3. Japan-US Joint Study on Hawaiian Hot Spot Volcanoes 1998-2002

Purpose of the Joint Study

Hawaii is the most active hot spot on Earth and is the classical locality of modern volcanology. Although numerous research papers have been written on Hawaiian volcanoes and their current activities those exposed on land, very little is known on their submarine roots. In 1998, a collaborative Japan-USA program was initiated to explore the evolution of Hawaiian volcanoes including their growth and degradation, making use of the deep-sea research capabilities of the Japan Marine Science and Technology Center (JAMSTEC). During a four week cruise in 1998, the ROV *Kaiko* (Remotely Operated Vehicle), supported by its mother ship RV *Kairei*, made 10 dives at depths to 5,200 m for direct sampling and video observations, supplemented by dredging, piston cores, and SeaBeam bathymetric surveys. During a seven week cruise in August-September 1999, the *Shinkai 6500* submersible made 29 dives from the RV *Yokosuka* for sampling and direct observations as deep as 5,560 m, and further SeaBeam surveys were obtained. A third cruise in 2001, the initial part of the current project, utilized the *Kairei* and *Kaiko* to make 17 ROV dives and collected about 300 outcrop samples, obtain 10 new piston cores, made several dredge hauls, and generated additional SeaBeam coverage. Finally fourth cruise of this series has been carried out in summer of 2002 again with the *Shinkai 6500* submersible and the RV *Yokosuka.* In total, 30 submersible dives were carried out in 2002 on to the newly discovered volcanic field SW of Oahu, submarine rifts of Haleakala and Kilauea, and submarine landslides from Mauna Loa, Kohala and Hualalai. Altogether 20 scientists from Japanese side, consisting of JAMSTEC, Geological Survey of Japan and 7 universities (Titech., Tokyo Univ., Hokkaido Univ., Shizuoka Univ., Osaka Univ., Shimane Univ., and Kumamoto Univ.) collaborated with 15 US scientists from US Geological Survey, University of Hawaii, Rice Univ., Bishop Museum and the Monterey Bay Aquarium Research Institute. Part of research results of this project have been published as collective papers in the AGU Geophysical Monograph vol. 128, *Hawaiian Volcanoes: Deep underwater perspectives*, in Feb. 2002.

Our knowledge of the submarine region around Hawaiian volcanoes has changed dramatically in the last few years as a result of these JAMSTEC expeditions to Hawaiian waters. These expeditions have generated improved images of sea-floor bathymetry (Naka *et al*., 2000; Smith *et al*, 2002), utilized ROV and submersible vehicles to collect a large suite of precisely located samples for petrologic study, and acquired detailed photo and video images for many critical areas. Such materials, supplemented by petrologic, geochronological, and other laboratory studies, provide the basis for investigating a wide variety of geophysical phenomena. These include the sources for and extent of plume magmatism, processes associated with active and ancient landslides on oceanic island volcanoes, seismic structure and tectonic processes on active volcanoes, nature of rift zone and other submarine volcanism, growth of oceanic island volcanoes, and hydrothermal processes. In concert with the field and laboratory studies, recent theoretical investigations have explored the causes and consequences of Hawaiian plume magmatism and the landslides associated with these unstable volcanoes.

One major objective of this JAMSTEC cooperative program is to explore the evolution of oceanic islands including their growth and degradation. Giant landslides are now widely recognized along the flanks of many oceanic volcanoes, such as Hawaii, Marquesas, La Reunion, Galapagos, and Canary Islands. The landslides form during the growth of the volcano as it is centered over the hot spot and after it drifts off. The abundance of landslides demonstrates that mass-wasting processes play an important role in the construction and evolution of oceanic-island volcanoes. Not only do such processes modify the surfaces and slopes of the islands, they also are closely linked with major geologic hazards, including earthquakes associated with slope failure, large-scale submergence or emergence of coastlines, and massive tsunamis, which can destroy life and property. Due to the unpredictable and sporadic nature of such massive landslides, the processes and timing associated with these events remain poorly understood. Yet the significance of landslide features in the evolution of volcanic islands, and their extraordinary destructive potential, make it imperative that we understand their history and behavior, and assess their impact on human development of volcanic islands and adjacent coastal areas.

Another major goal of the JAMSTEC program is to reconstruct the growth history of Hawaiian volcanoes through study on deep exposure of the volcanic edifices. The landslide blocks themselves are collapsed and dismembered interiors of the volcanoes, which is inaccessible by ordinal means. As discussed below, our study shed lights on early alkalic stage of Kilauea volcano through intensive survey on deep submarine Hilina slumps on the south flank of Kilauea volcano. We also found the multiple growth history of 3 Ma old Koolau volcano on Oahu through reconstruction of the giant Nuuanu landslide. Our result showed that this volcano has experienced at least three magma types, Kilauea-type, Mauna Loa-type and Koolau-type in its growth history. In this way, our joint research program demonstrated the importance of submarine geologic study to understand the long term evolutional history of ocean island volcanoes. Such study gives comparable but quantitatively different information in its special coverage to those obtained by deep drilling of a volcanic edifice (e.g., Hawaiian Scientific Drilling Project).

Early Growth Stage of Kilauea Volcano

In contrast to the dominantly constructional volcanic morphology along the crest of the Puna Ridge, the offshore south flank has more diverse morphologic, structural, and petrologic features. Visual observations during the 1998-99 JAMSTEC cruises, combined with sample characterization, indicate that the 3 km-deep mid-slope bench and lower scarp consist entirely of well-bedded volcaniclastic rocks: massive sandstone, debris-flow breccia, siltstone, and mudstone (Lipman *et al*., 2002). High-S compositions of many alkalic basalt clasts and some sandstone glasses indicate derivation from a submarine "Loihi" stage of ancestral Kilauea, prior to growth of its tholeiitic shield. In contrast, all observed outcrops above and east of the mid-slope bench, are massive pillow lava and broken pillows of transitional basalt, which define the initial submarine flank of subalkaline Kilauea. These features indicate that ancestral Kilauea was a sizeable submarine alkalic volcano, where recurrent slope failures generated a flanking apron of clastic debris that was subsequently overgrown by the modern tholeiitic Kilauea shield.

Compositions of submarine-erupted glass from the lower scarp (Sisson *et al*., 2002), which encompass a range far greater in silica, alkalis, and other elements than that known for Loihi Seamount, record magma-generation processes during early stages of volcanic growth, prior to tholeiitic shield-stage Kilauea. The general compositional sequence on the south flank of Kilauea and on other Hawaiian volcanoes is compatible with genetic models of increasing degrees of partial melting in the mantle source, but the diverse compositions preserved in the volcaniclastic sediments of the south flank cannot have been derived entirely from a homogeneous source. The volcaniclastic apron on the south flank of Kilauea thus provides a broad petrologic sampling of an early stage in Hawaiian hotspot volcanism, much like that sought for Mauna Kea volcano by the in-progress Hawaii Scientific Drilling Project. Recently acquired underwater and drill-hole samples have also documented greater compositional diversity than previously known for other Hawaiian volcanoes, such as Mauna Loa and Koolau. Compositional differences among tholeiitic basalts, previous considered characteristic of individual Hawaiian volcanoes (e.g., Kilauea, Mauna Loa, Koolau), now appear more likely to represent a general evolutionary sequence sampled to different extents during growth of Hawaiian shields.

The offshore observations, in conjunction with previously reported subaerial geologic information, provide new perspectives on the growth of Kilauea and other ocean-island volcanoes. Many previous studies have interpreted on-land features of Kilauea's south flank and adjacent offshore region as products of large-scale block-slumping and volcano spreading since growth of the tholeiitic shield. The new data obtained by submersible operations suggest a more complex compositional evolution and prolonged history of slope failures. Meanwhile, the success of JAMSTEC cruises in obtaining representative materials from the early alkalic growth stage of Kilauea volcano suggest that similar sampling strategies may be applicable to other ocean-island volcanoes, especially where flanks are disrupted by slumping and landsliding associated with volcano spreading.

Giant Landslides NE of Oahu Island

The presence of giant landslides on the flanks of numerous ocean island volcanoes including Hawaii, Reunion, and the Canary islands is well documented. The catastrophic failure associated with some of these giant landslides appears to be a common feature of ocean island volcanoes. Ocean island collapses are now recognized as important global erosional agent. The rapid growth (~1 to 1.5 million years) and enormous size of Hawaiian volcanoes (individually, up to 8.5 km of relief and 100,000 km^3 volume) causes them to be particularly unstable. The collapse of Hawaiian volcanoes has generated some of the largest landslides on Earth and colossal tsunami waves. Dozens of major landslides, some with volumes >1000 km^3 and large blocks >1 km in height, have been recognized along the Hawaiian Ridge. On average, a major landslide has been identified every 32 km along the ridge. Based on an average ~10 cm/year northwest motion of Hawaiian volcanoes, a giant landslide occurs about every 320 thousand years, and smaller slides must have occurred much more frequently. The wealth of information on Hawaiian landslides has led to Hawaii becoming the type example for ocean island landslides.

A major obstacle in gaining a better understanding of when, why and how giant landslides form in Hawaii has been the limited detailed bathymetric and side-scan sonar imagery coverage for Hawaii. This dramatically changed following the detailed surveying northeast of the island of Oahu during JAMSTEC cruises to Hawaii in the summers of 1998 and 1999. This new bathymetric data allow for comprehensive reconstructions of the Nuuanu and Wailau landslides. Moore and Clague (2002) conclude that the volume inequities between the size of the "holes" left by these slides and the volume of the blocks indicate that there was long-term bulging on the slopes of Koolau volcano before the landslide. Yokose (2002) enhances our understanding of the products and processes for both these landslides by combining the new bathymetric data with detailed submersible observations of landslide debris outcrops.

How big were the tsunamis associated with the Nuuanu and Wailau landslides? Satake *et al*. (2002) answered this question by determining the volume change associated which each landslide. Tsunami generation and propagation for these slides were computed using a kinematic landslide model. They calculate that mammoth waves were formed from these slides. For the Nuuanu slide, some waves would have been >100 m high and would have struck the Hawaiian islands within minutes. The tsunami from this slide was directed towards California. Waves up to 70 m high would have reached the shores of southern California in about 5 hours.

Another major obstacle to our understanding of giant Hawaiian landslides was the lack of sampling of the landslide debris. This was due in part to the landslide debris being in water depths of 3-5 km below sea level, which is outside the range of most submersibles. The JAMSTEC deep submergence vehicles are ideal for exploring the landslide debris because they can explore the full depth range of the debris. The papers by Shinozaki *et al*. (2002) and Tanaka *et al*. (2002) examine petrology and geochemistry of rocks recovered from the landslide debris. Using the geologic reconstruction of the landslide debris, these authors demonstrated that 3 Ma Koolau volcano had experienced multiple growth history. The main shield building stage of the volcano consists of olivine tholeiite lavas similar to modern Kilauea and Mauna Loa, successively. At the final growth stage of this volcano, the magma change abruptly to very silica-enriched tholeiite composition with distinct isotope signature.

Takahashi and Nakajima (2002) simulated melting processes in the Hawaiian plume consisting of peridotite and entrained oceanic crust (eclogite), they conducted series of high-pressure melting experiments. They showed that high-silica tholeiite characteristic of the subaerial Koolau volcano could be produced by direct partial melting of recycled eclogite at temperatures slightly below the peridotite dry solidus. On the other hand, Garcia (2002) studied submarine picrite lavas taken from northern flank of Koolau volcano, and he showed that primary magma of this volcano had picritic composition similar to those in modern Kilauea and Mauna loa. Distinct anomalies in rare-gases (e.g., $^{3}He/^{4}He$ in lavas from Loihi Seamount is up to 35 times that in the atmosphere) are a key signature of mantle-plume magmas that originated from a deep undegassed reservoir in the mantle. Kaneoka *et al*. (2002) reported new analyses of rare gas isotopes (He, Ne, Ar, Xe, and Kr) for deep-ocean samples from Loihi, Kilauea, and Koolau volcanoes. The new data and their previous studies document large variations in He isotopes among volcanoes in the Hawaiian hot spot. The highly variable He values are interpreted to represent different degrees of interaction between the rising plume magma and the uppermost asthenosphere.

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