud with 4 layers of black glassy sand.
D12	Dana Smt	S 2950 E 2490	18°37.4' 18°39.0'	155°58.2' 155°58.2'	Dredge 10 kg	Weathered, vesicular basalt; phosphorite.
B13	Alika Slide	4780	19°49.6'	156°40.2'	Box core	Full box of medium brown finely laminated mud, silty interbeds
D14	Mahukona W ridge	S 3105 E 2980	20°07.2' 20°08.0'	156°39.1' 156°38.5'	Dredge 0 kg	Empty

Sta.	Loc.	Depth, m	N. Lat.	W. Long	Type	Description
D15	Mahukona W ridge	S 3125 E 3050	20°07.3' 20°08.1'	156°39.3' 156°39.4'	Dredge 0 kg	7 ton hangup, but empty
D16	Mahukona W ridge	S 2715 E 2605	20°09.6' 20°10.5'	156°34.3' 156°33.5'	Dredge 2 kg	picritic sheet and pillow fragments, thick palagonite and 2 mm Mn
D17	Mahukona W ridge	S 2215 E 1920	20°10.5' 20°11.3'	156°29.9' 156°29.0'	Dredge 3 kg	small glass fragments of aphyric to sparsely olivine phyric sheetflows
D18	Mahukona Summit	S 1500 E 1345	20°09.1 20°09.6	156°25.9 156°25.6	Dredge 40 kg	Palagonitized pillow frag. sponge fragments
D19	Mahukona E ridge	S 1415 E 1305	20°07.1 20°08.3	156°20.5 156°20.4	Dredge 100 kg	Palagonitized pillow fragments of picrite
D20	Kohala Platform	S 1425 E 1315	20°09.1 20°10.2	156°19.0 156°18.3	Dredge 1 kg	Mn-crusted sparsely olivine phyric pillows, glass and foram sand
D21	1100m Reef	S 1222 E 1060	20°06.6' 20°07.3'	156°13.2' 156°12.7	Dredge 75 kg	Mn-crusted ves picrite, coral, & volcaniclastite.
D22	900m Reef	S 1165 E 1090	20°01.3' 20°02.1'	156°07.2' 156°06.7'	Dredge 300 kg	Dense ol-rich pillow basalt, hyaloclastite
D23	900m Reef	S 1150 E 1175	19°59.1' 19°59.3'	156°08.5' 156°08.3'	Dredge 12 kg	Both dense and vesicular basalt fragments
D24	900m Reef	S 1160 E 1175	19°57.6' 19°57.5'	156°08.3' 156°07.6'	Dredge 100 kg	Dense, bread-crusted pillow-like masses.
D25	Break in slope at 1300m	S 1400 E 1325	20°01.9' 20°02.2	156°17.0' 156°16.7'	Dredge 10 kg	Coquina, basalt fragments, in basaltic sand matrix
D26	Hualalai NW rift	S 2360 E 2300	19°55.6' 19°56.7'	156°18.3' 156°18.1'	Dredge 25 kg	Pillow fragments of glassy picritic tholeiite
D27	Hualalai NW Rift	S 2740 E 2625	19°55.8' 19°56.4'	156°20.1' 156°19.9'	Dredge 20 kg	Pillow fragments of glassy picritic tholeiite with more Mn than D26
B28	Alika Slide	4720	19°43.6'	156°24.1'	Box core	3 thick layers graded(?) buff mud with 2 thin graded, glassy, layers.
D29	Mahukona W ridge	S 3700 E 3440	20°06.9' 20°08.9'	156°41.2 156°41.9	Dredge 0.5 kg	100 kg mud with small, glassy crusts. MnO,3/4 mm; palagonite,1/4 mm

Sta.	Loc.	Depth, m	N. Lat.	W. Long	Type	Description
D30	Mahukona W ridge	S 2925 E 3100	20°08.9' 20°09.1'	156°38.5' 156°38.5'	Dredge 25 g	Two chips of olivine-rich glass w/palagonite and Mn, 1 kg foram sand.
D31	Haleakala E ridge	S 1720 E 1690	20°38.5' 20°39.1'	155°43.8' 155°42.2'	Dredge 0 kg	Empty; 1 kg sand in sock
D32	Haleakala E ridge	S 1705 E 1555	20°38.8' 20°40.7	155°44.0' 155°44.5'	Dredge 200 kg	Calcareous silt-sand, coral, beach rock.
D33	Haleakala E ridge	S 1750 E 1745	20°40.3' 20°39.7'	155°37.6 155°36.6	Dredge 0 kg	Empty; 1 kg sand in sock.
D34	Haleakala E ridge	S 2460 E 2160	20°32.6' 20°32.7'	155°20.05' 155°19.8'	Dredge 10 kg	Mn-encrusted and cemented hyaloclastite. Several frag. of vesicular basalt.
D35	Haleakala E ridge	S 2410 E 2250	20°32.2 20°32.5'	155°19.1' 155°19.1'	Dredge 7 kg	Mn-crusted basalt fragments, in hyaloclastite
D36	Haleakala E ridge	S 3670 E 3280	20°28.9' 20°29.9'	155°01.8' 155°01.8	Dredge 20 g	Glassy basalt rind, 1 mm Mn; 1/4 mm palagonite.
D37	Haleakala E ridge	S 3255 E 3055	20°29.4' 20°27.5'	155°03.3' 155°02.6'	Dredge 0 kg	2 g silty sand; forams & Mn
D38	Haleakala E ridge	S 3900 E 3885	20°26.5' 20°29.0'	155°00.6 155°00.7	Dredge 0 kg	1 g silty sand: forams & Mn
D39	Kilauea ERZ	S 5490 E 5480	19°59.8' 20°01.1'	154°22.9' 154°22.5'	Dredge 0.5 kg	Indurated mudstone with glass, forams, diatoms.
B40	Kilauea ERZ	5501	19°59.4'	154°26.4'	Box core	Brown mud with 6 graded glassy sand layers.
D41	Kilauea ERZ	S 5540 E 5400	19°23.7 19°30.7	154°21.4 15 4°21.2	Dredge 250 g	Aphyric basalt, no palagon. No mud in sock
D42	Kilauea ERZ	S 2375 E 2095	19°39.8' 19°40.3'	154°29.7' 154°30.1'	Dredge 150 kg	Pillow lava, several ages and several lithologies
D43	Kilauea ERZ	S 2060 E 1610	19°36.8' 19°37.3'	154°36.0' 154°36.5'	Dredge 40 kg	Pillow lava, 10 % olivine, 2 % vesicles; 2 flows?
D44	Kilauea ERZ	S 895 E 1015	19°36.8' 19°34.2'	154°36.0' 154°41.8'	Dredge 0 g	Empty
D45	Kilauea ERZ	S 765 E 715	19°32.8' 19°33.0'	154°45.3' 154°45.4'	Dredge 100 kg	Pillow basalt, 5% vesicles, sparsely olivine phyric

TABLE 2. CHRONOLOGIC LOG, F2-88-HW

JD/hr	Location, at arrival time	Stations
056/1900	Lv, Hilo Harbor	--
057/0000	Kilauea ERZ lava flows (Puna Ridge)	4D, 2C
059/2200	Loihi Seamount lava flows	G
060/0030	Apuupuu Seamount	G
060/0545	Regional graben	G
060/1145	Hawaiian Arch lava field	2D, 1C
061/1630	Ka Lae slide	2B
062/0615	Dana Seamount	1D
062/1900	Kailua port call	--
063/0000	Alika slide	1B
063/0520	Mahukona volcano	6D
064/0745	Mahukona terraces (submerged reefs)	6D
065/0235	Hualalai volcano	2D
065/0930	Alika slide	1B
065/1600	Mahukona volcano	2D
066/0800	Haleakala terraces	5D
067/0800	Haleakala east rift	3D
067/2355	Kilauea ERZ lava flows (Puna Ridge)	1B, 4D
069/1900	Ar Hilo	--

B, Box core; C, Camera station; D, Dredge station; G, Geophysical survey station, we inevitably found ourselves steaming back to the endpoint, rather than towards the next station. Such procedures are appropriate for GLORIA surveys but are inefficient for sampling cruises.

We had difficulty in changing from the main engines to the bow thrusters on several occasions and had to run two dredge stations using the main engines. The winch operated well until the wire jumped a sheave in the winchroom during dredge Station 40, which resulted in cutting off about 300 m of wire. On the final day, we lost 2 hrs on station when a winch transformer burned out, necessitating a temporary rewiring. The wire-out meter failed during station D41, and operated only intermittently during the remaining stations. Earlier in the cruise we cut off about 100 m of wire when one strand of the wire parted near where the pinger had been mounted on the previous station. The slow speed of the traction winch causes problems for station work including 1) difficulty in holding station for the long times required to lower equipment, 2) inordinant time to lower and raise equipment, particularly during stations at abyssal depths, 3) inability to pay out or pull in wire quickly limits use of the easiest method to get loose from snags.

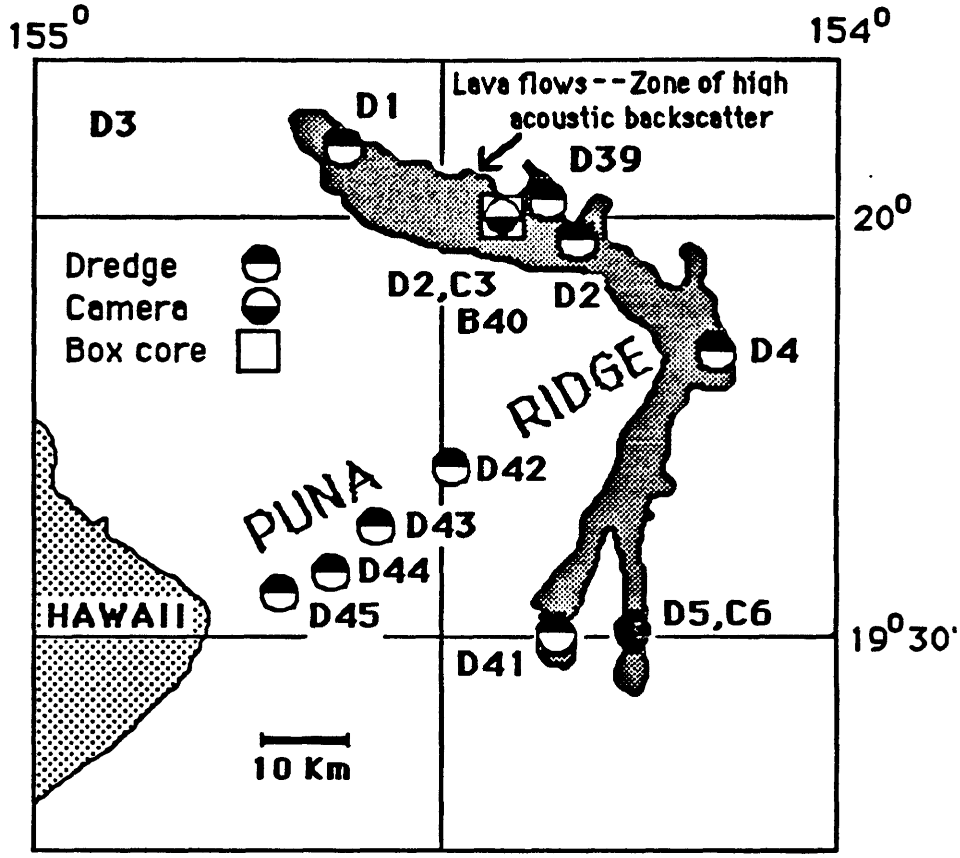
Large Flows Surrounding East End of the Puna Ridge.

Large submarine lava flows in the Hawaiian Trough , erupted from the deep submarine segment of Kilauea's east rift zone, were identified by their high backscatter and lobate outlines on the 1986 GLORIA images (Holcomb and others, 1988). Multiple flow units of differing ages are distinguished by contrasts in backscatter. This flow field extends as much as 40 nm to the west and south from the ridge terminus along the base of Hawaii Island (Fig. 2). These extensive flows appear to to be sheet flows, erupted at high discharge rates, that differ in form from pillow lavas dredged previously along shallower segments of the rift zone (Moore and Fiske, 1969). The voluminous submarine flows may be related to catastrophic eruptions associated with periodic collapse of the summit caldera of Kilauea, at intervals of centuries to millenia (Holcomb, 1986). Therefore, understanding of the age, periodicity, and volume of such eruptions is potentially significant for evaluating volcanic hazards and geothermal development at Kilauea, as well as providing new insights into the evolution of Hawaiian volcanoes.

We began work on the submarine flows at Station D1, 34 nm ENE of Hilo, on one of the darker backscatter flows imaged by GLORIA. Because of uncertainty about the strength of the wire and fear of losing expensive equipment, Station D1 was dredged without a pinger . We attempted to dredge the top of one of the older lava flows but recovered only a small sample of buff mud in the pipe-dredge. There were no strong bites, but nicks and scrapes on the blade of the dredge indicated that some hard rocks were encountered.

At Station D2, on another large lava flow about 30 km southeast of Station 1, we again tried to dredge the surface of the flow, this time with a 12 kHz pinger attached to the wire 100 m above the dredge. The pinger signal weakened with depth, and all trace was lost once the dredge hit bottom. Again, there were no strong bites, and only a small sample of dark brown mud was recovered in the pipe-dredge.

Figure 2. Stations on large lava flows around Puna Ridge



Having tested the wire up to 5 metric tons and wanting to see why no rocks were recovered in the dredge, we lowered the camera at Station C3, about 10 km northwest of Station D2. The camera station (Fig. 3 and Appendix 1) began near the base of the Mauna Kea edifice, where scattered pillows protruded from sediment, and extended northward across two bands of slightly differing high backscatter that we had interpreted as lava flows of different ages. The video recording showed that both areas were heavily sedimented; the area with higher acoustic backscatter had a sediment cover of about 90-95%, and the area with the lower acoustic backscatter was completely covered by sediment. Both areas were flat (Fig. 4); we infer that the smooth surfaces and thick sediment cover were responsible for our lack of dredging success.

While the camera batteries were being recharged, we dredged at Stations D4 and D5, located on areas of particularly bright sonar backscatter; Station D4 was near the end of the Puna Ridge, and Station D5 near the distal end of a flow extending about 50 km south from the end of the Ridge. The 3.5 kHz records were used to locate the flow margins, and the dredge was dragged up the steep margins of the lava flows from starting points on the older seafloor. For each station, the pinger was attached to the wire 300 m above the dredge. Dredging was done with the pinger only 50-150 m above the sea floor so that the dredge could bite horizontally into the flow margin. Large samples of olivine-rich basalt were recovered at both stations.

Following these successful dredges, we made a camera run (Station C6) in the area dredged for Station D5. This camera station (Fig. 5 and Appendix 2) began southeast of the flow, crossed the flow, and ended in sediment northwest of the flow. The flow consists mainly of sheet and lobate forms with pillow basalt near the flow margins. Sediment cover on this flow varied with morphology; cover was 90% over flat and folded sheet flows and 30% over pillow basalt (Fig. 6).

Returning to the Kilauea east rift area at the end of the cruise to augment the incomplete earlier results, we continued to have difficulty dredging on the north side of the Puna Ridge, in part because of the necessity to dredge on N to NE headings. We attempted to dredge the hummocky margin of a flow of intermediate backscatter (Dredge Station D 39), but recovered only weakly indurated turbidite sediment containing abundant grains of basaltic glass. The induration of this material raises the possibility that it may have been deposited on the flow surface while the flow interior was still warm and generating hydrothermal fluids.

Sediment cover on a flow lobe of slightly lower sonar backscatter, previously photographed and dredged at station D2 and C3, was then sampled (Box core station 40) to place limits on the sediment thickness. The box was overfilled (65-70 cm) with interlayered basaltic turbidites and dark yellow brown mud (Fig. 7). The sandy turbidite layers contain fragments of basaltic glass and devitrified material, presumably derived from the broad submarine valley draining Mauna Kea and Mauna Loa through Hilo Bay. Rapid sedimentation at the toe of this valley is probably largely responsible for the relatively thick sediment covering the Kilauea flows along the north base of the rift zone. This core sample demonstrates that GLORIA sonar readily penetrated more than 2/3 m of sandy sediment, still yielding a bright backscatter image of the covered lava flow.

Figure 3. Map of Camera Station C3

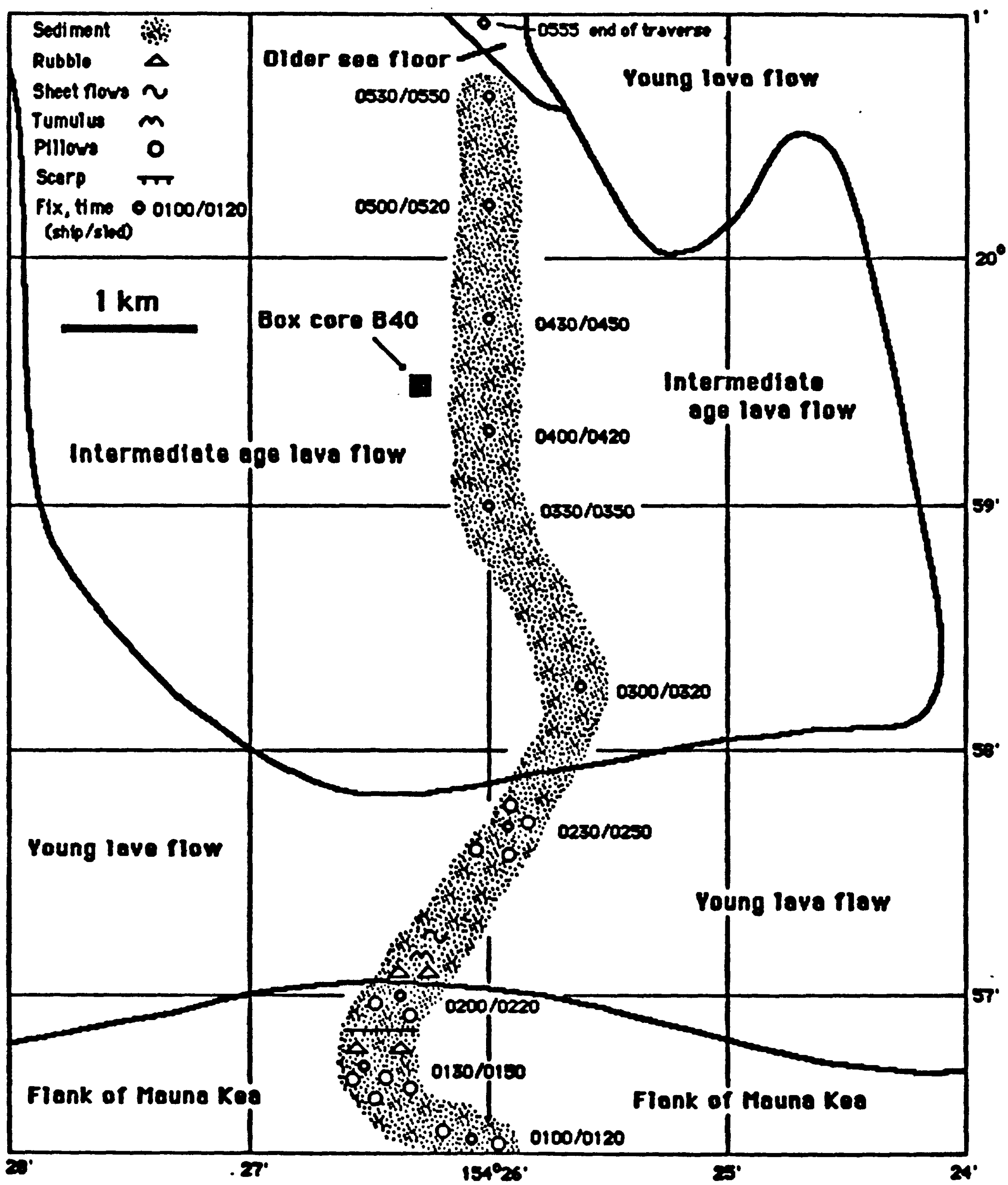
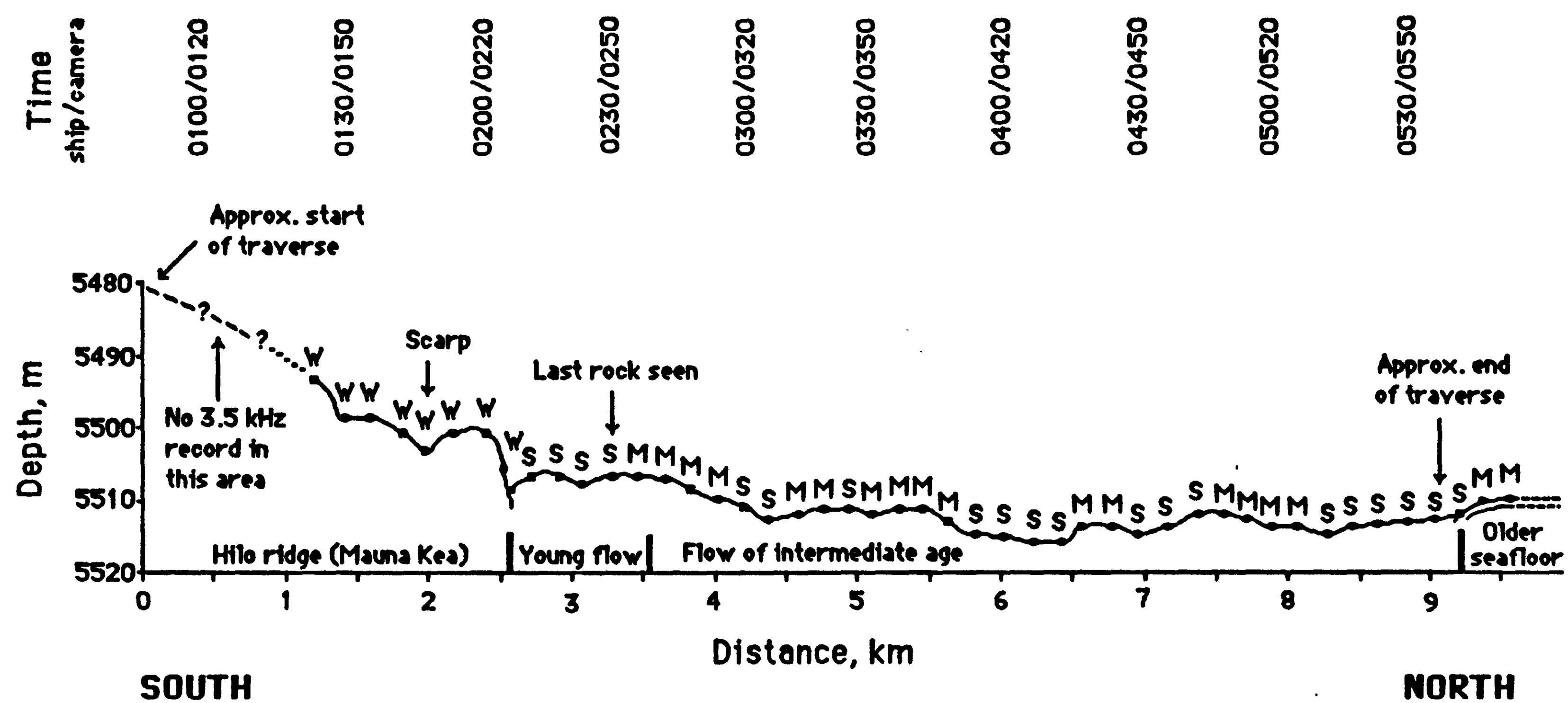


Figure 4. Profile along Camera Station C3



Vertical exaggeration = 50

Strength of 3.5 kHz reflection

W = Weak
M = Moderate
S = Strong

Figure 5. Map of Camera Station C6

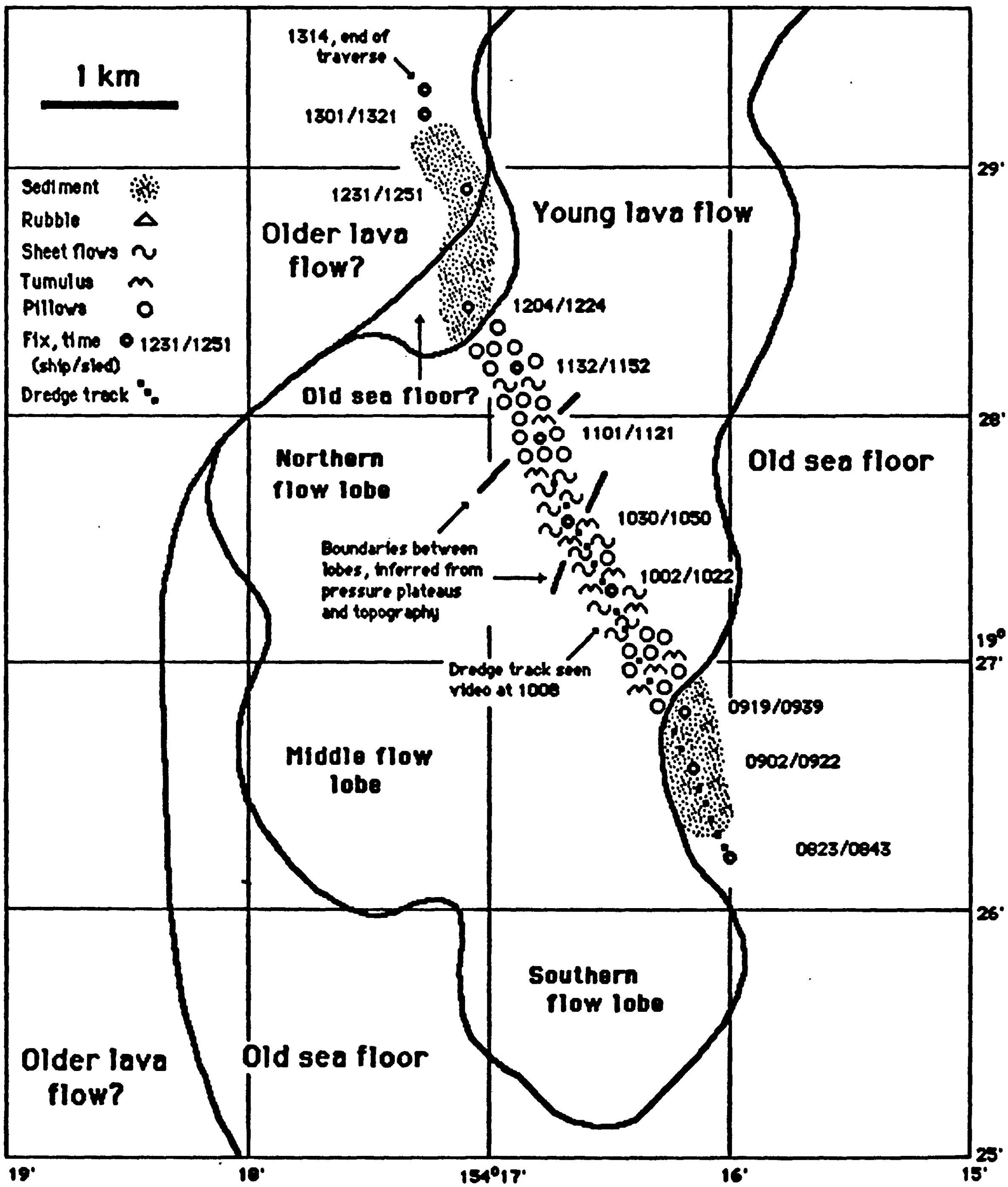
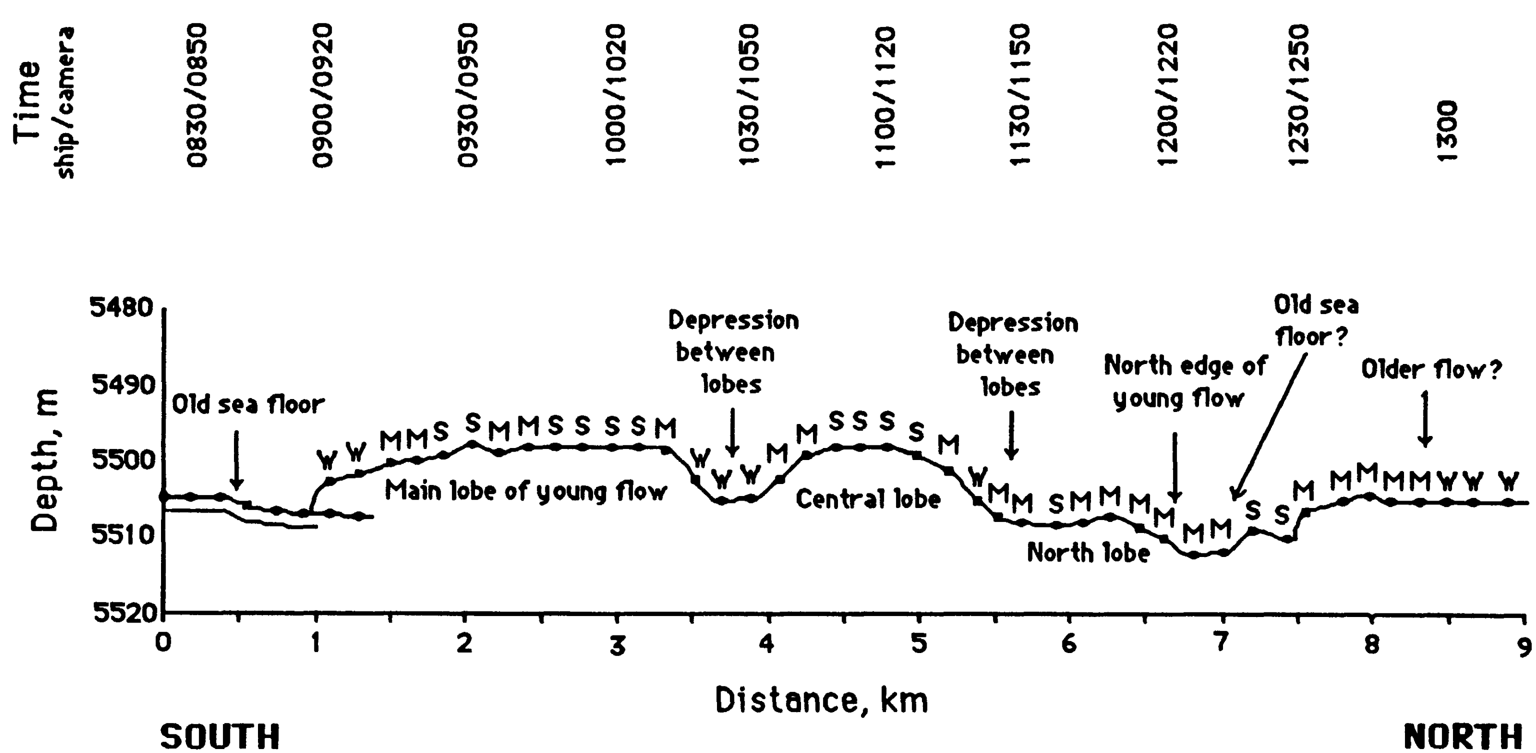


Figure 6. Profile along Camera Station C6

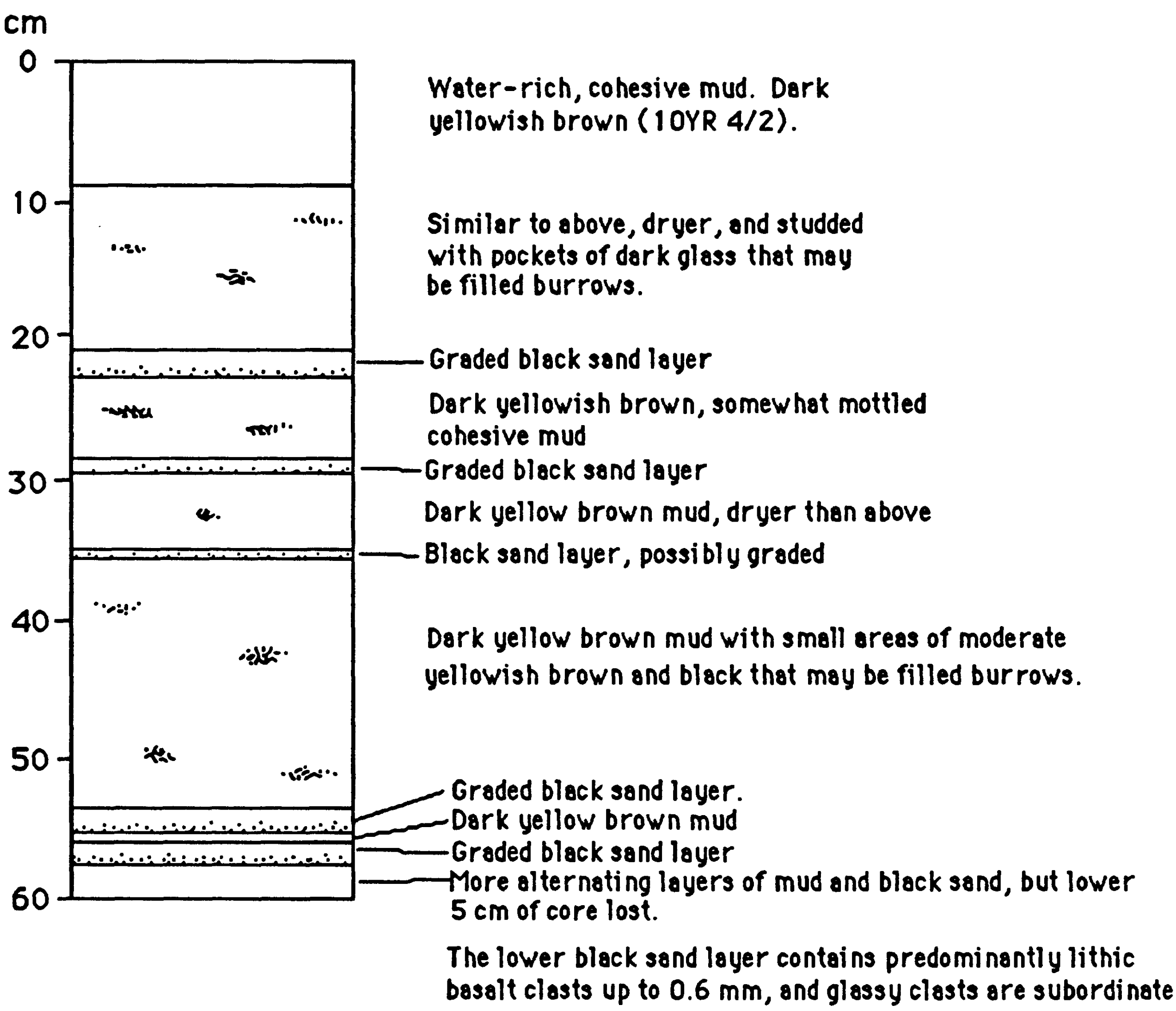


Vertical Exaggeration = 50

Strength of 3.5 kHz reflection

W = Weak
M = Moderate
S = Strong

Figure 7.
Statigraphy of box core B40
On lava flow, foot of east rift zone ridge, Kilauea



After additional 3.5 kHz surveying longitudinally along the flow lobes, (for a total survey length of about 250 nm), another flow was dredged on the east side of the ridge (Dredge station D41). This dredge station was located on a discrete flow lobe that clearly erupted from vents upslope on the rift zone at about 2400 m, rather than from the distal end of the rift. The dredge yielded small fragments of glassy aphyric basalt, caught in the nylon mesh, even though the bottom of the bag was ripped open. The dredge sock contained additional basalt fragments, but no silt or mud --the only dredge haul of the cruise to lack such fine sediment. Original exterior surfaces, preserved on 6 small fragments, are virtually nonpalagonitized (less than a fraction of a micron). Clearly, this flow is not covered by sediment and is exceptionally young, almost certainly historic. It may represent the lava eruption associated with the 1790 caldera collapse event at Kilauea (Holcomb and others, 1988). Alternatively, it might even be a 20th century flow and associated with the 300-m lava-lake subsidence and phreatic explosions at Halemaumau in 1924.

Finally we dredged the crest of the east rift zone at four points. The first dredge (Station D42), at about 2400 m water depth, is directly upslope from the young flow sampled at the base of the slope. It recovered a young flow petrographically similar to the young flow in the Hawaiian Trough. Dredges farther west on the crest of the rift zone ridge of Kilauea (Stations D43 and D45) recovered fragments of relatively young pillow basalts with varying degrees of palagonitization. These samples will compliment existing collections from the ridge which are ideal for studying changes in submarine lava erupted from the same rift zone at different depths. Dredge D44 was unsuccessful because of a combination of navigation, winch readout, and current problems. Dredge D45 yielded a large sample of finely vesicular pillow fragments of relatively young glassy basalt from a depth of 750 m.

In summary, this part of the cruise was highly successful. Although we did not succeed in collecting samples of large flows north of the Puna Ridge, we acquired photographs and samples confirming the existence of lava flows south of the Ridge, including flows having different ages and petrography. One flow probably is historic and may have caused collapse at the summit of Kilauea in A.D. 1790 or 1924.

Large Flows At Base of Loihi Seamount

Loihi is an active submarine Hawaiian volcano, the youngest in the Hawaiian chain, as indicated by seismicity and by previously dredged samples of young tholeiitic and alkalic basalt (Moore and others, 1982). A lobate lava field characterized by high backscatter on GLORIA images extends southwest and southeast of the south rift zone onto gentle flanking slopes at depths of as much as 5,200 m. This lava field covers approximately 600 km^2, but was not crossed by any ship tracks during the 1986 GLORIA surveys. The similar backscatter to the deep flows off Kilauea made comparisons desirable.

After some difficulty in getting power to the magnetometer winch (1 hr lost), we deployed the magnetometer before crossing the Loihi flows. Due to time limitations, we only completed a single survey line over the flows surrounding Loihi. Surfaces of these flows appear much rougher than those of the Kilauea lavas on the 3.5 kHz records. They appear to be smaller than the Kilauea flows and have accumulated on relatively steep slopes (1-5^{o}) adjacent to Loihi.

Regional Graben South of Hawaii

The regional graben identified on the GLORIA images, and variously called the East Hawaii Fracture Zone (Wilde and others, 1980) or Palmer fault zone (Normark and others, 1987), is bounded by two step faults to the north and a single fault with over 300 m relief to the south. The floor of the graben is punctuated by small, rough highs. The sediment in the graben is more opaque to 3.5 kHz than that in the surrounding areas. The origin of this feature is poorly understood but appears to be related to formation of the seafloor during the Cretaceous magnetic quiet period. This graben was crossed again on the transit north from the Arch lava field to Dana Seamount. Where we crossed it the second time, the southern fault scarp bounding the graben is a single step 450 m high, whereas the northern fault consists of a series of three small offsets. As discussed later, distal turbidites from the Ka Lae Slide apparently spill into the graben from the north.

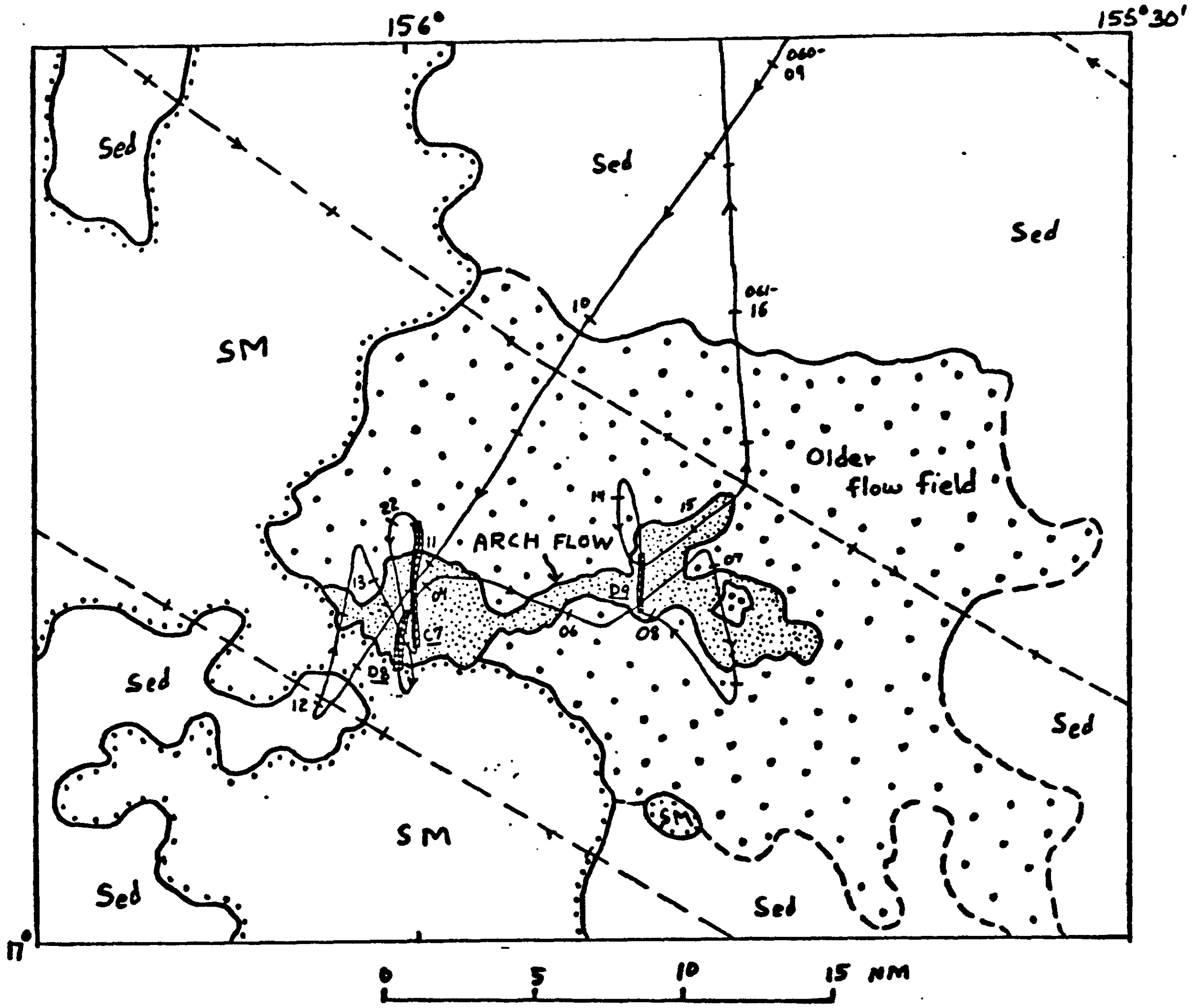
Hawaiian Arch Lava Field.

The 1986 GLORIA surveys identified a uniquely young-appearing lava field, approximately 20x30 nm in area along the crest of the Hawaiian Arch 100 nm south of Hawaii Island (Fig. 8). The Hawaiian Arch flow field obscures the sediment-draped horst-graben topography of the adjacent Cretaceous seafloor, and the 3.5 kHz records indicate an absence of comparably thick sediment cover on the flows. Outer areas of the lava field yield small hyperbolic reflections on 3.5 kHz records, probably due to uneven flow surfaces, but show relatively low backscatter on GLORIA images.

This field contains a lobate central flow area that is characterized by high backscatter and is therefore relatively young. This distinctive feature (Normark and others, 1987, fig. 6B?) seemed a promising target for study of young volcanic activity away from the Hawaiian Ridge. Such a flow may constitute a marginal leak related to progression of the Hawaiian hot spot, of potentially unusual composition that may bear on problems of hotspot evolution and oceanic crust-mantle interactions. Accordingly, we made a detailed survey of it, including two dredges, one camera station, and 90 nm of bathymetric survey (Fig. 8). Time did not permit detailed study or sampling of the outer older parts of the flow field.

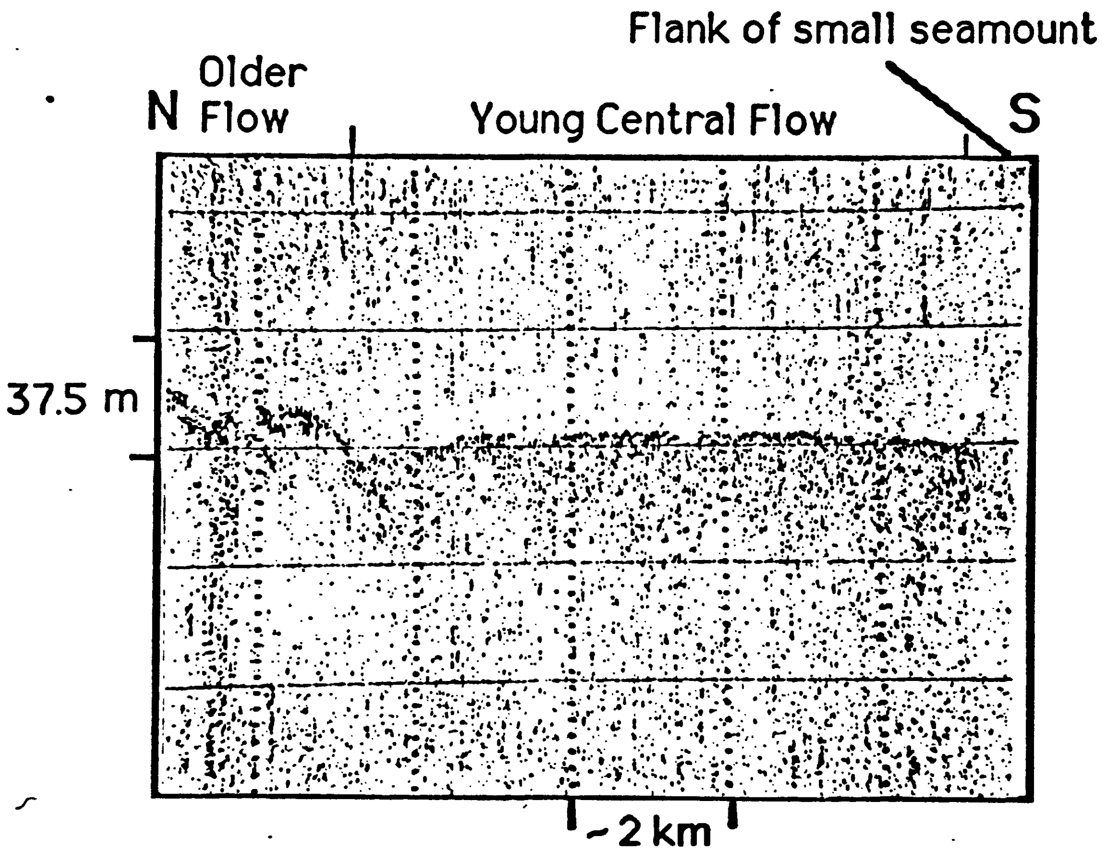
The young central flow unit on the arch has no sediment observable with the 3.5 kHz (Fig. 9); its surface is remarkably flat, sloping by only about 30 m in 15 nm (0.06^{o}) in longitudinal profile downflow to the west from a central area where the separate lobes diverge that is thought to mark the vent. The surface of the young flow is more uneven in this area than it is to the west, and it is generally similar on the 10 kHz records to the older flow field. Detailed interpretation of flow morphology in the eastern area was hindered by failure of the 3.5 kHz transducer during this part of the survey, but the bathymetric survey was completed using the 10 kHz echo sounder.

Figure 8. Map of the Arch Flow



Map of Arch lava field interpreted from combined GLORIA and acoustic-profile data. Dashed lines, 1986 GLORIA survey tracks; solid lines, 1988 survey lines; tick marks indicate Julian day and hour. Camera and dredge stations identified by triple-hatched lines. Sed is accoustically transparent and presumaby thick sediments that blanket the horst-graben terrain of generally low-relief Cretaceous seafloor. SM is cluster of seamounts varying in size from monogenetic volcanoes only 1-2 km across to edifices as much as 10 km across and rising as much as 700 m above the seafloor.

Figure 9. 3.5 kHz Across Hawaiian Arch Flow



Transverse 3.5 kHz bathymetric profile across the young central flow of the Arch flow field, recorded at a ship speed of 8 Kts.

In a transverse profile across the broad western lobe of the young flow, surveyed at 1 kt ship speed during the camera tow (Fig. 10), the south flow margin rises abruptly about 10 m relative to adjacent thickly sedimented seafloor, but its surface is remarkably flat, gradually rising by about 2 m in 7.5 km across the flow (slope of 0.02°). This planar surface is split by a medial depression, 60-90 m wide and a few meters deep, that geometrically resembles axial channels of subaerial flows. Alternatively, the depression may mark a boundary between separate flow lobes. The young central flow unit is located in a bathymetric basin, and its surface is deeper than the surrounding areas. A magnetic line across the widest part of the flow unit has uniform magnetization, suggesting that it erupted in a relatively short time. The young flow is bounded to the southwest by a cluster of small seamounts, and to the north and east by rough older parts of the flow field.

Camera Station C7 crossed the western part of the young central flow from south to north (Fig. 11) and shows volcanic outcrops protruding through a thin veneer of sediment (Appendix 3). The southern margin of the flow is dominated by pillow lava, and the flow top by flat and folded sheet flows. Overall appearance of the flow is similar to the less sedimented eastern Kilauea flows, especially the interior sheetflow lava, which may have ponded behind pillow-lava margins (Fig. 5). Compared to the Kilauea flows, the surface of the arch flow shows even less local relief, no more than a meter. Several lava coils (Peck, 1966) were imaged near margins of the axial depression, suggesting proximity to areas of differential flow velocity. Sediment cover is estimated at only about 10 cm, certainly less than 20 cm. The general character of the flat flow surface suggests high fluidity.

The northern part of the camera traverse climbs over a 20-m step dominated by pillow lava fragments and interpreted as marking the south margin of the older flow field. Above this pillowed margin are more exposures of accordion-folded sheetflow lava, possibly ponded behind the pillowed margin and partly covered by sediment estimated at 30-50 cm thick . The last kilometer (25 min) of the camera run is entirely over surface sediment with no rock exposed and inferred to be a meter or more thick. (The thickness of sediment cover is difficult to determine, however, because of the low local surface relief on this flow.) This sediment appears to be ponded in a depression on the older flow surface. On the concurrently acquired 3.5 kHz record, the exposed margin of the older flow is characterized by weak reflections, and the sedimented depression by stronger returns and multiple reflections. Continuation of the 3.5 kHz profile at low ship speed beyond the camera traverse shows several alternating weakly reflecting highs and lows, inferred to represent exposed flow rocks, and sedimented depressions. At normal survey speeds (7-8 kt), only parabolic reflections were obtained, without evidence for the sedimentary blanket. A small aphyric dense basalt chip with thin glass was recovered from the camera sled.

Dredge Station D8 recovered 100 kg of nearly-aphyric pillow lava with thin palagonite rinds (visually estimated at 40 microns). Most of the glass has spalled off the fragments. The interiors of pillow fragments contain sparse plagioclase microphenocrysts, and the groundmass is also feldspathic. The lava is dense but

Figure 10. Profile along Camera Station C7

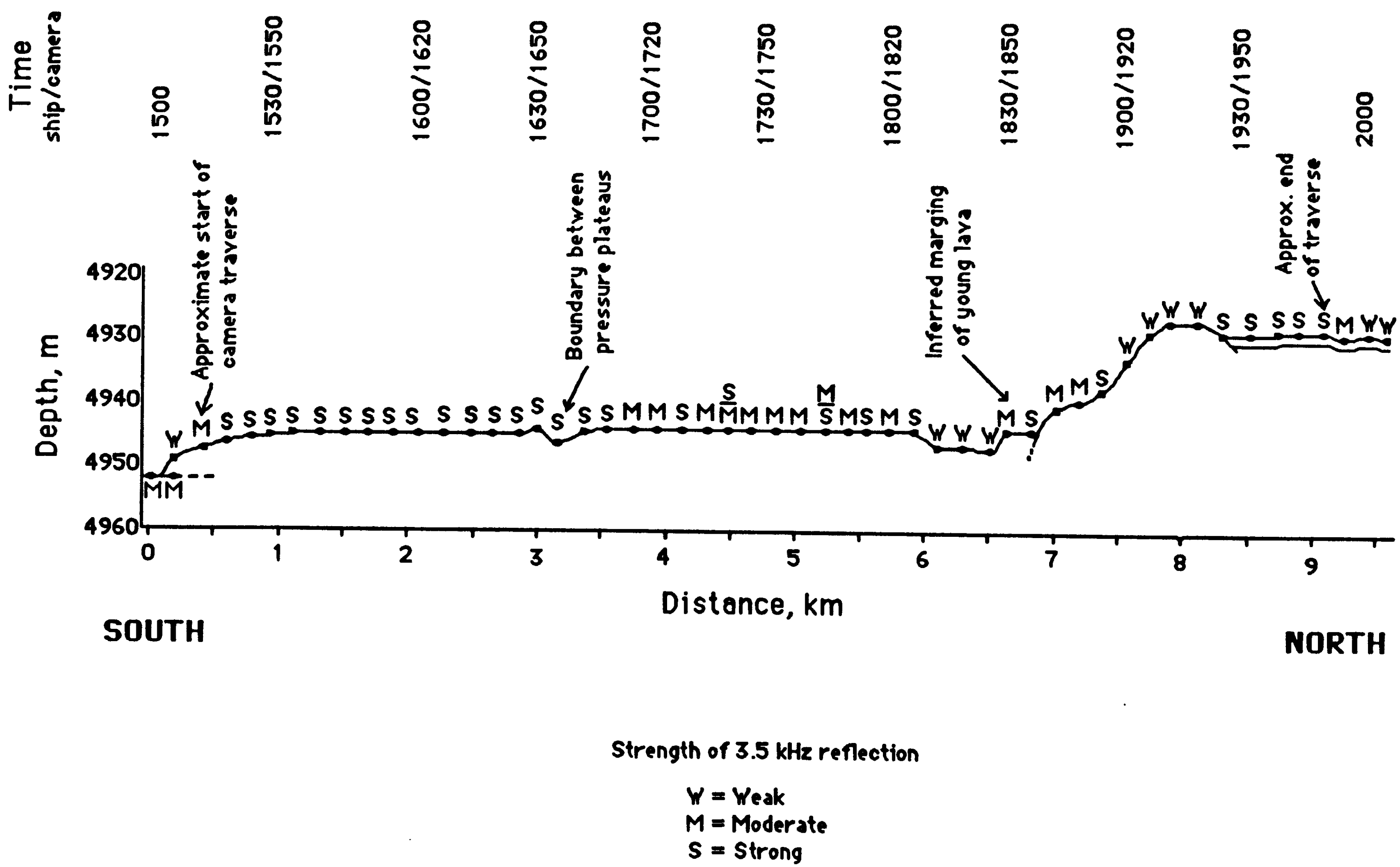
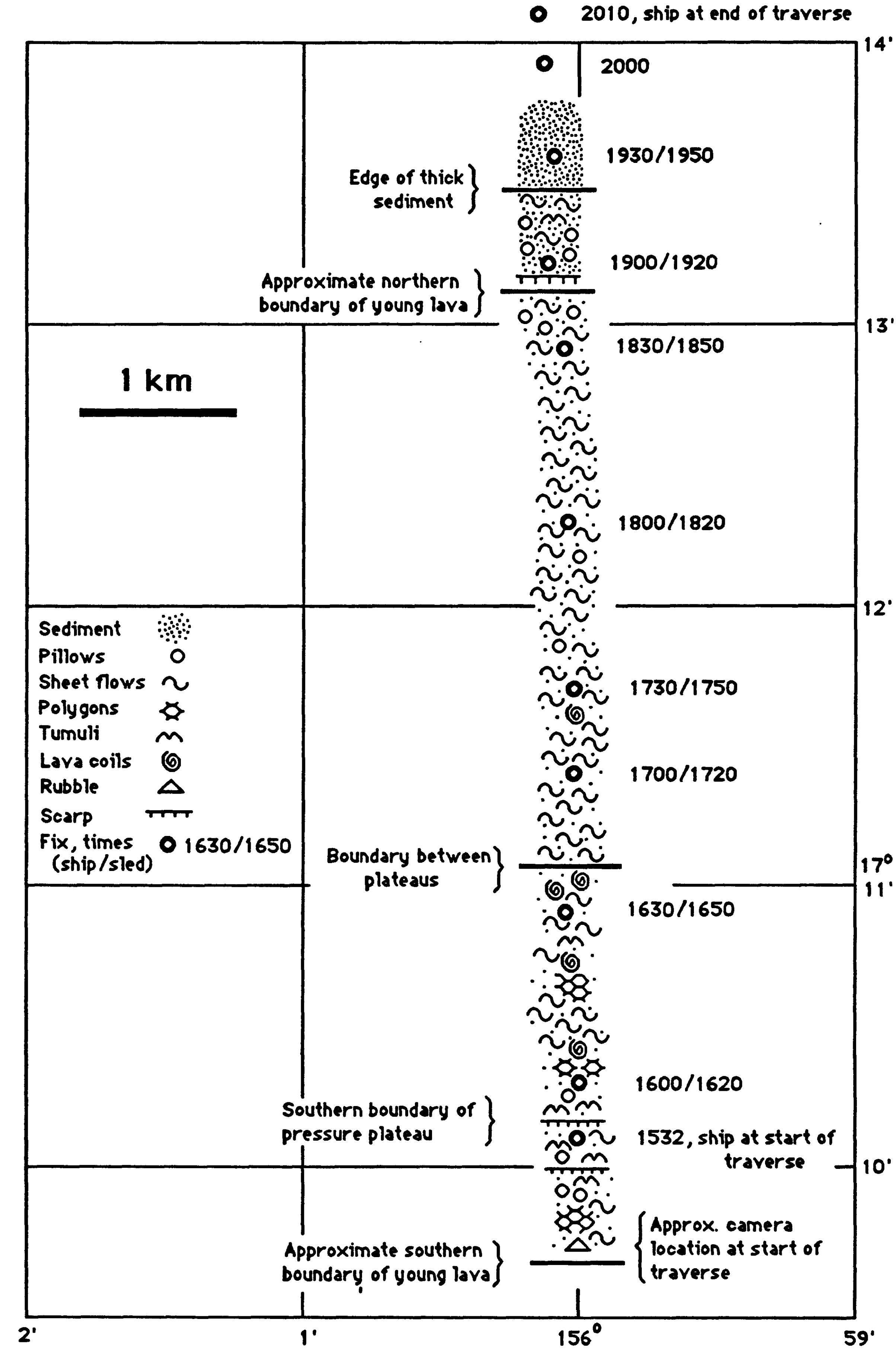


Figure 11. Map of camera station 7



displays unusual internal structure. Interconnected cavities several centimeters in diameter pinch and swell irregularly beneath the smooth surface sheetflow crust; these may be due to entrapment of water or drainback during rapid flowage. Fragments of mudstone were also recovered, probably from the base of the seamount to the south. Dredge Station D9 sampled the eastern part of the flow and recovered 75 kg of sheetflow fragments and pillow fragments of aphyric basalt similar to the basalt recovered at Station D8.

The limited sediment cover, thin palagonite rinds, and absence of manganese coatings suggest that the central flow is a few tens of thousand years old. Based on typical sediment thicknesses of 40 m on Cretaceous oceanic crust adjacent to Hawaii (Cruise Report F5-86-HW), the 10-20 cm sediment thickness on the central Arch flow could accumulate in approximately 20-40 ka. Typical deep-ocean palagonitization rates for basaltic glass of about 3 microns/ka (Hekinian and Hoffert,1975), indicate the central flow might be as young as 10-15 ka. The sediment cover on the adjacent older lavas of the Arch flow field appears to be an order of magnitude thicker, suggesting an approximate age of several hundred thousand years. The lower backscatter of these older flows on the GLORIA images appears to be due to combined effects of greater sediment cover and rougher surfaces. Despite the order of magnitude difference in apparent ages between these two units, they are interpreted together as components of a single volcanic field because they are much younger than the Cretaceous seafloor and are confocal in distribution.

The broad western lobe of the young flow, where studied in detail, resembles a large lava pond confined behind its pillowed margins. The location of this flow lobe in a broad basin between the older flows of the Arch field and adjacent seamounts suggests that its thickness may be little more than the 10 m height of its marginal levees. In the style of current volcanological terminology, it could be called a "low-aspect-ratio" lava flow. Development of the strikingly flat upper surface over so large an area probably results from a combination of high fluidity and discharge rate, inflation aided by well developed lava tubes, and full retention of magmatic gases owing to the deep water column (4800 m). The possibility of high discharge is surprising for such a small lava field so far from the axis of the Hawaiian hot spot track. The surface morphology of the young Arch flow may be comparable to that on large individual flows of subaerial flood basalt, such as those of the Columbia Plateau field, which flowed hundreds of kilometers on surfaces of 0.1 m/km (Shaw and Swanson, 1970). Comparable flat flows seemingly do not accumulate along ocean-ridge spreading centers despite presumed high discharge rates, probably because they are confined in narrow depressions of rough terrain.

Several additional areas to the west, broadly along the crest of the Hawaiian Arch, are comparable to older lavas of the Arch flow field in appearance on the GLORIA and 3.5 kHz records, especially adjacent to the flanks of Pensacola Seamount (Normark and others, 1987, Fig. 6); these also are tentatively interpreted as relatively young lava flows. No comparably young lava areas were imaged by GLORIA along the northeastern segment of the Hawaiian Arch, although anomalous features on geophysical profiles north of Oahu have been tentatively interpreted as young lava flows (Normark and Shor, 1968;Spiess and others, 1969). Thus, the presence of seemingly young flows at several sites along the crest of the Hawaiian Arch suggests a genetic relationship. Perhaps voluminous lava has been able to rise through normal oceanic crust only along extensional fractures related to load-induced subsidence of the Hawaiian Ridge. One implication of this hypothesis would be that all the flows of the Arch flow field should be younger than about 1 Ma, the inferred approximate age of initial growth of the large volcanoes on Hawaii Island, resultant loading of the underlying oceanic crust, and formation of the most southeasterly parts of the Hawaiian Trough and Arch. Similarly young flows should be increasingly rare to the northwest, where the Hawaiian volcanoes are older, and the Hawaiian Ridge is no longer subsiding. These hypotheses can be tested by subsequent GLORIA images to be obtained later in the spring of 1988.

Ka Lae Slide

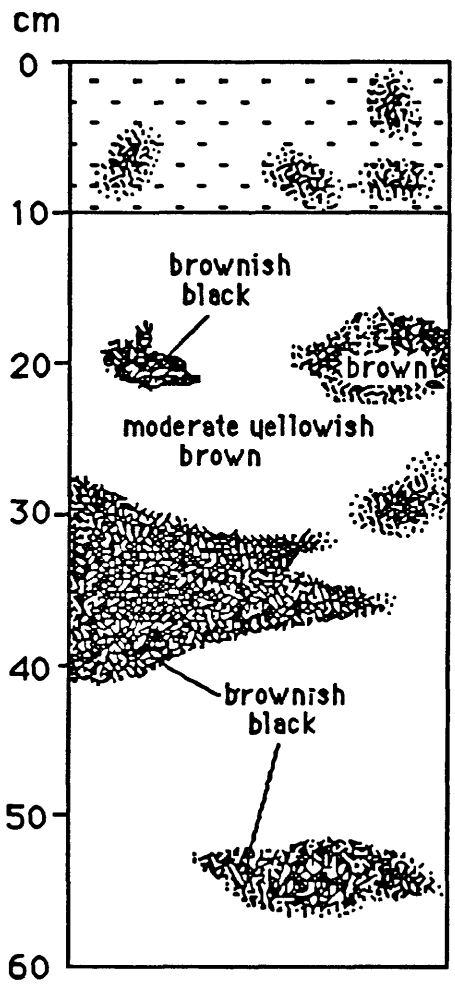
The Ka Lae slide, identified from the 1986 GLORIA images (Lipman and others, 1988), follows a channel from the upper submarine flank of Mauna Loa, immediately west of the southwest rift zone. The slide is about 65 km long and extends to a water depth of about 5,200 m. The toe of the slide spread out at the base of the volcanic edifice and appears as hummocky ground on GLORIA and accoustical records, similar to the Alika slide but much less widespread.

During the transit toward Dana Seamount, we collected two box cores (Stations B10 and B11) at distances of 55 and 8 nm in front of the Ka Lae slide. Because the 3.5 kHz system was down, we located these cores at intersections with 1986 GLORIA lines. The southern sample is a full box of soupy light brown mud from south of the graben (Fig. 12). On the GLORIA geophysical line at this site the sediment is transparent, and on the GLORIA image the sediment has moderate acoustic backscatter.

The second core site is from north of the graben and about 8 nm south of the most distal hummocks of the Ka Lae landslide. At this site, the sediment is opaque on the 3.5 kHz and slightly darker on the GLORIA record. The core box was full of interbedded dark brown mud and black sandy layers (Figure 13). The four sand layers consist of fresh light-brown sideromelane that is angular, dense, devoid of microlites, and contains abundant broken crystals of plagioclase and sparse olivine. The sand layers apparently represent turbidites that extended beyond the blocky portion of the landslide deposit. Alternatively, they may represent the failure of shallow water sands that accumulated rapidly during entry of lava into the sea and formation of littoral cones, which are abundant along the adjacent coastline of Mauna Loa. The high proportion of plagioclase is puzzling; this phenocryst is typically relatively sparse and subordinate to olivine in Mauna Loa lavas, especially those erupted from landward vents adjacent to Ka Lae (Lipman and Swenson, 1984).

After recovering the box core at Station B11, we completed a survey line across the blocky part of the deposit that shows the hummocky topography of the deposit. This

Figure 12.
Stratigraphy of box core, station B10
Hawaiian Arch

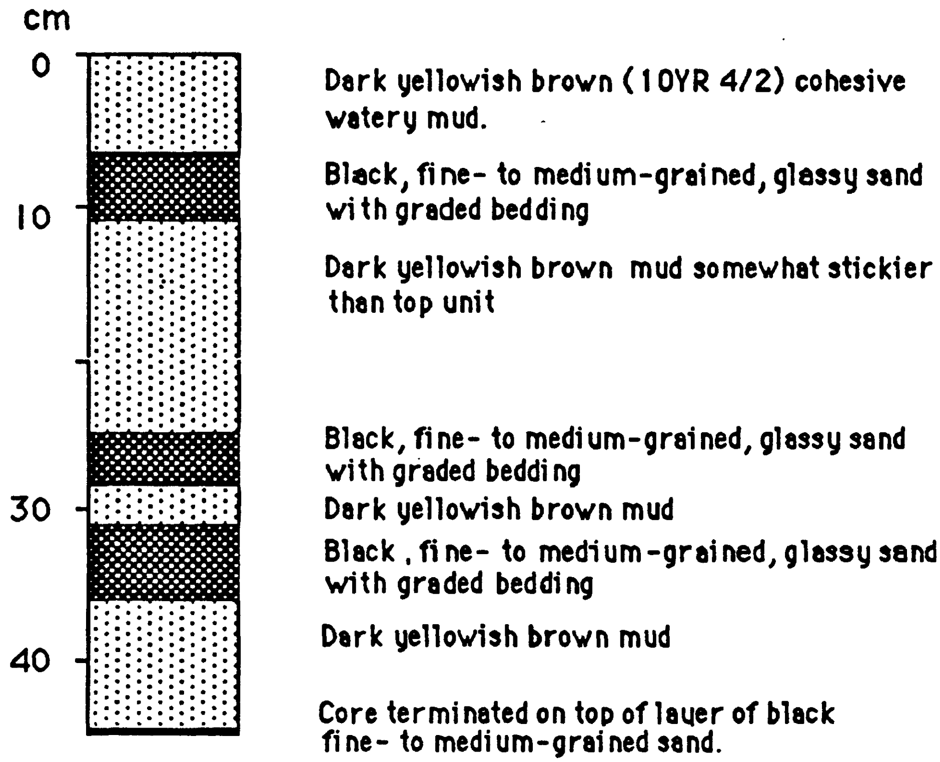


Alternating white to light gray mud with a faint apparent bedding and darker mottled areas

Massive moderate yellowish brown mud with no apparent bedding, but with spotty darker zones the show only a crude bedding control.

Entire core consists of clay and silt size material which includes a silt-size, transparent, micaceous-like mineral with a pearly luster.

Figure 13.
Stratigraphy of box core, station B11



was the first survey line crossing the toe of the Ka Lae slide; previously the landslide was only inferred from the GLORIA images.

Apuupuu and Dana Seamounts

Apuupuu and Dana Seamounts are parts of a cluster of aseismic seamounts around Hawaii that are all thought to be Cretaceous in age. Several seamounts to the west, especially Cross Seamount, have been studied in some detail as part of the assessment program for Co-rich Mn-crusts. A few of these seamounts have been dated by radiometric techniques and are between 84 and 92 Ma. Paleomagnetic pole positions, determined on several, constrain absolute plate motion models prior to the age of the northernmost Emperor Seamounts, about 80 M (Sager, 1987).

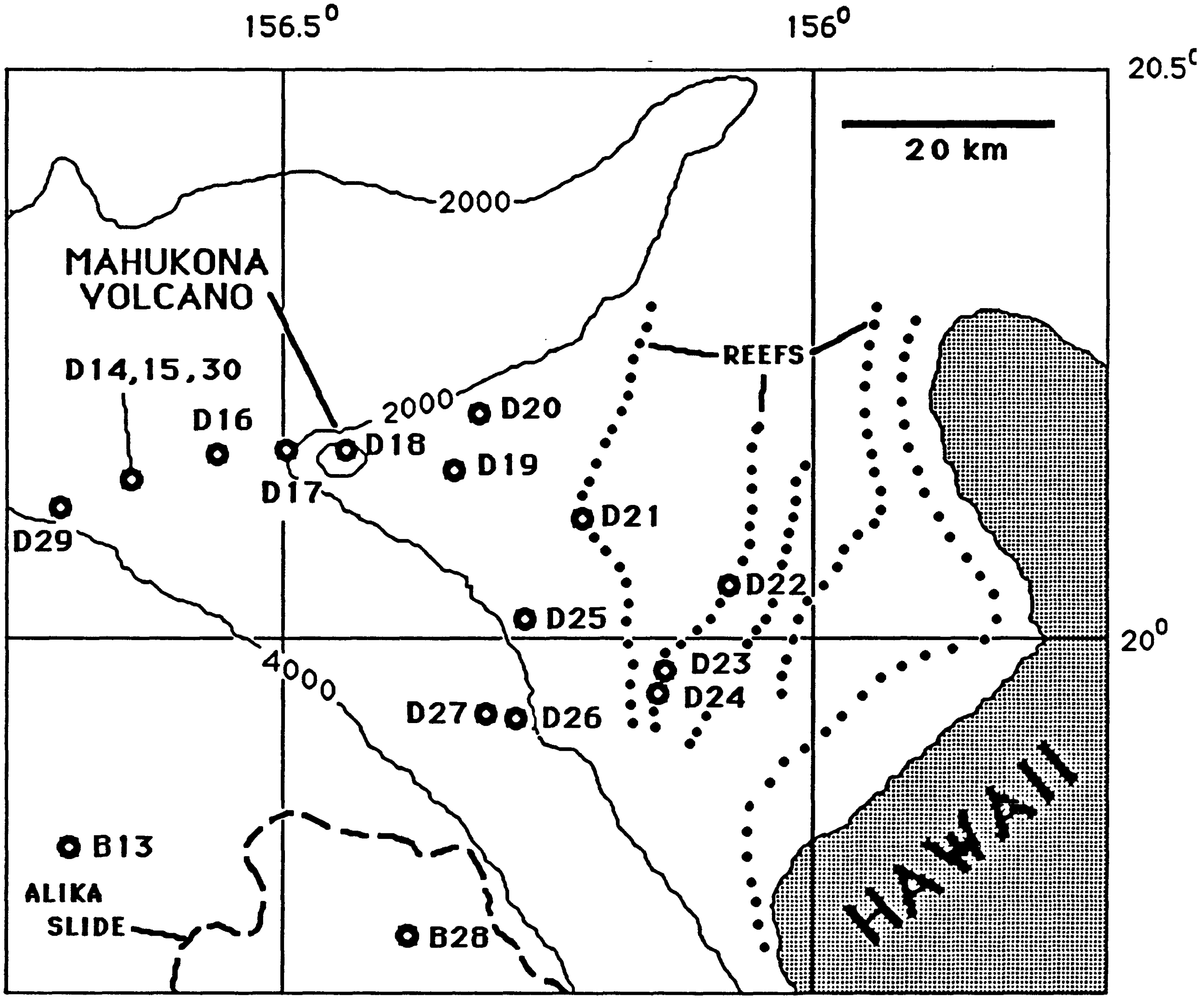
On the transit from Kilauea to the flow on the Hawaiian Arch, we completed a magnetic line from north to south across Apuupuu that completes a partial previous survey. Dr. Will Sager at Texas A & M will complete the paleomagnetic data reduction. This seamount is almost certainly Cretaceous in age but should be sampled for K-Ar age dating to complement the determined paleomagnetic pole position. The summit of the seamount is well located and rises to a depth of about 1870 m.

Dana Seamount had been crossed numerous times by earlier cruises, but the distribution of magnetic lines did not allow for calculation of a paleomagnetic pole location. In addition, no rocks suitable for K-Ar dating had been recovered from the seamount. We completed the paleomagnetic survey and attempted one dredge, Station D12, on Dana Seamount. The dredge, unfortunately, recovered only phosphorite and10 kg of altered vesicular basalt unsuitable for K-Ar dating. In addition, the recovered samples are coated by only thin Mn-oxide crusts. Chalky material in the dredge may provide some paleontologic age constraints. The presence of phosphorite indicates the seamount is at least as old as Eocene and therefore unrelated to Hawaiian volcanism.

Alika Slide

Emplacement of the large Alika slide, derived from the southwest flank of Mauna Loa, generated a morphologically diverse submarine hummocky terrain that covers about 4,000 km^3 and extends west into the Hawaiian Trough (Fig. 14). This major feature, discovered during work in Hawaiian waters with the R/V Lee in the late 1970's (Normark and others, 1979), was fully mapped for the first time during the 1986 GLORIA survey (Lipman and others, 1988). In order to provide a reconnaissance comparison of the sedimentary apron in front of this large slide complex with the Kae Lae slide area (Stations B10-11), we sampled the sediments in the axis of the Hawaiian Trough 10 nm northwest of the northern Alika slide lobe (Box core Station B13). This basin is positioned to receive distal sediment derived from several petrologically distinct sources: (1) large slides off Mauna Loa, (2) similar slide-related sediment associated with debris slides from the Lanai platform, and (3) erosional and other sediment generated along the coastline of Hualalai. The recurrence intervals for relatively infrequent but catastrophic debris slides from the Hawaiian Ridge remains an elusive

Figure 14. Map of Stations on Alika Slide, Mahukona Volcano, Hualalai Rift Zone, and Reef Terraces



chronologic problem, of great importance in hazard evaluations, for which the sedimentary aprons in front of the direct slide deposits may provide the most promising material.

The core box was recovered full, containing dominantly tan mud with many dark gray silty laminae each about 1 mm thick (Fig. 15). The laminae consist of coarse silt, including basaltic glass, crystals, and angular devitrifed lithic material. The coarsest and thickest silt layer was at the bottom of the recovered core. No sand was present comparable to that at Station B11. Possibly, the entire box core section of the Station B13 core postdates the Alika slide, and the dark laminae consist of wind-blown volcanic ash associated with eruptions from Kilauea, Mauna Loa, and/or Hualalai.

A second box core (Station B28) was recovered from the distal end of the hummocky part of the Alika slide. This core was a full box of stiff brown mud with two interlayers of graded sand (Fig. 16). Both of these layers are graded, from volcanic glass at the bottom to foraminiferal ooze at the top. The foramifera are dominantly pelagic rather than nearshore benthic forms. The location of the core is well below the carbonate compensation depth, so the foramiferal ooze must have accumulated at a considerably shallower depth and been emplaced into the Hawaiian Trough as a turbidite which was then quickly buried before the carbonate could dissolve.

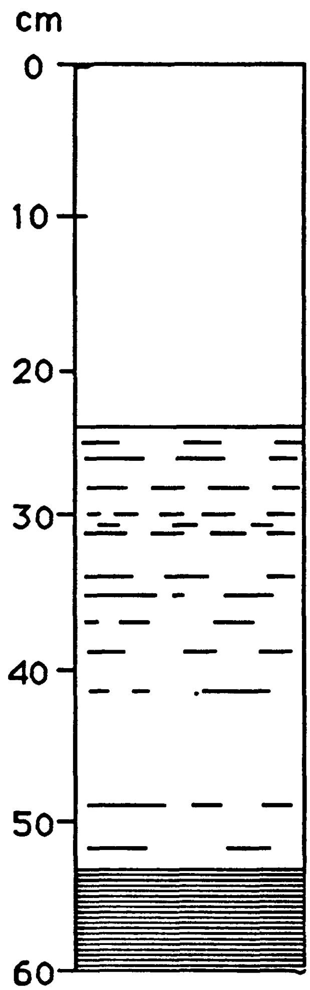
The lateral diversity of shallow sediments in this sector of the Hawaiian Trough indicated by our four reconnaissance core samples, suggests that a detailed study of offshore sediments could document features of the evolution of Hawaii Island that are nowhere preserved on land.

Hualalai Submarine Rift Zone

Hualalai Volcano, the third youngest volcano on Hawaii Island, is now in the postshield eruptive stage. The entire subaerial surface consists of alkalic basalt (Moore and others, 1987), but tholeiitic basalt of the shield stage has been recovered from the submarine northwest rift (Clague, 1982), from several water wells, and as blocks in a maar deposit (Moore and others, 1987). Lava quenched at high confining pressure, such as occurs beneath several hundred meters of water, contains the volatile components that degas during subaerial eruption. Lavas recovered previously from the submarine rift are all subaerially erupted but submarine emplaced flows. These lavas had degassed and lost these critical volatile components. Previously dredged samples were recovered from as deep as 1800 m, suggesting that Hualalai has subsided by at least this amount since the tholeiitic lavas were erupted, at least 105 ka (Clague, 1987).

Two dredges were located deep along the submarine northwest rift of Hualalai (Figure 14) to recover lava erupted and emplaced under water. Dredge Stations D26 and D27 recovered 25 and 20 kg of glassy dense olivine-rich pillow fragments. The glass rinds were surprisingly thick (up to 2 cm) and the palagonite rather thin (<200μ) for lava greater than 105 ka. The olivine-rich petrography and the previous exclusive recovery of tholeiitic basalt from the submarine rift indicates that the recovered lava is tholeiitic basalt of the shield stage. Analysis of the volatile and rare gas components

Figure 15.
Stratigraphy of box core, station B13
10 km northwest of toe, Alika slide

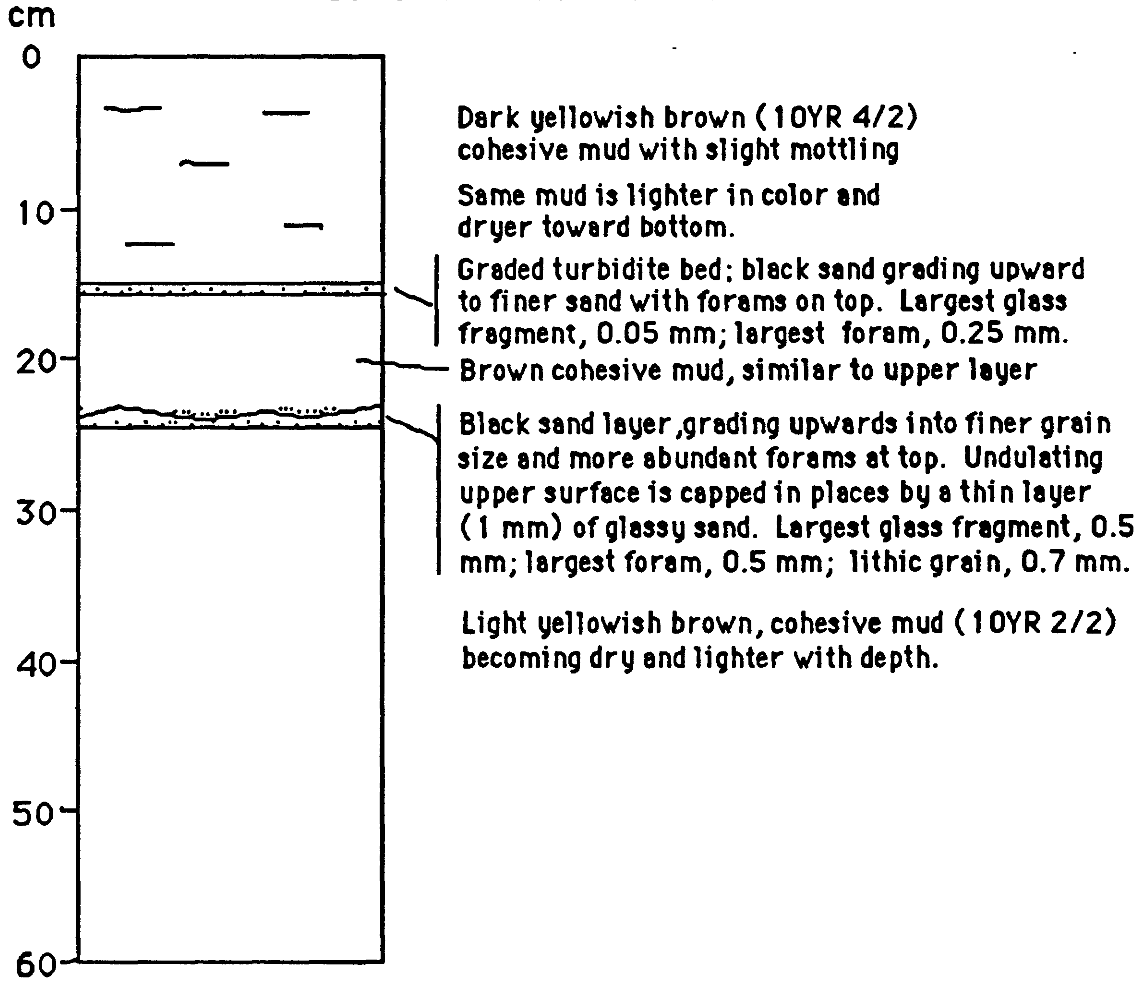


Dark, yellowish brown (10 YR 4/2) cohesive mud, water-rich at upper part. Contains benthic agglutinated forams and other microfossils.

Cohesive mud, dusky yellowish brown to olive gray in color. When box was opened, horizontal open partings formed suggesting a horizontal foliation of some kind. Faint laminations 1-3 mm thick at 1-3 cm intervals.

Dusky, yellowish brown (10YR 2/2) laminated mud. Dark layers contain coarse silt-sized. brown, angular glass fragments (0.05 mm). Layers about 1 mm thick.

Figure 16.
Stratigraphy of box core B28
On toe of Alika slide



will determine if these lavas erupted underwater, thereby constraining the subsidence rate in this area.

Mahukona Volcano

Mahukona volcano (Fig. 14) is a submerged edifice only recently recognized (Moore and Campbell, 1987) as the link on the Loa volcanic lineament between Kahoolawe and Hualalai volcanoes. Mahukona is partly ringed by submerged reefs, indicating that the summit area was previously above sea level. In addition to the area of reefs, samples were dredged primarily from the west rift zone in order to characterize the petrologic evolution of the Mahukona volcano and to better understand the lavas of its subaerial neighbors.

We dredged Mahukona Volcano at 6 sites including the summit (Station D18), a small cone east of the summit (Station D19), and the western rift zone (Stations D16, D17, D29, and D30). Two additional west rift dredges (Stations D14 and D15) were empty. The two dredges that recovered more than 3 kg of volcanic rock are both located near the summit. The recovery of stiff sandy brown mud in dredge Station D29, coupled with the difficulty in dredging volcanic rock, indicates that the flanks of Mahukona volcano are blanketed by sediment. The sediment cover and the presence of thin Mn-crusts on the volcanic rocks suggest that Mahukona is considerably older than nearby Hualalai. Much of the sediment may be wind-blown volcanic ash, most probably from Mauna Kea and Hualalai Volcanoes. The lavas recovered from depths greater than about 2000 m are dense olivine-rich (5-25%) sheet and pillow fragments with fresh glass, thick palagonite, and thin Mn-crusts. The lavas recovered from the two cones at and near the summit are petrographically similar to the deeper lavas but contain up to 40% vesicles.

Mahukona-Haleakala Coral Reefs

Recent refined bathymetric mapping in the region between Hawaii and Maui (Campbell, 1986), along with the 1986 GLORIA survey, has revealed a remarkable succession of submerged coral reefs between the northwest coast of Hawaii and the summit region of Mahukona volcano. Six distinct reefs have subsided as much as 1300 m below sea level; they document the interrelation between sea level oscillation caused by Pleistocene ice ages, island subsidence, and volcanism (Moore and Campbell, 1987) . The three shallowest reefs have been successfully sampled previously by dredging and submersible, and dated (Szabo and Moore, 1986; Szabo and Moore, 1988) at 13 ka (-150 m reef), 125 ka (-360 m), and 240 ka (-700 m reef).

The 1986 GLORIA sonographs imaged additional submerged reefs on the submarine east rift zone of Haleakala volcano extending as much as 75 km east of the east cape of Maui. Preliminary interpretation suggests that all the Haleakala reefs should be older than those preserved on the Kohala platform. The chief focus of the current work was to dredge the deeper reefs on both Mahukona and Haleakala, which have not been previously sampled, in order to date the coralline material by U-series and strontium isotope techniques. Aside from its utility in defining the Pleistocene history of the Hawaiian hotspot, this work may provide a unique new data set important for understanding the global problem of Pleistocene sea level fluctuations.

Samples were successfully obtained at all six stations within the Kohala reef area (Fig. 14). Of these, apparently datable coralline material was obtained from dredges on the two deepest reefs: Station D21 from the 1100 m terrace, and Station D25 from the main slope break (representing the time and position of the cessation of shield-building of the Mahukona volcano) at 1400 m.

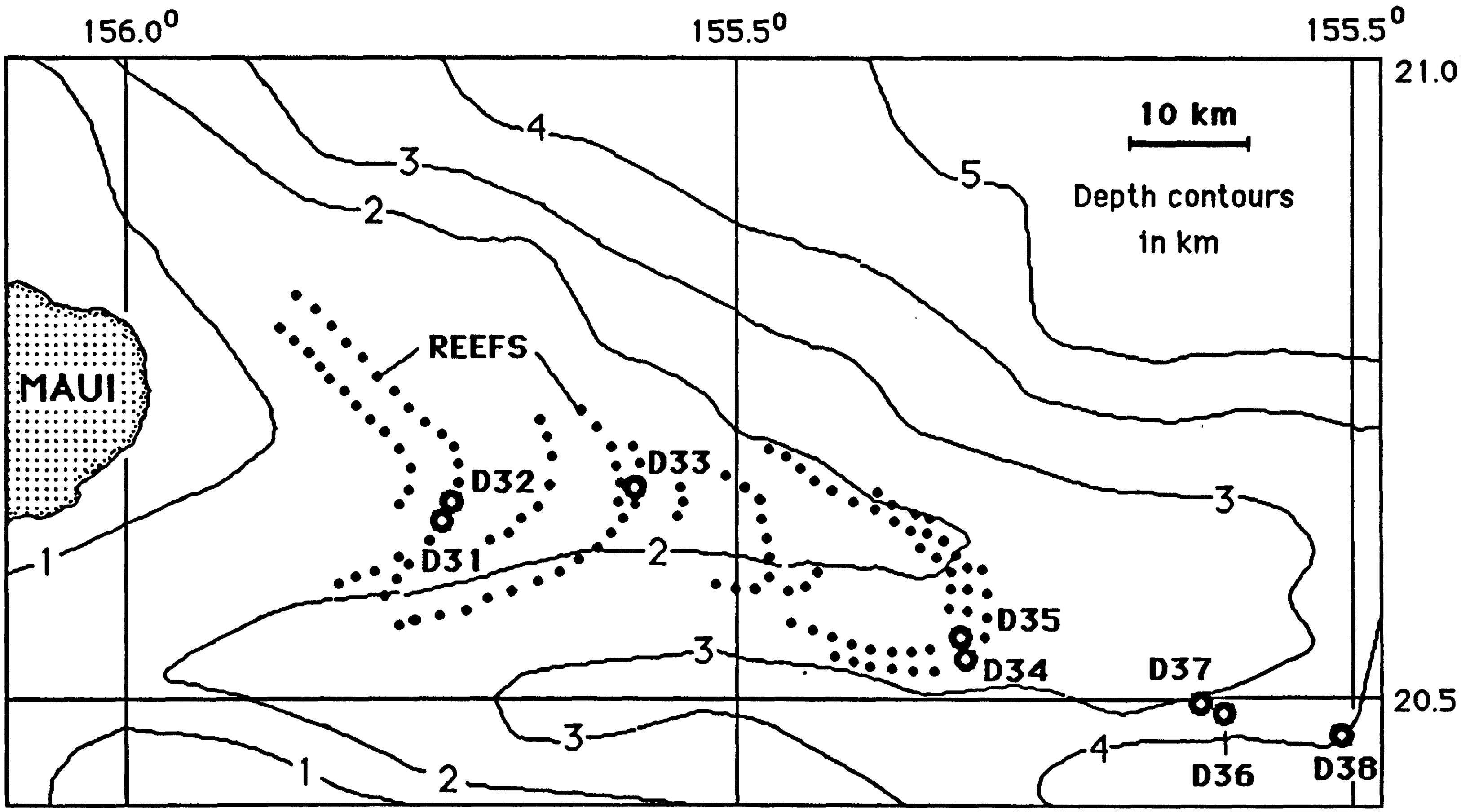
Despite three attempts (Stations D22, D23, D24), no carbonate was obtained from the 900 m reef. Instead, some pillow lava, as well as a black, glassy, bedded, coarse sand was sampled. This hyaloclastite perhaps represents an accumulation of littoral explosion material deposited on top of the reef when lava flows crossed the reef and poured into the sea. This area is a probable depositional locus for subaerial lavas from Mauna Kea, Mauna Loa, and possibly Hualalai volcanoes (Fig. 14). Sulfur content of hyaloclastite glass, as well as that of the associated lava will help determine whether these materials were erupted subaerially or subaqueously; chemical analyses should allow us to identify the source volcanoes for the flows. The difficulty in sampling reef material may result from solution of the reef face beneath younger volcanic layers,consisting of lavas and hyaloclastics,which was followed by collapse to form a mantle of basaltic rubble along the reef face.

Reef and volcanic materials collected from the Mahukona reefs are coated by manganese layers 0.1-0.3 mm thick. The manganese layers are somewhat thicker (0.5-1 mm) on deep lavas from the Mahukona west rift zone. The growth rates of manganese layers (as well as palagonite layers) will be investigated in this unique area where the reef-lava juxtaposition can provide age control.

Along the submarine east rift zone of Haleakala, several deep, arcuate belts of high backscatter on GLORIA images and bathymetric steps on 3.5 kHz profiles (Cruise Report F5-86-HW) were tentatively interpreted as submerged coral reefs. The offset of the horseshoe map pattern of these features from the axes of the bathymetric contours was interpreted as resulting from southward downtilting of the entire ridge toward the post-reef region of active volcanic loading centered on the island of Hawaii (Fig. 17). However, this offset is so large (5-9 km, see figure 17) that questions arose about the GLORIA navigation or the quality of existing bathymetric maps. These arcuate features were dredged at five sites, ranging from 1600 to 2300 m depth (Stations D31 to D35) and the results confirmed that the arcuate features are reefs and are correctly located relative to the bathymetry. D32 recovered 200 kg of coralline material from one of the shallowest (and youngest) reefs at a depth of 1600 m. The haul included two coral heads, abundant fragments of staghorn coral, and beach rock containing fragments of echinoid spines, pelecypods, coral, and gastropods. This haul confirmed the interpretation that the arcuate reflectors are reefs, dispelled some uncertainties about GLORIA navigation in this area, and provided a wealth of material for study, particularly age dating.

Dredge hauls D34 and D35 on the deepest apparent reef complex recovered primarily manganese-coated, bedded hyaloclastite, similar to the material mantling

Figure 17. Map of Stations on East Rift of Haleakala



the -900 m reef on Mahukona volcano. These deposits apparently record a regime of such stable sea level and infrequent volcanic overflows that a reef (or at least a mature wave-cut platform) could develop, yet was followed by a period of volcanic activity when lava flows entered the sea, produced littoral explosions, and mantled the reef with debris.

Haleakala East Rift Zone

We attempted 3 dredges (Stations D36, D37, and D38) deep on the submarine rift zone of Haleakala volcano to sample submarine-erupted and emplaced lavas (Fig. 17). These dredges yielded two empty bags and a third that contained only two small fragments (20 g) of Mn-encrusted basalt. All three attempts recovered small amounts of foraminiferal ooze in the pipe dredge. This sampling objective was not fulfilled, apparently because of a combination of conditions including in-place pillow flows, Mn-cemented talus, and partial cover by sediments. These same conditions, probably dominated by excessive sediment cover, also limited our success during dredge operations on Mahukona volcano. Hawaiian rift zones on mature volcanoes apparently have little loose talus exposed. Dredging on steeper slopes farther from the rift zones might yield more rock, but these samples will have erupted at some unknown shallower depth and flowed downslope to the sample site. Many of our studies, such as magma degassing, require well-constrained eruption depths.

Remaining Problems; Future Work

The 1986 GLORIA sonar images delimited several major features of Hawaiian submarine geology that were previously unknown, including the large Kilauea east rift flows, the Hawaiian Arch volcanic field, deeply submerged reefs off Kohala and Haleakala volcanoes, and the large submarine slides off the west flank of Hawaii Island. This first Hawaiian GLORIA ground-truth survey resolved many interpretive problems posed by the sonar images, but critical aspects of all major results require additional study:

Kilauea East Rift Flows: Understanding the age and eruptive history of these large flows, in relation to observed features on the GLORIA images, was impeded by the unexpectedly thick sediment cover in most areas. Three dredged samples of picritic and aphyric basalt may represent only two flows of distinctly different ages. No samples were obtained from the northwest side of the Puna Ridge; further dredging is needed along flow margins based on more detailed bathymetric and geologic mapping. Drilling to collect vertically oriented samples can provide a means to date the lava flows using the inclination of their remanent magnetization (Holcomb and others, 1986). More detailed surveys, including bottom photography, are needed in the area of the young aphyric flow. Bathymetric details of the relations of flow and turbidites to subsidence and development of the Hawaiian Trough can provide a model balancing volcanism and subsidence.

Sediment penetration by GLORIA: A major surprise of our work was the thickness of sedimentary cover penetrated by the sonar images in some basalt areas of high backscatter. Additional coring with greater penetration in the sedimentary cover on the flow tops--using gravity or piston coring techniques--would improve understanding of GLORIA backscatter characteristics and provide additional information on flow ages.

Hawaiian Arch Lava Field: Only the high-backscatter central flow of the field was dredged; the composition and age of the older flows that constitute the bulk of the field remain unknown. Seismic profiles and bottom photography are needed to understand the morphologically more complex eastern parts of the young central flow that include the vent area, and bathymetric data are inadequate for the older outer parts of the field. Comparisons of the Arch lava field with similarly young-appearing lava areas near Pensacola Seamount, and any similar features found farther northwest along the Hawaiian Arch, are needed to evaluate relations between these young lavas and evolution of the Hawaiian hot spot.

Deeply Submerged Reefs: The dating of submerged reefs on the flanks of Hawaiian volcanoes can provide a powerful tool for age control of tectonic, volcanic and sedimentary processes. Moreover, the reefs, having formed horizontally at sea level, can be used as tiltmeters. Additional collection and dating of reefs linking the major volcanoes northwest to Kauai can provide a chronological framework important in all other regional investigations, including the rate of formation of manganese crusts of possible economic significance. This work will stimulate (and require) the improvement of dating techniques. Many of the reefs apparently span an age range of about 0.5-2 millon years, an age "window" not accurately controlled by either the uranium-series or strontium isotope methods.

Hawaiian Rift Zones: The submarine rift zones of the older inactive volcanoes (Mahukona and Haleakala) proved difficult dredge targets, with recovery limited to a few small samples from depths greater than 2500 m. Combined effects of flanking sediment aprons and cementation by MnO coatings appear to be responsible. Additional dredging, including sampling along fault scarps, is needed because eruptive vents become localized toward the upper, central part of the volcanoes as they grow and evolve. Therefore, acquisition of deep samples on the rift zones is necessary to access the early magmatic history of the volcanoes.

Turbidites in the Hawaiian Trough: Discovery of abundant basaltic turbidite sands in the Hawaiian Trough offers potential tools to study the sedimentation record of shoreline lava-flow processes and deep water landslides off the steep island flanks. For example, west of Hawaii Island, petrologically distinguishable basaltic sand (using microprobe analyses of glass grains) can be derived from Mauna Loa, Hualalai, and Kohala volcanoes, as well as older material from the Lanai area. Sets of closely spaced cores located laterally and longitudinally with respect to the toe of the Alika slide would be particularly useful. Such core samples should reveal the lateral continuity of individual turbidite sands, provide estimates of turbidite volumes, and constrain their relation to different volcanic sources. Similarly spaced cores adjacent to the young lavas at the base of the Kilauea east rift and the Arch flow should permit determination of sedimentation rates which can be used to date the lavas.

Landslides: Landsliding at many scales is an important process in the growth and degradation of Hawaiian volcanoes. GLORIA images have already defined and partly mapped three large slides that rank among the largest known on Earth. The upcoming Spring 1988 cruises will undoubtedly image other known slides and discover new ones. The comparative study of these landslides, and attempts to date them should be a major objective of future ground-truth cruises. These landslides, although infrequent occurrences, pose a severe hazard to the Islands because of evidence that landsliding has generated gigantic waves in the past (Moore and Moore, 1984).

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References Cited

Campbell, J. F., 1987, Bathymetric atlas of the southeast Hawaiian Islands; Special Public., Hawaii Institute of Geophysics, Honolulu, 20 p.

Clague, D.A., 1982, Petrology of tholeiitic basalt dredged from Hualalai volcano, Hawaii: Eos, v. 63, p. 1138.

Clague, D.A., 1987, Hawaiian xenolith populations, magma supply rates, and development of magma chambers: Bull. Volcanology, v. 49, p. 577-587.

Hekinian, R.,and Hoffert,M.,1975, Rate of palagonitization and manganese coating on basaltic rocks from the rift valley in the Atlantic Ocean near 36o50' North: Marine Geology, v. 19, p. 91-109.

Holcomb, R.T., 1987, Eruptive history and long-term behavior of Kilauea volcano, in Decker, R. T., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii, U.S. Geological Survey Professional Paper 1350, p. 261-350.

Holcomb, R.T., Champion, D.E., and McWilliams, M.O., 1986, Dating recent Hawaiian lava flows using paleomagnetic secular variation: G.S.A. Bulletin, v. 97, p. 829-839.

Holcomb, R. T., Moore, J.G., Lipman, P.W., and Belderson, R.H., 1988, Voluminous submarine lava flows from Hawaiian volcanoes: Geology, in press.

Lipman, P.W., and Swenson, A., 1984, Geologic map of the southwest rift zone of Mauna Loa volcano, Hawaii: U.S. Geological Survey Miscellaneous Investigation Map I-1323.

Lipman, P.W., Normark, W. P., Moore, J.G., Wilson, J.B., and Gutmacher, C.E., 1988, The giant submarine Alika debris slide, Mauna Loa, Hawaii: Journal of Geophysical Research, in press.

Moore, J.G., and Fiske, R.S., 1969, Volcanic substructure inferred from dredge samples and ocean-bottom photographs, Hawaii, Geological Society of America Bulletin, v. 80, 1191-1201.

Moore, J. G. and Campbell, J. F., 1987, Age of tilted reefs, Hawaii: Journal of Geophysical Research, v. 92, p. 2641-2646.

Moore, J.G., Clague, D.A., and Normark, W.R., 1982, Diverse basalt types from Loihi seamount, Hawaii: Geology, v. 10, p. 1191-1201.

Moore, R.B., Clague, D.A., Rubin, M. and Bohrson, W.A.,, 1987, Hualalai Volcano: A preliminary summary: U.S. Geological Survey Professional Paper 1350, p. 571-586.

Moore, J. G., and Moore, G. W., 1984, Deposit from a giant wave on the island of Lanai, Hawaii: Science, v. 226, p. 1312-1315.

Normark, W.R., and Shor, G.G., Jr. 1968, Seismic reflection study of the shallow structure of the Hawaiian Arch: Jour. Geophys. Res., 73,6991-6998.

Normark, W.R, Lipman, P.W., and Moore, J.G., 1979, Regional slump structures on the west flank of Mauna Loa volcano, Hawaii (abs.): Program, Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, p. 72.

Normark, W.R., Lipman, P.W., Wilson, J.B., Jacobs, C.L., Johnson, D.B., and Gutmacher, C.E., 1987, Preliminary cruise report: Hawaiian GLORIA Leg II, F6-86-HW: U.S. Geological Survey Open-File Report 87-298, 34 p.

Peck, D.L, 1966, Lava coils of some recent historic flows, Hawaii: U.S. Geological Survey Prof. Paper 550B, p. B148-B151.

Sager, W., 1987, Late Eocene and Maastrichtian paleomagnetic poles for the Pacific Plate: Implications for the validity of seamount paleomagnetic data: Techtonophysics, v. 144, p. 301-314.

Shaw, H.E., and Swanson, D.A., 1970, Eruption and flow rates of flood basalts: Proc. of the Second Columbia River Basalt Symposium, East Washington State College Press, p. 271-299.

Spiess, F.N., Luyendyk, B.P., Larson, R.L., Normark, W.R., and Mudie, J.D., 1969,Detailed geophysical studies on the northern Hawaiian Arch using a deeply towed instument package: Marine Geology, v. 7, p. 501-527.

Szabo, B., and Moore, J.G., 1986, Age of -360 reef terrace, Hawaii, and the rate of late Pleistocene subsidence of the island: Geology, v. 14, p. 967-968.

Szabo, B., and Moore, J.G., 1988, Age of the -700 m reef, Kona, Hawaii: (Abs.) Geol. Soc. Am. Abs. with Program, in press.

Appendix 1: Camera Station C3

This lowering on February 27, 1988 (JD 058) began at 0100Z and ended at 0555Z. The starting point was at a depth of 5480 m near the base of the Hilo ridge, from which the sled descended in the first hour to a depth of 5505 m and then stayed within 5500-5510 m until it left the bottom.

In addition to crossing the base of the Hilo ridge (built along the east rift zone of Mauna Kea), the sled seems to have crossed a contact between a younger flow having 90-95% sediment cover, inboard, and an older flow having 100% thick sediment cover, outboard. This contact was not recorded clearly by the camera; its location is inferred from GLORIA imagery. No outcrops at all were seen on the older flow ("intermediate age" flow in three-fold age classification of Holcomb et al, 1988); this suggests that sediment thickness is more than 1/2 m, perhaps more if the flow has pillows or tumuli with higher relief. This thickness is surprising in light of the fairly high sonar backscatter from this flow on GLORIA images, and it suggests that GLORIA penetration is greater than was thought previously. In order to study this question further, box core B40 was collected later from the surface of this flow near the camera track.

Time	Notes
0100	Sled reaches bottom when ship is at 19°56.4'N, 154°26.1'W. The sea floor is completely covered by sediment having many worm tracks.
0103-0104	Cluster of pillows.
0107	Scale bar sinks into thick sediment.
0108:00	White object; may be a sponge.
0110:25	Scattered low rocks; apparently slab-shaped and having rough surfaces.
0111:33	Ditto
0113:40	A rough-surfaced rock, about 40 cm long.
0118-0121	Scattered rough-surfaced rocks in sediment.
0123	Pile or mound of rough-surfaced rocks.
0124	Mottled sediment may contain basalt pebbles; but some pebbles have light color.
0125	Ripple marks?
0126	Scattered cobble-like rocks.
0128:44	The scale bar is hitting bottom repeatedly, roiling clouds.
0133	Many small dark objects protrude from sediment; they are probably organisms of some sort.
0140:00	Small squid (?) about 40 cm long.
0142	Many small dark objects, only a few cm wide, still protrude from the sediment.
0142:46	Two rocks.
0143-0144	Mound of pillows protruding from sediment.
0143:26	White-armed sessile creature on pillow.
0144:44	Another large pillow?
0145:09	Elongate pillow about 30 cm in diameter.
0146:41	Rough-surfaced rocks.
0147:00	Rubble of angular blocks 10-20 cm wide, in a band 2-3 m wide; then more sediment.
0152	Still sediment, with worm tracks.
0156	Two cobble-sized rocks?
0159:44	Red lobster-like creature 20-40 cm long swimming just above the sediment.
0203:50	Round rock (?), followed by a small cobble.
0204	Rubble of blocks and broken pillows; possibly a small talus deposit.
0205	South-facing vertical scarp a few meters high, with rim of rubble or rough lava.
0207:26	Cluster of rough boulders.
0207:49	Scattered rounded blocks.
0208:14	Ribbed pillows, followed by broken pillows; cracked but still hanging together.
0209	Pillows are still present, but with thicker sediment cover.
0210	The camera is once again above featureless sediment.
0211:17	One small cobble?
0212:35	Prominent tracks.

0215:12	Dark object shaped like a fat cigar; a holothurian?
0220+	A rock? Then a fish?
0222:10	Rocks? Rounded cobbles?
0223:50	Fish or squid.
0224:25	Boulder-sized outcrop.
0224:40	More angular rocks having high relief.
0225:02	Possibly the medial crack of a tumulus or marginal crack of an inflated flow.
0225:10	Back on featureless sediment. Worm tracks appear to be absent here, and other creatures less numerous; but maybe the sled is just flying too high to see them.
0226.30	Coral on a rock; then a starfish.
0227+	Flat cobbles (?) in sediment.
0228:20	Worm tracks still visible when up close.
0232:12	Nice track.
0235+	View is dark; apparently sledding on bottom.
0245+	Fish
0247:47	Rock, half meter wide.
0248	Another block; smaller and more angular, possibly a pillow fragment.
0248:25	Hump, perhaps another pillow.
0249:16	More rocks along left side of view.
0249:40	Angular block about 30 cm wide.
0250	Group of pillow-like blocks.
0253	Camera riding high above sediment.
0254:57	Small cluster of rocks having widths of 2 m or less.
0255+	More scattered cobbles, covered by sediment.
0256:25	Big cluster of pillows; then more pillows or pillow fragments.
0258	Flying high above bottom.
0300	On and off the bottom again.
0306	Close-up view of sediment with worm tracks, and then fly high again.
0307:32	Beautiful large concave tracks.
0308	Sledding on bottom.
0310	Many more worm tracks.
0313:20	Rock?
0315:12	Close-up of beautiful concave track.
0317	Still many tracks, but no rocks.
0319	Sledding again on sediment, then up.
0321	Featureless sediment yet, with no rocks; worm tracks visible in close-ups.
0329:00	Still no rocks; all sediment.
0333:20	Worm tracks still visible in close-up views.
0336	Conical depressions, like ant-lion traps.
0337	Bumps, then dark; sledding?
0338	Brief glimpses of sediment, then sledding near surface so that it is out of focus.
0341	Brief glimpses of sediment; mostly sledding. Still worm tracks, but no rocks.
0344	Still a hash of worm tracks.
0348	A few possible rocks, cobble-sized and thickly veneered by sediment to produce small mounds. Or are they burrows?
0350:10	More little bumps or mounds, 5-10 cm wide.
0352:05	Sediment mound 20 cm wide, with dimple in top.
0354	Worm tracks still visible.
0400	Still just sediment with worm tracks; no rocks at all.
0429	Ditto.
0459.35	Nice concave worm track.
0511.50	A big track of some sort, fairly straight.
0519.11	Nice worm tracks.
0535	End of tape.
0555	Camera sled off bottom when ship is at 20°00.95'N, 154°26.02'W.

Appendix 2: Camera Station C6

This lowering on February 28 (JD059) began at 0824Z and ended at 1315Z. The starting point was at a depth of 5505 m on Cretaceous sea floor near the southern end of a prominent young lava flow in the Hawaiian Trough southeast of the Puna Ridge. Moving NNW, the camera sled crossed the eastern margin of the lava flow at 0950Z and the western margin at 1212Z. The traverse ended at 1314 Z near the western edge of the young flow on sediments possibly overlying an older lava flow (oldest flow in the three-fold classification of Holcomb et al, 1988), perhaps after crossing a small kipuka of sediment-covered Cretaceous sea floor.

A thin but surprisingly extensive layer of sediment occurs on top of the young flow. Dredge sample D5 had been collected earlier along the southern part of the camera traverse, and the track of the dredge in the sediment atop the flow was recorded by the video at 1008Z. The sediment cover, and palagonite rinds found in the dredge sample, suggest that this flow is older than 1 ka. If it is about 2 ka, its eruption may have caused the Kilauea summit collapse that formed the Powers caldera.

Despite extensive sediment cover, the surface morphology of the flow was well recorded. Both flow margins consist largely of pillow lava, and several tumuli were seen near the eastern margin. The axial part of the flow, in contrast, consists mostly of flat and folded surfaces of low relief and consequently is somewhat more obscured by sediment. The marginal heaving suggests that this distal end of the flow is inflated; if so, the pillows probably represent slow extrusions from marginal cracks.

Evidence of heaving was seen also in two areas near the axis of the flow, at1048Z and 1121Z, where the 3.5 kHz record shows that the flow surface is depressed several meters. These zones are interpreted as the boundaries between three flow lobes, which probably correspond to three distal lobes seen on GLORIA images. The 3.5 kHz profile shows that the three lobes stand at different levels, with the northern lobe standing lowest along the southern boundary of the older flow. The three lobes of the younger flow probably were emplaced successively from north to south, with the northward spreading of the northern lobe constrained by the older flow, and the two other lobes following in succession as the preceding lobes stagnated. The lobes probably inflated to successively higher levels because the flow upstream from them was gradually thickening by inflation.

Time	Notes
0831.01	Begin video over sediment having no visible outcrops, south of lava flow. Roiling clouds of sediment as the scale bar hits the bottom.
0835.20	The sediment looks featureless when the camera is high enough for the scale bar to dangle above the sea floor; but close-up views show many fecal tracks, having convex transverse profiles, and many little black objects protruding from the sediment. There are also some white objects resembling golf balls. In some places there appear to be sharp but wavy boundaries between light and dark sediments.
0841	Still sediment, with some worm tracks.
0844	Worm tracks still, and small light and dark objects.
0848	Ditto.
0851	Worm tracks seem more numerous.
0900	Still just sediment.
0902	White projection, maybe a coral.
0915	The scale bar is still generating roiling clouds as it skips over sediment; no rocks are visible yet.
0922.20	A white creature, apparently a crab, is at the left, and nearby there appears to be a rock covered by sediment.

0923.30 (?)	A dark patch here may be a flat rock. The field of view appears to have shrunk and dimmed since we began; have we lost some of the flood lights recently?
0930	Still above sediment.
0944	Ditto.
0945:06	A white holothurian occurs near well-defined worm tracks having concave profiles.
0948:03	Nice worm tracks having internal structures resolved.
0949:30	Dark holothurian on rock.
0950:44	Southern edge of lava flow, with rough-surfaced rocks along left side of view.
0950:56	The flow surface near its margin has 1-3 m of local relief and consists of rounded, globular pillows having both smooth and striated surfaces, and heaved tumuli having medial cracks. Sediment ponds fill hollows between pillows, covering about 40% of the surface.
0951:50	Trapdoor pillow? Surface textures are visible on some pillows, and some elongate pillows project steeply.
0952:58	Tin can; it provides a good scale.
0953:22	Another tin can, perhaps with Olympia beer logo, among pillows. The pillows are connected and evidently belong to a coherent lava flow having a surface relief of 2-3 m; this is not a landslide deposit.
0953:50	Some globular pillows have wrinkly textures.
0954:53	A tall, rounded protrusion.
0955	The flow surface here consists almost entirely of pillows having well-developed striations or corrugations and spreading cracks. The sediment cover is less than 1 m thick.
0956:26	The sled hits solid rock, jarring the video image; and the scale bar is torn off as its suspension cable goes slack. Worm tracks are still numerous in sediment ponds filling hollows among pillows.
1001	The pillows now seem to have a more continuous veneer of sediment; has the sediment been swept off more from pillows nearer the flow margin?
1002:32	Cylindrical lava toe.
1003	The sediment is more extensive now, covering perhaps 80% or even 90-95% of the local flow surface.
1004:10	Rocks have begun to project through the sediment again.
1004:30	Another impact of sled with rock, and view goes dark as sled slides over bottom.
1006	Ditto.
1007	The sled is dragging over the bottom, and unobscured views are rare.
1007.49+	A brief glimpse of worm tracks in sediment.
1008:10-20	Fresh sharp striations in the sediment prbably are drag marks left along this same track by our dredge during Station D5.
1008:30	Scattered rocks in sediment.
1009:48	Subdued rock outcrop in sediment.
1010	Sediment cover now exceeds 95%. Is this because the top of the flow has less relief away from its edges? Maybe the marginal pillows are products of only the last slow spreading along the edge of a flow having a ponded center.
1012	Protruding through the sediment is some rock, including parallel ribs that vaguely resemble channel levees. Worm tracks still occur on the sediment.
1013:20	Another white holothurian.
1014:10	Entirely sediment now.
1014:25	Tumulus having a medial crack.
1014:40	Rock protruding from sediment.
1014:50	Entirely sediment.
1015:20	A pebbly-textured surface, followed by rocks.
1016:00	Large pillows come into view again, briefly; then more sediment.

1016:40	Small rocks protrude, but mostly sediment, which is perhaps about 2 m thick, depending on relief on flow.
1016:55	Beautiful worm tracks.
1018:50	View is dark as sled slides over bottom.
1019:19	A few flat-topped rocks protrude from sediment.
1019:40	The sediment thickly drapes pillows here, and must cover more than 95% of the surface.
1021	Rock outcrops are more common now, perhaps comprising about 20% of the surface.
1023	The lava here is rough and slabby, and cobble-sized blocks are also common, with extensive sediment.
1025:25+	Strange tracks here, having concave profiles, consist of central open spirals and shorter arcs diverging to either side. Short gaps separate the lateral arcs from the central spirals.
1026:22	Big blocks here resemble heaved parts of tumuli.
1026:30	Rocks project through sediment.
1027:30	Sediment cover is about 50%.
1028:30	Ledge of lava.
1029:45+	The sled is crossing an expanse of heaved lobes and pillows that are broken but still in place; resembling inflated tube-fed pahoehoe.
1030:35	Angular broken blocks.
1036:09	The sled repeatedly crashes against rock, and slides over sediment.
1037:50	The sled is still crashing over heaved tumuli having a sediment-pond coverage of 60-80%.
1038	Outcrops have become more sparse again.
1039:20	Here are more of the strange branched-spiral tracks.
1040:30	Rock fragments have reappeared.
1041:30	Pillows among fragmental lava.
1043:40	Jagged lava fragments and some textured pillows, with a sediment cover of about 50%.
1044:40	Rocks protrude through sediment.
1045:30	Now we are beginning to see some broadly draped folds.
1046:30	Draped and broken folds are more common now; they may or may not be shelly.
1047:30	Folds with sediment cover of about 50%.
1048	We are now seeing mostly a mixture of draped folds and tumuli without pillows, which seem concentrated near the flow margin and may represent the final, slower spreading of the flow.
1049:00	Folded or wrinkled sheets about 5-15 cm thick.
1049-1050	Thin polygonal plates among broad sediment ponds having many worm tracks.
1052	There is much sediment here.
1053-1054	Here again are many of the branched-spiral tracks.
1054	Here are more platy fragments of flat and folded lava as sled continues to crash along.
1058:05	Mostly sediment, with some folded lava.
1058:35	Mostly sediment, with some rocks projecting.
1100:19	A striated thin plate is tilted steeply upward.
1100:33	Nicely wrinkled or folded sheets.
1102:30	Mostly sediment with rocks projecting.
1103:50	A white holothurian, and its trail.
1104:38	Sediment.
1105:07	Platy or shelly lava.
1105:54	Nice folds; should look good in still photos.
1106:29	Folded sheets.

1107:30	Expanse of shattered, blocky rubble with 10% sediment.
1109	Pillows have appeared again.
1110:39	Cylindrical pillow.
1111:10	Draped folds again.
1112:10	More pillows, and a white creature on one of them.
1114:20	Platy fragments with 50% sediment cover.
1115:20	Heaved, broken slabs, and scattered pillows having smooth surfaces and sediment cover of 50%; then a pillowed area.
1116:30	Well-formed pillows having breadcrust cracks.
1117:00	Elongate cylindrical pillows.
1117:50	Ditto, with some corrugated textures.
1118:50	Corrugated pillows.
1120:55	Here is a cluster of thin polygonal plates, broken apart but still retaining their original orientation such that their respective surface lineations are still aligned; then more pillows with scattered signs of heaving.
1121:40	Well-formed pillows.
1122:40	Pillows.
1123	The flow surface now consists entirely of pillows and has relief of 1-3 m of and sediment-pond coverage of10-30%.
1123:50	Some large pillows, sediment cover 10%.
1126:02	Pillows.
1127	Sediment ponds among the pillows now appear to cover 30-40% of the surface.
1128:09	Small siliceous sponge.
1129:06	Smooth pillows.
1129:17	The sled crashes here again; many other crashes have not been noted.
1130	The flow surface here still consists predominantly of pillows, many of them being cracked and heaved.
1130:30	Corrugated pillows with 10% sediment cover.
1132:50	Intact pillows with 20% sediment cover.
1135	Sediment cover is patchy among these pillows, covering about 10% of the surface in some places but 30-40% in other places nearby; there appears to have been some redistribution of sediment.
1138-1140	Several crashes of the sled against rock.
1139:59	After crashing for a few minutes, the sled now seems to be above continuous sediment. Perhaps we have crossed the northern margin of the lava flow.
1140:55	There appears to be a dull black coating, perhaps Mn, on pillows or blocks. But a review of this stretch suggests that the dark areas may instead be shadows.
1141:13	Once again we are crossing draped folds etc, much like those seen previously; apparently these are of similar age too, having sediment-pond coverage of 50-90%.
1143	Sediment cover is now 100%, with many worm tracks.
1145:30	Still entirely sediment.
1145:40	Here again are blocks, smooth pillows, and some folds, all thickly veneered by sediment.
1146:30	Smooth sediment again, with no outcrops.
1146:56	Some folds protrude through the sediment.
1147:06	Outcrop.
1147:30	Platy lava cropping out through 80% sediment cover.
1148:20	Nice view of a squid and his shadow.
1148:40	Pillowed terrane having extensive sediment, with sediment ponds covering about 60-80% of the surface and veneering the rest of the pillows.
1150:50	A few folds, and then more pillows, all with much sediment.

1153-1154	The sled is crashing repeatedly, and view is often dark.
1154:30	Slabby lava projecting through sediment.
1154:45	Some smooth, polygonal slabs, and then broad folds.
1156:15	Unbroken, rather flat lava.
1157:20	Smooth pillows initially having sediment-pond cover of 20-40%; then sediment cover decreases to 10-30%.
1158:22	Intact pillows.
1158:50	Sponge? Shadow of a lobster or squid?
1159:35	Field of pillows.
1200:30	Camera is sitll above pillows, rarely striated, having sediment cover of abhout 40-60%.
1202	The sled is crashing repeatedly again, into pillows.
1204:30	Broken pillows and tumuli with 40-60% sediment cover.
1204:40	Pillows and slabby lava.
1205:20	Largely sediment now.
1205:30	Sediment cover exceeds 90% and has many creatures and tracks.
1206:19	Pillows project through sediment.
1207:40	Dominantly pillows.
1209:00	The camera is still flying above pillows and heaved areas having some broad folds and sediment cover of 40-60%.
1210:11	Here is a field of pillows having higher relief and less sediment cover of about 10-30%.
1211:07	Elongate pillows along steep flow margin.
1212:40	Northern edge of the flow.
1213:50	Sediment cover is now 100% and contains many worm tracks and small dark objects that are probably some kind of organism.
1214:40	Worm tracks on mottled sediment.
1215:20	Entirely sediment.
1216:12	Ditto.
1217:37	Ditto.
1217:50	Odd dark object; an organism?
1219:45	We get a brief glimpse of sediment after a long interval of darkness. There are no sounds of crashing; the sled must be sliding across soft sediment.
1221:35	Another glimpse of sediment.
1222	Ditto.
1222:58	Fat white holothurian.
1231:07	The sled is still flying low over sediment.
1235:11	A crab?
1249	Sediment.
1257	Sediment.
1306:06	Sediment; end of tape.

Appendix 3: Camera Station C7

This camera station traversed a southwestern part of the Hawaiian Arch lava field. The camera sled reached the seafloor near the southern margin of the lava field, in a pillowed terrain having a few meters of relief. As the sled moved northward, it climbed about 5 m up the margin of the central young flow onto its top. The flow top has remarkably low relief (generally less than 1 m) and only 5-10% rock outcrop, mainly thin crinkled sheetflow surfaces and scattered small pillows. This part of the flow appears to consist of two very broad, very flat plateaus, standing at depths about 1 m apart. The boundary between the two plateaus shows up as a shallow depression near the axis of the central lava flow. Lava coils along the southern side of the boundary indicate shearing on the surface of the southern plateau while its crust was still very thin; this suggests that the northern plateau represents an older flow lobe (or discrete flow) that confined the spreading of a younger southern flow lobe. The unconfined southern margin of the southern plateau is fringed by uninflated marginal ooze-outs composed both of pillows and broader sheetflow lobes. Though the proportion of pillows increases again near the northern margin of the flow, the 3.5 kHz recording suggests that this margin is confined against a slope that rises about 20 m, in two steps. The video indicates that both steps are composed of lava that is morphologically similar (mixed pillows and sheet flow forms), but probably older, lava of the outer unit of the Arch lava field.

Although extensive, the sediment cover on the young central flow seems thin, probably less than 10 cm, judging from widespread exposure of low-relief flow top and failure of the scale bar to submerge in sediment. The lava in the steps along the northern boundary of the central flow seems to have more sediment cover, about 30 cm thick, and the final 23 minutes of the traverse crossed featureless sediment that appears, on the 3.5 kHz records, to be more than a meter thick.

Uncertainty remains in the comparison of video and bathymetric data because the time delay between the 3.5 kHz bathymetry and trailing camera sled is not known exactly. The delay appears to be about 20 minutes, but it probably varied during the traverse. Refinement of the time delay could require revision of the geologic interpretation; in particular, the northern pillow basalts might not conicide with the bathymetric steps. If the steps do coincide with the pillows, they are mostly likely the clean-swept fronts of much older flows whose tops are elsewhere buried under sediment as thick as several meters.

Time	Notes
15.32.34	Video begins in water column, still descending.
1533:39	Bottom comes into view (nice timing!); pillow fragments and rubble are on a surface of low relief (about 0.5 m). The largest pillows have diameters of 0.5-1 m; some pillows are knobby and composite. Sediment cover is about 50%.
1533:53	Flat polygonal plates 1-3 m side are separated by shallow cracks 10-30 cm wide; looks like a lava-lake crust, but could be slight heaving on a pressure plateau.
1535:16	More polygonal plates, with scattered pillows.
1535:37	Scale bar impacts in sediment among pillows; then pillows become more numerous, commonly 0.5 m wide, among flat lobes 1-3 m wide. Successive impacts suggest that this pillowed surface is rising; probably climbing up a pillowed flow margin.
1537:04	Heaved-open tumulus, to right.
1537:36	Beautiful tumulus or edge of pressure plateau, to left, with cracks 10-30 cm wide separating polygonal plates. Sediment cover is 80-100% on flat areas, and about 20-30% among pillows and knobby pillows.
1538:39	Some elongate pillows; on a slope?
1539:16	Pass over the edge of a flat sediment pond, but soon (by about 1539:40) see more knobby pillows and squat spires.
1540:18	Scale bar is impacting some more as the sled climbs a fairly steep slope of pillows and tumuli having about 10-20% sediment ponds and extensive thin sediment veneer.
1541:13	Edge of pinnacle or scarp rising about 1-3 meters.

1542:17	More pillows.
1542:34	Begin featureless sediment with occasional pillows and more subdued lobate forms.
1542-1544	Mostly sediment.
1544:08+	Series of sled crashes and darkened views out of focus. Still mostly sediment in view, but crashing sounds like rock; sediment must be very thin on a flat surface.
1544:44	Fish, which we have seen rarely at these depths.
1545:02	Some cracks in a mostly flat surface covered by sediment.
1545:23	Scale bar impacts bottom and kicks up roiling plume of sediment, but does not submerge in sediment; suggests that sediment is less than 10 cm thick, perhaps as little as 5 cm?
1545:33	Very nice draped folds protrude from sediment.
1546:00	Sled is flying high; seafloor out of view.
1546:24	Sled still high, but can see shadow of scale bar on seafloor having sediment cover of about 70%. Rock patches look like flat lobes about 10 cm wide, but they could be larger pillows; hard to judge height of scale bar without knowing locations of floodlights.
1546:50	Sled crashing again; view goes dark.
1547-1549	Sea floor out of view; but noise indicates that sled is dragging on bottom, and there are occasional glimpses of bottom, close-up.
1549:28	Close-up of rubble (blocks 10-15 cm wide?) in sediment.
1550-1552	Mostly sediment, about 80%.
1550:19	Nice close-up of spiral worm fecal track.
1550:35	Scale bar flying over flat sediment surface with many small rock patches; looks like a sheetflow surface with 80% sediment cover only 5-10 cm thick, depending on relief.
1550:46	White object, and more shortly after; probably organisms.
1551:42+	Sediment clouds kicked up by scale bar, which again fails to submerge. Sediment in some places seems to have ripples.
1553:00	Mostly sediment; occasional views of fecal tracks.
1553:45	Sudden step up to North over a scarp; above it broken pillows are abundant, and wide fissures penetrate 1-2 m to give rugged rugged relief along rim. Could be a fault, but more likely the edge of a pressure plateau; on rim are many signs of local heaving, and scattered pillows that seem to have oozed from primary cracks. Is this broad lobe the distal part of an inflated tube-fed flow? If so, the marginal pillows are analogous to the pahoehoe ooze-outs that occur along the margins of such flows. RTH has seen inflated submarine flows previously, but not this big and not with the different parts this well defined.
1554:56	Upheaved flank of a tumulus, with anemone perched on it.
1555:06	Wide, shallow cracks outline elongate polygons on flat lava surface.
1555:40	Flat surface with 90% sediment cover; patches of shelly lobes and possibly some pillows, mostly along right side.
1556:51	Pillowed mound, with anemone, rising from mostly flat area.
1557:19	Scale bar rests briefly on low, elongate swell with medial crack.
1557:47	Some broadly lobate forms at edge of flat area, then a rubbly area that may be rising ahead; sled almost crashes, giving many close-ups of rubble with sediment.
1558:57	Scale bar skipping over a surface that looks lobate but could be rubbly, with sediment filling interstices.
1559-1604	Mostly sediment.
1600:00	Scale bar flying a few m above flat sediment; little rock is visible, maybe because too high.

1601:30	Scale bar near bottom; sediment cover still looks like 100%.
1602:30	Some rock to right, maybe lobate, then more rocky patches.
1603:10	Close-ups of100% sediment at least several cm thick, with fecal tracks.
1605:00	Small knobby pillows, 10-25 cm wide, and shelly or rubbly patches surrounded by sediment; but mainly flat, featureless.
1606-1612	Sled mostly flying high, giving dim views of large sediment ponds generally covering 90% of the surface. Sometimes the seafloor is completely out of view, but usually the shadow of the scale bar can be seen on otherwise nearly featureless sediment.
1612-1618	Sediment cover exceeds 90%, is generally 95-100%.
1614:30	Scale-bar impact suggests that sediment thickness may be 10-15 cm, thicker than previously but still thin for extent.
1615:35	Patch of straight, parallel wrinkles.
1618-1624	Sediment cover about 70-80%; mixed small knobby pillows and crinkled sheet flow. Relief is low.
1618:50	Scale-bar impact, to left of star-shaped imprint, once again suggests that sediment thickness is only 5-10 cm.
1621:10	Rock seems to have some shallow cracks, probably primary cracks in a flat, pond-like surface of pressure plateau.
1622:00	Scattered patches of shelly rubble; ditto at 1623:07.
1624-1632	Mostly flying high over 100% sediment cover again. Boring!
1627:30	Vaguely-defined lava coil, to left.
1630:36	Scale-bar impact; sediment looks rippled.
1630:54	Prominent concave track 5-10 cm wide.
1632-1636	Sediment cover 70-90%, with some small, fragile sheet-flow fragments.
1633:26	Outcrops have been increasing and seem to be rubbly.
1633:40	Sediment cover of 90% again.
1634:15	Scale bar hits100% sediment cover with broad concave tracks.
1634:41	Scale bar hits again but does not submerge; then close-up views of sediment with coiled fecal tracks and some of the peculiar spiral tracks with branches.
1636-1637	Flying high over 100% sediment, almost featureless.
1637:16	Brief glimpse of sheety lava surface, perhaps the flank of a local swell.
1637:50	Crashing sounds, as sled hits bottom, suggest that the bottom is rocky and that sediment is very thin despite its great extent. View goes dark for more than a minute as camera sleds over the surface.
1639-1641	Mostly sediment.
1639:11	Brief view of shelly lava.
1639:30	Lava coils and folds with 70% sediment cover.
1639:50	Sediment cover is back up to 90%; totally featureless.
1640:20	Another straight to segmented concave track about 5-10 cm wide; what creature makes these wide tracks? Have not seen holothurians leaving tracks like this.
1641-1658	Folded sheet flows in 90% sediment cover.
1641:09	Scale bar almost submerges in sediment; about 10 cm thick?
1641:30	Primary crack in bumpy, platy surface of a broad, low swell typical on lava lakes and pressure plateaus; then back to 100% sediment cover until 1643.
1644:27	Sediment cover is back down to 90%.
1644:43	Nice broad track, sinuous.
1644:58	Nice anemone.
1645:12	Bluish purple holothurian; scattered small pebbles and some larger patches of rock, but sediment cover more than 95%.

1646:00	Rocky patches 0.5-1 m wide comprise 5% of surface. Most of this looks like flat sheetflow morphology; it doesn't look folded. It does have some low heaving of broad slabs. It looks very much like a lava-pond surface, but could just as well be the top of a pressure plateau.
1648+	Close-up views of sediment with broad concave tracks.
1650:49	Close-ups of cracks and broken plates 10-20 cm wide, then some lobate forms.
1651:20	Scale bar is off the bottom again over 10-15% outcrop that apparently consists of broken pillows 0.5-1 m wide, probably ooze-outs from a low swell.
1651:50	Sediment cover 100% again, about 10 cm thick. Some broad concave tracks again; they often occur in pairs.
1653:26	Still 100% thin sediment cover, on amazingly flat substrate.
1653:41	Low tumulus with anemone.
1654:34	Patches of lobate and shelly, platy rubble, then all sediment.
1656:00	Close-ups of sediment with coiled fecal tracks.
1656:20	Broadly folded sheet flow in a band about 2 m wide, slightly oblique to camera track, to left, like similar bands earlier. Another anemone occurs on this band; they seem to prefer even the slightest swells on this very flat surface. Then 100% sediment again
1657:30	Beautiful high-relief (10-20 cm high?) lava coil about 1.5-2 m wide, followed by broader coils (2-3 m wide) of less relief that barely protrude from sediment. This must have been a zone of shearing, perhaps a lava channel; it might coincide with the narrow topographic low shown on the center of the 3.5 kHz profile.
1659-1708	Sediment cover 100%.
1659:14	Intricate system of many broad concave tracks.
1700:00	Close-ups of tracks reveal bands of small imprints along outside of each raised rim, as if the creature had used little appendages to drag itself along.
1706:00	After many close-ups, the sled rises up to show scale bar skimming over the sediment, leaving behind a plume of sediment probably accumulated while dragging.
1707:56	Beautiful accordion-like folds of lava protruding.
1708-1720	Sediment cover 100%.
1713:55	Scale-bar impacts still suggest that sediment thick is less than 10 cm. For sediment cover to be this thin but extensive, the underlying surface must be extremely flat. Many tracks are still seen in close-up views, but are not worth logging.
1719:43	First rock seen in a long time, a cobble about 20 cm long.
1720-1730	Discontinuously exposed lava folds with 90-99% sediment.
1720:25	Now getting scattered outcrops, mostly linear and probably folds, but some equant slabs or lobes.
1722:00	More patches of folds trending in various directions.
1724-1729	Camera sliding, crashing; dark views mostly of sediment.
1730:13	Scattered rock slabs visible; sediment cover exceeds 95%, and there are still long stretches of 100%.
1732:00	Nice band of broad, shelly folds; video skips ahead to
1737	Sediment cover 100%.
1740:00	Flying high over featureless 100% sediment cover.
1740:50	Beautiful elliptical lava coil1.5 X 2.5 m wide, followed by 1 or 2 other coils; uncertain direction of rotation. Then 100% sediment cover.
1743:43	More patches of folds and rubble, apparently slightly shelly or slabby areas on a flat surface having 70% sediment cover.
1744-1755	Mostly flying high over extensive but variable sediment cover.

1744:30	Sediment cover 100%.
1745:45	Another band appears to be a broad fold, or ooze-out along a crack, about10-15 cm high; then100% sediment again.
1750:24	Brief view of broad slabs with 70% sediment cover.
1755-1811	Sediment cover greater than 95%.
1758:49	Dark object; isolated pillow, lobe, or organism.
1759:50	A few low, irregular slabs or lobes, then sediment again.
1801:18	Another cluster of low outcrops.
1802:17	More low slabs.
1802:36	Low mound of slabby rubble, perhaps 0.5-2 m high and 3-4 m wide, with individual pieces 20-40 cm wide; could see no real pillows.
1804:50	Possibly a broad, shallow primary crack in lava surface, followed by scattered shelly folds and a holothurian.
1809:00	Scattered outcrops, 95% sediment cover.
1810:15	Still about 5% outcrop, apparently as low swells.
1811-1819	Sediment cover 100%, with many tracks visible.
1816:33	Beautiful tracks with fringes of many little footprints, followed by coiled fecal tracks, etc. One sharply defined concave track with fringe is less than 1 m long, as if the creature moved on the bottom only briefly.
1818:26	Nice close-up view of coiled fecal track.
1819:19	Outcrops appear after a long absence; initially 10% of surface, but decrease steadily to 0% over next minute.
1820:10	Broad, shelly folds protrude briefly, then no more outcrops.
1820-1826	Camera sledding and crashing repeatedly; some views of sediment, out of focus. No rocks seen, despite noise.
1826:50	Brief close-up of shelly folds protruding from sediment.
1827-1832	Camera sledding; some sediment, no rock visible.
1832-1845	Sediment cover exceeds 95%; some small lobes, 20-40 cm wide, and slabs of low relief.
1832-1834	Sledding.
1832:14	Brief view of shelly fragments in sediment.
1832:54	Ditto; crashing noise almost continuous.
1834:27	About 10% small slabs or swells of rock, then 100% sediment again within 10-15 seconds.
1836:00	Flying over featureless sediment with less than 1% outcrop, which looks mostly like shelly folds and slabs.
1837:40	A few lobe-shaped rocks in the sediment.
1838:09	Patch of slabby rubble in sediment.
1839:30	Motionless fish above shelly rock; why is it hanging there?
1840:51	Still about 1-10% scattered shelly-look outcrops.
1841:23	Folds, maybe belonging to a broad lava coil.
1844:30	Still getting scattered outcrops over about 1% of the surface, which is distinctly different than the previous long stretches of 100% sediment cover.
1845-1852	Sediment cover 95%.
1846:26	Many of these scattered exposures are quite small, only 10 cm wide in many cases. Sometimes they occur in chains, as if along axes of folds or very low linear swells.
1854:48	A few small pillows?
1855-1900	Sediment cover almost 100%. Scale-bar impacts suggest that sediment thickness is still 10 cm or less.
1856:40+	Brief glimpses of pillow-like rocks among clouds of sediment streaming from sled.

1858:30+	Scattered shelly rocks 20 cm wide; some could be pillows. Later review suggests that a fundamental change in flow morphology occurs near here, as pillows begin to appear toward the northern margin of the lava flow.
1859:54	Strange rock with pillow-like shape but folded surface.
1900-1902	Scattered small pillows.
1900:38	Pillows are definitely identifiable now, with striations and spreading cracks; sediment cover about 90%.
1901:34	Pillows about 1 m high, then close-up of sediment.
1902-1907	Mostly sledding and close-up views of sediment.
1904:28	Brief view of sharp shelly folds, accordion-like.
1907-1912	Scattered isolated pillows 0.5 m wide; sediment cover 95%.
1907:29	Nice cracked pillow, then others about 0.5 m wide, protruding from 70% sediment. The sediment may be thicker here than previously, if robust pillows like these protrude only this much. Alternatively, the pillows could be merely scattered over a dominantly flat substrate; but if so, why?
1909+	Sediment cover is 100% again.
1910:50	Brief glimpse of a few more isolated pillows, which must be strewn widely over this surface. A peculiar distribution.
1911:17	More isolated pillows; then outcrops become more common, though still not exceeding 5% of the surface.
1912-1914	Sledding; mostly sediment.
1914:17+	Beautiful prismatically-cracked pillow 1 m wide, and a few other isolated, slightly elongate pillows 0.5 m wide by 1.5 m long. There may also be some broad, high-amplitude folds.
1915:10	The sled crosses a scarp, possibly pillowed, about 1-2 m high, and the scale bar is broken off. Scattered big pillows about 1 m high. This scarp may bound the edge of the young lava flow, and from here we may be going up a steeper slope of old pillows. If so, how do we explain the scattered pillows seen previously? Are they old pillows that have rolled down onto the flat younger surface? Or young pillows extruded from cracks in the carapace of the younger flow? Or does the pillowed topography also belong somehow to the young lava field?
1916:00	Higher relief now on pillows.
1917:29	Crack about 15-20 cm wide, possibly marginal to a pressure plateau.
1918-1934	About 90% sediment.
1918:08	This fissure could be secondary, but others that follow look primary.
1921:00	Beautiful draped shelly folds.
1922:00	More draped folds, not standing in a high block as previously.
1922:50+	Series of draped, coiled, and fanned folds, which still look shelly and delicate. A flow contact may occur between these folds and the pillows that follow.
1924-1929	Scattered pillows, 0.5 m wide.
1924:25	Possible isolated pillows.
1926:03	Ditto.
1926:40	Scattered pillows about 0.5 m wide protruding from sediment. Relief is 1-1.5 m. Sediment thickness is difficult to estimate but may be 20-50 cm; it must be greater than previously, in order to smooth out the pillowed surface so much. (These pillows do not seem to be isolated like the previous ones.)
1928:37	Knobby pillows.
1928:54	Cracked pillows with a weathered appearance.
1931:05	Thin, upturned plates, followed by fanning folds, then 100% sediment.
1934-1937	Scattered pillows.
1934:13	Rude, knobby folds, then sediment.

1934:44	Scattered pillows begin, 0.5 m wide. Sediment cover of about 70% between pillows may average about 30 cm thick.
1936:19	Upturned slab with folds; looks like a tumulus.
1936:49	Pillows 0.5-1 m wide, then sediment.
1936:57	A shelly fold protrudes, then 100% sediment.
1937-1940	Mostly sediment.
1940:30	Very nice patch of draped folds, then sediment again.
1942:04	One rock, possibly a pillow.
1942:30	Upthrust block of draped folds, then more draped folds.
1943-2007	Sediment cover 100%; probably off of the lava flow, especially if the camera is about 20 minutes behind the 3.5 kHz fish, because the 3.5 kHz record shows the edge of thick sediment at about 1924:00.
1945:00	Feautureless sediment with many tracks. No clue of thickness in view. It's too bad we've lost the scale bar; it should submerge in this deeper sediment. Could this be another flat flow surface, like the other one, but older, such that sediment about 30 cm thick covers it? But the 3.5 kHz record suggests that this sediment is thicker, at least a few meters thick.
2007	End of survey.