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## Widespread Secondary Volcanism Near Northern Hawaiian Islands

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Hot spot theory provides a key framework for understanding the motion of the tectonic plates, mantle convection and composition, and magma genesis. The age-progressive volcanism that constructs many chains of islands throughout the world's ocean basins is essential to hot spot theory. In contrast, secondary volcanism, which follows the main edifice-building stage of volcanism in many chains including the Hawaii, Samoa, Canary, Mauritius, and Kerguelen islands, is not predicted by hot spot theory. Hawaiian secondary volcanism occurs hundreds of kilometers away from, and more than 1 million years after, the end of the main shield volcanism, which has generated more than 99% of the volume of the volcano's mass [Macdonald *et al.*, 1983; Ozawa *et al.*, 2005]. Diamond Head, in Honolulu, is the first and classic example of secondary volcanism.

Attempts to explain secondary volcanism in the context of the hot spot phenomenon—in particular, as attributed to mantle plumes—include hypotheses of conductive heating of the lithosphere by the plume, lateral spreading and uplift of the plume after its ascent, and flexure-induced decompressional melting related to the rapid growth of new volcanoes above the ascending plume [e.g., Bianco *et al.*, 2005]. Even more enigmatic than the shield volcanoes are recent discoveries of secondary

volcanism not being confined to the islands but extending many tens of kilometers offshore [e.g., Clague *et al.*, 2000] and occurring in several pulses [Ozawa *et al.*, 2005].

To determine the where, when, and what of secondary volcanism on and near the northern Hawaiian Islands (Figure 1), the U.S. National Science Foundation (NSF) recently sponsored a multidisciplinary investigation (volcanology, marine geology, geochemistry, gravity, magnetics). A 4-week marine expedition in September 2007, aboard the University of Hawai'i's R/V *Kilo Moana* and using the JASON2 robotic submarine, revealed several fields of offshore volcanoes and lava flows, with each field spanning areas much larger than the nearby islands. Such expansive volcanism well away from the islands themselves raises many questions about hot spot evolution and magma genesis in general.

### Seafloor Mapping

The seafloor around the islands of Kaua'i, Ni'ihau, and Kā'ula (Figure 1) was the focus of the marine expedition because Kaua'i has the most voluminous (~58 cubic kilometers) and enduring (~2.5 million year old (C. E. Gandy *et al.*, Implications of the volume of Kauai's Koloa volcanics for the origin of Hawaiian rejuvenated volcanism, submitted to *Geology*, 2008)) secondary volcanism of Hawaii's main islands and because this seafloor had not previously been completely mapped. For comparison, the volumes and lifetimes of Hawaiian shield volcanoes younger than Kaua'i are  $9\text{--}74 \times 10^3$  cubic kilometers [Robinson and Eakins, 2006] and approximately 1.5 million years old [Garcia *et al.*, 2006]. During the 2007 expedition, an area approximately 50% greater

than the entire state of Hawaii was surveyed, yielding the first detailed bathymetry and acoustic backscatter maps of Kā'ula and the Middle Bank volcanoes, and confirming that secondary volcanism is widespread offshore rather than focused on the islands.

### Extensive Secondary Volcanism

The new acoustic imagery map (Figure 2) highlights areas of extensive secondary volcanism around the islands of Kā'ula and Ni'ihau. More than 100 secondary submarine volcanoes surround these islands, most of which have a distinctive pancake shape (steep-sided and flat-topped) similar to some Venusian volcanoes [Smith, 1996]. To form flat-topped cones, sustained but slow effusion of low-viscosity magma from a point source is thought to be necessary [Clague *et al.*, 2000]. The question as to why these conditions should prevail throughout this area is being investigated using bathymetry and lava chemistry data. Some of the newly identified lava flows have areas of up to approximately 400 square kilometers, larger than some Hawaiian islands (e.g., Lana'i at 364 square kilometers and Ni'ihau at 180 square kilometers) and comparable to the flood basalt from Iceland's Laki volcanic fissure (565 square kilometers). Furthermore, the volcanism extends 100 kilometers off the axis of the Hawaiian Ridge and well into the surrounding flexural moat.

During 11 JASON2 dives (Figure 1), a wide variety of lava flow types and sedimentary rocks were observed on 71 seamounts (<http://4dgeo.whoi.edu/jason/>, km718 cruise link), and 363 rocks weighing more than 1200 kilograms were sampled. The compositions of these lavas range widely from shield stage tholeiitic basalts (especially south of Kaua'i) to secondary stage alkalic basalts (common around Kā'ula). Our geochemical study of approximately 5 million years of volcanism on Kaua'i has shown that secondary volcanism

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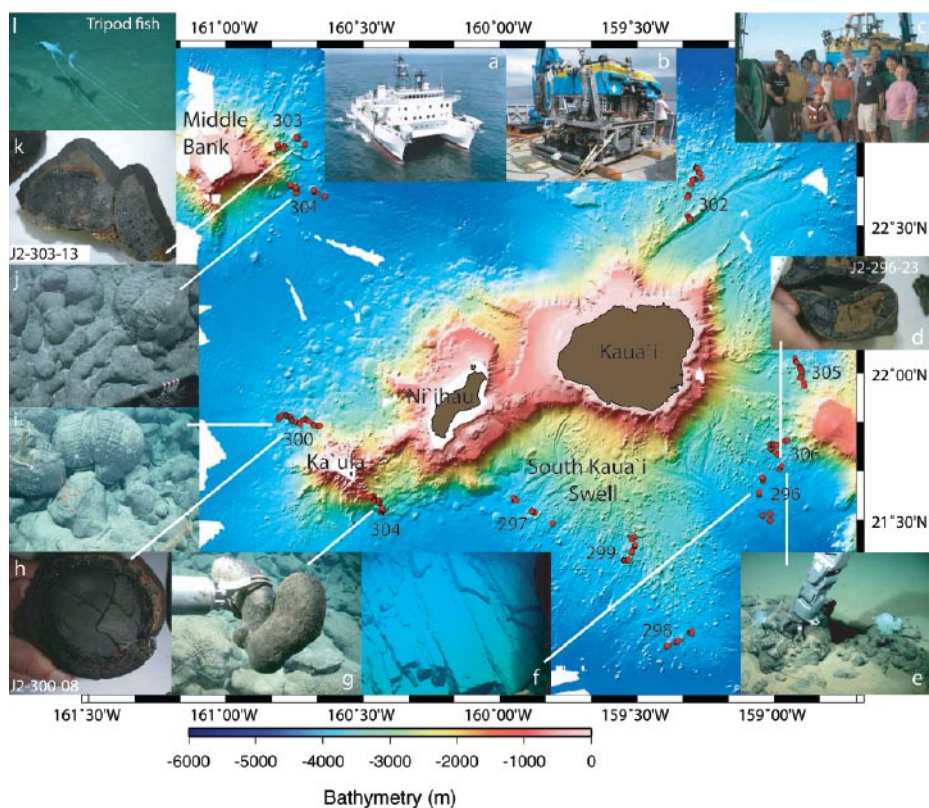


Fig. 1. Bathymetric map of the seafloor around the islands of Kaua'i, Ni'ihau, and Ka'ula, based on new results from the expedition. Inset photos: (a) R/V Kilo Moana. (b) JASON2. (c) Members of the science team. (d) Slab of hollow pillow lava. (e) JASON2 collecting pillow lava with white sponge. (f) South Kaua'i swell columnar jointed outcrop. (g) Mechanical arm of JASON2 collecting pillow lava. (h) Slab of pillow lava lobe shown in Figure 1g. (i) Ka'ula pillow lavas. (j) Outcrop of pillow lavas on ocean floor. (k) Slabbed vesicular pillow lava. (l) Tripod fish. Figures 1d–1f are slabbed rocks and outcrops being sampled by JASON2 from the east Kaua'i area, Figures 1g–1i are from Ka'ula, and Figures 1j and 1k are from the Middle Bank.

is related to the Hawaiian mantle plume rather than to lithospheric sources (L. Swinard et al., Geochemistry of rejuvenated, post-shield and late shield volcanism on the island of Kauai, Hawaii, submitted to *Earth and Planetary Science Letters*, 2008). Thus, isotopic and geochemical studies of the new submarine rocks provide greater temporal and spatial resolution on the Hawaiian plume and are likely to elucidate its structure.

#### South Kaua'i Swell

One enigmatic Hawaiian submarine feature is the South Kaua'i swell (SKS; Figure 1), which covers an area of approximately 5500 square kilometers and has an estimated volume greater than 5% of that of the Kaua'i shield. The swell, which previously had been interpreted as a landslide deposit, has 169 cone-shaped seamounts greater than 50 meters tall with variable acoustic backscatter. Submersible observations and sampling show that most of the seamounts are draped with fragmental lava debris. Intact pillow lava was found on only a few SKS cones. Many deposits contain lithologically identical angular clasts, indicative of a local origin; other deposits have rounded, matrix-supported clasts suggesting a landslide origin. Similar fragmented

lava deposits greater than 1 kilometer thick were found on the flanks of Mauna Kea volcano during subsequent drilling as part of the Hawaii Scientific Drilling Project [Garcia et al., 2007]. Our new geochemical data for SKS samples from 13 of 15 seamounts are tholeiitic and similar to Kaua'i shield lavas, although the SKS data extend to higher zirconium/niobium (14 versus 12) and radiogenic lead-208/lead-206 (0.960 versus 0.948) and also extend to lower neodymium isotopic composition (epsilon values of 6.9 versus 7.6). A broad, low-amplitude (~10 milligals) residual gravity high is centered approximately 50 kilometers south of Kaua'i, indicating slightly elevated subsurface densities. Together, these results support either (1) a huge landslide (one of Hawaii's largest) from an early Kaua'i shield (>5.0 million years ago) or (2) a separate submarine shield that experienced extensive explosive volcanism and erosion. The absence of a scar on the flanks of Kaua'i and a young age for the one dated SKS cone (3.9 million years ago) are inconsistent with a landslide origin.

#### Outreach Program

A three-phase community outreach program was coordinated with the expedition

(see Figure S1 in the electronic supplement to this *Eos* issue ([http://www.agu.org/eos\\_elec/](http://www.agu.org/eos_elec/))). A Kaua'i public school teacher joined the science team at sea to facilitate outreach activities, including electronically interacting with K-12 classes via a cruise Web site (<http://www.soest.hawaii.edu/expeditions/Kauai/>). In addition, a professional development course for Kaua'i public school teachers provided marine science education and the creation of hands-on science demonstrations related to the expedition. Also, visits by the expedition's outreach coordinator and cochief scientist, and by three graduate students who participated in the mission, as well as three "family science night" workshops, allowed children and their families to participate in the expedition via science demonstrations. In total, 23 public and private school teachers participated in all phases of the outreach program and 200 families attended the community workshops. This demonstrated public excitement for opportunities to participate in ongoing science programs and to learn about the research being undertaken offshore of their island.

#### Ongoing Work

New maps of the seafloor around the Hawaiian Islands are available at the University of Hawai'i School of Ocean and Earth Science and Technology (SOEST) Web site (<http://www.soest.hawaii.edu/>). Our international team of scientists is determining the compositions and eruption ages of the new samples. The integration of these results with preexisting onshore data will feed a new geodynamic model to better explain the cause of secondary volcanism in Hawaii and other oceanic islands. It will also enhance our understanding of mantle dynamics, including plume structure and evolution.

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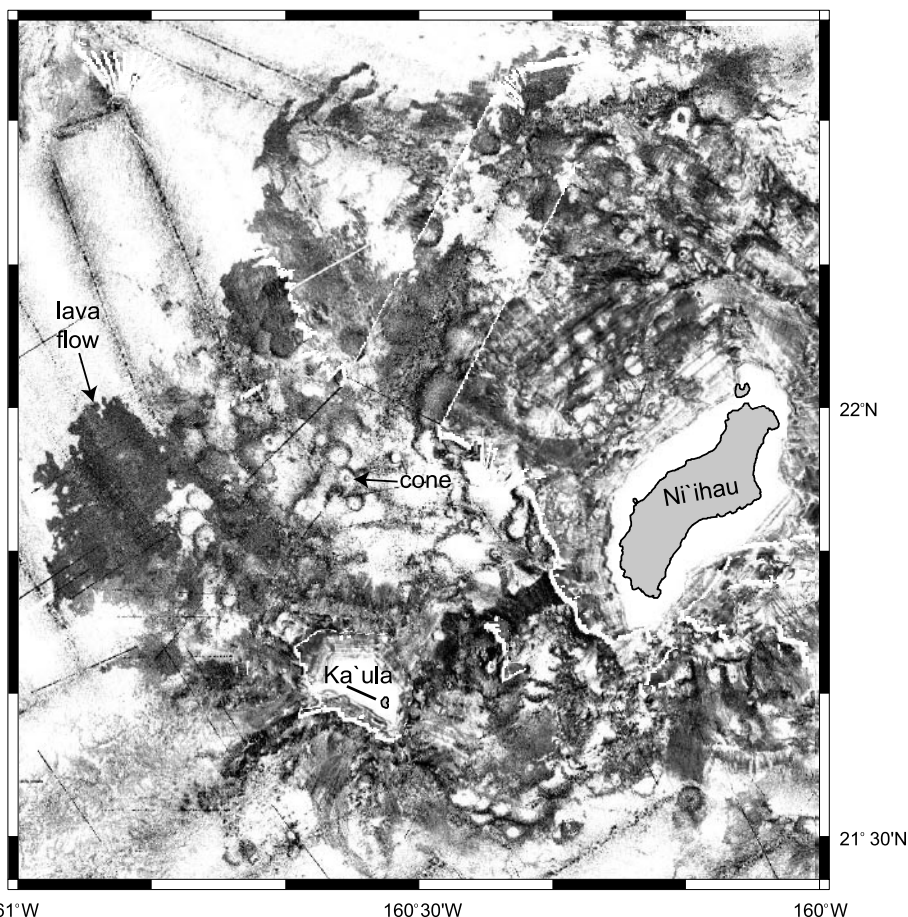


Fig. 2. Acoustic imagery of the seafloor around the islands of Ni'ihau and Ka'ula. Dark areas on the map indicate strong acoustic return from hard surfaces such as lava; light areas indicate weak acoustic return from relatively soft and thick sediments.

## U.S. Federal Water Quality Web Service Collaboration

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The U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (USEPA) have developed collaborative capabilities for the retrieval of water quality data using the World Wide Web [Young, 2008]. Since September 2008, these new capabilities have facilitated searches of millions of analytical measurements from water quality samples collected during the past 100 years. The new system improves, in several ways, on the previous approach to obtaining data from these agencies, and it establishes a framework for future enhancements. As a result of creating these capabilities, an investigator will be able to explore the entire USGS and USEPA water quality data holdings without needing to know which agency manages the desired data.

#### The New Web Service Approach

"Web services" have evolved in the past decade to become a fundamental building block for the development of a collaborative computing infrastructure. Generically, Web

services provide computer-to-computer query and retrieval capabilities. In this application, the Web services implemented by USEPA and USGS provide the mechanism for the integration of two separate water quality databases residing on different computer systems with different architectures and purposes. The Web service outputs include data elements recommended by a task force representing U.S. federal, tribal, state, and local agencies; academia; and the private and public sector water industries [National Water Quality Monitoring Council, 2006]. The two agencies have each deployed separate Web services that are interoperable because the Web services accept the same types of queries and return output in a consistent format that conforms to a standardized nomenclature. Output from both sets of services can be merged, thus greatly simplifying the problem of combining data retrieved from the two databases.

#### Comparisons With Previous Approaches

USGS maintains a national, long-term database of water resources data known as the National Water Information System (NWIS).

A major subset of NWIS consists of water quality data primarily from USGS studies, but it also includes data from other organizations. NWIS is used primarily by the USGS for hydrologic data collection and research, and it integrates water quality with water quantity, water use, and geohydrologic information. USEPA maintains a national water quality database known as the Storage and Retrieval System for Water and Biological Monitoring Data (STORET). The STORET system is a data warehouse for water quality data primarily collected by USEPA and other organizations, including state and local environmental agencies, Native American tribes, and volunteer monitoring organizations.

Historically, USGS and USEPA periodically copied water quality data from NWIS into STORET. That approach occasionally caused users to retrieve incorrect or incomplete copies of USGS data from STORET, if NWIS had been updated subsequent to when the copy was stored in STORET. That approach also denied users access to recent data, until a new copy was provided to STORET. A modernized version of STORET was implemented in 1999 that made the periodic copying of data no longer feasible for USGS. Users needing water quality data from both NWIS and STORET had to make separate retrievals from each system and then reformat and