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RESEARCH ARTICLE

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Formation of submarine flat-topped volcanic cones in Hawai'i

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Abstract High-resolution bathymetric mapping has shown that submarine flat-topped volcanic cones, morphologically similar to ones on the deep sea floor and near mid-ocean ridges, are common on or near submarine rift zones of Kilauea, Kohala (or Mauna Kea), Mahukona, and Haleakala volcanoes. Four flat-topped cones on Kohala were explored and sampled with the *Pisces V* submersible in October 1998. Samples show that flat-topped cones on rift zones are constructed of tholeiitic basalt erupted during the shield stage. Similarly shaped flat-topped cones on the northwest submarine flank of Ni'ihau are apparently formed of alkalic basalt erupted during the rejuvenated stage. Submarine postshield-stage eruptions on Hilo Ridge, Mahukona, Hana Ridge, and offshore Ni'ihau form pointed cones of alkalic basalt and hawaiite. The shield stage flat-topped cones have steep (~25°) sides, remarkably flat horizontal tops, basal diameters of 1–3 km, and heights <300 m. The flat tops commonly have either a low mound or a deep crater in the center. The rejuvenated-stage flat-topped cones have the same shape with steep sides and flat horizontal tops, but are much larger with basal diameters up to 5.5 km and heights commonly greater than 200 m. The flat tops have a central low mound, shallow crater, or levees that surrounded lava ponds as large as 1 km across. Most of the rejuvenated-stage flat-topped cones formed on slopes <10° and formed adjacent semicircular steps down the flank of Ni'ihau, rather than circular structures. All the flat-topped cones appear to be monogenetic and formed during steady effusive eruptions lasting years to decades. These, and other submarine volcanic cones of similar size and shape, apparently form as continuously overflowing submarine lava ponds. A lava pond surrounded by a levee forms above a sea-floor vent. As lava continues to flow into the pond, the lava flow surface rises and overflows the lowest point on the levee, forming elongate pillow lava flows that simultaneously build the rim outward and upward, but also dam and fill in the low point on the rim. The process repeats at the new lowest point, forming a circular structure with a flat horizontal top and steep pillowed margins. There is a delicate balance between lava (heat) supply to the pond and cooling and thickening of the floating crust. Factors that facilitate construction of such landforms include effusive eruption of lava with low volatile contents, moderate to high confining pressure at moderate to great ocean depth, long-lived steady eruption (years to decades), moderate effusion rates (probably ca. 0.1 km^3/year), and low, but not necessarily flat, slopes. With higher effusion rates, sheet flows flood the slope. With lower effusion rates, pillow mounds form. Hawaiian shield-stage eruptions begin as fissure eruptions. If the eruption is too brief, it will not consolidate activity at a point, and fissure-fed flows will form a pond with irregular levees. The pond will solidify between eruptive pulses if the eruption is not steady. Lava that is too volatile rich or that is erupted in too shallow water will produce fragmental and highly vesicular lava that will accumulate to form steep pointed cones, as occurs during the post-shield stage. The steady effusion of lava on land constructs lava shields, which are probably the subaerial analogs to submarine flat-topped cones but formed under different cooling conditions.

Key words Volcanic cone · Submarine eruption · Lava pond · Hawai'i · Rift zone · Rejuvenated stage eruptions · Pancake domes

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Introduction

Submarine flat-topped, or disk-like, volcanic cones have been documented on or near active spreading centers (Lonsdale 1983; Batiza and Vanko 1984; Batiza et al. 1989; Smith and Cann 1992; Kleinrock and Brooks 1994; Magde and Smith 1995; Scheirer and Macdonald 1995; Rappaport et al. 1997) and from the deep sea floor (Hollister et al. 1978; Batiza 1982, 1989; Searle 1983; Smith 1988, 1996; Smith and Jordan 1988; Bridges 1995, 1997) where they constitute approximately half of the volcanic edifices. Similarly shaped, although usually much larger, volcanic landforms are also common on the surface of Venus (McKenzie et al. 1992; Pavri et al. 1992; Fink et al. 1993; Bridges 1994; Sakimoto 1994; Smith 1996). Above sea level on Earth, such volcanic landforms are extremely rare, although several have been described from the Newer Volcanics in northeastern Australia (Ollier 1967, 1969).

We have recently discovered that similar landforms are common on the submarine rift zones and upper submarine flanks of the Hawaiian Islands. High-resolution bathymetric data, combined with visual observations on several of them, shed light on the processes that form these flat-topped volcanic cones.

In this report we describe these volcanic features from around the Hawaiian Islands and develop a model for their formation that accounts for their presence on Earth primarily in the submarine environment. Throughout this paper we refer to these features as flat-topped volcanic cones. The evidence, discussed herein, suggests that they are monogenetic vent constructs on much larger volcanoes. These cones have the shape of a truncated cone, or frustrum. However, they did not form originally as complete cones that subsequently had their apices removed, but rather grew from the beginning with the flat-topped shape. None of the terms commonly used to describe these features convey their extreme flatness or low-aspect nature. Their height/diameter is similar to that of a U.S five-cent coin.

Methods

Flat-topped volcanic cones were mapped around the Hawaiian Islands in March 1998 using a 30-kHz multibeam Simrad EM300 sonar system hull mounted on the *M/V Ocean Alert*. The EM300 system consists of 137 beams that can be divided into three to nine independently beam-steered sectors for independent active steering according to pitch, heave, roll, and yaw. The system has a variable beam angle from 1–4°, operator adjusted as a function of depth. All navigation was done using shore-based differential GPS.

Bathymetry has a vertical and horizontal resolution approximately 2.0 and 0.2% of water depth, respectively. The bathymetric data were gridded at 30 m and the backscatter data were mosaicked at 10 m for all but the shallow section of Kilauea's Puna Ridge, which were gridded at 10 m and mosaicked at 5 m. Perspective images of the bathymetry were computed with apparent illumination from azimuth 335° and an elevation of 45°. All the figures are UTM projections. The surveys imaged more than 100 flat-topped volcanic cones, previously unrecognized around the Hawaiian Islands.

Previous work

The common presence of these curious flat-topped volcanic cones on the upper submarine slopes of the Hawaiian volcanoes was not known before they were imaged during this high-resolution survey. Previously, a single one had been identified at a depth of 700 m on the Puna Ridge, the submarine east rift zone of Kilauea Volcano, based on single beam surveys (Moore 1971) and SeaBeam surveys (Clague et al. 1993). Similarly shaped volcanic cones were described from the deep ocean floor at several localities and were variously called low domes (Lonsdale 1983; Batiza and Vanko 1984), flattened domes (Rappaport et al. 1997), truncated cones (Searle 1983; Batiza and Vanko 1983; Smith and Jordan 1988), knobs (Kleinrock and Brooks 1994), flat-topped seamounts (Bridges 1995, 1997), or disk seamounts (Lonsdale 1983). They are thought to have formed near mid-ocean ridge spreading centers.

Many of these studies have used quantitative parameters (flatness, the radius of flat top divided by radius of base; or aspect ratio, the height divided by basal diameter) to describe these general shapes (e.g., Batiza and Vanko 1984; Smith 1988; Scheirer et al. 1996; Rappaport et al. 1997). An examination of 145 submarine volcanoes on the deep ocean floor of the southeast Pacific revealed that most are roughly circular in plan and that 56% have a flat top creating a flat-topped cone shape (Searle 1983). Such volcanoes have a mean diameter of 5.4 km, an aspect ratio of 0.1–0.05, and an average volume of approximately 3 km^3. Surveys of two young seamounts on the East Pacific Rise at 12°45′ N at depths of 2800–2500 m show flat tops (Fornari et al. 1987). One is approximately 5 km and the other 8 km in diameter, and their aspect ratios are 0.04 and 0.02, respectively.

On the deep ocean floor flanking the Hawaiian Ridge, GLORIA side-scan sonar showed 390 seamounts, of which approximately 55% were considered flat-topped or pancakes (Bridges 1997). Like the submarine flat-topped volcanic cones imaged in the eastern Pacific, they were thought to have formed on young crust near a mid-ocean ridge, unrelated to Hawaiian hotspot volcanism. These sea-floor volcanoes average approximately 4 km in diameter with only 7 of 217 exceeding 9 km in diameter. Bridges' interpretation of the side-scan images was that the volcanoes are flat on top and flanked by relatively steep scarps. Large flat-floored craters indent their summits in some places. In general, they have a low, flat profile compared with subaerial volcanoes and have aspect ratios from 0.01 to 0.1.

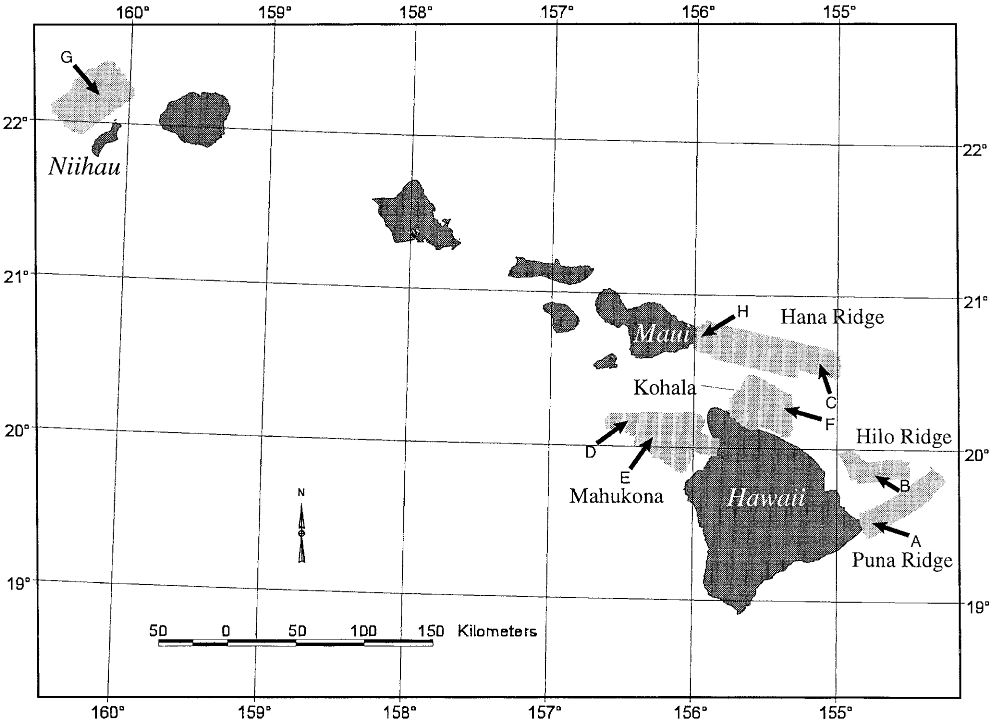
Near-ridge cones with this shape have been described as monogenetic in origin (Smith and Cann 1992; Kleinrock and Brooks 1994). They are distinct from submarine volcanoes that have higher aspect ratios and polygenetic construction. Surveys of some larger seamounts (~10 km in diameter) in linear arrays near mid-ocean ridges show them to also have flat tops and steep margins (Clague et al., in press); however, these were constructed during numerous sequential eruptions over time periods of up to ~100,000 years, as seen in the multiple offset calderas that indent their summits (e.g., Hammond 1997; Clague et al., in press). These volcanoes tend to be somewhat larger (diameter 7–10 km), but are also significantly taller (most are >800 m) which gives them higher aspect ratios (0.10–0.21, average 0.15 for 17 seamounts; Clague et al., in press).

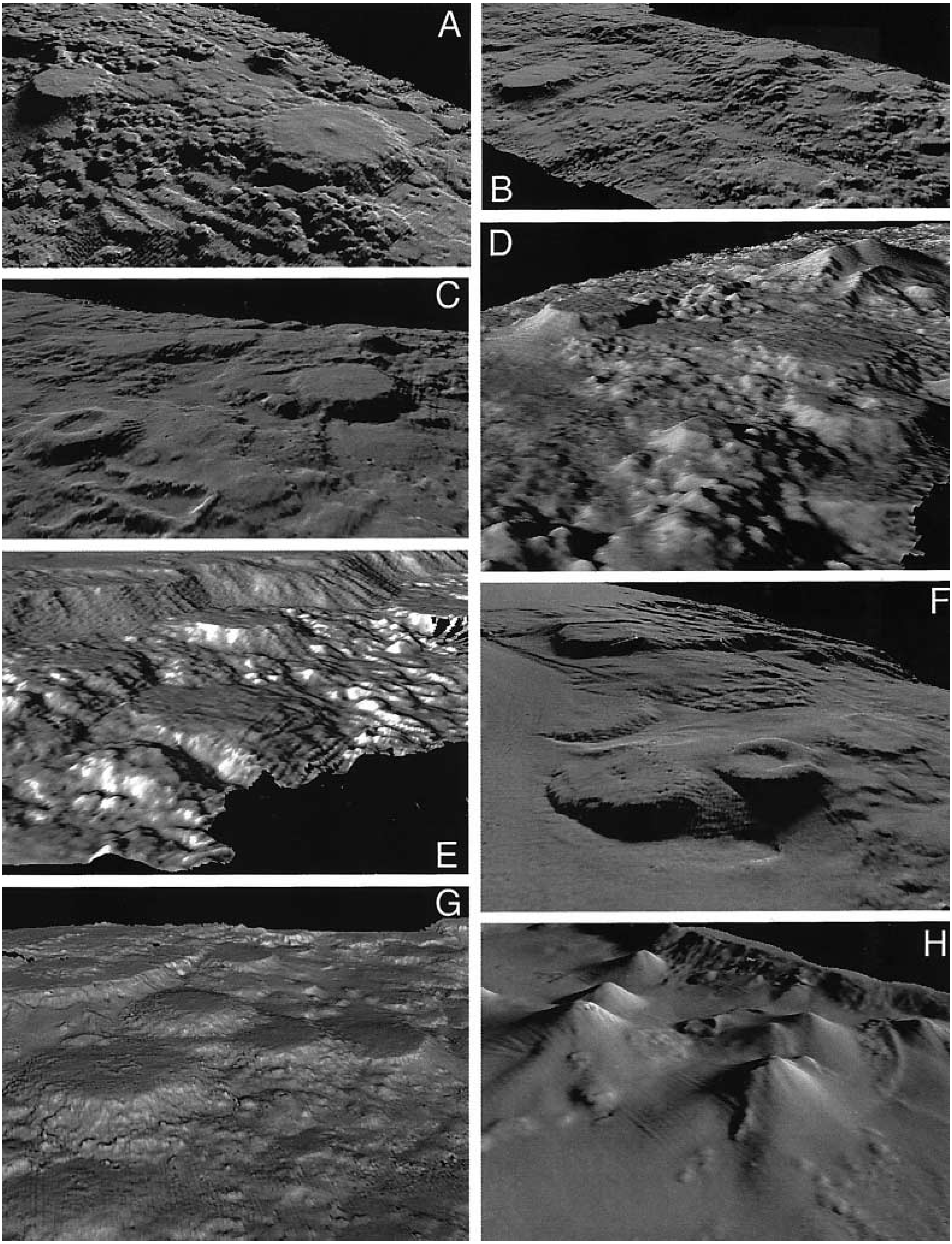
Fig. 2A–H Perspective views of the groups of flat-topped volcanic cones at sites offshore Ni‘ihau, Maui, and Hawai‘i, and one group of pointed volcanic cones offshore Maui as shown in Fig. 1. All views shown with no vertical exaggeration. **A** The Puna Ridge viewed from the east-southeast. The summit of the large flat-topped cone is 2.6 km across. This cone is shown in detail in Fig. 3A. **B** The Hilo Ridge viewed from the southeast. The top of the large, flat-topped cone on the left edge is 2.2 km across. This cone is shown in detail in Fig. 3B. **C** The deep Hana Ridge viewed from the southeast. The top of the flat-topped cone near the right edge is 2.0 km across. **D** The Mahukona rift zone viewed from the southwest. The top of the flat-topped cone in the upper left is 1.9 km across. The flat-topped cone with a central crater located in the middle of the right edge is shown in detail in Fig. 5B, and the pointed cone in the background is shown in detail in Fig. 10B. **E** The south flank of Mahukona viewed from the southwest. The top of the largest flat-topped cone in the foreground is 1.7 km across. **F** The northeast flank of Kohala viewed from the southeast. The top of the flat-topped cone in the lower left is 3 km across. This cluster of flat-topped cones is shown in more detail in Fig. 8. **G** The northwest flank of Ni‘ihau viewed from the northwest. The flat top of the largest flat-topped cone at the left center is 3.7 km across. The *star-shaped* lava pond levee on top of this cone is shown in detail in Fig. 9C. The lava delta in the center background is shown in Fig. 9D. **H** The shallow Hana Ridge viewed from the northeast showing a cluster of pointed volcanic cones. The top of the steep slope in the background is a near-shoreline reef at about –130 m

Submarine Hawaiian volcanic cones

We imaged 112 flat-topped volcanic cones and 22 pointed volcanic cones from seven locations around Hawai‘i, Maui, and Ni‘ihau (Figs. 1, 2). The flat-topped volcanic cones are divided into two groups, which we think are related to the composition of the lava that formed them and therefore to the eruptive stage in which they formed. All the flat-topped cones located near Maui and Hawai‘i apparently formed during the shield stage and consist of tholeiitic basalt. Those on the northwest flank of Ni‘ihau probably formed during its rejuvenated stage and most likely consist of alkalic basalt. The pointed volcanic cones are inferred to have formed on shallow submarine rift zones during the postshield stage and limited samples show they consist of alkalic basalt and hawaiite. In map view, all these cones are remarkably circular, or in the case of most of those on Ni‘ihau, semicircular.

Fig. 1 Map of the Hawaiian Islands shows offshore areas where flat-topped volcanic cones have been mapped (*pale gray shading*). The *lettered arrows* indicate the view direction for the eight oblique images in Fig. 2

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Shield stage flat-topped volcanic cones

Sixty-three flat-topped volcanic cones were imaged at five sites offshore from Maui and Hawai‘i. Only the 42 cones that are circular or nearly circular with a well-defined basal depth were measured. In general, three characteristics mark them as unique volcanic constructs. They are remarkably circular in plan, they are nearly flat and horizontal on top, and they are almost disk-like, surrounded by a steep scarp with an aspect ratio (height/basal diameter) less than 0.14. Many variants occur, but most show these general features.

The shield stage flat-topped volcanic cones are common along the submarine rift zones (Fig. 2A–D) of Kilauea Volcano (Puna Ridge), Kohala (or Mauna Kea) Volcano (Hilo Ridge), Haleakala Volcano (Hana Ridge), and Mahukona Volcano, and a few are located on the submarine northeast flank of Kohala Volcano and the south flank of Mahukona Volcano, as shown in Fig. 2E and F. Most of this group of flat-topped cones have a basal diameter between 1 and 3 km and a height between 100 and 300 m (Figs. 3, 4). The volume of individual cones is between 0.1–1.4 km^3. Most have a remarkably horizontal summit plateau with a low central dome, or a central crater. Related features are drained lava ponds formerly impounded by horizontal levees (Fig. 5A).

All these flat-topped cones are probably formed of tholeiitic basalt erupted during the shield stage of the parent volcano because all samples known to be from flat-topped cones on rift zones are tholeiitic and because flat-topped cones do not increase in abundance after the shield stage. All lavas from Puna Ridge are tholeiitic (Moore 1965; Garcia et al. 1989; Clague et al. 1995). In addition, several tholeiitic samples from Mahukona were recovered during *Pisces V* dive 72 in 1988 from two flat-topped cones (Clague and Moore 1991). All 25 volcanic samples recovered from four flat-topped cones on the flank of Kohala during *Pisces V* dives 405 and 406 in 1998 are tholeiitic basalt (D.A. Clague and J.G. Moore, unpublished data). Dredges on the Hilo Ridge that recovered tholeiitic basalt are too poorly located or were on the bottom for such long distances that it is not known if they sampled any of the flat-topped cones (Moore 1966; Garcia et al. 1989; Moore and Clague 1992; Yang et al. 1994). Dredges on Hana Ridge did not sample near any of the flat-topped cones revealed in our new surveys (Moore et al. 1990).

The overall characteristics of the flat-topped cones are similar. The outer slope is steep at 25–30°. The basal diameter averages 1.25 to 2 times the diameter at the outer rim of the summit plateau (Fig. 4A). The diameters of the volcanic cones are 20 to 7 times their height, so that the aspect ratio (height/diameter) ranges from 0.05 to 0.14 (Fig. 4B). This range of aspect ratios includes that of a U.S. five-cent coin (0.086).

The flat tops of most of the volcanic cones are remarkably horizontal. The lowest and highest points of the rim are commonly within 10–20 m of each other; however, it is common for the nearly flat top to be slightly dome shaped so that it is higher in the center. The dome generally rises from 10 to 60 m above the abrupt slope change at the edge of the plateau (Fig. 4C). The slope from the edge of the plateau to the domed central summit is generally from 1 to 4°. Profiles of several slopes are shown in Fig. 6.

Some flat-topped volcanic cones were modified by one or more craters in their summit plateaus. The craters may be large and extend nearly to the edge of the plateau, or they may be smaller leaving a circular band of horizontal terrain between their outer edge and the rim of the plateau (Fig. 5B, profiles in Fig. 6). Most craters are centrally located, but some are off center. The craters are never deeper than the level of the surrounding terrain. A few flat-topped cones have been modified by later faulting and extension across the rift zone (Fig. 5C).

In some locations the tops of the flat-topped cones are distinctly non-horizontal. Those on the Hana Ridge are tilted to the southwest towards Hawai‘i (Fig. 7) at 1.0–1.3° (profiles in Fig. 6). Previous work, based on the non-horizontal nature of submerged coral reefs, has shown that the entire ridge has tilted as a result of the volcanic load added to the oceanic crust during the growth of new volcanoes making Hawai‘i (Moore et al. 1990). Because of the original nearly horizontal nature of the summit plateau of the flat-topped cones, they also serve as indicators of post-volcanic tilt. The flat-topped cones are more reliable tiltmeters than the reefs because of their regular, circular shape.

The four Kohala flat-topped cones also have flat, but not horizontal, tops. Three of them (labeled A, B, and C in Fig. 8) are tilted towards Hawai‘i 4–5°, whereas the fourth is apparently less steeply tilted. The cones may either be rooted in landslide blocks that slid down as part of the Pololu landslide (Moore et al. 1989) and came to rest tilted towards Hawai‘i, or, more likely, they are tilted for the same reason as those on the Hana Ridge.

Most of these cones did not form at their present depths. Submerged coral reefs around the islands indicate that the flat-topped volcanic cones on Kohala, Mahukona, Hilo Ridge, and Hana Ridge have isostatically submerged at least 1000 m, so that the original depth of formation for the flat-topped cones was at least that much shallower than their present-day depths. On the still active Puna Ridge, there are flat-topped cones as shallow as 700 m. This 700 m depth is similar to the shallowest formation depth of the old, subsided flat-topped cones.

These flat-topped cones have simple forms and volumes consistent with formation during single, long-lived eruptions. The lack of complexities in their vent structures suggests a monogenetic volcanic history. The presence of craters in some cones indicates that an episode of draining occurred after construction of the horizontal flat tops.

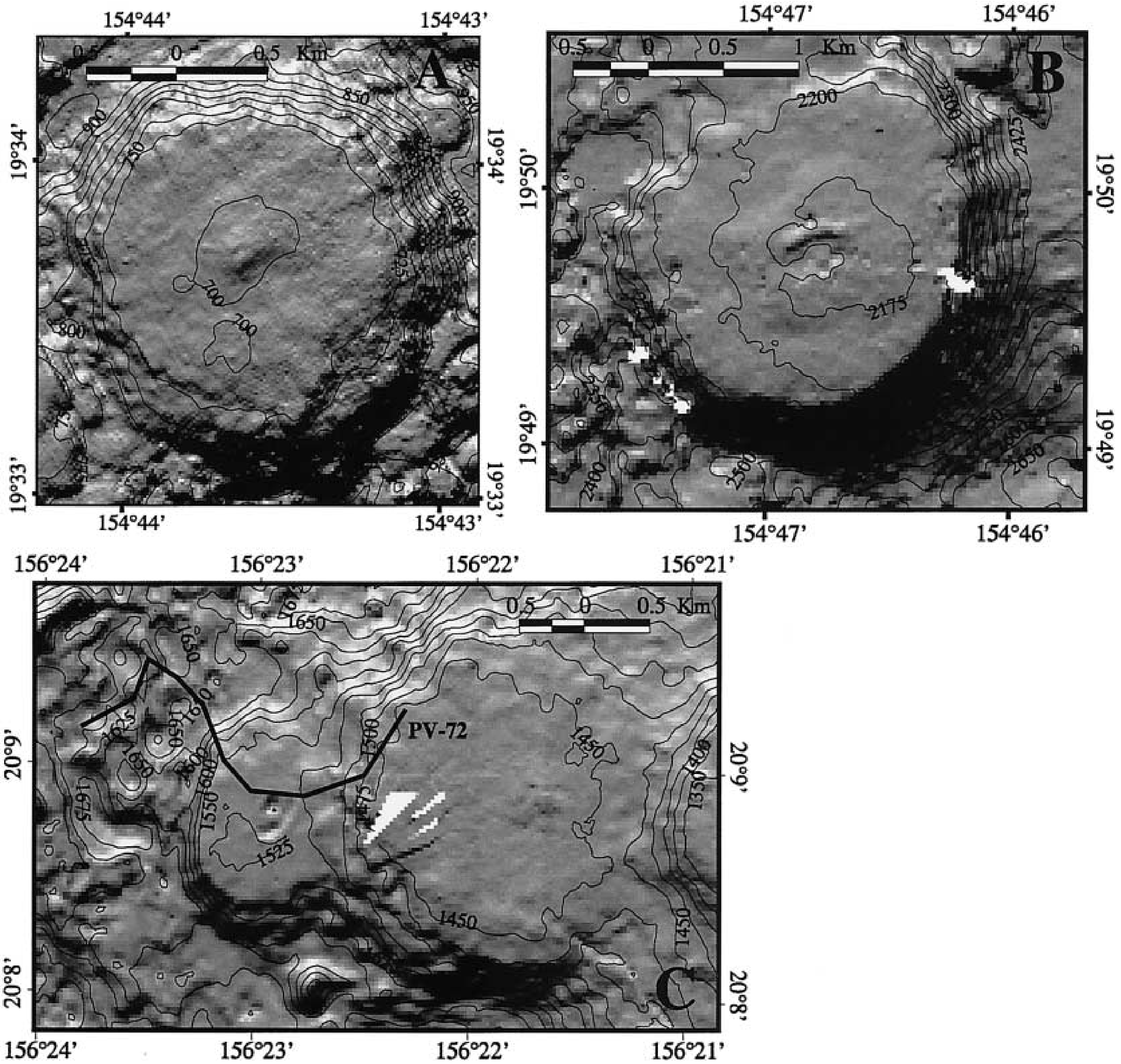

Fig. 3A–C Northwest illuminated multibeam maps of three flat-topped volcanic cones. Note circular shape, steep outer walls (20–30°), and nearly horizontal summit plateau with small hump a few tens of meters high. Contour interval is 25 m **A** on Puna Ridge, **B** on Hilo Ridge, and **C** on Mahukona. The track of Pisces dive PV-72, adjusted to fit the new bathymetry, is shown in **C**

Rejuvenated stage flat-topped volcanic cones

Other circular and semi-circular flat-topped volcanic cones occur on the northwest submarine flank of Ni‘ihau (Figs. 1, 2G). Few of the 44 identified flat-topped cones could be measured accurately because, due to overlap and steep slopes, the depth of the base could not be determined accurately. Most of these features are larger and taller than those on the rift zones, reaching 5.5 km in diameter and >300 m in height (Figs. 4, 9 A), but with the same low aspect ratio. Most of the cones in this second group have semicircular terraces abutting against them. The terraces were apparently fed from the cones upslope (Fig. 9B). These lower, terrace-like edifices tend to assume a semi-circular shape, because they are molded on one side against the higher flat-topped cone from which they were apparently fed in much the same way as a subaerial sequence of terraces on Mt. Etna (Guest et al. 1984). The summit of each terrace stands below the base of the terrace above it, and in places several such terrace constructs step down a regional slope, each lower one apparently fed from a breach in the side or near the base of the upper adjacent one. The large Ni‘ihau flat-topped cones are

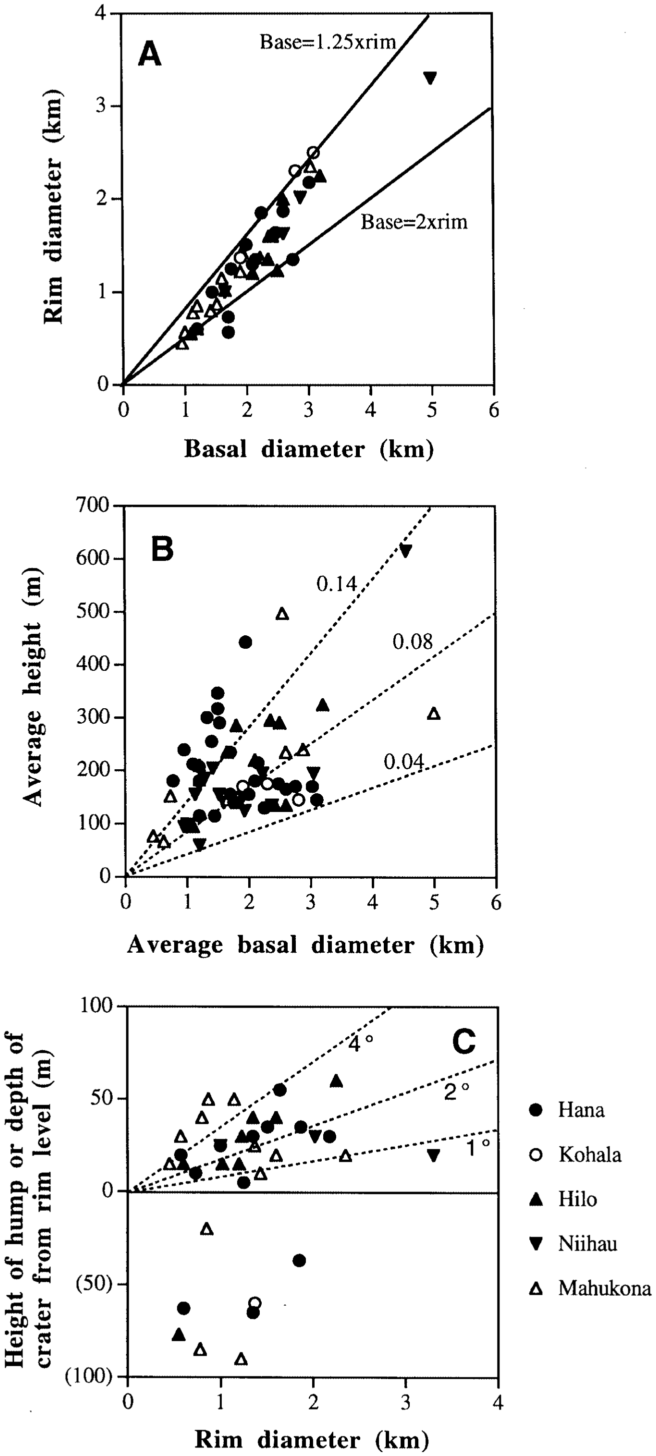

Fig. 4A–C Characteristics of pointed and flat-topped volcanic cones at five to six locations. **A** Basal diameter ranges from approximately 1.25 to 2 times the diameter at the rim of the summit plateau of flat-topped volcanic cones. **B** Basal diameter vs height of all cones; *dashed lines* indicate values of aspect ratio (height/diameter). Pointed volcanic cones generally have aspect ratios >0.14, and flat-topped volcanic cones have aspect ratios <0.14. **C** Height of central hump (or depth of central crater) relative to the diameter of the summit plateau of flat-topped volcanic cones. Inclination from rim to top of central hump ranges from approximately 1 to 4° (*dashed lines*)

mostly of this terrace type that resemble a flight of stairs.

Measurement of the sizes, particularly the heights, of many of these volcanic cones is somewhat arbitrary because they are overlapping and constructed on the slope of the island; however, they share numerous features with the shield-stage flat-topped cones including the common presence of a central mound (Fig. 9A). Only two of the flat-topped cones have craters, and one has a nearly 1-km-diameter irregular lava pond perched on its summit (Fig. 9C). The perched pond apparently formed late in the history of the cone after most of the original lava pond within the cone had solidified to provide a crust rigid enough to support the levee-impounded younger pond which stood as much as 30–35 m above the nearly flat summit plateau. The levee surrounding the pond is breached on the south side and 100- to 200-m sections of the levee were rafted on the flow that emerged when the levee breached and drained the pond. These blocks are strewn to the south of the pond.

Lava that erupted above the main break-in slope at one location flowed over the break-in slope and formed a sloping lava delta (Fig. 9D) that superficially resembles the circular flat-topped volcanic cones, mainly in its nearly circular plan and the nearly flat summit region. The lava that formed the delta was tube-fed from above the break-in slope. Other rejuvenated stage eruptions above the break-in slope (Fig. 2E) formed irregular volcanic constructs instead of circular flat-topped cones.

The summits of the Ni‘ihau flat-topped cones display high backscatter, which we interpret as thin sediment cover, indicating their relative youth. We think they are rejuvenated stage cones erupted as part of the rejuvenated stage Kiekie Volcanics on Ni‘ihau and thus are probably composed of alkalic basalt (Macdonald 1947; Clague 1987).

The rejuvenated stage flat-topped cones, like the shield stage ones, all have simple forms and appear to be monogenetic.

Postshield stage pointed volcanic cones

Pointed cones are common on long Hawaiian submarine rift zones, often in clusters, but tend to be located in shallower water than the flat-topped cones (Figs. 2F, 10). They are steeper with an aspect ratio from 0.11 to 0.25 (average for 19 is 0.183; Fig. 4B). Unlike subaerial cinder/spatter cones, they do not have summit craters and they tend to be taller (67–615 m tall, average for 19 is 265 m). The 615-m-tall pointed cone on Mahukona has been sampled (Fig. 10B; Clague and Moore 1991; Garcia et al. 1990) as has one on the Hana Ridge (D.A. Clague, unpublished data). Another may have been sampled on the Hilo Ridge (Reiners et al. 1997). They are formed of alkalic basalt (Mahukona) or hawaiite (Hana Ridge) that probably erupted during the post-

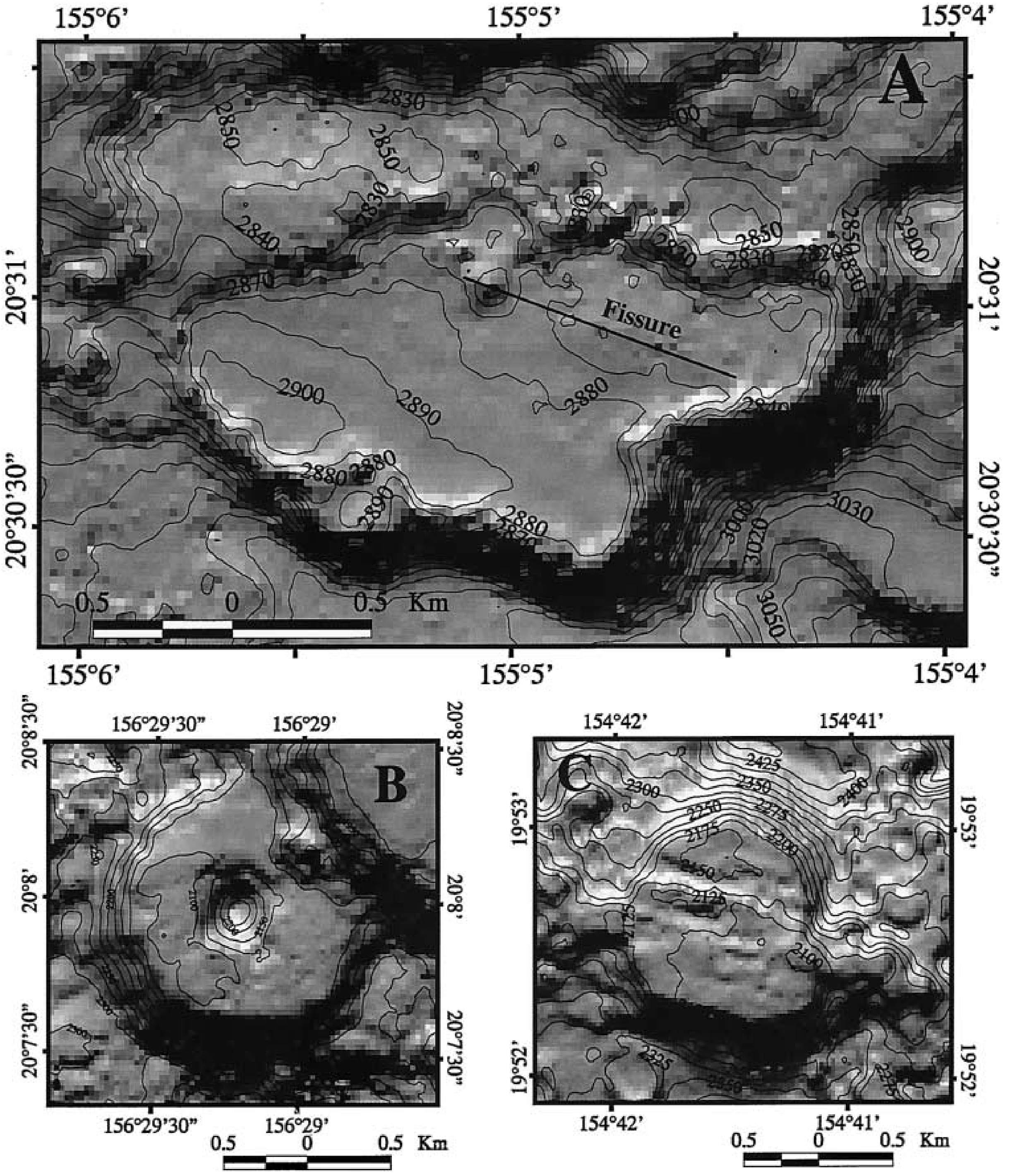

Fig. 5A–C Multibeam bathymetric maps showing volcanic and tectonic features from three locations. **A** Irregular 2.3 × 1.2-km lava pond with raised levee on Hana Ridge. Contour interval is 10 m. The levee is approximately 20–30 m tall. The eruptive fissure includes the 20-m tall cone near 20°31' W, 155°5′ N and trends approximately 105°, parallel to the rift zone. The floor of the pond has been tilted down towards the southwest after solidification. **B** Flat-topped volcanic cone on Mahukona rift zone with central crater apparently formed by late-stage draining of lava within the cone. This cone has a flat rim surrounding a small crater, whereas most cratered cones have narrow rims and larger craters. Contour interval is 25 m. **C** Flat-topped volcanic cone on Hilo Ridge which has been faulted and partially split by extension across rift zone. Contour interval is 25 m

shield stage based on the compositions of the few recovered samples. During this stage subaerial rift zones are typically still active. All of the pointed cones, including the three on Ni‘ihau, have been found on the submarine extension of these rift zones.

It is difficult to define the eruption depth of these different types of cones without determining their respective ages. However, we can compare water depths at the base of these cones, and consider the amount of probable subsidence. On Ni‘ihau and Hana Ridge, there is an 800-m deep gap between the shallowest flat-

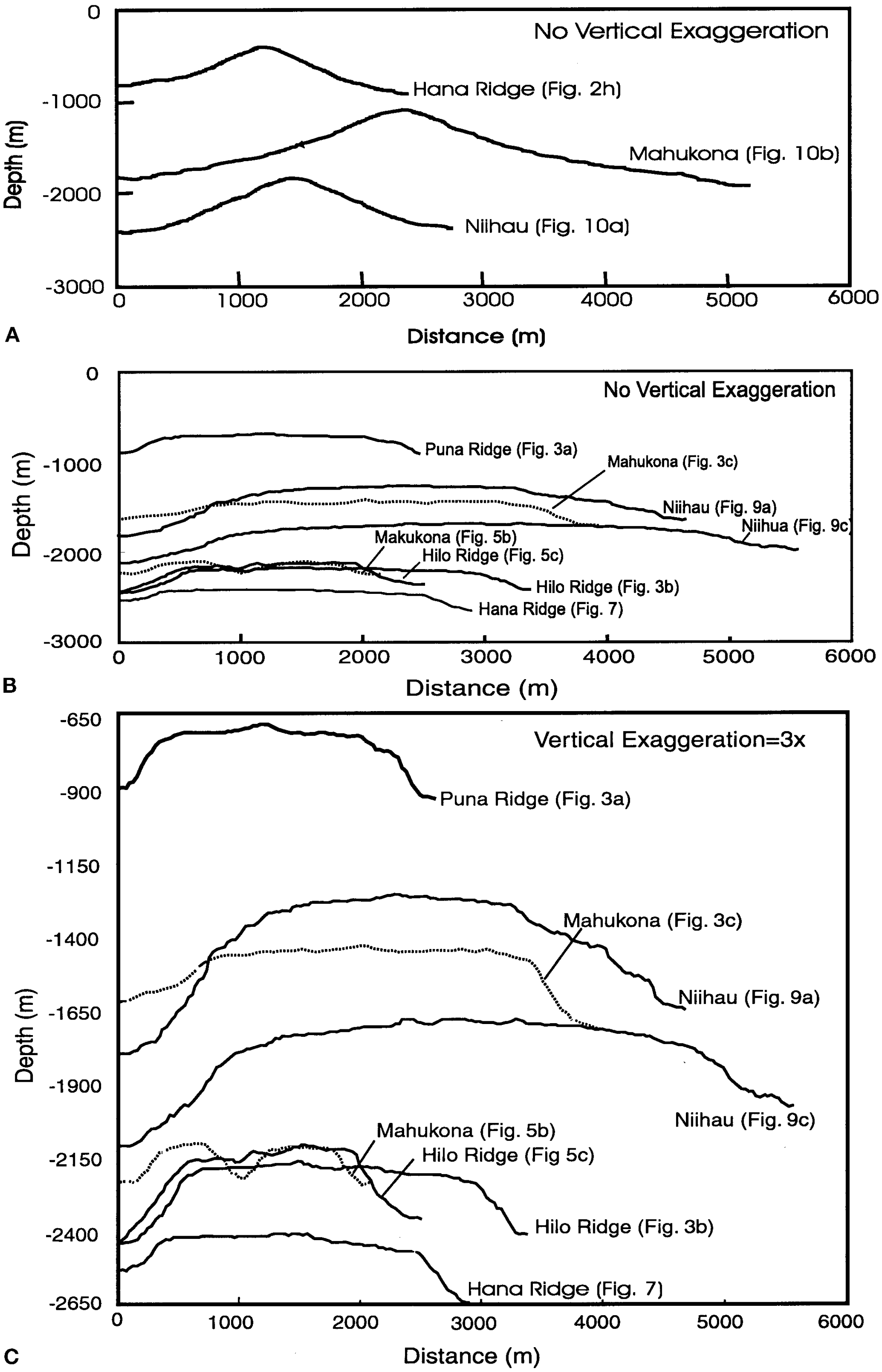

Fig. 6A–C Profiles of some volcanic cones keyed to map views of the same cones. **A** Profiles of pointed volcanic cones with no vertical exaggeration. **B** Profiles of flat-topped volcanic cones with no vertical exaggeration. **C** Profiles of same flat-topped cones as in **B**, but at 3 × vertical exaggeration to show details of the summits. The central summit hump can be best seen on the Puna Ridge profile but is also evident on several of the other profiles. The levees and central hump within a summit lava pond on the Ni‘ihau (Fig. 9C) profile are shown clearly. Summit tilting can be seen in the Hilo Ridge (Fig. 3B and Hana Ridge (Fig. 6) profiles. The central crater is evident in the Mahukona (Fig. 5B) profile

topped cones and the deepest pointed cones. The deepest pointed cones and the shallowest flat-topped cones on the submarine north slope of Ni‘ihau occur at 2300 and 1500 m, respectively. If the Ni‘ihau pointed cones formed during the postshied stage, then they subsided ~1100 m with the island, whereas the young flat-topped cones formed more or less at their present depths. The Niihua pointed cones probably erupted in 1200 m of water. On the Hana Ridge, the deepest pointed cones are at 1500 m and the shallowest flat-topped cones are at 2300 m. All cones have subsided with the island and formed in much shallower water.

However, on Mahukona and on Hilo Ridge the depth ranges of pointed cones and flat-top cones over-

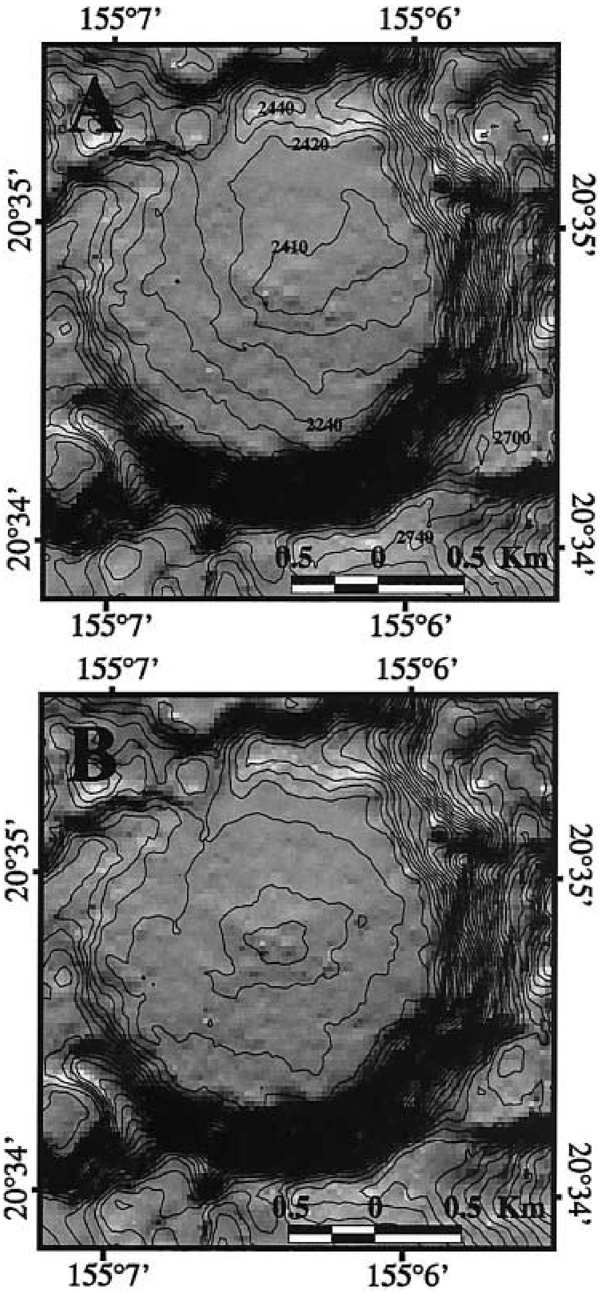

Fig. 7 **A** Original map of flat-topped volcanic cone on the Hana Ridge (east rift zone of Haleakala Volcano) which is tilted 1.1° down towards the southwest (329°) after formation. **B** Computer-derived map shows contours after correction for tilting. Contour interval in both figures is 10 m. The entire ridge has tilted as a result of the volcanic load added to the ocean crust during the growth of new volcanoes making Hawai'i. See text for discussion

lap, suggesting that water depth alone does not determine the type of cone constructed. On Mahukona, the deepest pointed cones and the shallowest flat-topped cones are at nearly the same depth, 1400 and 1500 m, respectively. They have all subsided approximately 1325 m which suggests that the difference in shape is not simply due to confining pressure. On Hilo Ridge, the deepest pointed cones and the shallowest flat-topped cones are also at approximately the same depth, 2000 and 2040 m, respectively. They have all subsided approximately 1150 m since their formation.

Pointed cones have not been mapped on the flank of Kohala Volcano and only one (160 m tall and 500 m basal diameter) has been identified at 154°30.5′ W, 19°40.5′ N, and 2120 m basal depth on the Puna Ridge. The pointed cone on Puna Ridge has the smooth sides, symmetrical shape, and 20° slopes typical of the post-shield stage pointed cones. It is almost certainly constructed of tholeiitic basalt erupted during Kilauea's current shield stage, at its current depth, rather than of alkalic basalt. Clague et al. (1995) describe low-SiO_2, high-TiO_2 tholeiitic glass fragments from Puna Ridge that are highly vesicular. Other glass fragments in the same turbidite layer erupted at approximately 2000 m depth, based on their H_2O and CO_2 contents, and we suspect that the Kilauea pointed cone is constructed either of this lava or lava with a similar composition and vesicularity.

The reason for the apparently shallower formation of the pointed cones is most likely related to the greater expansion of a gas phase in the lower pressure, shallower regime during their eruption. Expansion of magmatic gas as well as of steam generated by boiling of seawater will be greater in the lower pressure of shallower water and will tend to cause more vigorous eruption and expulsion of magma from the vent. This in turn will cause more rapid cooling and piling up of fragmental ejecta around the vent and the formation of a pointed volcanic cone. The alkalic compositions inferred for most of these cones are consistent with higher initial contents of magmatic volatiles than the tholeiitic lavas that form most of the flat-topped volcanic cones. These inferred high volatile contents are consistent with the presence of highly vesicular lavas (up to ca. 25–30% vesicles) recovered from the two pointed volcanic cones.

The lavas that comprise the Kiekie Volcanics on Ni'ihau, although alkalic in composition, have low concentrations of incompatible elements (Clague 1987) and presumably of volatile constituents as well. Their eruptive characteristics were apparently similar to those of tholeiitic lava erupted during the shield stage, and formed the large field of flat-topped cones on the submarine flank of the island. Other, more alkalic rejuvenated stage lavas (basanites, nephelinites, melilitites, as in the Honolulu or Koloa Volcanics; e.g., Clague and Frey 1982; Clague and Dalrymple 1988), if erupted in similar water depths, might be expected to produce pointed volcanic cones.

Field observations

In 1988 one flat-topped cone on Mahukona Volcano was examined during dive PV-72 of the *Pisces V* submersible operated by NOAA's Hawai'i Undersea Re-

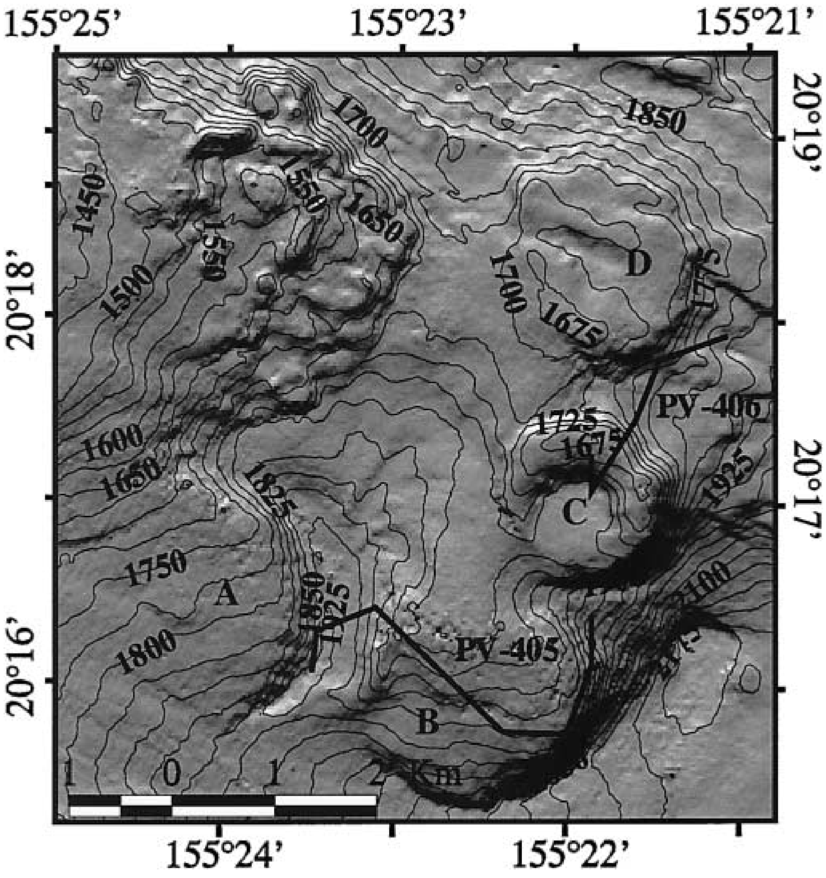

Fig. 8 Four flat-topped volcanic cones, one (labeled *C*) with a central crater, on northeast flank of Kohala Volcano that have been tipped 4–5° toward Hawai'i. The westernmost cone (labeled *A*) is partly buried by subsequent sediment but can be returned to level by 4.3° of tilting to the south (169°). These cones could be part of a landslide block in the Pololu landslide (Moore et al. 1989), or they may be tilted during growth of Hawai'i to the south. The steeper tilt than is observed on the Hana Ridge may simply reflect their proximity of the center of the volcanic load. Pisces V submersible tracks for dive PV-405 and PV-406 done in 1998 are shown

search Laboratory. The dive track contoured 3 km around the north side of a flat-topped cone (Fig. 3C), where a sequence of pillow lavas (up to >1 m in diameter) associated with pillow joint block talus and pillow scree mantled the slope (Clague and Moore 1991).

In 1998 four flat-topped cones were examined during submersible dives PV-405 and PV-406 again utilizing the *Pisces V.* This cone cluster is on the northeast flank of Kohala Volcano, the oldest and most northern volcano on Hawai'i. The Kohala flat-topped cones range from 2 to 3 km in diameter and 100 to 200 m in height with volumes of 0.3–1.5 km^3. They occur at depths of 1800–2100 m. Three are flat-topped and one has a broad, flat-floored crater (Fig. 8).

All four cones were investigated during the two dives (Fig. 8). Samples indicate that the cones are composed of relatively fresh, glassy, dense (0–5% vesicles in glassy rims) tholeiitic basalt. The outer flank of all the cones, as seen in five traverses, are consistently draped with large pillows and pillow flows elongate directly downslope and inclined approximately 35°, but draping near vertical scarps in places. The elongate pillow flows pass outward to nearly horizontal pillow flows near the base. In some places the pillows on the walls are extremely large, attaining ~10 m in diameter. Similar elongate pillow lavas from the flat-topped cone on Mahukona are shown in Fig. 11A.

Little structural information can be gained from the flat tops of three of the flat-topped cones because they are covered with sediment. That the entire surface is buried beneath sediment suggests that the upper surface consists of sheet or lobate flows; otherwise, pillows would occasionally project above the sediment. The cone with a central crater has well-formed columnar joints (<1 m in diameter and 5 m long) present on the inside wall of the crater (Fig. 11B). These columns indicate thick cooling units that required significant time to cool, such as the interior of a lava pond, before draining and collapse formed the crater and exposed the cooled and jointed margins of the lava pond.

Model for formation of flat-topped volcanic cones

Simkin (1972) proposed a mechanism to form flat-topped subaerial volcanoes in the Galapagos Islands whereby eruptions occur along circumferential ring faults. Such a model has been embraced to explain the flat tops of larger volcanoes near mid-ocean ridges (e.g., Batiza 1989, p 302), although Clague et al. (in press) found no evidence to support such a model in their high-resolution bathymetric data for similar near-ridge volcanoes. Details of summit morphology indicate that they develop their flat tops due to caldera collapse and central volcanism that fills and eventually overtops the old caldera rim. Such a multistage mechanism is unlikely to explain the formation of the small structures imaged around the Hawaiian Islands which

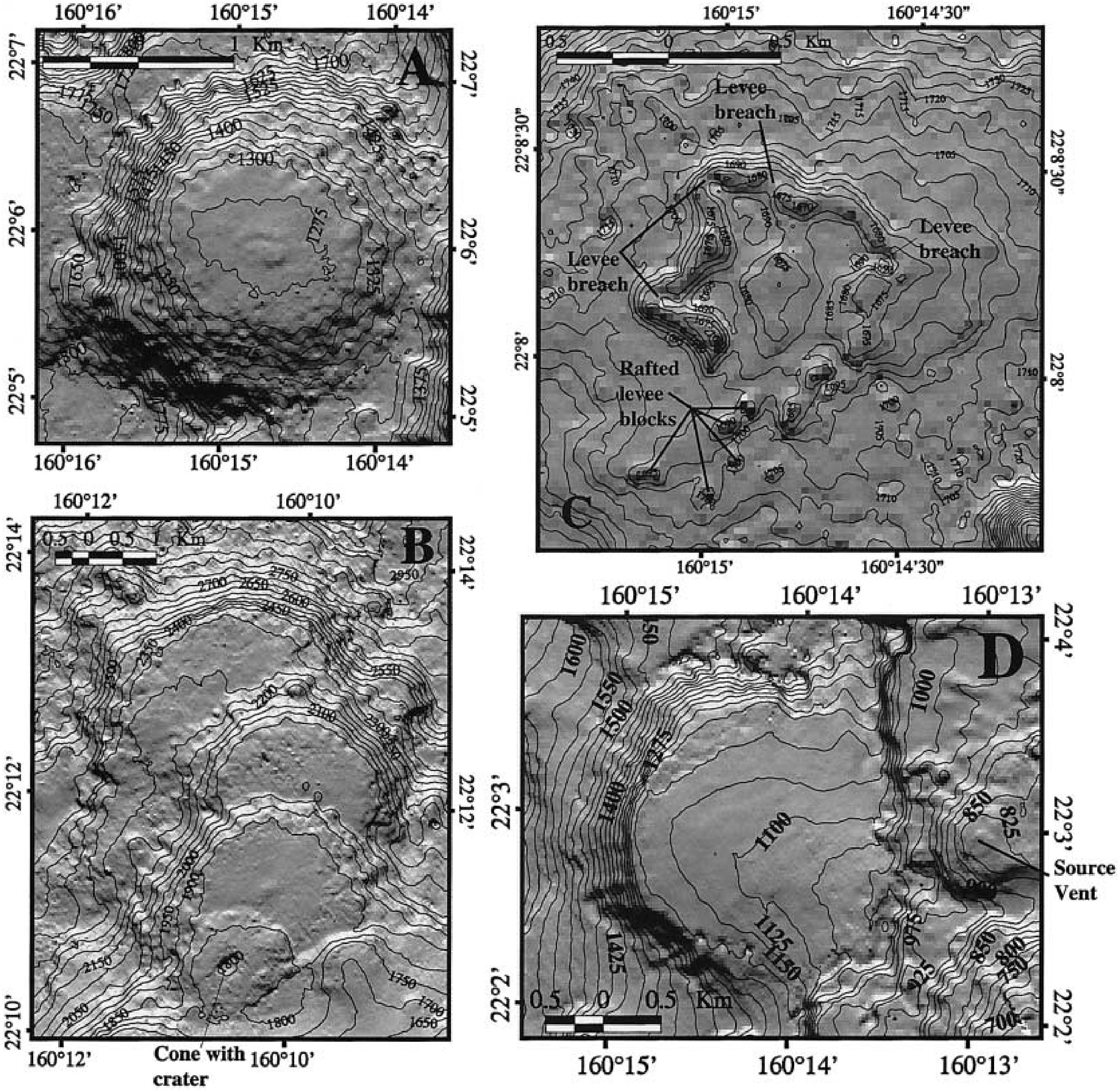

Fig. 9 **A** An example of a typical flat-topped volcanic cone from flank of Ni'ihau. These rejuvenated stage cones are significantly larger than the shield stage cones shown in Fig. 3 but otherwise have similar characteristics. There is no evidence that they tilted after they formed. Contour interval is 25 m. **B** A stairstep series of parasitic, flat-topped semi-circular terraces formed by leaking from the flat-topped cone with the summit crater. Each terrace is 25–100 m below the top of its parent volcanic cone or terrace. Note that the geometric center of the parasitic terraces is close to the edge of the upper feeding edifice. Contour interval is 25 m. **C** Levees surrounding irregular perched pond centered on top of a flat-topped cone. The levees are approximately 30 m tall. Contour interval is 5 m. **D** Lava delta formed from lava that flowed over break-in-slope. Note similarity in shape to flat-topped cones, but that entire delta slopes offshore. The inferred source vent is located above the break in slope at 22°3′ N, 160°13′ W

appear to be monogenetic flat-topped cones built entirely during a single eruptive sequence.

The subaerial lava ponds that sometimes develop above active basaltic vents that extrude lava onto a horizontal surface are a good analog for formation of submarine monogenetic flat-topped cones. Such lava ponds were common in Halema'uma'u Crater of Kilauea Volcano prior to the great collapse of 1924 (Fig. 12; 1892–1893 lava pond: Jaggar 1947; the 1894 lava pond: Macdonald and Abbott 1970, their Fig. 37; 1894 lava pond: Wright et al. 1992, their Fig. 62). Similar features also formed above vents during the Pu'u 'O'o eruption, for example at the beginning of episode 49 (Mangan et al. 1995). These lava ponds (also called lava rings) are impounded by a ring-shaped levee built

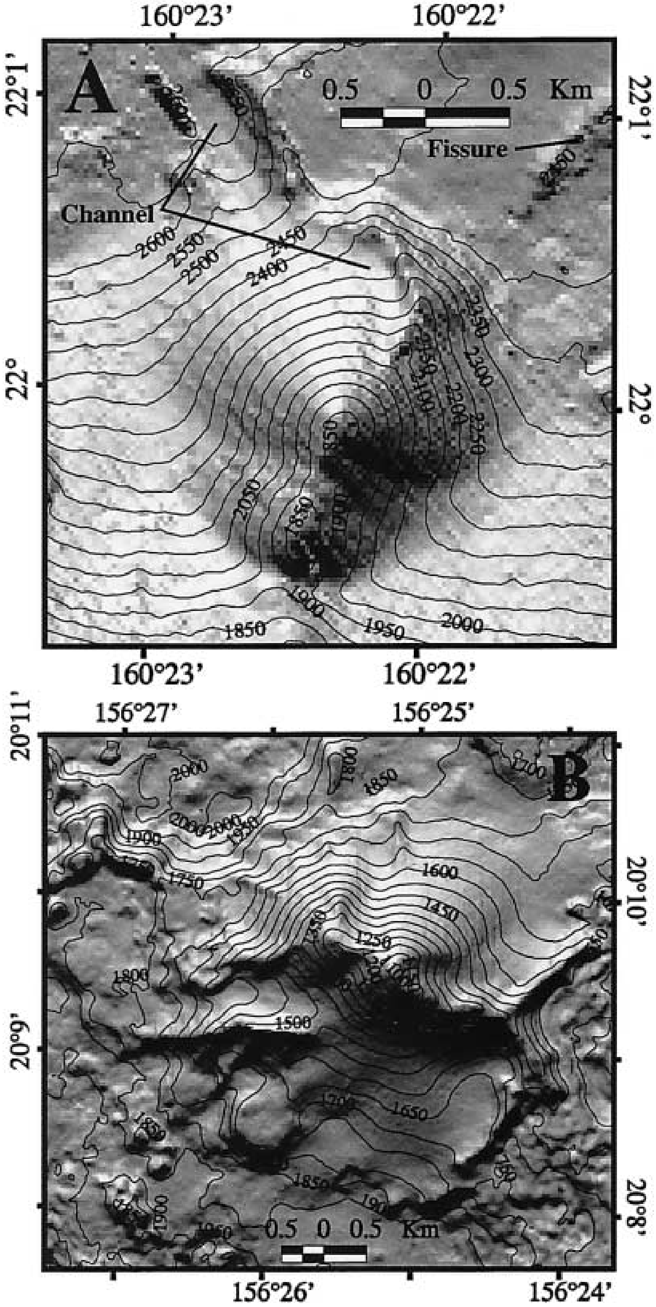

Fig. 10A,B Multibeam maps of pointed volcanic cones. These cones have no summit craters, steep slopes, and smooth surfaces. **A** Pair of coalesced pointed cones offshore Ni'ihau. The cones rise nearly 300 m from the deeper northern base. The eruptive fissure on which the cones grew extends to the northeast. A broad lava channel (ca. 0.5 km wide) with marginal levees extends first north and then northwest. Contour interval is 25 m. **B** Large pointed cone (615 m tall) on Mahukona west rift zone. Despite the smooth surfaces imaged, the only samples dredged from the cone are pillow lavas (Garcia et al. 1990; Clague and Moore 1991)

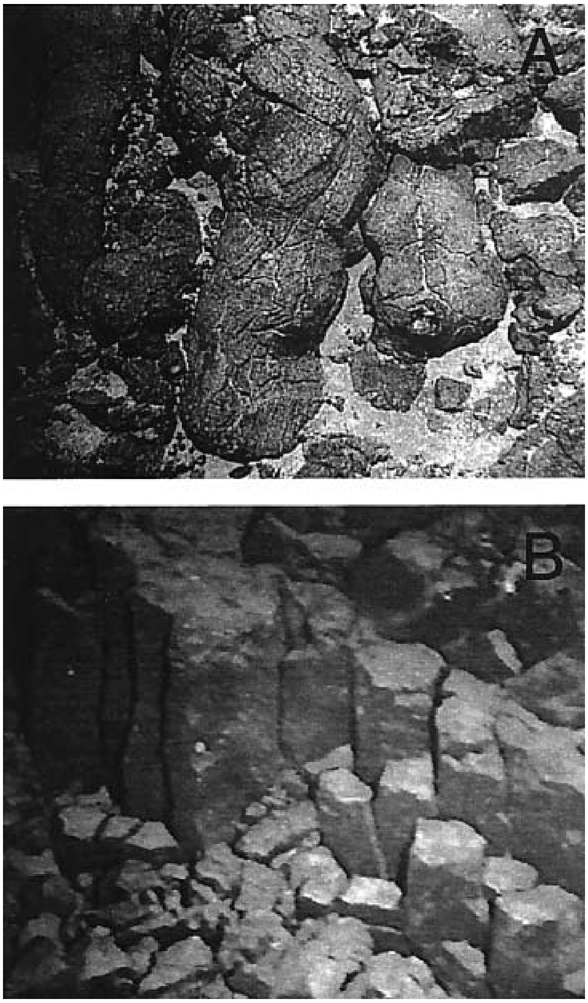

Fig. 11A,B Bottom photographs taken from the Pisces V submersible. **A** Elongate pillow lavas on outer slope of a flat-topped volcanic cone on Mahukona's west rift zone. Photograph is 3–4 m across and was taken near the northeast end of Pisces V dive PV-72 (Fig. 3C). **B** Columnar joint blocks from within crater in flat-topped volcanic cone on Kohala's northeast flank. Photograph is a framegrab from the video and is approximately 10 m across and was taken inside the crater in the flat-topped cone at the southeast end of Pisces V dive PV-406 (Fig. 8)

by accumulation of outward rafted crust, small overflows of lava, and spattering of secondary fountains at the edge of the pond. This outer levee may reach heights of several meters thus causing the brim-full lava pond to stand considerably above the general ground surface surrounding it. The late nineteenth century subaerial lava ponds commonly had aspect ratios of 0.04–0.05. The lava ponds surrounded by levees formed in the 1968–1969 Halemaumau eruption (Kinoshita et al. 1969) were somewhat more than 100 m in diameter and stood an average of 9 m above the surrounding terrain, hence showing an aspect ratio somewhat less than 0.1.

Lava ponds can also form away from primary vents. For example, a small perched pond formed on Kilauea Volcano when lava flowing down the north flank of the Mauna Ulu shield in late January 1974 was impounded in the saddle between Mauna Ulu and Pu'u Huluhulu (Wilson and Parfit 1993). Such ponds may be better

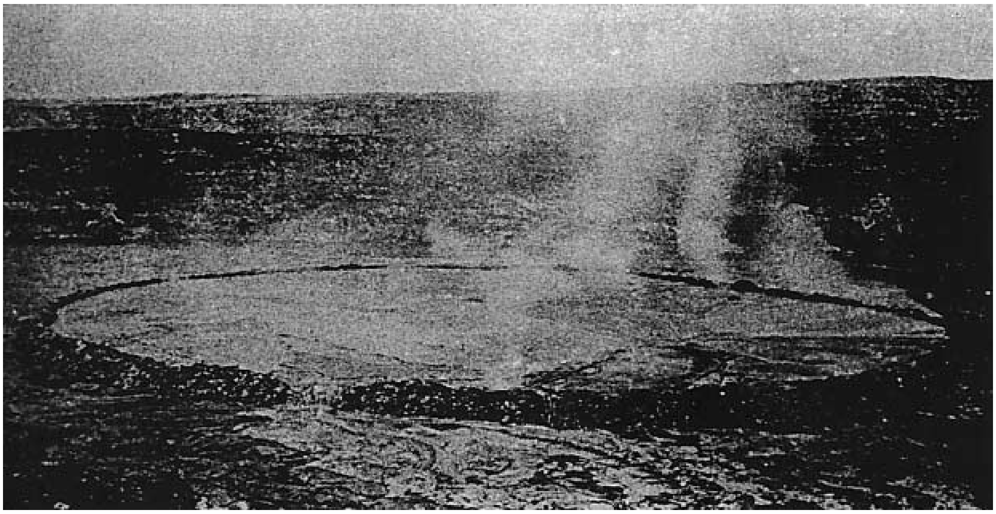

Fig. 12 Active lava pond in Kilauea caldera (near present site of Halemaumau) approximately 1892–1893. Note ongoing isolated flow of incandescent lava over confining levee near center; aspect ratio of pond is 0.04–0.05. (From Jaggar 1947, his plate 10d)

analogs to the semicircular parasitic flat-topped terraces that form nested on the flanks of primary flat-topped cones, such as on the flank of Ni‘ihau.

A model for the formation of these cones must account for the ubiquitous low height/diameter ratio, the flat, originally horizontal top, and the outer wall draped with pillow lava. In addition, the presence of a low central dome or a flat-floored crater, and the evidence for thick cooling units in the interior, must be considered. Our preferred model for formation of these volcanic cones is outlined in Fig. 13.

As lava is extruded, cooling immediately produces a flexible outer skin on a sheet flow, and this flow will move downslope. If eruption rates are low enough, and the terrain flat enough, the flow may divide into flow lobes which will tend to pile up and impede the flow movement, as will any obstruction on the overrun terrain. As the flow advances and spreads laterally, the outward movement of its front slows as the circumference grows as modeled by Fink and Griffiths (1990) for more viscous domes. The crust thickens and confines incoming lava, thereby causing the flow to inflate (Hon et al. 1994). In this way an inflated flow or crusted pond is produced above the vent. This early stage in the development of the flat-topped cones may be represented by the lava ponds with irregular levees imaged on the Hana Ridge and shown in Fig. 5A. Such ponds are similar to those described from mid-ocean ridges (Francheteau et al. 1979; Gregg et al. 1996) and probably form during brief, moderate-extrusion rate fissure eruptions.

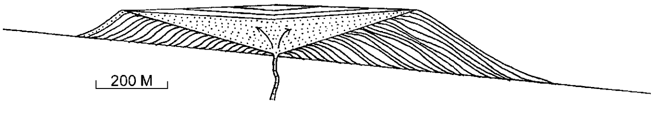

Fig. 13 Formation of a flat-topped volcanic cone from a long-lived, continuously overflowing, ocean-floor lava pond. A leveed lava pond becomes established above a sea-floor vent, perhaps resulting from the marginal rupturing of an inflated flow. As lava within the pond rises, it overflows at the lowest notch on the rim and a pillow flow spills down the levee where it quickly cools and solidifies causing the levee to grow upward and outward. Repetition of this overflowing process causes the lava pond to increase in diameter and height. A horizontal floating crust, thickest in its oldest, central part reduces heat flow to the overlying seawater. *Dotted pattern* is molten lava

The inflated flow banks up against its distal edges and continues to thicken as lava is pumped into it from the underlying vent. Eventually the inflated flow ruptures at the weakest or lowest point of the upper margin, thereby feeding smaller pillow flows that move laterally, cool and solidify, and buttress this side of the ponded flow. Continued inflation and upward growth causes the pond to rupture on another side feeding more pillow lobes that cool and produce an embankment on that side. In this way the confined, inflated pond-like flow expands laterally, always breaking out on the lowest or weakest side and feeding small pillow flows that mantle the low point on the margin, dam it at that point, and build up a confining levee. With continuing eruption, the confined pond continues its outward and upward growth. Such dynamic effects explain why a circular edifice is constructed, even on a slope. Laboratory wax models (Fink and Griffiths 1990; Griffiths and Fink 1992, 1993; Fink and Bridges 1995) have not created circular constructs except when extrusion was on horizontal surfaces. We suspect that either the “magma supply” rates or the cooling rates are too great for their wax experiments to be analogs to formation of basaltic flat-topped cones.

The upward growth of the confining levee may also be accomplished by fluctuations or oscillations of the lava level in the lava-pond resulting from surges of lava rising through the vent. High lava levels will periodically cover and overflow the levee, and low levels will enable the overflowed lava to solidify, particularly on the outer levee face. In this way fresh lava will be repeatedly plastered over the entire levee causing it to grow up and out. A similar process builds the levees on the margin of vigorous lava flows where surges periodically overflow the channel (Lipman and Banks 1987) and more rapid cooling and solidification of the overflowed lava builds up the marginal levees (Pinkerton and Sparks 1976).

The inflating lava pond develops a solidified top crust as it ages and loses heat to the overlying water. Eventually a nearly horizontal floating upper crust – or lid – is formed that insulates the molten interior from the cooling affect of seawater. The horizontal upper surface of the pond is maintained because lava always overflows (and dams) the lowest point of the levee. Overflows will most likely occur at points on the rim that are closer to the center of the pond because the lava is hotter, of lower viscosity, and slightly higher nearer the pond center where lava surges up from the vent. These factors cause the reentrants of the levee to be continually overtopped, dammed, and moved outward at these points, thus shaping the pond plan into a nearly perfect circle.

The central mound may simply be a result of the flow dynamics of the growing pond that can be considered to be like a lava flow fed in the center and flowing downhill radially in every direction. The general slope from the humped center to the rim is approximately 1–4° (Fig. 4C). Such dynamic support of the center of the lid would be preserved only if the lid were thick enough to behave rigidly (5–10 m?) after the flow of lava under the lid stopped.

Alternatively, if the eruption wanes toward the end over a long period of time, the main lava pond may solidify and fracture before the eruption has ceased entirely. In this scenario the last lava delivered to the volcanic cone may erupt through the now-solidified lava pond and build a secondary mound or pond on top. This appears to be the case for the example from Ni‘ihau shown in Fig. 9C, where a smaller pond with levees clearly formed on top of the flat-topped cone. These levees presumably formed after most of the lava pond had solidified and a small, centrally located liquid lava pond was extruded on top of the lid. The irregular shape of the pond in the center of the summit of this flat-topped cone suggests that this late stage pond breached or drained before it attained a circular shape.

During the active formation and growth of the pond, internal circulation probably leads to overturn of the crust. However, as the eruption rate wanes near the end of the eruption and the pond stagnates, the crust eventually stabilizes and thickens. This leads to yet another alternative mode to form the central mound. The floating pond crust should be oldest in the center and youngest at the expanding edges of the pond; hence it will grow thickest in the central, older region because of the longer cooling time at this location. In addition, gas bubbles would more likely be incorporated in the growing crust directly above the vent in the center of the pond. Both of these processes would favor a thicker and more vesicular crust in the center of the pond. Such a light, thick central crust would float higher and may account for the low central mound surmounting the otherwise flat summit plateau, which owes its horizontal surface to the top of the liquid, nearly stagnant lava pond.

Partial or complete draining of the confined lava-pond before solidification produces the flat-floored craters that are found in approximately 10% of the flat-topped cones (Fig. 5B). Molten pond lava either drains back down the feeding conduit or leaks laterally through breaks near the base of, or beneath, the levees, where the magma pressure is greatest. Such lateral outbreaks may produce the parasitic, terrace-like edifices that mold against their parent flat-topped volcanic cone, although we note that only two of the flat-topped cones on Ni‘ihau, where such terrace-like semicircular volcanic cones are common, have summit craters.

The processes that may dominate and shape the floor of the growing lava pond are problematic because of the dynamic nature of growth. The floor is unmodified and maintains a constant outward rise dependent on the ratio of upward vs outward growth of the confining levee during lava overflow (Fig. 13). Perhaps the floor of the lava pond may continually rise as the lower crust cools by heat loss through the bottom as well as by settling and accumulation of early-formed crystals on the bottom. On the other hand, the floor may continually deepen as new, hot lava enters the system, and softens and erodes the bottom as occurs in long-sustained lava flow systems (Kauahikaua et al 1998).

Growth and solidification

The time required to construct subaqueous flat-topped cones can be estimated from eruption rates of the active Hawaiian volcanoes. The ongoing Kilauea eruption that began in 1983 has erupted at a constant rate of approximately 0.1 km^3/year. Moreover, the longer-term magma production at Kilauea is estimated to be approximately 0.08 km^3/year (Denlinger 1997). At a 0.1 km^3/year rate, the tholeiitic flat-topped cones (volumes of 0.1–1.4 km^3) would require from 1 to 14 years of continuous centralized eruptive activity. The rejuvenated stage flat-topped cones on Ni‘ihau, with volumes up to 5 km^3, would require up to 50 years. The nature of the eruptive process is such that a period of quiescence (weeks to months?) or interruption in steady activity would cause the lava pond to partly solidify, thereby requiring construction of a new edifice should activity resume.

When eruption at the vent stops, new, hot lava will cease entering the pond, which will stagnate, cool, and solidify. Drilling programs in the crust of stagnant modern terrestrial Hawaiian lava ponds have provided information on the rate of growth of the upper crust (Peck et al. 1964). Drilling in Kilauea Iki and Alae lava ponds indicates that the crust grows approximately 2.4 m in the first month, and continues thickening at an exponentially decreasing rate of 2.4 m times the square root of its age in months. At this decreasing rate a terrestrial lava pond would develop a crust 14 m thick in 3 years (36 months), 32 m thick in 15 years (180 months), and 83 m in 100 years (1200 months). On active subaerial ponds, foundering of the thin plates of crust is common so that subaerial lava ponds are continually resurfaced with molten lava. This may occur at submarine lava ponds as well, but the crust on the pond will grow thicker and stronger more quickly under water due to higher cooling rates.

Comparison of the cooling and solidification of a lava pond (or lava flow) crust on the ocean floor as compared with that above sea level poses difficulties because no measurements have yet been made on cooling rates of hot subaqueous lava flows, and the processes of heat transfer are uncertain (Shaw and Moore 1988). After stagnation, the pond crust will probably grow somewhat faster in the subaqueous than subaerial environment, but at moderate oceanic depths the heated water will not expand as much as the rainwater falling on terrestrial ponds and the convective heat loss may actually be smaller. One critical factor is the extent to which the crust is fractured so that water convects into cracks thus removing heat from the crust. The fact that thick, uniform columns grew in the interior of the lava pond within the cratered flat-topped cone on Kohala suggests that deep cracks that convected water freely did not reach into the region where these columnar joints were developing.

Several studies address the formation of a crust on subaqueous lava (Griffiths and Fink 1992, 1993; Gregg and Fink 1995), but have been aimed at understanding the formation of pillow-scale features. Nevertheless, they provide some insight into the factors that control formation of the crust on lava ponds. The upper crust of the subaqueous lava ponds is no doubt thickening at the same time as the pond is growing, provided it does not founder, but certainly less rapidly than when the introduction of hot lava ceases. The actual eruptive growth of a 3-km-diameter pond (the largest of the tholeiitic ones) might require approximately 14 years. Solidification and cooling to ambient temperature of this mass of hot lava up to 125 m thick (depth of the deepest crater) would require perhaps 50 to several hundred years, based on the time required to solidify the Kilauea Iki lava pond. Hence, each of these larger lava ponds would probably remain a source of high heat flow into the overlying water for a period of several centuries after the eruption ended.

What conditions are needed to form flat-topped volcanoes?

Numerous conditions are required to form flat-topped volcanic cones. They include eruptions that are (a) submarine and effusive; (b) low- to moderate effusion rates; (c) from a point source; (d) steady with minimal interruptions; (e) on low slopes; and (f) of long duration. Low viscosity is apparently required since we think that all the flat-topped cones are constructed of basaltic lava with relatively low viscosity.

Submarine effusive eruption

Low initial magmatic volatile contents and relatively great eruption depth (and confining pressure) minimize separation of a gas phase so that the eruption takes place by the quiet effusion of lava. By analogy with subaerial eruptions, this may be preceded by a brief initial phase with more vigorous degassing and production of spatter along fissures. If the confining pressure is too low (water depth is too shallow) or the volatile content or effusion rate too high, then degassing will drive lava fountains that will produce fragmental ejecta or highly vesicular pillow lava that will accumulate over the vent. Because of the rapid cooling of fragmental ejecta, such eruptions cannot produce submarine lava ponds, and hence, cannot produce flat-topped volcanic cones.

The limiting pressure and volatile contents can be estimated from the ocean depth of formation and the types of lava that produce flat-topped cones. The shallowest flat-topped cone on the active Puna Ridge is at approximately 700 m depth. The lavas erupted on Puna Ridge in general are hybrids of subaerially degassed tholeiitic magma and relatively undegassed magma resulting in water and sulfur contents approximately half that of undegassed magma (Dixon et al. 1991). Unfortunately, we cannot estimate their carbon dioxide content, except to say that it is greater than the saturation values at their eruption depth. In any event, these tholeiitic magmas have lost a significant portion of their volatile components due to degassing through the subaerial summit, probably by eruption and recycling of degassed lava back into the magma chamber. We suspect that tholeiitic lavas that erupted before such degassing and recycling could take place, i.e., before the volcano had built above sea level, would have gas contents too high to form flat-topped cones. The absence of such structures on Loihi Seamount, which has had no opportunity to degas at low pressures, and where vesicular tholeiitic lavas (Moore et al. 1982) and fragmental ejecta (Clague et al. 2000) are common, supports this speculation.

The rejuvenated stage Kiekie Basalt flows on Ni‘ihau (and we presume, the offshore equivalents described herein) are compositionally unique among Hawaiian rejuvenated stage lavas in that they have very low concentrations of incompatible elements, and probably of volatile constituents as well. Using a H_2O/Ce ratio of 210 for rejuvenated-stage submarine North Arch lavas (Dixon and Clague, in press), and Ce contents of 21–34 ppm from Clague (1987), we estimate that these magmas contained as little as 0.44–0.71 wt.% H_2O, comparable to that in submarine Kilauea tholeiite (Dixon et al. 1991). Despite such low volatile contents, vents shallower than 1100 m did not form circular flat-topped volcanic cones. The volatile contents of these magmas were great enough that significant degassing took place during eruption at shallower depths, but confining pressure was great enough below 1100 m to produce effusive eruptions and flat-topped cones. Other rejuvenated stage lavas from the North Arch, which are commonly much more strongly alkalic than those from Ni'ihau, have high enough volatile contents (1.3–1.9 wt.% H_2O, estimated 2.0–5.4 wt.% CO_2; Dixon et al. 1997) that they can produce lava fountains, hyaloclastite, and vesicular pillow lava at the vent at pressures of 460 bars (4600 m depth; Clague et al. 1990; Dixon et al. 1997).

Low-to-moderate effusion rates

On land and in the shallow submarine environment, most vent structures consist of accumulated pyroclastic deposits, which accumulate to form steep conical structures. If the eruption rate is too high, then flows move away from the vent as thin sheets that develop with time into lava tubes that can transport lava long distances, even under water. On land, fluxes of 5 m^3/s develop such tubes (Peterson et al. 1994). This analogy suggests that the submarine eruptions may occur at similar to somewhat lower volume fluxes than the present eruption on Kilauea (ca. 0.1 km^3/year or 3.2 m^3/s), or else sheet flows rather than flat-topped volcanic cones would form. In addition, if eruption rates exceed the magma supply rate significantly, the magma system will depressurize quickly and the eruption will stop. We suspect that all long-lived rift eruptions, both subaerial and submarine, take place at rates more or less equivalent to magma supply rates, which may vary somewhat with time (Denlinger 1997).

Point source of eruption

The eruptions probably emanate from a point source in order to produce the circular cones. Submarine Hawaiian eruptions, like their present-day subaerial counterparts on Kilauea and Mauna Loa, almost certainly commence as fissure (line source) eruptions, although our bathymetric data is not high enough resolution to detect such fisssure-fed lavas adjacent to the cones. As the eruption progresses, the feeder dike solidifies in all but the most vigorous locations (Delaney and Pollard 1982) and the original "curtain of fire" activity consolidates to a point source. Eruptions of short duration do not construct circular vent structures regardless of the volume erupted. Long-lived eruptions, such as the current Kilauea eruption, consolidate their activity to a single point source within a matter of hours to days, although that location may shift from time to time.

Steady eruption

The eruption must be continuous, at a relatively steady effusion rate, to avoid allowing the lava pond to solidify. Probably short eruption hiatuses, like those lasting days to weeks that have characterized the current eruption on Kilauea (Mangan et al. 1995), will not have adverse effects on construction of the flat-topped volcanic cones.

Low slopes

The flat-topped volcanic cones form on relatively low slopes along the axes of the rift zones. These slopes are commonly 2.5–5° along the axis where these cones apparently form. On the steeper flank of Ni'ihau, the circular flat-topped volcanic cones are generally replaced by semicircular terrace-like constructs, presumably because the slope was too steep ($\sim 10°$) to build a complete circular structure. On the deep sea floor, many flat-topped cones are constructed on nearly flat surfaces. No circular flat-topped volcanic cones have been imaged on slopes around the Hawaiian Islands steeper than $\sim 7°$.

Long eruption duration

Generally, as an eruption becomes long-lived it will evolve to become a point source eruption. Most long-lived eruptions on land first build cinder cones from the near-vent accumulation of pyroclastic ejecta as well as lava flows that may move many kilometers from the vent. Such eruptions are usually highly gassy and are characterized by fountains. The subsequent steady effusion of lava on land constructs lava shields, which are probably the subaerial analogs to submarine flat-topped cones but formed under different cooling conditions.

The effusion rates estimated above imply that the eruptions that formed the tholeiitic cones had durations from perhaps 1 to 14 years. Such long-lived eruptions require continuous or at least episodic widening of the feeder dike from the sub-summit chamber to the eruption site on the rift zone to prevent solidification of the feeder dike, which is crystallizes from the margins inward as the eruption proceeds. Such widening of the rift zone conduit is accommodated by seaward movement of the unbuttressed flank of the volcano, as is presently observed for Kilauea's south flank (Owen et al. 1995).

The maintenance of a central conduit to feed the rejuvenated stage eruptions, such as those that formed the flat-topped cones on the flank of Ni'ihau, must differ from that maintaining the tholeiitic feeder dikes since there is no mobile flank of the volcanoes to accommodate widening of the feeder dike. The flat-topped cones are also scattered over the flank of the volcano instead of being located along rift zones. Here, the eruptive conduits may remain open because rejuvenated stage magmas have high temperatures (most probably erupt at >1250–1300 °C) and can melt the tholeiitic wallrocks of the feeder conduit. In this case, continuing flow of magma through the conduit apparently maintains the temperature and width of the conduit for long time periods.

Low lava viscosities

The basaltic lavas that formed flat-topped cones have a range of compositions and estimated viscosities. The tholeiitic lavas that make up Puna Ridge have estimated bulk viscosities ranging from approximately 20 to 170 Pa s (Clague at al. 1995), although none of these samples is known to be from a flat-topped volcanic cone. The lavas recovered from Kohala are more differentiated than the Kilauea lavas, and therefore have slightly higher viscosities. Tholeiitic samples from Mahukona (Clague and Moore 1991) and Hana Ridge (Moore et al. 1990) have MgO contents similar to those from Kilauea and have similar bulk viscosities. The Ni'ihau lava composition is not known, but if we assume it is similar to rejuvenated stage Kiekie lavas on Ni'ihau (Clague 1987), their viscosities will be similar to those of the Kilauea lavas, although slightly lower due to their lower SiO_2 content. It appears that basaltic lava composition and low viscosity are necessary, but not sufficient, criteria for the formation of flat-topped cones, because lavas recovered from the rift zones of many of the volcanoes have similar compositions and viscosities, but did not form such constructs.

Conclusion

Circular, flat-topped submarine volcanic cones around the Hawaiian Islands have low aspect ratios, basal diameters as large as 5 km, and heights as great as 300 m. The flat-topped cones form as continuously overflowing lava ponds. The cones have horizontal flat tops because the top formed as a lid floating on liquid lava. They form during submarine, long-lived, steady, effusive, point source eruptions on gentle slopes. The cones grow upward and outward by repeated overflows at the weakest or lowest point on the rim, which spill pillow lava down the flank and dam the breach. The final form is a flat-topped structure with steep margins constructed of pillow lava. Occasionally, the lava in the pond drains back down the conduit forming a central crater. In other cases, particularly for the larger flat-topped cones built on steep slopes, lava breaches at or near the base of an upper semicircular structure to construct a secondary lower semicircular structure molded to its base.

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