DISCUSSION

The Hawaiian Islands form the southeast leg of a 5,000-km-long string of underwater and subaerial volcanoes called the Hawaiian-Emperor Chain (fig. 1, map sheet, inset). Volcanoes of the Hawaiian Islands form part of a long, discontinuous ridge known as the Hawaiian Ridge (Clague and Dalrymple, 1987). In 1983, the United States defined an Exclusive Economic Zone (EEZ) around the Hawaiian Islands extending from the coastline to 200 nautical miles offshore (fig. 2, map sheet). The U.S. Geological Survey (USGS) had the primary responsibility to map this zone and in 1984 began the EEZ-SCAN program to systematically map the EEZ at a reconnaissance scale. For assistance with the data collection, the USGS partnered with the Institute of Oceanographic Sciences (IOS) of the United Kingdom. The IOS developed a long-range side-scan-sonar system well suited to this purpose. This system, called GLORIA (Geologic LOng-Range Inclined ASDIC, where ASDIC is another acronym for SONAR, SOund NAvigating Ranging), is capable of imaging a swath of sea floor 40 km wide with each pass of the ship (fig. 3). The map is derived from GLORIA data collected in 1986-1989 from the southeastern Hawaiian Ridge EEZ, which covers more than 1,000,000 km^2 of sea floor (fig. 2; Groome and others, 1997). The Hawaiian Islands cap the northwest-southeast-trending ridge.

Over the past 80 m.y., the Hawaiian-Emperor Chain developed, one volcano after another, as the Pacific Plate moved slowly northwestward over a stationary hot spot. At the hot spot, magma from the Earth's mantle continually rises through the ocean crust, and lava erupts frequently to slowly build a volcanic seamount. Many of the seamounts grow tall enough to break the surface of the water, forming the Hawaiian Islands (Clague and Dalrymple, 1987). Because they sit on the ocean floor in water depths greater than 5 km, the Hawaiian volcanoes are some of the tallest mountains on Earth. Because of the size of the volcanoes, the Hawaiian Ridge is heavy. The weight of the ridge depresses the oceanic plate beneath it, as much as several kilometers. In reaction, the surrounding crust bulges upward a few hundred meters to form the Hawaiian Arch (Moore, 1987).

As the Pacific Plate continues to move northwestward, it carries the once-active volcano away from the magma source. Over time the extinct volcano gradually sinks below sea level owing to its weight and continued cooling of the ocean crust. Meanwhile, a new volcano develops on the adjacent area of seafloor newly moved over the hot spot. All of the Hawaiian volcanoes in the map area are younger than about 8 m.y., becoming younger toward the southeast. Lōʻihi Seamount is the newest volcano growing off the southeast coast of the Island of Hawaiʻi (Clague and Dalrymple, 1987).

Extensive young lava flows are visible on the GLORIA imagery hundreds of kilometers from the Hawaiian volcanoes: the North Arch, Southwest Oʻahu, and South Arch Volcanic Fields (fig. 1). These flows occur in several areas north and south of the Hawaiian Islands. The most extensive field is the North Arch Volcanic Field, which covers an area of about 25,000 km^2 north of Oʻahu. The lava erupted from fissures that cross the crest of the Hawaiian Arch. Thin tongues of lava more than 100 km long flowed both southward and northward from this topographic high. The southern ends of some lava flows are interbedded with landslide debris from the Hawaiian Islands, showing that this lava field developed at the same time as the nearest Hawaiian volcanoes, apparently in response to the same hot spot. This suggests that the hot spot affects a much wider expanse of the sea floor than was suspected previously (Clague and others, 1990; Hamilton, 1957).

The Molokaʻi Fracture Zone is visible in the eastern and southwestern sections of the GLORIA imagery (fig. 1). It extends more than 6,000 km eastward to offshore of central Baja California. This fracture zone consists of groups of linear faults caused by offsets in the mid-ocean ridge. The pattern of short, linear bands perpendicular to the fracture zone is called spreading fabric and is composed of volcanic ridges that formed, one after another, at the spreading center of the mid-ocean ridge. The segment of the East Pacific Rise spreading center that produced both this spreading fabric and the Molokaʻi Fracture Zone is now being overridden and disrupted by the North American continent. The spreading fabric and fracture zone developed long before the Hawaiian Islands and were locally buried by the development of the Hawaiian Ridge when this section of the Pacific Plate traveled over the hot spot (Atwater, 1989; Searle and others, 1993).

GLORIA data help scientists to understand the important role of landslides in the erosion of underwater volcanoes. Large-scale submarine landslides are quite common throughout the Hawaiian Islands; at least 68 landslides are visible on the GLORIA data between Hawaiʻi and Midway Island, each more than 20 km long (Groome and others, 1997). While various kinds of mass movement occur on the slopes of the Hawaiian Ridge, the predominant types are slumps and debris avalanches or slides (Holcomb and Searle, 1991; Moore and others, 1989).

Slumps consist of coherent blocks that slip episodically over extended periods of time, rotating along deep faults. Sheer coastal cliffs, or pali in the Hawaiian language, provide some of the most dramatic scenery around the Hawaiian Islands. These cliffs are the eroded headwall scarps of large slumps (Moore and Mark, 1992). The submarine landslide deposits are visible on the GLORIA imagery directly offshore of the cliffs. The Hilina Slump (fig. 1) is offshore on the southeast flank of the active Kīlauea Volcano on the Island of Hawaiʻi. It moves episodically along steep faults that extend to depths of more than 5 km. In 1975, a brief episode of slumping caused the magnitude 7.2 Kalapana earthquake and associated tsunami that startled 32 people camping on the southeast shore of Hawaiʻi near the head of this huge landslide (Tilling and others, 1976).

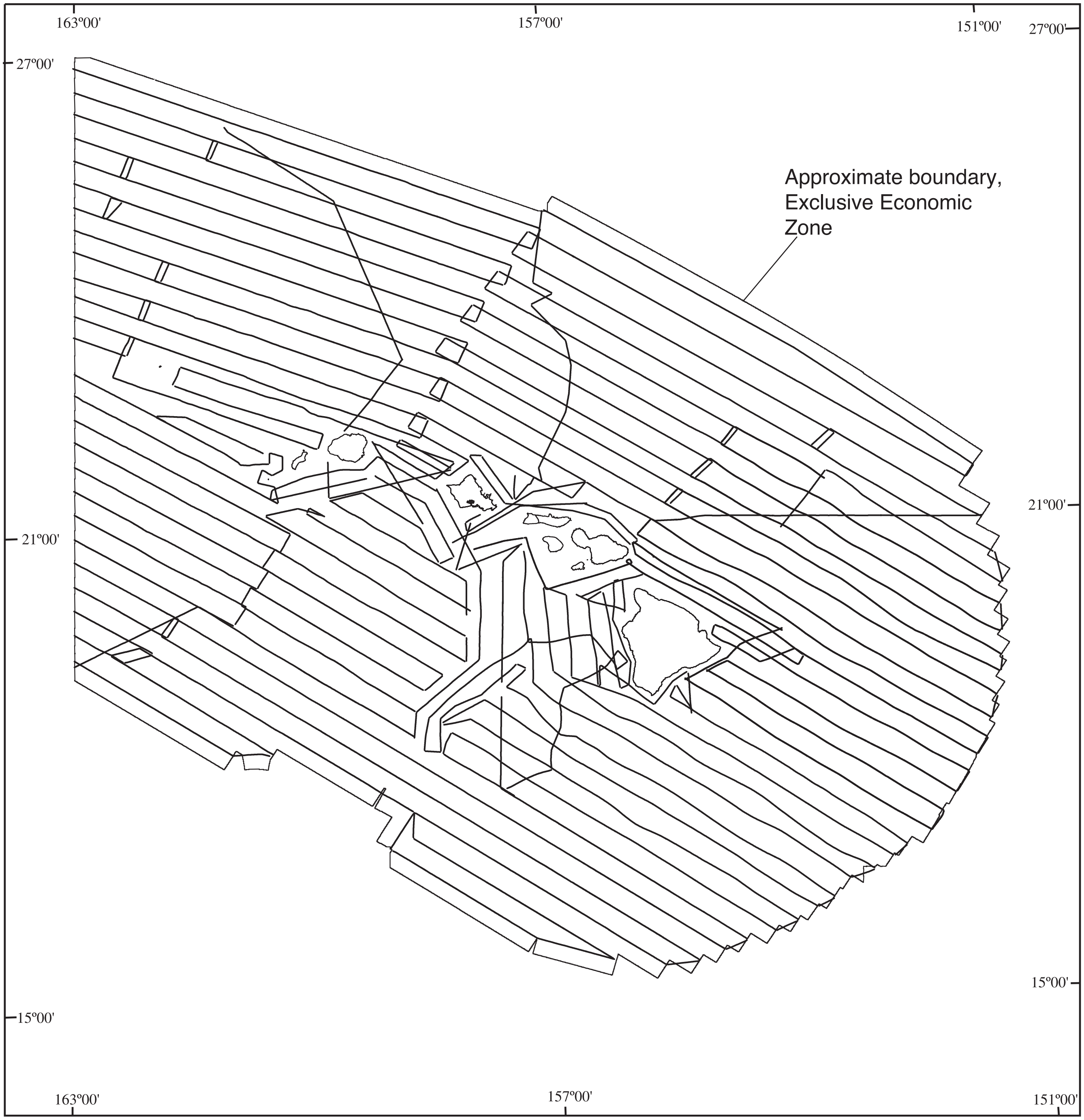

Figure 3. Map showing locations of the nadir or shiptrack for the GLORIA data collected in 1986-1989 from the southeastern Hawaiian Ridge EEZ. Each swath is 40 km wide.

Debris avalanches are rapidly moving, catastrophic landslides that deposit chaotic debris extending as far as hundreds of kilometers from the source. They occur when huge areas of solid rock break into many smaller blocks that travel along the sea floor in a great flowing mass. The Nuʻuanu and Wailau Slides (fig. 1), which collapsed in two or more catastrophic events, are among the largest landslides known on Earth, estimated to represent about a third of the Island of Oʻahu and half of Molokaʻi, respectively. The avalanche debris is strewn downslope 145 km and then continues upslope another 90 km, climbing more than 400 m in elevation. Before the GLORIA imagery was available, the huge blocks in the debris avalanche deposit were thought to be separate underwater mountains. Tuscaloosa Seamount, the largest such block, measures 26 km long, 14 km wide, and about 1,600 m high (Hamilton, 1957; Moore and others, 1994).

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LETTER CODE FOR STRATIGRAPHIC UNITS

The code for each unit consists of 2 to 4 letters, the first 1 to 3 denoting age (chronostratigraphic division) and the last denoting terrain type (morphostratigraphic division). Holocene units are not differentiated on this map. Type b terrain designations are followed by plus (+) or minus (-) symbols to indicate polarity of bedrock magnetization, inferred from data from a towed magnetometer.

Chronostratigraphic divisions

Q	Quaternary
Qp	Pleistocene
QT	Quaternary and (or) Tertiary,
T	Tertiary
Tp	Pliocene
Tmu	late Miocene
K	Cretaceous
Kuu	latest Cretaceous; informal designation used to distinguish some Upper Cretaceous units that are younger than the Cretaceous Magnetic Superchron
Ku	Late Cretaceous

Morphostratigraphic divisions

a	smooth apron
b	lineated seafloor-spreading terrain
c	small central volcano
d	debris flank
e	intact flank
f	former island
h	undivided volcanic terrain
i	present island
j	coarse debris avalanche
k	fine debris avalanche
n	narrow volcanic ridge
q	sonar-dark sediment pond
r	diapiric ridge
s	slump
t	landslide deposit
v	large central volcano
w	wide volcanic ridge
x	lava field of strong backscatter
y	lava field of intermediate backscatter
z	lava field of weak backscatter

DESCRIPTION OF MORPHOLOGIC DIVISIONS

a **Smooth archipelagic apron**—Generally featureless areas of weak backscatter. Aprons obscure lineations of the Cretaceous seafloor around superimposed volcanoes. Surface of aprons is nearly flat in most places and slopes generally less than 5° and commonly less than 0.5° away from nearby volcanoes or axis of the Hawaiian Arch. Interpreted as thick (>100 m) aprons of lava and volcaniclastic deposits overlain by fine sediment that thins away from a volcanic source. Southeast of Kaua‘i the apron of Cenozoic age surrounding the Hawaiian Ridge is almost entirely featureless on GLORIA imagery, but northwest of Kaua‘i that apron is marked by sinuous streaks interpreted as bedforms and (or) shallow slumps in the sediment. Whereas the part of this Cenozic apron west of Moloka‘i is mostly of Tertiary age, the part east of Moloka‘i is entirely of Quaternary age. In a few locations—for example, east of Hawai‘i—faint lineations in aprons are interpreted as ghosts of seafloor-spreading structures, still barely visible where an apron is comparatively thin

b **Lineated seafloor**—Typical “abyssal hill” terrain that is lineated by parallel faults, horsts, and grabens that trend generally north-south. Also includes east-west faults of the Moloka‘i Fracture Zone, where structures of the north-south fabric commonly bend sharply in a left-lateral sense as they approach structures of the fracture zone. Relief on this terrain is variable and depends upon the type of faulting and thickness of the sedimentary mantle. Relief across sediment-draped normal faults of the north-south fabric is generally less than 150 m and decreases to less than 50 m in western areas of thicker sediment. Relief across strike-slip faults of the Moloka‘i Fracture Zone commonly is several hundred meters. Interpreted as primary seafloor-spreading terrain of Cretaceous age produced sequentially from west to east as newly formed seafloor moved westward away from the spreading center of the East Pacific Rise

c **Small central volcano**—Roughly circular volcanic hills less than 10 km wide and 1,500 m high. Includes five classes that are not differentiated separately on this map:

(1) Relatively large shields 5-10 km wide and 1,000-1,500 m high, having rough convex slopes of moderately high backscatter. Interpreted as small polygenetic volcanoes or as large monogenetic domes that were deformed and roughened in response to slow endogenous growth

(2) Pancake domes 1-10 km wide and 100-500 m high, having steep sides and nearly flat tops. Apical depressions—as wide as 2-3 km but usually less than 1 km—are resolved on some domes, and apical mounds of similar size can be seen on others. Interpreted as monogenetic volcanoes that grew episodically, with episodes of rapid effusion punctuated by intervals of quiescence

(3) Subdued plateaus along the base of the Hawaiian Ridge. Plateaus are lower and less circular than other types and are commonly less than 50 m high but 5-10 km wide. Interpreted as sediment-covered, rootless lava fans at distal ends of lava flows in which spreading rates decreased abruptly at the bases of steep volcanic slopes

(4) Circular hills, typically 1-3 km in diameter and 50-300 m high, with a summit crater rarely resolved. Occasionally associated with a strongly backscattering lava field. Interpreted as small monogenetic volcanoes, though some clustered near the bases of large volcanoes may instead be landslide blocks

(5) Small hills less than 1 km wide rising from lineated seafloor-spreading terrain (unit b) distant from landslides or other aprons of younger volcanic material. Interpreted as small monogenetic volcanoes that may have grown either along the axis of the East Pacific Rise during seafloor spreading or at some later time. Diameters of such hills have been exaggerated on this map in order to show them at publication scale

d **Debris flank**—Steep submarine flanks mantled by debris on Hawaiian volcanic edifices. Slopes are greater than 10° and on young volcanoes around the Island of Hawai‘i typically consist of an upper slope steeper than 20° rising about 1,000 m above a lower slope of 10-15°. In GLORIA images these flanks have moderate backscatter and are nearly featureless except for backscatter stripes parallel to the direction of maximum slope. Such flanks are interpreted to be mantled by sandy to blocky debris near the angle of repose in their upper reaches and to consist of coalesced bajada-like fans of debris-slide deposits in their lower reaches. The stripes are interpreted as sediment chutes expressed by variations in grain size and (or) strike of slope relative to sonar illumination. The debris probably was derived from the adjacent island (unit i) or former island (unit f) and was comminuted by shoreline processes or small-scale landsliding of unstable slopes. Much of the debris offshore from young islands probably is basaltic and was produced by fragmentation of hot lava in water and by collapse of shoreline lava deltas; whereas debris offshore from older islands probably is a mixture of basaltic and organic materials derived from subaerial erosion of the islands and shedding of material from fringing reefs

e **Intact flank**—Submarine flanks composed of undisturbed lava flows on Hawaiian Islands. Slopes are generally less than those of unit d, commonly about 10°, but are highly variable (0-45°) over distances of less than a few kilometers. This variation gives a hummocky appearance to such flanks. The hummocks are interpreted as bulbous accumulations of lava along flows that spread slowly and were thickened by inflation of their molten cores behind quenched margins. Such flanks are common where submarine segments of Hawaiian rift zones are isolated from sources of shoreline debris. Whereas such flanks of young shield volcanoes have uniformly strong backscatter owing to their composition and rugged surfaces, the flanks of older volcanoes are smoothed and darkened by superposed sediment. Flanks of intermediate age are mottled owing to variable sediment cover; thicker deposits render the tops of hummocks darker than adjacent steeper slopes that are accumulating sediment less quickly

f **Former island**—Submerged shallow platforms or benches with slopes of generally less than 10° above deeper slopes of generally 10° or more (units d and e). The intervening slope breaks commonly are sharp and occur at a depth of less than 2,000 m. These surfaces commonly are stepped by concentric reef terraces that are successively younger at shallower depths. These shallow platforms are interpreted as former islands, with the outer slope break marking the shoreline at the end of island growth, except where the original slope break has been removed by landsliding (for example, as a part of unit s). Although the slope break commonly is accentuated by a reef, the break is inferred to have originated through processes of volcano growth during which lavas accumulated to form steeper slopes in the submarine environment than in the subaerial environment. GLORIA coverage of these submerged platforms is patchy because the sonar system cannot be operated in water depths of less than 400 m; consequently the distribution of submerged reefs and other shallow features shown on this map is incomplete. All such platforms but one in this area represent former islands of Cenozoic age in the Hawaiian Islands; the one exception is the small summit platform of Cross Seamount (fig. 1), which is about 7.5 km wide at a depth of about 500 m. Labeled ages of these former islands are the ages of their growth not their subsidence

h **Undivided volcanic terrain**—Hummocky volcanic terrain that has moderate sonar backscatter and relief typically less than 100 m. Terrain obscures the Cretaceous seafloor-spreading terrain or is superimposed upon the flanks or archipelagic aprons of the Hawaiian Ridge. Sonar backscatter from this terrain is variable but generally stronger than that from thick deposits of fine pelagic sediment and weaker than that from extensive horizontal lava flows. Individual hummocks commonly resemble small central volcanoes in size and backscatter but lack regular shapes, which suggests they are fragments or clusters of such volcanoes

i **Present island**—Presently subaerial terrain. Includes a basaltic core surrounded by reefs and other sedimentary structures. Islands in the area of this map range in height from less than 200 m to more than 4,000 m above sea level and are composed mainly of volcanic materials. Because the islands themselves were not a subject of the GLORIA survey, they generally are not subdivided on this map—except for Moloka‘i, which is divided by the Pliocene-Pleistocene boundary. Labeled ages of islands are ages of principal growth; consequently some extant islands are labeled as Pliocene or Miocene, and the islands having still-active volcanoes are labeled as Pleistocene instead of Holocene

j **Coarse debris avalanche**—Chaotically broken, hummocky terrain characterized by abundant blocks more than 100 m wide. Larger blocks commonly are several kilometers long and several hundred meters high. Tops of blocks and swales between blocks commonly are draped by thick deposits of weakly backscattering fine sediment, but steep sides of blocks backscatter strongly and are inferred to be comparatively free of sediment. Such avalanche deposits commonly extend from the distal ends of slumps from Hawaiian volcanic edifices. Distinguished from the slumps (unit s) by more chaotic patterns, smaller block size, and lack of contact between adjacent blocks. Inferred to originate from catastrophic collapse of the distal segments of slumps

k **Fine debris avalanche**—Hummocky terrain characterized by sparse blocks more than 100 m wide, rarely more than 2 km wide, with areas between blocks consisting of fine sediment having weak backscatter. Inferred to represent relatively small avalanches, peripheral facies of large avalanches, or scattered outcrops of large avalanches from Hawaiian volcanic edifices that have been buried by thick deposits of younger sediment

n **Narrow volcanic ridge**—Inconspicuous small ridges, possibly monogenetic, less than 20 km long and 1 km wide and probably less than 100 m high, parallel to nearby larger ridges and rows of small central volcanoes. The ridges occur just north of Nihoa. Width of ridges are exaggerated slightly on map to show at publication scale

q **Sonar-dark sediment pond**—Featureless areas of very low backscatter in local depressions that may be isolated by surrounding relief. Surface inferred to be covered by a thick layer of fine ooze having especially weak backscattering properties, probably owing to a lack of coarser particles. Only a few prominent examples are shown on this map because no systematic attempt was made to map them

r **Diapiric ridge**—Prominent ridges 5-15 km wide, 50-150 km long, and generally more than 500 m high. Similar in size and overall shape to wide volcanic ridges (unit w) but smoother, with no sign of small central cones although ribbed in some places by closely spaced oblique ridges parallel to nearby seafloor-spreading fabric. Three examples occur northeast of Maui along a major fault of the Moloka‘i Fracture Zone, where young strands diverge obliquely from an older strand. Interpreted as serpentinite diapirs

s **Slump**—Faulted and warped terrain on Hawaiian volcanic edifices. Terrain consists of large blocks or slices, commonly several kilometers wide and tens of kilometers long, generally elongate parallel to the flanks of the Ridge and forming flights of steps perpendicular to the flanks. Although some fault blocks step progressively downward away from the Ridge, they commonly form less regular flights of alternating horsts and grabens. Whereas treads generally are mantled by thick sediment producing weak sonar backscatter, steep bedrock risers are comparatively free of sediment and backscatter strongly or form deep shadows, depending upon their orientation relative to sonar illumination. Slumps are of two general types: those in which distal parts have collapsed in debris avalanches and those in which the distal parts are still intact. The distal parts of uncollapsed slumps differ from proximal parts in that they are less prominently faulted and have broad convexities that apparently result from incipient folding, although steep fronts of some distal lobes are scalloped by small landslides. The proximal faulted terrain generally occurs downslope from steep debris flanks of the Hawaiian Ridge (unit d), whereas the distal warped terrain commonly extends laterally beyond the debris flanks along the base of lava flanks (unit e)

t **Landslide deposit**—Irregularly hummocky terrain, similar to unit h but generally smoother and less extensive, on seafloor adjacent to a large seamount. Interpreted as the blocky deposit of a small landslide from the seamount. The one example in this map area is adjacent to the southeast flank of Cross Seamount (fig. 1)

v **Large central volcano**—Prominent seamounts more than 10 km wide and 1,000 m high; typically 15-30 km wide but occasionally wider than 50 km and higher than 5 km. Generally conical shape with width about 10 times height. Flanks commonly are ribbed by ridges radiating from the summits. Small satellitic cones are resolved on the flanks of a few, and clusters of small cones, landslides, or other hummocky volcanic terrain (unit h) commonly occur around the bases. Probably polygenetic, though calderas are not observed

w **Wide volcanic ridge**—Prominent ridges more than 3 km wide, 15 km long, and 500 m high. Irregular surfaces possess many knobs and hills more than 100 m high, commonly arranged in dense linear clusters. Interpreted as large volcanic ridge, probably polygenetic

x **Lava field of strong backscatter**—Irregularly shaped, sharply defined areas of exceptionally high backscatter. Generally have flat, nearly horizontal (commonly about 0.1°) surfaces and steep margins 10-20 m high. Margins commonly have an intricately lobate pattern on low slopes of archipelagic aprons (unit a) but are relatively straight along contours against bases of steeper slopes. May extend for more than 100 km with a width as small as 1-2 km along the axes of long, narrow depressions. Interpreted as lava fields that are unobscured by superposed sediment. Thickness of sedimentary mantle and inferred ages of flows are variable, depending upon rates of sedimentation and sonar transparency of the sediments. Photographic traverses have shown that bright flows around the distal end of the Puna Ridge, 50-100 km east of Hawai‘i, and in the South Hawaiian Arch lava field, 200 km south of Hawai‘i, are equally free of sediment; their ages, however, are quite different (estimated at 200 yr and 20 ka, respectively) owing to differences in rate of sedimentation. In contrast, many flows in the North Hawaiian Arch lava field, 100-400 km north of O‘ahu, are mantled by more than 0.5 m of sediment and are estimated to have ages of 0.5-2 Ma yet are similarly bright, apparently because their mantles consist of very fine pelagic sediment that is transparent to the GLORIA sonar

y **Lava field of intermediate backscatter**—Flat-surfaced areas of strong backscatter with lobate margins. Similar to unit x but is somewhat darker, commonly with a finely mottled or speckled appearance. Mottling may arise from variations in mantle thickness, owing to variations in age and (or) surficial roughness on the lava or to bedforms in the sediment. Margins in sonar images are less distinctive than unit x. Interpreted as lava fields having sedimentary mantle that is less transparent than that of lava fields of high backscatter (unit x) because the mantle is thicker or consists of coarser sediment

z **Lava field of weak backscatter**—Flat areas having backscatter that is stronger than is typical of archipelagic sediments (unit a) but weaker than lava fields of intermediate backscatter (unit y). Shapes are commonly irregular and occasionally lobate, and margins are so indistinct as to be mapped only approximately. Interpreted as lava flows that have been buried by sediment to thicknesses of approximately 5-25 m, thick enough to obscure the lava but thin enough to permit elevated backscatter

DESCRIPTION OF MAP SYMBOLS

Contact—Boundary between adjacent terrain units. Many boundaries are gradational, especially those of smooth aprons (unit a), avalanche deposits (units j and k), and undifferentiated volcanic terrain (unit h); some other boundaries are assumed to be sharp but are obscured and appear indefinite (for example, most lava fields of weak backscatter). Internal contacts denote individual volcanic centers

Fault—Linear escarpment or slope that is inferred to represent the trace of a fault; also used to denote a horst or graben that is too narrow to show both boundary faults. Relief on this terrain is variable, depending upon the type of faulting and thickness of the sedimentary mantle. Relief across sediment-draped normal faults of the north-south fabric is generally less than 150 m, decreasing to less than 50 m in western areas of thicker sediment, but relief across strike-slip faults of the Moloka‘i Fracture Zone commonly is several hundred meters. Fault is shown with a continuous, dashed, or dotted line to indicate degree of mapping certainty. Solid line indicates a fault scarp that is shown by a bright backscatter anomaly facing toward nadir, by a sharply defined shadow facing away from nadir, or by a row of sharply truncated structures oblique to the fault. Dashed line indicates a linear backscatter anomaly that is clearly defined though lacking sharp boundaries. Dotted line indicates a linear backscatter anomaly that is vaguely defined, in many cases a continuation of a structure that is more clearly defined elsewhere along trend. Dotted lines are also used in the southern part of the map to indicate alinements of short gaps in several adjacent north-trending structures—gaps which may represent east-trending cross structures are more likely to be sonar artifacts

Levee—Ridge or shelf bordering channel of a debris avalanche, with steeper flank facing inward toward the channel. Dimensions variable, depending upon size of avalanche; may be more than 100 m high, 1 km wide, and 50 km long along a channel more than 5 km wide. Morphologically similar levees occur also on some lava flows but are too small to be shown at this map scale

Leveed channel of distal avalanche—Long, shallow channel that is too narrow—less than 3 km—to show its levees individually at this map scale. The single example shown on this map is a channel near 153° W. longitude and 21°30′ N. latitude; it is approximately 2 km wide and 30 km long and is bordered by low levees of undetermined height. Interpreted as the channel of a large density flow, probably a distal feature of a large debris avalanche from the Hawaiian Ridge

Sediment chute—Stripe of strong sonar backscatter—less than 1 km wide but more than 5 km long—on a flank (usually steep) of the Hawaiian Ridge, trending in the direction of maximum slope. Interpreted as a zone of coarse debris—a lag deposit or relatively fresh avalanche that is mantled less thickly by fine sediment than are adjacent slopes. On submerged islands, such chutes commonly are confined to the bottoms of submarine canyons and are inferred to represent bouldery debris left by confined density flows. On the archipelagic apron, such chutes generally occur in distributary patterns downslope from the mouths of submarine canyons and are inferred to represent lag deposits where the density flows debouched from the canyons onto the apron. On steep debris slopes, such chutes are inferred to represent the axes of the most recent small avalanches on the unstable slopes

Archipelagic streak—Sinuous streak of anomalous backscatter several kilometers long, more than 1 km wide, and less than several dekameters high, with backscatter slightly stronger or weaker than that of its surroundings, depending upon direction of sonar illumination. Elongation is roughly perpendicular to local slope. Interpreted as the slightly steeper flank of a small, elongate swell; in most cases a sedimentary bedform, but in some cases perhaps a shallow slump surface in fine sediment of archipelagic apron

Axis of volcanic rift zone—Axis of broad submarine ridge radial to Hawaiian volcano, extending to deep seafloor from apex of volcano; in some cases, the submarine continuation of an island rift zone. Interpreted as a principal locus of eruption and growth of the volcano

Carbonate reef—Curvilinear streak of high backscatter—generally less than 1 km wide and more than 5 km long—resembling a sediment chute but trending along contour, perpendicular to the direction of maximuim slope. Detailed bathymetry, where available, shows that these streaks correspond to short, steep slopes, and sampling in a few localities has returned blocks of carbonate reef material. Streaks commonly occur in a parallel set forming a flight of steps and are interpreted as submerged carbonate reefs. Concentric reefs record progressive submergence of the island during episodes of rise and fall in sea level. GLORIA coverage of these submerged platforms is patchy because the sonar system cannot be operated in water depths of less than 400 m; consequently the distribution of submerged reefs and other shallow features shown on this map is incomplete. Reefs are shown with a continuous, dashed, or dotted line to indicate degree of mapping certainty. Solid line indicates reefs that are well-expressed as a strong backscatter anomaly or bathymetric escarpment. Dashed line indicates a weak backscatter anomaly that may represent a reef but alternatively could represent a ghost image produced by multiply reflected sound. Dotted line indicates conjectured extension of an observed reef into an area of no data

Hawaiian Arch axis—Axis of broad swell on seafloor surrounding the Hawaiian Ridge at a distance of approximately 250 km from the axis of the Hawaiian Ridge, rising about 500-1,000 m above the Hawaiian Trough bordering the Ridge and about 300-700 m above seafloor more than 500 km from the Ridge. The Arch is developed better northeast than southwest of the Ridge. Along the southwest side of the Ridge, the Arch is shown only to the southern edge of the Moloka‘i Fracture Zone; farther northwest it appears to be obscured by the thick apron of sediment leeward of the islands