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Large Landslides from Oceanic Volcanoes

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Abstract *GLORIA sidescan sonar surveys have shown that large landslides are ubiquitous around the submarine flanks of Hawaiian volcanoes, and GLORIA has also revealed large landslides offshore from Tristan da Cunha and El Hierro. On both of the latter islands, steep flanks formerly attributed to tilting or marine erosion have been reinterpreted as landslide headwalls mantled by younger lava flows. Large landslides have also been inferred from several oceanic islands elsewhere by other workers using different evidence, and we suggest that seacliffs previously attributed to marine erosion of many additional islands may instead be headwalls of still other landslides. These landslides occur in a wide range of settings and probably represent only a small sample from a large population. They may explain the large volumes of archipelagic aprons and the stellate shapes of many oceanic volcanoes. Large landslides and associated tsunamis pose hazards to many islands.*

Keywords Landslides, volcanoes, atolls, seamounts, archipelagic aprons, GLORIA, sidescan sonar, Hawaiian Islands, Tristan da Cunha, Canary Islands.

Introduction

Sidescan sonar surveys have shown recently that giant landslides play a major role in shaping the Hawaiian Islands (Fig. 1) and La Réunion (Lenat et al. 1989), where basaltic shield volcanoes have collapsed after growing to volumes of about 20,000 km^3 in subtropical climates on sediment-covered seafloor of Cretaceous age. Those findings have prompted us to reexamine older sidescan records obtained near a few other oceanic volcanoes of greatly different size and setting; we wanted to know if large landslides are ubiquitous or are limited to a small range of environments. We found that large landslides had been imaged (though previously were not recognized) on early GLORIA sonographs near Tristan da Cunha and the Canary Islands—settings quite different from Hawaii and La Réunion.

GLORIA produces sonar images in which light tones represent high sonar backscatter (Somers et al. 1978). The images published herein represent an early version of GLORIA technology, being made with analog methods and mosaicked by hand. On

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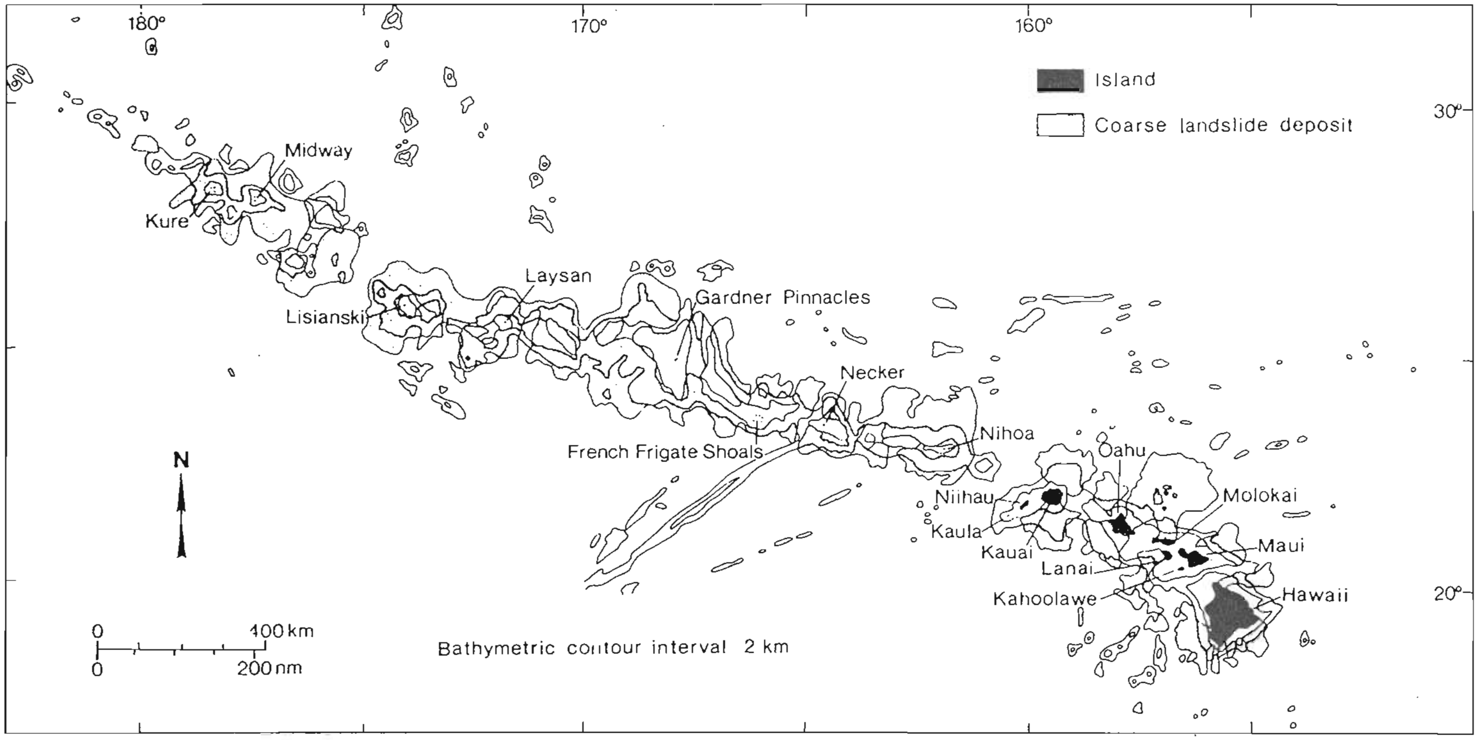

Figure 1. Deposits of large landslides mapped by the GLORIA sidescan sonar in the Hawaiian Exclusive Economic Zone during 1986–1991. (Lipman et al. 1988; Moore et al. 1989; Normark et al. 1987, 1989; Torresan et al. 1989, 1991; and unpublished data of U.S. Geological Survey).

these images the distance along ship's track has been corrected for variations in ship speed, and the distance from ship track (center of swath) to far range has been set equal to the along-track scale. No other slant-range correction has been applied, however, leaving along each ship track a dark strip corresponding to the ocean's water, with the seafloor image compressed into the remaining space. The amount of this slant-range distortion and the width of the central strip vary with water depth.

Tristan da Cunha, South Atlantic

Tristan da Cunha and neighboring islands (Figs. 2 and 3) are the summits of three volcanoes about 200 km east of the Mid-Atlantic Ridge crest; they rise above seafloor having an age of 9 Ma and depth of 3500 m. Each volcano has a volume of 1000–3000 km^3 and distinct irregularities in its plan-view shape.

Inaccessible and Nightingale appear to be small remnants of formerly larger islands. The submarine edifice of Inaccessible is elongate east–west and rises steeply to a depth of about 200 m, where it flattens to form a shallow platform about 20 km long × 10 km wide with a broad embayment in its northwest side. Rising from the wider eastern part

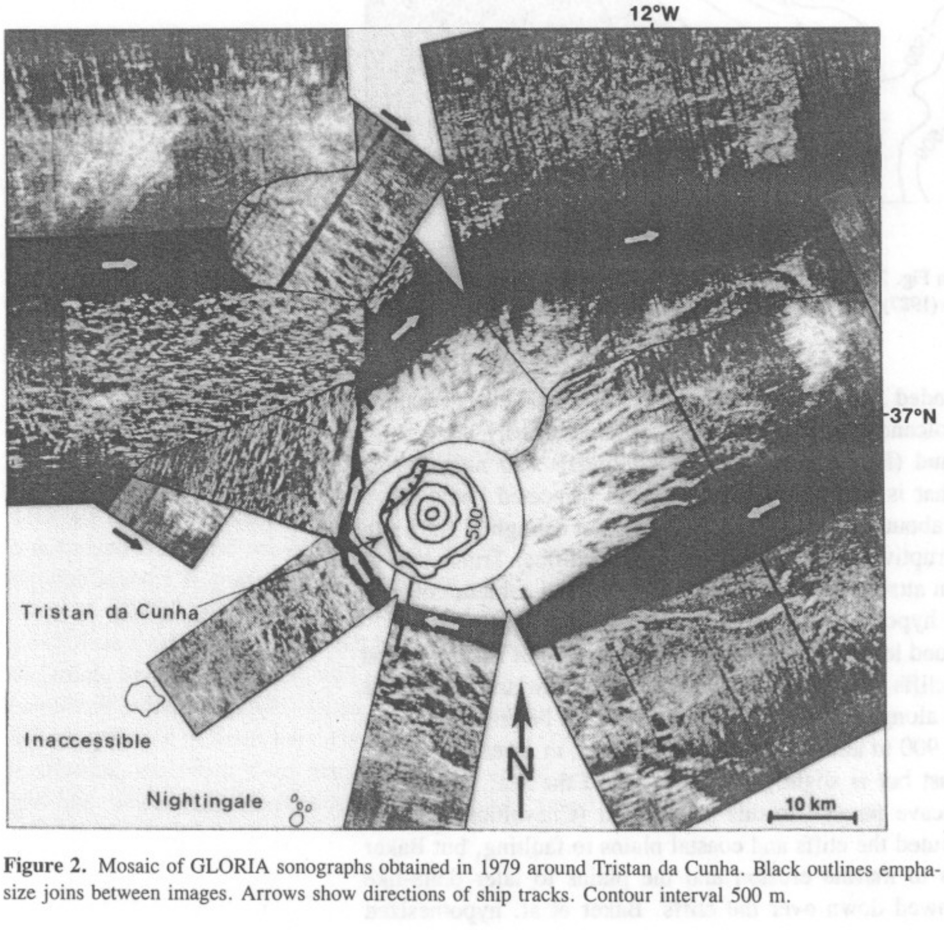

Figure 2. Mosaic of GLORIA sonographs obtained in 1979 around Tristan da Cunha. Black outlines emphasize joins between images. Arrows show directions of ship tracks. Contour interval 500 m.

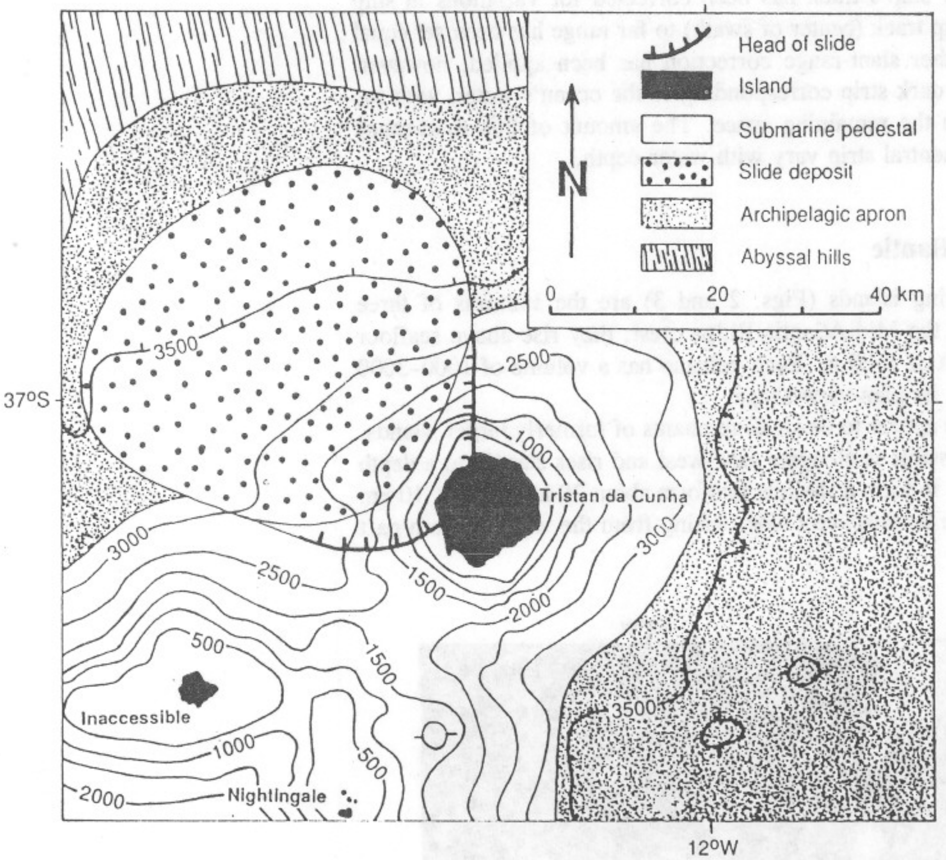

Figure 3. Interpretation of area shown in Fig. 2. Contour interval 500 m. Isobaths to 1000 m around Tristan da Cunha from Chevallier and Verwoerd (1987); others from Needham et al. (1986).

of this platform, the island is bounded almost everywhere by near-vertical cliffs reaching elevations of 150–550 m. The volcano's principal eruptive center probably lay a short distance west of the present island (Baker et al. 1964). Nightingale and neighboring islets sit atop a similar edifice that is elongate north–south and truncated about 50 m below sea level to form a plateau about 9 km wide (Ollier 1984); not enough is known to locate confidently the principal eruptive center of this submarine edifice. Truncation of both volcanoes has generally been attributed to marine erosion, though caldera collapse and other mechanisms have been hypothesized for Nightingale (Ollier 1984).

Tristan da Cunha is younger and less eroded than the other islands but is surrounded by cliffs higher than 500 m. The cliffs are fronted in a few places by lowland plains, the largest being the Settlement Plain along the northwest coast. The cliff behind Settlement Plain is especially high, reaching 900 m and cutting across the flank in a nearly straight line that trends generally northeast but is slightly concave toward the sea; isobaths at least as deep as 1000 m are concave parallel to this escarpment (Chevallier and Verwoerd 1987). Dunne (1941) attributed the cliffs and coastal plains to faulting, but Baker et al. (1964) attributed the cliffs to marine erosion and the plains to later delta-like accumulation of lava that had flowed down over the cliffs. Baker et al. hypothesized recent rates of erosion and island growth to be matched so that the island has continued to grow in height but not in width.

GLORIA sonographs (Fig. 2) show that the linear abyssal hills (seafloor-spreading relics that trend 350° in this region) are obscured to about 50 km from the islands by a younger archipelagic apron (Menard 1956), which must be more than 300 m thick in order to cover the hills. Backscatter variations suggest that various materials occur in the apron. Prominent curvilinear features on the submarine east flank of Tristan da Cunha probably represent channels and levees of debris slides or lava flows.

The apron northwest of Tristan da Cunha is distinctively speckled by small patches of contrasting backscatter. Speckles of similar scale on sonographs around Hawaii characterize large debris-slide deposits (Lipman et al. 1988), and they are inferred to represent a similar deposit here, with individual speckles representing blocky hillocks commonly a few hectometers wide. Images of blocks are compressed normal to ship track by slant-range distortion and smeared out parallel to ship track by the finite width of the sonar beam, so as to appear differently on different sonographs.

Westerly bulges in the 2500- and 3000-m isobaths (Fig. 3) show that the landslide slopes away from the volcano and suggest that the deposit is about 100 m thick. The deposit covers an area about 40 km wide; its volume must therefore be about 150 km^3.

Because the high northwest cliff of Tristan de Cunha rises above the concave submarine flank and landslide deposit at the base of the volcano, that cliff probably is the headwall of the landslide. K-Ar ages of lavas in the cliff (Gass 1967) suggest that the landslide occurred more recently than 100 ka; the Settlement Plain probably accumulated as a lava delta within the landslide scar, partly filling it. The irregular shapes of the Inaccessible and Nightingale edifices may reflect additional landslides from those older volcanoes.

El Hierro, Canary Islands

The western Canary Islands rise from the continental slope of northwest Africa, in water depths of 3000–4000 m; they have played a prominent role in the development of volcanology (e.g., Buch 1825). The high seacliffs and large cliffed basins of these islands have long been debated, one school of thought attributing them mainly to erosion, and another school attributing them mainly to faulting and collapse (Mitchell-Thomé 1976). Giant landslides have been hypothesized to explain the asymmetries of several large depressions that gape open toward the sea, including the Orotava Valley, Guimar Valley, and Las Cañadas depression of Tenerife (Bravo 1962; Ridley 1971; Hausen 1971), the Taburiente caldera of La Palma (Hausen 1969), and two coastal embayments of El Hierro (Hausen 1973).

El Hierro is the summit of a large shield (about 13,000 km^3) rising from seafloor having an age of about 156 Ma and depth of about 4000 m (Fig. 4). It is triangular, with embayed sides to the north (El Golfo), east (Las Playas), and southwest (El Julan)—similar to the stellate shapes of many guyots and seamounts in the Pacific (Vogt and Smoot 1984). Its alkalic basalt (Adventive Volcanic Formation) of latest Pleistocene and Holocene age is draped uncomfortably over nearly horizontal tholeiitic lavas (Tableland Series) older than 190 ka (Hausen 1973; Abdel-Monem et al. 1972). Tholeiitic lava is well exposed in the cliffs of El Golfo and Las Playas but not the Julan flank, which is completely mantled by alkalic layers dipping steeply southward away from El Golfo.

El Hierro is generally viewed as the remnant of a formerly circular shield volcano whose north flank has disappeared beneath the sea, splitting an El Golfo caldera (Knebel

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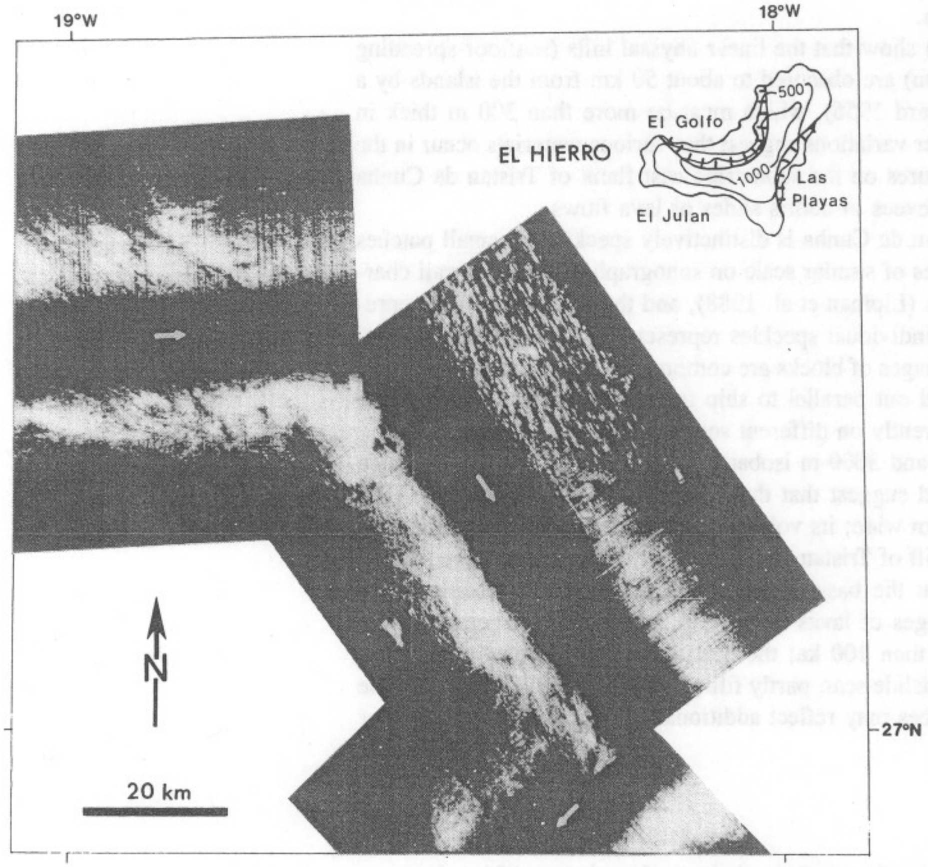

Figure 4. Mosaic of GLORIA sonographs obtained southwest of El Hierro in 1981.

1906). Hausen (1973) attributed the embayments of El Golfo and Las Playas to landslides that postdated the tholeiitic shield but predated its alkalic cap. Hausen apparently did not consider a similar origin for the Julan flank, attributing its steepness instead to southward tilting of the tholeiitic basalt prior to mantling by the alkalic rocks.

A GLORIA sonograph southwest of El Hierro (Fig. 4) reveals the speckled pattern characteristic of large debris-slide deposits. This deposit occurs at the foot of the Julan embayment and must be derived from that embayment; if the landslide produced the embayment after growth of the tholeiitic shield, it must be younger than 190 ka. The Julan slide must be older than the alkalic basalt that is draped over the embayment, but it seems to be overlapped by the Saharan sediment slide (Fig. 5), which probably is not much older than 15 ka (Embley 1976, 1982).

If the Julan embayment is a landslide scar, it represents a volume loss of nearly 100 km^3. The exposed part of the Julan deposit appears to have a smaller volume; it covers only about 900 km^2, and isobaths below 3600 m on the deposit bulge only slightly away from El Hierro, indicating that a 50-m thickness is achieved only in some parts. If the mean thickness of the exposed fraction is about 30 m, its volume is less than 30 km^3; but if a thicker toe of the Julan side is overlain by the Saharan slide (as hypothesized in Fig. 5), the Julan deposit in toto should be large enough to account for all of the embayment.

If Hausen's (1973) interpretations of El Golfo and Las Playas are correct, similar landslide deposits also should occur on the seafloor north and east of El Hierro. These Golfo and Playas landslides should be younger than the Julan slide because their headwalls truncate much of the alkalic lava that caps the volcano and postdates the Julan slide. Similar deposits also may occur offshore from other Canary coasts, including the western shore of La Palma and the northern and southeastern shores of Tenerife, where large landslides may have played a significant role in the development of Ridley's trapdoor calderas.

Volcanic Islands of Other Regions

The examples of El Hierro and Tristan da Cunha show that large landslides can occur on volcanoes differing significantly in size and setting from those of Hawaii and La Réunion. This has prompted us to review available literature on oceanic volcanoes in order

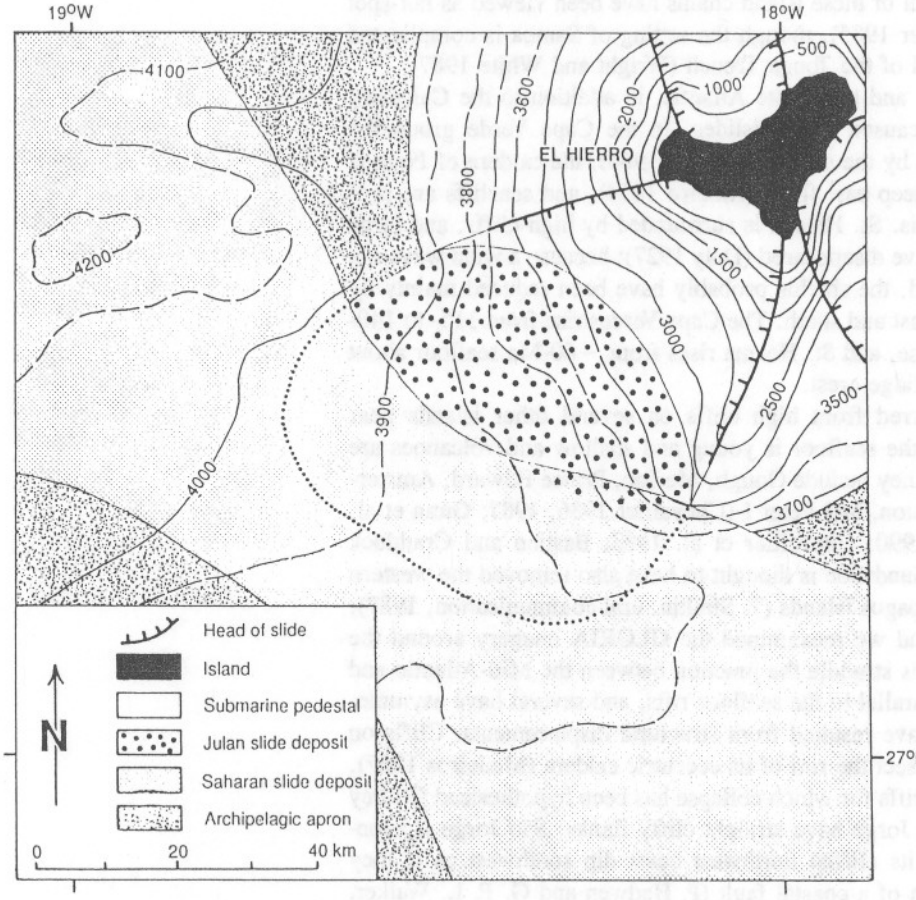

Figure 5. Interpretation of area shown in Fig. 4. Bathymetry at 500 m intervals except where 100-m contours are shown by broken lines (Hunter et al. 1983). Dotted line, buried front of Julan slide inferred beneath Saharan slide.

to evaluate further the frequency and range of conditions under which large landslides might have occurred.

Giant landslides have long been suspected from bathymetric and subaerial studies of many islands. Hypothesized landslides are especially common in the south-central Pacific, where they are thought to have removed large parts of Tau, Ofu, and Olosega in American Samoa (Daly 1924), Savaii and Upolu in Western Samoa (Kear and Wood 1959), and Rarotonga, Mangaia, Aitutaki, and other islands of the Cook chain and other nearby groups (Summerhayes 1967; Wood and Hay 1970). Although large landslides per se have not been reported in French Polynesia, faults inferred from island asymmetries and high coastal cliffs of Tahiti (Davis 1928; Williams 1930), Moorea (Crossland 1928; Williams 1933), and Bora Bora (Stark and Howland 1941) in the Society chain, and all of the islands of the Marquesas group (Chubb 1930) can be interpreted as heads of giant landslides that removed large parts of each island. The setting for most of these islands is similar to those of Hawaii and La Réunion, with the seafloor generally exceeding 4 km in depth and 50 Ma in age, and the climate tropical to subtropical. Their highest seacliffs commonly face away from prevailing winds and seas, and reefs commonly protect their shorelines from marine erosion. All of these island chains have been viewed as hot-spot traces (e.g., Jackson 1976; Brocher 1985), though the setting of Samoa is complicated by its nearness to the northern end of the Tonga Trench (Wright and White 1987).

Several islands in the tropical and temperate Atlantic, in addition to the Canaries, have asymmetries that could be caused by landslides. In the Cape Verde group the caldera of São Vicente is breached by the sea (Serralheiro 1966), the caldera of Fogo is breached above an anomalously steep east flank (Ribeiro 1954), and seacliffs are pronounced around some of the islands. St. Helena is surrounded by high cliffs, and large parts of its two shield volcanoes have disappeared (Daly 1927); because a wide wave-cut bench does not surround the island, the shields probably have been reduced mainly by landslides, especially to the northeast and south. The Cape Verdes rise from 115- to 140-Ma seafloor near the continental rise, and St. Helena rises from ~60-Ma seafloor about 900 km east of the Mid-Atlantic Ridge crest.

Large landslides can be inferred from high cliffs on several other islands near oceanic spreading centers, where the seafloor is young and shallow and volcanoes are small. In the cold Southern Ocean they include Gough, Marion, Prince Edward, Amsterdam, St. Paul, Bouvetøya, Possession, and Peter I (Chevallier 1986, 1987; Gunn et al. 1971; Nougier 1982; Verwoerd 1990; Chevallier et al. 1983; Bastien and Craddock 1976; Anonymous 1988). A giant landslide is thought to have also removed the western half of Volcán Ecuador in the Galápagos Islands (T. Simkin, oral communication, 1987).

With these possibilities in mind we reexamined the GLORIA imagery around the Azores (Searle 1980). These islands straddle the junction between the Mid-Atlantic and Terceira rifts; most are elongate parallel to the seafloor rifts, and several have asymmetries or high seacliffs that could have resulted from structural displacements. Cliffs on the west side of Corvo nearly intersect the rim of its eccentric caldera (Medeiros 1967), and Flores is surrounded by high cliffs for which collapse has been hypothesized (Ridley et al. 1974). Pico, Faial, and São Jorge have straight cliffy flanks; São Jorge is especially narrow, and lava flows in its cliffed northwest coast dip southwest as if they originated from vents further north of a coastal fault (P. Hadwen and G. P. L. Walker, cited by Ridley et al. 1974). On São Miguel, broad embayments in the north coast resemble headwalls of giant landslides (G. P. L. Walker, oral communication, 1989), and the Povoaçao caldera is breached by the south coast. Despite these hints of landslides, however, the GLORIA data reveal only one, not entirely convincing, landslide deposit centered south of Pico near 38.2 °N, 28.1 °W. Most faulting and subsidence in the Azores may arise from deformation of young lithosphere along the oceanic rifts; alternatively, the early GLORIA system in use in 1978 might not have been able to resolve the small mounds characteristic of debris-slide deposits.

Atolls, Guyots, and Seamounts

The plan-view shapes of many atolls and guyots also may record large landslides. Though atolls above intact volcanoes should be simple circles or ellipses, many are in fact highly irregular owing to cuspate embayments. Deep embayments up to a few kilometers wide can arise from submergence of fluvial valleys (Davis 1928), but broader embayments must have other causes. Broad embayments in many atolls such as Niue (Summerhayes 1967) rise above bulges in the archipelagic aprons surrounding the atolls, and this association has been taken as a sign of landslides (Fairbridge 1950). Large landslides have recently been confirmed beneath embayments of several atolls and guyots within the Hawaiian Exclusive Economic Zone (R. Holcomb and others, unpublished data).

Large landslides or escarpments interpretable as landslide scars have also been inferred on some of the few seamounts that have been studied in detail, such as Henderson in the Pacific (volume about 900 km^3, seafloor age about 27 Ma; Taylor et al. 1980) and Gilliss in the Atlantic (volume about 400 km^3, seafloor age about 105 Ma; Taylor et al. 1975). These are members of a large population, including in the Pacific about 10^4 seamounts taller than 1 km (Menard 1964). Because Henderson and Gilliss seem typical of the larger members of that population, many others may also have landslides with volumes greater than 50 km^3. The smaller members, having volumes of about 20 km^3, are comparable in size to subaerial stratovolcanoes such as Mount St. Helens, and they might generate landslides as large as several cubic kilometers.

Discussion

Although the examples cited above are not an exhaustive list, they are sufficient to suggest that giant landslides have occurred on many oceanic volcanoes in various climates and tectonic settings spread widely over the earth. They are not limited to a narrow set of conditions, but represent a process having wide significance. They occur over a broad range of sizes, some having volumes greater than 1000 km^3 (Fig. 6). Many single landslides appear to have removed half of the subaerial fraction and 10–20% of the total volcanic edifice. Continued mapping of the seafloor probably will reveal a great profusion of landslides, and landslide deposits of many sizes probably will be found to dominate the archipelagic aprons around most volcanoes. If Menard's (1964) estimates for aprons are correct, landslide deposits may cover nearly 10% of the ocean floor and have a total volume much greater than 10^6 km^3.

A profusion of landslides may explain the puzzlingly large volume difference between oceanic volcanoes and their archipelagic aprons. Menard (1956) estimated pre-erosion volumes of oceanic volcanoes by extrapolating their present submarine slopes upward to a point, a procedure that yielded volumes only about 25% those of the aprons. He concluded that only a small part of the aprons can be derived from erosion of the volcanoes, and he hypothesized the aprons to consist largely of lava flows (Fig. 7*A*). But although some lava flows have been confirmed on a few aprons (Holcomb et al. 1988), they have not been found to dominate (Moore et al. 1989). If the volcanoes have been reduced by giant landslides, especially during their growth, the extrapolation of present slopes could greatly underestimate former volumes of the volcanoes. Several Hawaiian shields appear to have lost at least 30% of their volumes to multiple landslides after their growth ceased, and some appear to have lost at least as much to giant landslides when they were large but still growing (Holcomb 1976, 1983, 1985). We suspect that oceanic volcanoes repeatedly lose large volumes to landslides as they grow, so that the total volume of the collapsed material greatly exceeds the volume of the more coherent, steeper edifice (Fig. 7*B*). Many early landslide deposits are probably buried beneath the later, larger edifice, contributing to instability of its foundation.

As landslides are attributed a greater role in the reduction of oceanic islands, the role of marine erosion must be correspondingly reduced because many of the high seacliffs formerly attributed to marine erosion will be reinterpreted as eroded headwalls of landslides. The effects of marine erosion may be doubted especially in climates that

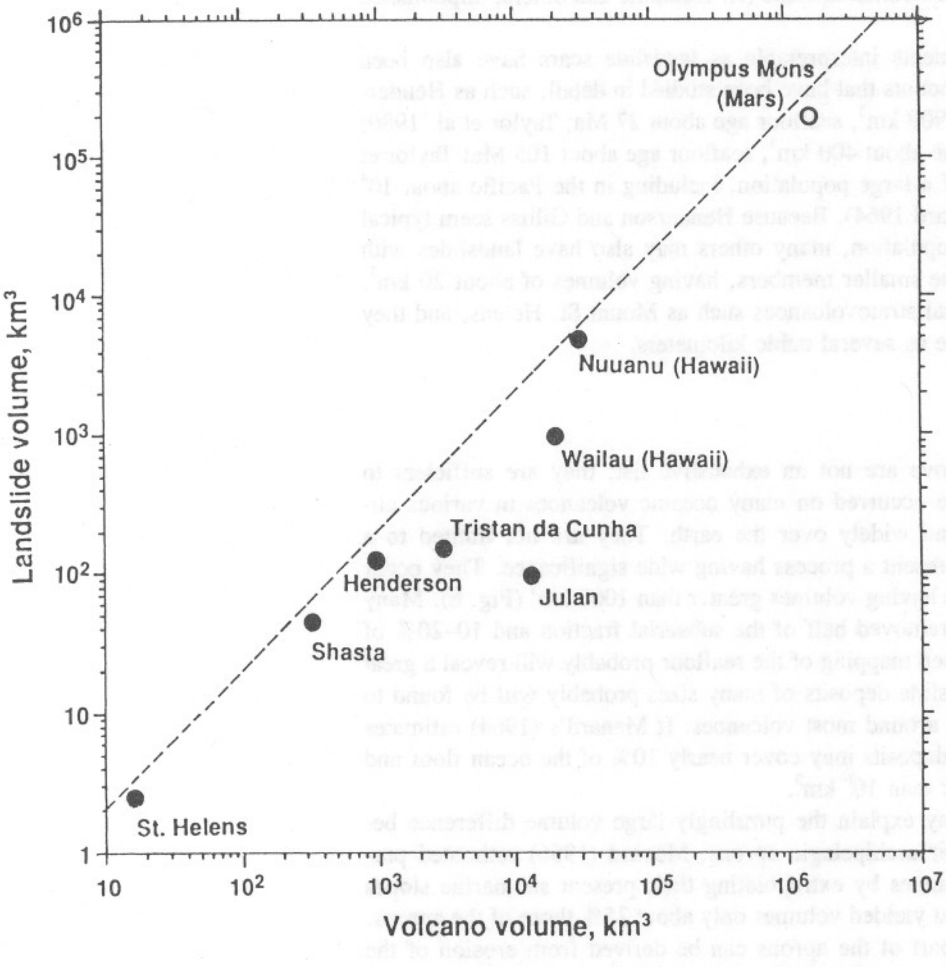

Figure 6. Volumes of landslides and source cones. Dashed line, possible limit where slide is 20% of volcano, used to predict maximum volume (○) for inferred slide of Olympus Mons (Francis and Wadge 1983). Shasta slide only recently considered the largest known Quaternary landslide on Earth (Crandell et al. 1984).

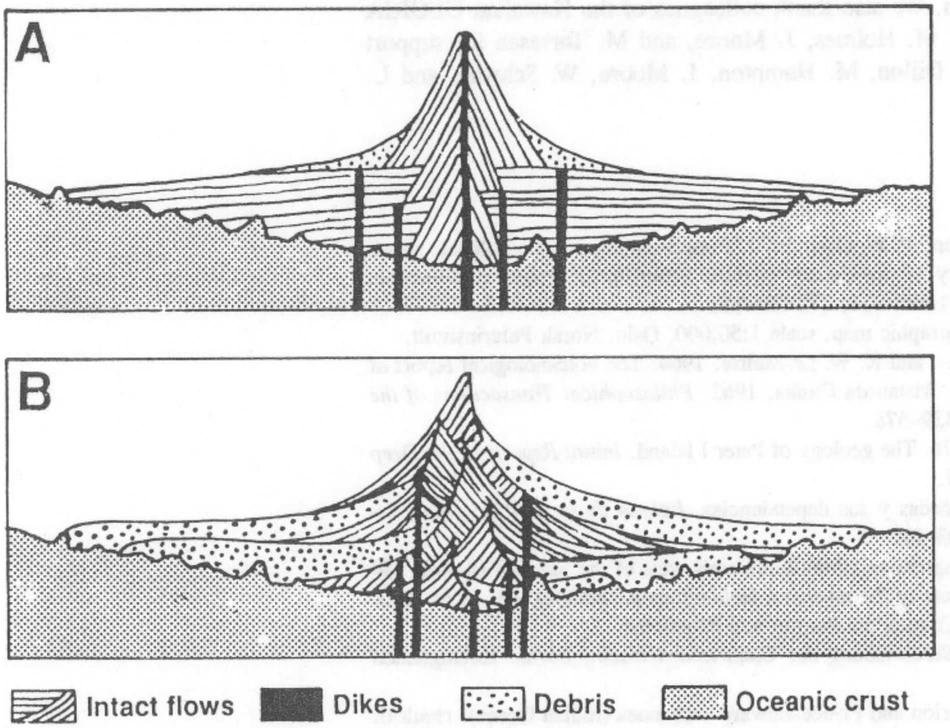

Figure 7. Hypotheses for composition of archipelagic aprons. (*A*) Aprons consist mostly of lava flows interbedded with steep edifice (Menard 1956). (*B*) Aprons consist mostly of landslide debris interbedded with edifice remnants.

permit the growth of coral reefs; the principal effect of strong wave action in such climates may be to promote the growth of protective reefs instead of eroding the islands.

Landslides may also produce the stellate shapes of many oceanic volcanoes, which have been attributed previously to growth along radiating rift zones (Vogt and Smoot 1984). Similar shapes could arise from collapse of shields, even in the absence of well-developed rift zones; many rift zones may even owe their origin to landsliding.

It should be noted that large landslides pose hazards to many islands, especially those composed of actively growing volcanoes. Unbuttressed flanks of such volcanoes are the most vulnerable, especially their coastal lava deltas. Tsunamis generated by landslides pose hazards also to other flanks and islands nearby (Moore and Moore 1984, 1988). Although we cannot yet estimate reliably the magnitude of such hazards, at least one catastrophic collapse within human memory may be recorded by a Polynesian tradition about the disappearance of a once populous island in the Marquesas (Christian 1910, p. 204).

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