Giant Hawaiian Underwater Landslides

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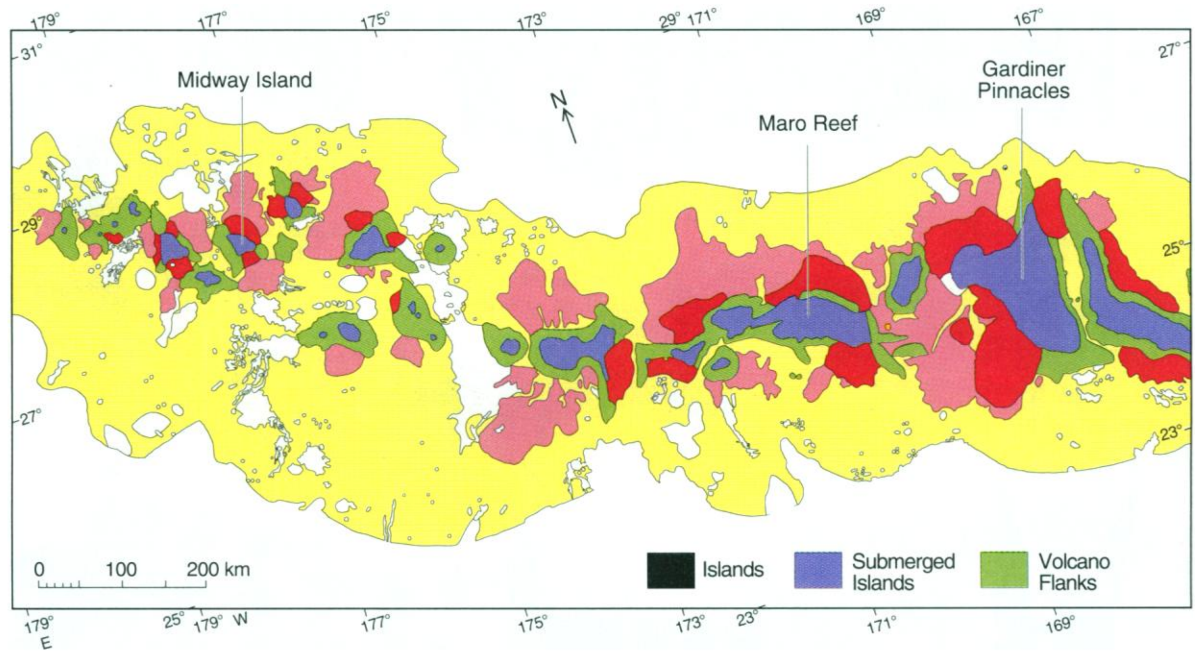
After declining to sign the United Nations–sponsored Law of the Sea Treaty in early 1983, President Reagan proclaimed U.S. sovereignty over seabed resources in a U.S. Exclusive Economic Zone (EEZ) extending 370 km offshore from U.S. territory. As the primary mapping agency for the United States, it was the job of the U.S. Geological Survey (USGS) to map this newly claimed territory, which totaled 13 million square kilometers. An astonishing result of the survey was the discovery of many giant landslides on the submarine flanks of the Hawaiian Ridge (see figure) (*1*). A few of these landslides were previously identified from available small-scale bathymetry, limited marine geophysical studies, and extrapolation of structural features mapped on land. About 70 major landslides over 20 km in length were delimited by sonar imagery, and their deposits cover half the flanks of the ridge. Some of the landslides attain lengths of over 200 km, volumes exceeding 5000 km^3, and are among the largest on the planet.



The daunting task of surveying an area as large as the EEZ required acquisition of marine geophysical data involving more than a half million kilometers of ship track and could not be accomplished without the use of a swath-mapping system capable of obtaining information from the ocean floor over a broad strip. The mapping method selected was the GLORIA (for geologic long-range inclined ASDIC, where ASDIC is the naval acronym for sonar) side-scan sonar system, which had been developed at the Institute of Oceanographic Sciences (IOS) in the United Kingdom (*2*). The mapping was done cooperatively by the USGS and IOS and, in addition to the side-scan sonar imagery, it also included bathymetry, seismic-reflection profiling, and gravity and magnetic field measurements. The GLORIA vehicle is towed at a depth of about 50 m and produces an acoustic backscatter image of the ocean floor over an effective width of as much as 50 km in a water depth of 5 km. Initial systematic EEZ surveys were begun off the west coast of the United States in 1984, and mapping of the entire 2200-km-long (2,380,000 km^2) Hawaiian EEZ was accomplished from 1986 to 1991. This, the largest mid-ocean sea-floor imaging survey, required more than 400 days at sea. Processing of the preliminary digital mosaics has recently been completed for the 74 2° quadrangles (scale 1:500,000) that cover the Hawaiian EEZ.

Two forms of landslides have been identified: slumps and debris avalanches (*1*), but many intermediate examples exist. Slumps generally moved on an overall slope >3°, and debris avalanches, <3°. Slumps involve mass movement with little disruption of the structural coherence of the volcano flanks, and the debris avalanches produce fragmentation that totally disrupted and dispersed original volcanic structures. Large slumps are deeply rooted in the volcanic edifice; they may extend back to the volcanic rift zone and down to the base of the volcanic pile and reach thicknesses of 10 km. They may creep slowly as they keep pace with the load of volcanic material erupted on their upper part, or they may abruptly surge forward several meters, causing the largest of Hawaii's historic earthquakes, in 1868 and 1975.

Debris avalanches are thinner and longer than the slumps. They commonly have a well-defined amphitheater at their head and are marked by hummocky terrain in their lower part, with individual blocks commonly 1 to 10 km in diameter. Rapid movement during single events is indicated by the thinness and great length of the avalanches, by movement uphill in their distal reaches in some places, and by their hummocky, fragmented surfaces that resemble the hummocky terrain of subaerial rapidly emplaced landslides, such as the 1980 Mount St. Helens debris avalanche (*3*).

Rapidly moving avalanches that carried blocks up to 10 km in size for tens of kilometers would produce major disturbances in the water column, which could have created giant tsunamis (*4*). Coral-bearing marine conglomerates considerably above sea level on several of the Hawaiian Islands are interpreted to have been deposited by tsunamis triggered by the giant debris avalanches. Such tsunami-wave deposits, at elevations as high as 70 m on Molokai and 325 m on Lanai, have been dated at about 200,000 and 100,000 years ago, respectively, and similar but undated deposits occur on Oahu, Maui, and Hawaii. In addition to on-land tsunami deposits, volcanic sand recovered from an ocean drilling site more than 265 km from the nearest volcano was probably deposited by turbidity currents related to major landslides on the Hawaiian Ridge (*5*).

Interestingly, the Hawaiian discoveries

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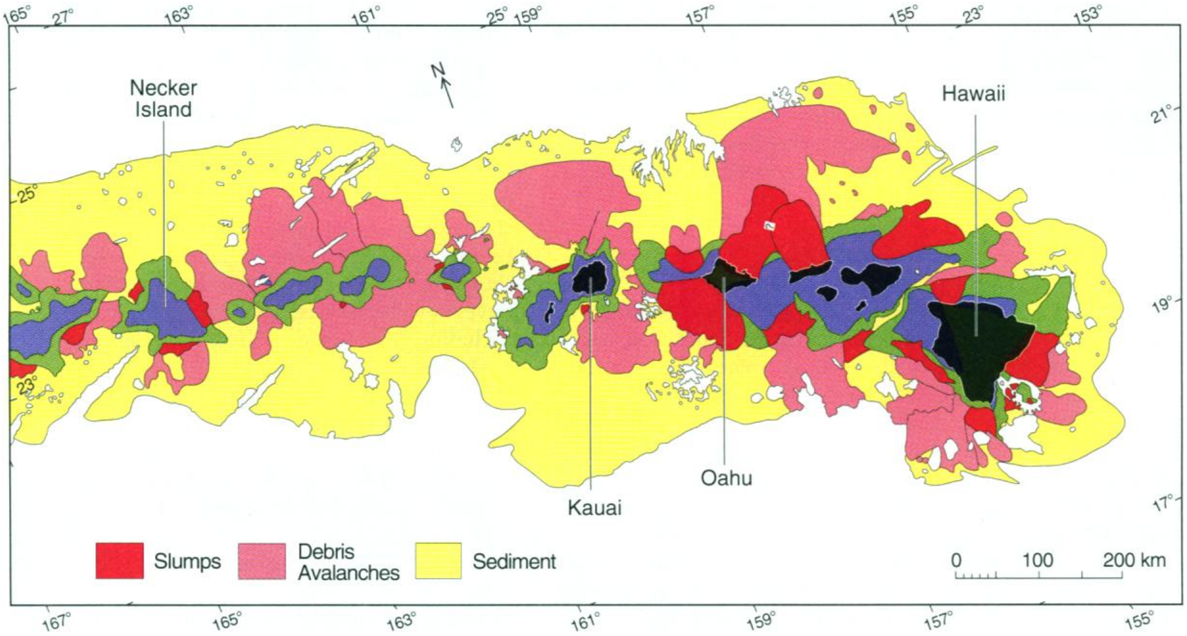
came less than a decade after the significance of major subaerial volcanic landslides was realized, following the catastrophic eruption of Mount St. Helens in 1980. During this eruption, a 2.8-km^3 debris avalanche, the largest landslide in recorded history, removed the summit and north flank of the mountain, depressurized the volcanic system, and caused the explosive eruption of the volcano (*3*). Within a few years, about 70 examples of major landslides on subaerial volcanoes, mostly prehistoric, had been tabulated, including many with associated explosive eruptions (*6*).

Just as interest in major subaerial volcanic landslides burgeoned after the St. Helens eruption, published descriptions of major submarine landslides elsewhere on Earth greatly increased as the Hawaiian discoveries were made. Many submarine landslides, ranging widely in size and geologic setting, have now been documented worldwide. Because marine volcanoes on average are larger than their on-land counterparts, submarine volcanic landslides are likewise larger than subaerial landslides. The volcanic island of Reunion in the Indian Ocean has failed repeatedly by massive landsliding (*7*); Mount Etna, the largest volcano in Europe, shows evidence of gravitational spreading both above and below sea level (*8*); and a large submarine landslide was mapped offshore of the active crater of the island volcano of Stromboli (*9*). Recently released bathymetric data obtained by the U.S. Navy reveal large-scale landslides on the Michelson Ridge and the Emperor, Mapmakers, and Marcus-Wake seamount groups (*10*). Peculiar morphology of the Marquesas Islands, coupled with recent bathymetric surveys, indicates major collapses of eight of the volcanoes in this archipelago (*11*).

Reexamination of early GLORIA images has revealed large landslides on the submarine slopes of the Canary Islands and Tristan da Cunha that had previously gone unrecognized; general surveys of such failures suggests that many single submarine landslides have removed 10 to 20% of their source volcanoes, and that larger fractions have been removed from a single edifice by multiple landslides (*12*). These large landslides on oceanic volcanoes are exceeded in volume only by mass failures observed on Mars (*13*).

The giant Hawaiian landslides have provided new insight into structural features of the volcanoes, but the role of cause and effect remains blurred. Much of the seismic activity shallower than 15 km near the active volcanoes is presumed to be generated by landslide-related processes, and the largest quakes in Hawaiian history (magnitude $M>7$) are apparently associated with gravity failures. Major normal fault systems, some previously difficult to interpret, can now be related to the upper tensional part of slumps, and anomalous slope changes can be attributed to lava-buried, landslide-related fault systems. The volcanic rift zones, which conduct magma laterally from the summit reservoirs, are regarded as the pull-apart zone at the slump headwall. Large, rapidly cut canyons are common in the newly excavated amphitheaters of debris avalanches, and the presence of such canyons is now employed as evidence of ancient landslides. Broad benches and closed depressions half-way down the submarine slopes are attributed to thrusting in the lower compressional parts of slumps. The giant submarine landslides have stimulated interest in the concept of gravitationally induced volcanic spreading, a topic that was the subject of an entire session at the fall American Geophysical Union meeting. The close parallel in the structure of marine volcanic rift zones and oceanic spreading ridges has led to the proposal that large oceanic volcanoes are small analogs of global plate tectonics (*14*).

Many questions have been raised by the discovery of these large gravity failures. How do the debris avalanches carry blocks 10 km in size, perhaps rapidly, more than 50 km down a slope averaging less than 3°? What effects do such landslides have on the sedimentary record? How might their deposits be recognized in ancient deposits? How are they related to the life history of large marine volcanoes? What is the frequency of such landslides, how are they triggered, and what sites favor them—in short, what hazards do they pose? These and many other issues are matters of debate, and the answers, at present, remain elusive. The mapping of the Hawaiian EEZ helped us to identify some of the questions and maps provide a consistent, reliable basis for future studies.



Shifting territory. Geologic interpretive map generated from GLORIA backscatter imagery of the Hawaiian Ridge showing the position of giant landslides.

References and Notes

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15. Critical reviews by D. W. Peterson and R. I. Tilling are appreciated.