Submarine growth and internal structure of ocean island volcanoes based on submarine observations of Mauna Loa volcano, Hawaii

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ABSTRACT

A recent model for the submarine growth of Hawaiian volcanoes indicates that these volcanoes are composed mainly of fragmental lava debris formed as lavas enter the ocean. This model has major implications for locating earthquake hypocenters and for the landslide hazard potential of these and other ocean island volcanoes. Observations from submersible dives and analyses of volcanic glasses collected from the western submarine flank of Mauna Loa indicate that subaerially erupted pillow lavas are abundant at depths of 950 to 1900 m below sea level. Fragmental lava is an important component of ocean island volcanoes, as witnessed during the most recent eruption of Kilauea volcano, but probably is the dominant lithology only in the upper 1 km of the submarine section. A submarine dike complex was discovered 17 km west of the assumed axis of Mauna Loa's southwest rift, which indicates that its intrusive complex is much broader than previously suspected (~20 km vs. ~8 km). The great width of this dike complex may be a consequence of crustal unloading following the South Kona landslide or a normal feature of Hawaiian rift zones that was previously unrecognized.

Keywords: Mauna Loa, Hawaii, submarine geology, pillow lava, dike complex.

INTRODUCTION

The recent eruptions of Kilauea volcano in Hawaii (Fig. 1) have provided insights into the growth of ocean island volcanoes (e.g., Moore et al., 1973). These subaerial eruptions produced lava that entered the ocean over sea cliffs and shattered during quenching to form mostly sand-sized glassy fragmental debris (hyaloclastite). This debris is transported down the volcano's submarine flanks by tidal and gravity currents and mass-wasting events, which create smooth submarine slopes (Moore and Chadwick, 1995). In addition, some subaerially erupted lava flows have been observed to cross the shoreline as coherent flows, especially in lava tubes, forming pillow lavas offshore (Tribble, 1991). These subaerially erupted pillow lavas are thought to be minor in abundance and to have flowed into the ocean for only short distances (<1 km; Moore and Clague, 1987).

These observations led Moore and Chadwick (1995) to propose that the vast bulk of Hawaiian volcanoes are composed of fragmental debris (Fig. 2A). Their model has a thick mantle of fragmental lava (to 7 km thick on the southwest flank of Mauna Loa) covering a central core of pillow lava, which is invaded by the volcano's intrusive complex. The fragmental debris is capped by several kilometers of subaerially erupted flows on mature shield volcanoes (Fig. 2A). Similar models for the structure of ocean island volcanoes, were based on studies of Icelandic subglacial volcanoes (Jones, 1966) and the geology and geophysics of some other ocean island islands (e.g., Cotton, 1969). These models have fundamental implications for ocean island volcanoes, including their internal structure, locating their earthquake hypocenters, and their landslide hazard potential. Here we present the results of four submersible dives and one remotely operated vehicle (ROV) dive that allowed us to evaluate this fragmental-lava model for the submarine growth of Mauna Loa volcano's western flank.

GEOLOGIC SETTING

Mauna Loa is the largest volcano on Earth with a volume of ~80 000 km^3 and a height of ~8.5 km above the surrounding seafloor. It is a broad shield volcano with a central caldera, a short northeast rift zone, and a long arcuate southwest rift zone (Fig. 1). There have been at least 39 Mauna Loa eruptions since 1832; the last was in 1984 (Barnard, 1995). Lavas from six of these historical eruptions entered the sea on the west flank of the volcano. A 1950 eruption produced a river of lava that poured into the ocean and killed fish to a depth of at least ~800 m (Gosline et al., 1954). A 1919 eruption produced coastal explosions and littoral cones similar to recent Kilauea eruptions, but also left submarine lava channels several meters wide and deep. This eruption persisted for about a month and had 10 times the daily output of the most recent Kilauea eruption (Tribble, 1991). An 1877 shallow submarine eruption (vents between 600 and 1200 m below sea level,

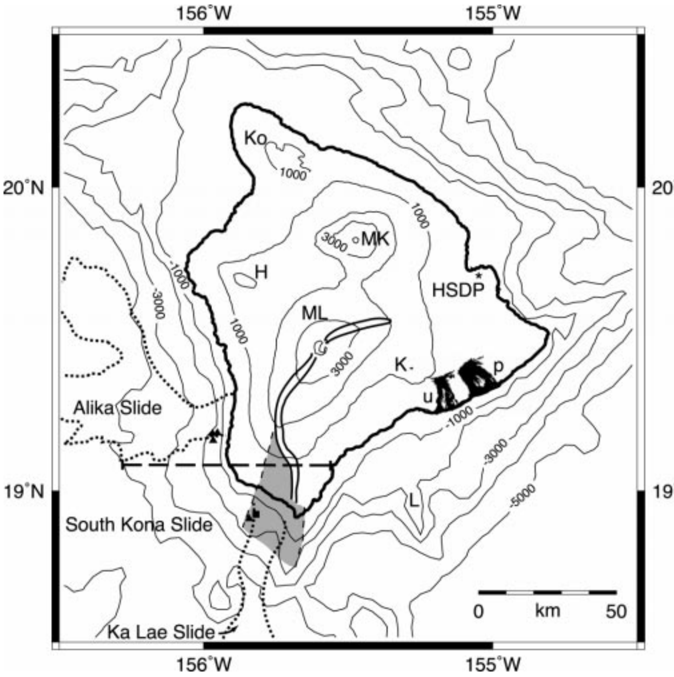

Figure 1. Relief map of island of Hawaii (after Moore et al., 1995) showing locations of dive sites (triangles, except dive 389, which is a square), locations of shield volcanoes (L—Loihi, K—Kilauea, ML—Mauna Loa, H—Hualalai, MK—Mauna Kea, Ko—Kohala), areas of recent Kilauea eruptions along south coast of Hawaii (u—Mauna Ulu, p—Puu Oo), rift zones of Mauna Loa (parallel lines), large, ca. 100 ka, western Mauna Loa landslides (bounded by thick, short dashed line), the Hawaiian Scientific Drilling Project site (HSDP, location shown by star), and cross section of Figure 2 (horizontal thick dashed line). Proposed southwest rift-zone dike complex is patterned and bounded by thin, dashed lines. Contour interval is 1000 m, and thick line marks coastline.

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Geology; February 2001; v. 29; no. 2; p. 163–166; 3 figures; 1 table.

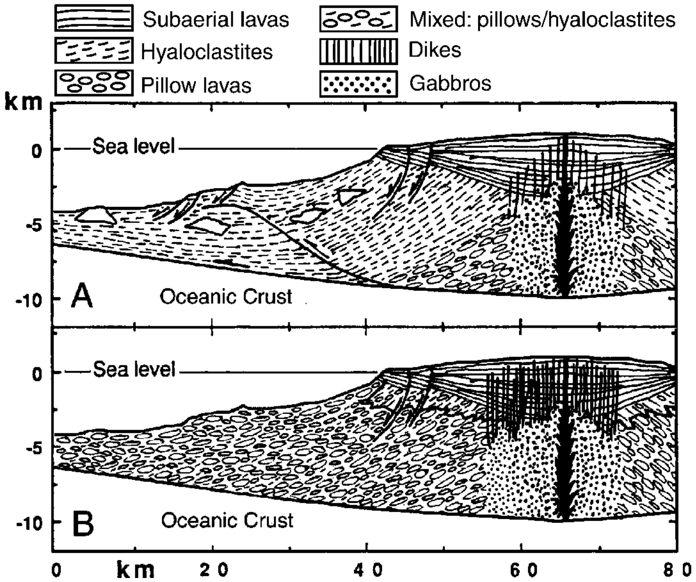

Figure 2. Two cross sections of southwest flank of Mauna Loa volcano resting on Cretaceous oceanic crust (see Fig. 1 for location of cross section). A: Fragmental lava model (from Moore et al., 1995). B: Pillow-lava model (after Moore and Fiske, 1969; Fornari et al., 1979a). Note in B that hyaloclastites are interbedded with pillow lavas except near base of submarine section. Hyaloclastites are dominant rock type in upper 1 km of submarine section. Pillow lavas dominate rest of submarine section. Vertical exaggeration 2×.

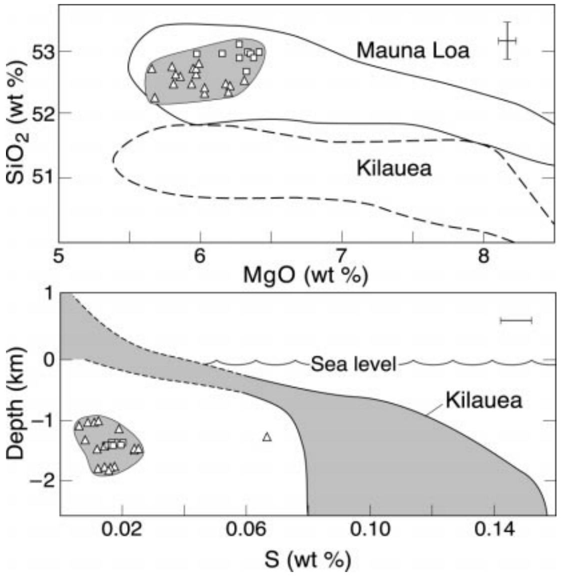

Figure 3. Glass chemistry for submarine volcanic rocks collected along western flank of Mauna Loa (all samples are plotted as open triangles except recent lavas from dive 389, which are squares). Glasses have relatively high SiO_2 contents like other Mauna Loa glasses (fields based on data from Garcia et al., 1995; Garcia, 1996). The low S contents of these glasses ($<$0.03 wt%, except sample P391-3) are indicative of subaerial eruption. Field for Kilauea glasses is from Garcia et al. (1995). Error bars (2 σ) are given in upper right corner of each plot.

mbsl) produced pillow lava glasses with high S contents ($>$1000 ppm; Fornari et al., 1980).

The submarine geology of the island of Hawaii has been mapped via high-resolution bathymetry and side-looking sonar images and is thought to consist of "fragmental quenched lava" and landslide debris (Moore and Chadwick, 1995). Pillow lavas are interpreted to be present only in areas where they are erupted from submarine vents (Moore and Chadwick, 1995). However, observations from submersible dives on steeply dipping parts of Mauna Loa indicate that pillow lava is the dominant rock type (Fornari et al., 1979a). The western submarine flank of Mauna Loa is incised by several landslide scars including the Alika and Ka Lae landslides (Fig. 1), which were inferred to have occurred at ca. 100 ka (Lipman et al., 1990). The eastern scarp of the Ka Lae slide exposes an ~1.5-km-thick section of Mauna Loa's southwest rift zone, which consists of pillow lavas cut by abundant dikes (Fornari et al., 1979a; Garcia et al., 1995).

DIVE OBSERVATIONS

Two areas with landslide-generated scarps along the western flank of Mauna Loa were studied during four PISCES V submersible dives and one autonomous tethered vehicle (ATV) dive (Fig. 1). These areas were selected to allow us to see beneath the surface debris that mantles the submarine slope of the volcano and into the volcano's interior. The northern site is on the southern margin of the Alika slide. The southern site includes the western margin and basal surface of the Ka Lae slide.

The dominant surface rock type in both areas is coherent pillow lava. Pillow lavas were found as far as 13 km from the coastline and are locally covered with a thin veneer ($<$1 m) of talus and mud. The gently dipping floor of the Ka Lae landslide scar between 1380 and 1410 mbsl is draped by very young pillow lava (it has a dark glassy surface and no sediment cover) along a 2.5-km-long traverse. A skylight into an ~2-m-wide lava tube was observed in this flow. On the ridge that forms the western margin of the Ka Lae landslide scarp, a ~600-m-thick section of mostly fragmental debris is cut by numerous, high angle (70–90°), ~0.1- to 2.5-m-thick dikes (Fig. 3). This section probably contains some of Mauna Loa's oldest exposed rocks because the landslide that created this section is thought to have occurred at ca. 100 ka (Lipman et al., 1990). The fragmental lava is predominantly a coarse breccia with pillow fragments from 2 to 20 cm in diameter, although some intervals of sand-sized debris were observed. The discovery of a dike complex 17 km west of the assumed axis of Mauna Loa's southwest rift zone was completely unexpected and indicates that the dike complex is much wider than previously thought (e.g., 20 vs. 8 km; Lipman et al., 1990). Dike complexes are thought to be at least twice the width of surface vent systems on Hawaiian volcanoes (Swanson et al., 1976), which is 2–3 km wide for Mauna Loa.

Near the Alika slide, we made two PISCES dives and one ATV dive across the submarine flanks of Mauna Loa between 1800 and 1300 mbsl, which covered a total distance of ~7.5 km. The steep slope in this area is draped with pillow lavas with only a thin veneer of talus and mud. No fragmental lava was observed. However, we were unsuccessful in finding exposures of stratigraphic sections of $>$10 m thickness in this area.

GLASS COMPOSITIONS

Glass compositions were determined by electron microprobe for 25 volcanic rocks collected along the western submarine flanks of Mauna Loa (Table 1). The submarine glasses are all tholeiitic with relatively high SiO_2 (Fig. 4) and low TiO_2 and K_2O contents, which are features of Mauna Loa basalts (Fig. 4). They are chemically distinct from glasses from recently active shield volcanoes to the north (Hualalai, whose glasses are alkalic; Moore and Clague, 1987) and east (Kilauea; Fig. 4). A limited range in composition was observed for these glasses despite their apparent large age range (recent for dive 389 to older than 100 ka for dive 390). These results support the conclusions of other studies that there has been no change in the major element geochemistry of Mauna Loa lavas since ca. 100 ka (e.g., Lipman et al., 1990; Garcia et al., 1995). The MgO contents of these glasses are relatively low (5.7–6.4 wt%), indicating that they quenched at mod-

TABLE 1. MICROPROBE ANALYSES OF GLASSES FROM MAUNA LOA PILLOW BASALTS

Sample	P389-1	P390-1	P391-3	P392-3	ML1-2
SiO_2	52.97	52.54	52.28	52.81	52.45
TiO_2	2.32	2.37	2.79	2.65	2.46
Al_2O_3	13.56	13.60	13.10	13.24	13.61
FeO*	11.22	11.07	12.43	11.75	11.45
MnO	0.18	0.18	0.19	0.18	0.19
MgO	6.42	6.31	5.68	5.99	6.21
CaO	10.45	10.54	9.96	10.25	10.31
Na_2O	2.42	2.47	2.56	2.43	2.40
K_2O	0.47	0.49	0.53	0.49	0.48
P_2O_5	0.24	0.25	0.27	0.26	0.26
S	0.018	0.010	0.067	0.013	0.016
Sum	100.26	99.83	100.02	99.95	99.65

Note: Values are an average of five spot analyses; see Garcia et al. (1995) for methods used.

erate temperatures (1142–1162 °C based on the geothermometer of Montierth et al., 1995).

A distinctive feature of this new suite of Mauna Loa submarine glasses is their low S content ($<$0.030 wt%; Fig. 4). These low values are indicative of subaerial eruption (e.g., Moore and Clague, 1987; Garcia et al., 1995). One glass, P391-3, which was collected near an ~1-m-deep lava tube in the northern dive area, has a moderate S content (0.067 wt%), which indicates that the glass was probably formed in a submarine eruption. This would be the southernmost eruption of Mauna Loa not associated with its southwest rift zone (see Lockwood et al., 1988).

SUBMARINE GROWTH OF SUBAERIAL MAUNA LOA

Models for the internal structure of Hawaiian shield volcanoes have changed considerably over the past four decades. Early models of a typical Hawaiian shield volcano had a broad foundation of pillow lavas overlain by a thin layer (0.2–2 km thick) of fragmental debris that was capped by several kilometers of subaerial lavas (e.g., Moore and Fiske, 1969; Fornari et al., 1979a). This basic model is supported by seismic and gravity data for the flanks of Hawaii volcanoes (e.g., Hill and Zucca, 1987) and deep drilling on Ascension Island (Nielson and Stiger, 1996). This pillow lava model has served as the structural prototype for interpreting other ocean island volcanoes (e.g., La Palma, Canary Islands; Staudigel and Schmincke, 1984).

A new paradigm for the structure of Hawaiian volcanoes has recently emerged that is based on observations of long-lived eruptions and side-scan images of Kilauea volcano (Moore and Chadwick, 1995). The striking difference between this model and previous structural interpretations of ocean island volcanoes is the extensive thickness of fragmental debris ($>$7.5 km on mature volcanoes; Fig. 2A). The presence of such a vast thickness of fragmental debris under a carapace of subaerial flows has major ramifications for the structural stability and seismic velocity models of ocean island volcanoes. Verifying the mode of submarine growth of Hawaiian subaerial volcanoes is of fundamental importance for understanding the basic structure and landslide hazard potential of ocean island volcanoes and for determining the precise location of earthquakes within these islands.

Our discovery of coherent pillow lavas forming the dominant surface rock type along several segments of the western submarine flanks of Mauna Loa in areas that were previously mapped as ‘‘fragmental quenched lava’’ conflicts with the fragmental lava model for Hawaiian volcanoes. However, our observations are consistent with those from previous submersible dives on Mauna Loa's western flank, which observed pillow lavas to depths of at least 1900 m (Fornari et al., 1979a). In addition, almost all of the pillow rim glasses collected along this coast are degassed, indicating they were erupted subaerially (Table 1). Thus, the dominant recent form of submarine growth along the western flank of Mauna Loa has been by deposition of subaerially erupted lavas that crossed the coastline and quenched on the submarine flanks of the volcano as pillow lavas (Fig. 2B).

How were these subaerially erupted lavas able to cross the shoreline and travel many kilometers down the submarine flanks of a volcano? Although such eruptions are seldom observed, the importance of lava tubes is emphasized by observers in allowing the lava to cross the shoreline without fragmentation (e.g., Macdonald and Finch, 1950). During the most recent eruption of Kilauea, most of the lava entering the ocean during the days of submarine observations flowed through lava tubes rather than as surface flows. Some of these tubes fed open lava ‘‘streams’’ ~1 m wide that carried molten lava at speeds of 1 to 3 m/s (Tribble, 1991). Similar but larger submarine lava channels were observed after the 1919 Mauna Loa eruption (Tribble, 1991). It was even noted for one Mt. Etna eruption that the submarine lavas appeared to have been more fluid than their subaerial counterparts (Moore et al., 1971).

These results are consistent with new findings from the 3-km-deep scientific drill hole into Mauna Kea volcano that indicate that fragmental lava (hyaloclastite) is interbedded with pillow lava. Hyaloclastite is the dominant lithology (~80%) in the upper part of the submarine section ($<$0.9 km) but represents only ~35% of the rock types in the underlying 1.1-km-thick submarine section (DePaolo et al., 1999). The same lithologic variations were observed for the ~3-km-deep Ascension Island drill hole (Nielson and Stiger, 1996) and for the uplifted basement of La Palma in the Canary Islands (Staudigel and Schmincke, 1984).

Why are pillow lavas so abundant along Mauna Loa's submarine west flank? Is it related to the giant South Kona landslide? This slide may have oversteepened the slope of the volcano allowing subaerial lava flows to cross the coastline without fragmentation. There is, however, no evidence of precursor landslides for other ocean island volcanoes with abundant pillow lavas (e.g., Ascension Island) and fragmental deposits have formed on the steep southern slope of Kilauea (Moore and Chadwick, 1995). On the basis of submarine observations on Mauna Loa volcano and the results from scientific drilling and structural studies, we propose that subaerially erupted pillow lavas are a dominant component within ocean island volcanoes, especially below 1 km in the submarine section (Fig. 2B).

An implication of the pillow lava model is that landslides will be smaller and more rare than predicted for the hyaloclastite model (Fig. 2A). Seaward-dipping, poorly lithified fragmental deposits form unstable foundations for ocean island volcanoes. The presence of pillow lavas interlayered with hyaloclastites probably adds stability to the submarine section, making it less prone to failure. Ocean island volcanoes are probably most prone to failure when the hyaloclastite section is overlain by thick lava flow sections, a situation analogous to the most recent Kilauea eruption. Surface flows build a lava bench on top of the hyaloclastites along the shoreline. The poorly indurated hyaloclastites are unstable foundations for the lava benches and periodically collapse (Tribble, 1991). This scenario is consistent with the observation that the headwalls of many large Hawaiian landslides formed near sea level, especially near rift zones (Lipman et al., 1990).

WIDTH OF HAWAIIAN DIKE COMPLEXES?

The width of Hawaiian dike complexes is poorly known. The best-known subaerial exposure of a Hawaiian dike complex is the north rift of Koolau volcano (Walker, 1986), although its eastern flank is below sea level. The subaerially exposed part of Koolau's dike complex is ~8 km wide near where it joins the central magma system (Walker, 1986). Seismic studies of Hawaiian rift zones have indicated that dike complexes are 10–18 km wide (Hill and Zucca, 1987).

The eastern scarp of the Ka Lae landslide exposes a dike complex along what is assumed to be the axis of Mauna Loa's southwest rift (e.g., Fornari et al., 1979b; Garcia et al., 1995). Our discovery of a dike complex 17 km to the west (Fig. 1) that is equal in dike density to the assumed axis of the rift was a complete surprise. Although this newly found dike complex could be part of a landslide block, there is no evidence that the block has rotated (e.g., its two intersecting sets of dikes with parallel strikes have retained their steep dips, which is thought to be characteristic of Hawaiian dike complexes; Walker, 1986). Therefore, the submarine part of Mauna Loa's southwest rift dike complex could be at least 20 km wide, which is wider than most models for Hawaiian rift zones (e.g., ~8 km; Lipman et al., 1990) but is consistent with the width of dike complexes for rifts of similar length on other volcanoes (Walker, 1999).

Why is this rift so wide compared to previous models for Hawaiian volcanoes? It has been suggested that the active zone of Hawaiian rifts migrates toward areas involved in recent landslides or slumping (e.g., Swanson et al., 1976; Lipman, 1980). The large curvature in Mauna Loa's southwest rift (Fig. 1) has been interpreted to have formed by rift migration following the Ka Lae and Alika landslides (e.g., Lipman et al., 1990). However, the newly discovered dike complex predates these slides and lies along the extension of the rift's large curvature (Fig. 1). Prior to the Ka Lae slide there was a giant, late Pleistocene South Kona landslide that removed much of the western flank of the volcano (Moore et al., 1995). It is curious that recent volcanic activity along the southwest rift has been concentrated along the eastern margin of the lower part of the rift, which is opposite to the dike migration hypothesis. Alternatively, this rift may be a composite of two different rifts like the north rift of Loihi and the east rift of Haleakala volcanoes, or Hawaiian rift zones may be much broader than commonly thought, which is consistent with some geophysical interpretations (e.g., Hill and Zucca, 1987).

ACKNOWLEDGMENTS

We thank the Hawaii Undersea Research Lab sub team, especially Chief Pilot Terry Kerby, for their technical help during our dive programs. Discussions with Dan Fornari, Pete Lipman, James Moore, Ed Stolper, and Frank Trusdell on Hawaiian geology, and a review by L.D. Geist were helpful in preparing this paper. This work was supported by National Science Foundation grant OCE-9729894 and the National Oceanic and Atmospheric Administration Underwater Research Program.

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Manuscript received July 17, 2000
Revised manuscript received November 6, 2000
Manuscript accepted November 6, 2000

Printed in USA