

pools of portable instruments for seismological investigations of continental and oceanic environments at higher resolution than that afforded by the current global network of permanent stations. The pools of three-component, short-period, and broadband sensors need to be expanded, in the oceans and on land, for the next generation of 3-D and 4-D imaging efforts of crustal, lithospheric, and deep mantle and core structure.

In addition, a new facility should be established to make controlled seismic sources for land studies more available to

the academic community. Further, the new seagoing R/V *Marcus G. Langseth* (owned by NSF and operated by Lamont-Doherty Earth Observatory of Columbia University) needs to be fully supported in a way that makes its 3-D imaging capabilities more readily accessible to investigators.

There is a common need for the development and coordination of advanced data products to make the results of seismological research more accessible to the public and to Earth scientists in other disciplines. Finally, strong synergisms within the Earth science arena between

seismology and other disciplines need to be fostered and strengthened. Progress on the seismological grand challenges noted here, and on the many societal applications of seismology, hinges on improved interdisciplinary interactions and communications, in addition to the shared, practical requirements described above.

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Probing the Hawaiian Hot Spot With New Broadband Ocean Bottom Instruments

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The Hawaiian hot spot is regarded as the textbook example of the product of a deep-rooted mantle plume [Wilson, 1963; Morgan, 1971]. Its isolated location, far from any plate boundary, should provide an opportunity to test most basic hypotheses on the nature of plume-plate interaction and related magmatism [e.g., Ribe and Christensen, 1999]. Yet the lack of crucial geophysical data has sustained a debate about whether Hawaii's volcanism is plume-related or is instead the consequence of more shallow processes, such as the progressive fracturing of the plate in response to extensional stresses [Turcotte and Oxburgh, 1973].

In the plume model for Hawaii's volcanism, hot material is expected to ascend near vertically within the more viscous surrounding mantle before ponding and spreading laterally beneath the rigid lithosphere. Mantle convection in general, and the fast moving Pacific plate in particular, shear and tilt the rising plume. The plume top is dragged downstream by the plate, and this dragged material may give rise to an elongated bathymetric swell [Davies, 1988; Olson, 1990; Sleep, 1990; Phipps Morgan *et al.*, 1995]. However, identifying the dominant cause of the swell remains elusive, and proposed mechanisms include thermal rejuvenation, dynamic support, compositional buoyancy, and mechanical erosion (see Li *et al.* [2004] for a summary). There is also considerable debate about the continuity of the plume within the mantle, how discrete islands are formed, and how a deep-rooted plume interacts with the mantle transition zone [e.g., van Keken and Gable, 1995].

Seismic Imaging of Hawaiian Mantle

Seismic imaging can help distinguish among plausible models, but the deployment of seismic stations that has been limited to the nearly aligned Hawaiian Islands has so far led to incomplete images of the crust and mantle beneath and around Hawaii. The Hawaiian Plume-Lithosphere Undersea Mantle Experiment (PLUME) is

a multidisciplinary program whose centerpiece is a large network of four-component broadband ocean bottom seismometers (OBSs) and three-component portable broadband land stations (Figure 1). Occupying a total of 82 sites and having an overall aperture of more than 1000 kilometers, this experiment is one of the first large-scale, long-term deployments of the new broadband OBSs in the U.S. National Science Foundation-supported national OBS Instrument Pool (OBSIP). PLUME is providing an

opportunity to use the full range of seismic techniques that have been applied successfully in land-deployed experiments. Body wave and surface wave tomographic imaging as well as receiver function and compliance analyses will provide new constraints on elastic and anelastic seismic structure and major discontinuities from crustal depths into the lower mantle. The analysis of shear wave splitting and surface wave azimuthal anisotropy will help reveal mantle fabric and flow patterns.

Now, about 18 months after the last OBSs were recovered from the ocean floor, the high overall return and quality of PLUME data allow for the production of

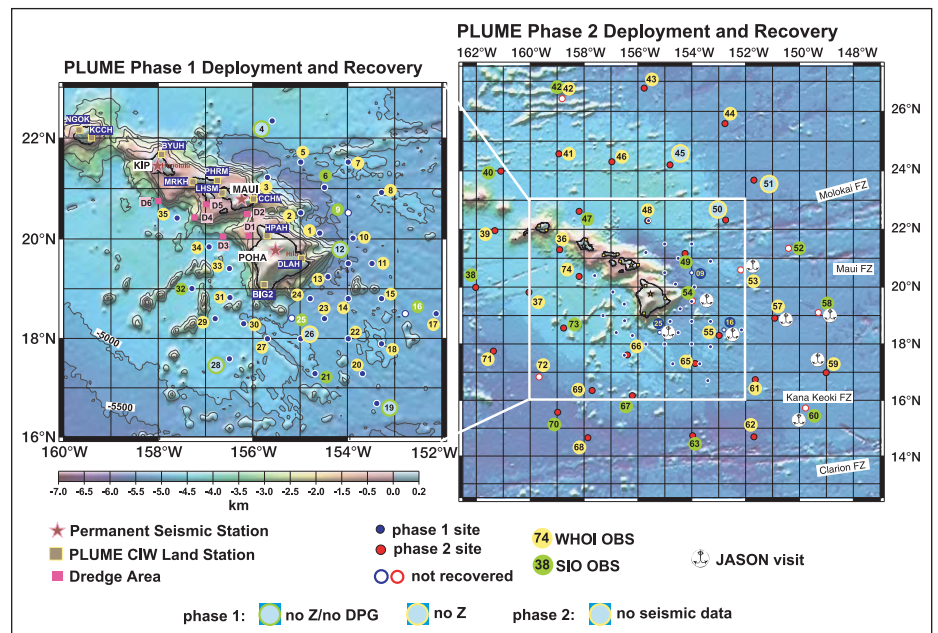


Fig. 1. Site locations of the two deployment phases of the Hawaiian Plume-Lithosphere Undersea Mantle Experiment (PLUME). Also shown are sites of permanent stations of global seismic networks relevant to this study. Station KIP (Kipapa, Oahu) is jointly operated by the French Geoscope program and the U.S. Geological Survey (USGS); POHA (Pohakuloa, Hawaii) is operated by USGS; and MAUI is operated by the German Geo-ForschungsNetz (GEOFON). USGS station MIDW (Midway; see Figure S1 in the electronic supplement) is not shown. Phase 1 operated from January 2005 through January 2006, and phase 2 operated from April 2006 through June 2007. Two sites with unrecovered ocean bottom seismometers (OBSs) from phase 1 and six sites from phase 2 were visited by Woods Hole Oceanographic Institution's remotely operated vehicle (ROV) Jason in November 2007. The OBSs at sites 57 and 59 were recovered at that time. Four sites with five lost OBSs (sites 9, 42, with two OBSs; 52; and 72) remain unvisited. Open numbered circles mark instruments with a loss of differential pressure gauge ("no DPG") and/or vertical-component seismometer data ("no Z"). During the first deployment cruise, 11 dredge hauls were performed at six locations to retrieve fossil corals and deep-rift volcanic rocks.

tomographic images that reach well into the lower mantle. Because of the broad geographical coverage, the seismic images have unprecedented three-dimensional resolution for the region. The experiment also demonstrates that OBS technology has matured to the point that the long-term deployment of broadband OBSs has become a viable counterpart to land-based experiments.

The OBS network included 72 sites occupied in two phases by 73 instruments that were provided by the Woods Hole Oceanographic Institution (WHOI) and the Scripps Institution of Oceanography (SIO), both of which are institutional operators of OBSIP. The Carnegie Institution of Washington (CIW) operated the 10 land stations. An inner OBS network of 35 sites was deployed around the island of Hawaii and recorded continuously from January 2005 through January 2006 (phase 1). An outer OBS network of 37 sites covered the entire swell around the island chain and recorded from April 2006 through June 2007 (phase 2). PLUME was the first experiment to deploy these broadband OBSs in such large numbers. Together with the recordings from permanent seismic observatories at stations KIP, MAUI, and POHA, the PLUME project allows for a comprehensive surface wave analysis of swell structure and facilitates body wave imaging to lower mantle depths.

Network Instruments

During both deployment phases, the WHOI instruments were equipped with Güralp CMG-3T sensors (orthogonal components; -3-decibel corner period of the instrument response is at 120 seconds). The SIO instruments featured a Nanometrics Trillium-40 (symmetrical triaxial components, -3-decibel corner period at 40 seconds) during phase 1 and a Trillium-240 (-3-decibel corner period at 240 seconds) during phase 2. All ocean bottom instruments included a Cox-Webb differential pressure gauge [Cox *et al.*, 1984]. The recording of time in the OBSs relied on the stable temperature conditions on the ocean floor, and drift of the internal oscillator was assumed to be linear throughout the deployment. For the PLUME deployments, drifts usually were less than 1.5 seconds per year, although drifts of several seconds were logged in a few cases.

Carried by ocean currents, an instrument can drift substantially from its sea surface launch position before arriving on the seafloor. Therefore, after each

OBS reached the seafloor, it was surveyed acoustically by sailing a 4-kilometer-wide diamond-shaped course around the drop location. In some instances, apparent horizontal instrument drifts from the launch location were as large as 1 kilometer before an OBS reached the ocean floor. A subsequent troubleshoot-and-rescue visit with WHOI's remotely operated vehicle (ROV) *Jason* to some ocean bottom sites suggested that this survey method determines OBS locations to within a few tens of meters. The orientations of the horizontal seismometer components were determined during postprocessing using earthquake data. Consistent orientations were obtained for most instruments, even though the horizontal components are expected to be particularly noisy on unburied seafloor seismometers that are exposed to ocean currents.

Assessment of the Field Campaign

With 32 of the 35 OBSs recovered, the phase 1 deployment can be regarded as successful. From the phase 2 deployment, only 28 of 38 instruments initially were recovered. At sites 57 and 59 (Figure 1), each of the OBSs responded to anchor release commands, but they remained on the seafloor. The *Jason* visit revealed that these instruments were stuck in the mud despite the OBSs having 65 pounds of positive buoyancy. The ROV retrieved them, bringing the instrument recovery to 30 of 38, and data from these two instruments filled a crucial gap in data coverage. The other lost instruments were unresponsive. This unresponsiveness could be due to many potential causes, including dead batteries in the acoustic release system or a shift in the acoustic response frequency. The *Jason* visit established that five instruments (four phase 2 OBSs and one phase 1 OBS) experienced catastrophic failure as a result of imploding glass flotation balls. On the WHOI instruments, these balls enclose the instrument's electronics. On the SIO instruments, the glass ball implosions triggered failure of the aluminum pressure cases that hold the electronics and are mounted below the glass balls. Records of auxiliary data on the recovered seismometers document that these failures occurred over time and were not a response to impact on the seafloor. The implosions occurred in the deep ocean at about 5500-meter depth, but a clear correlation of implosions with water depth cannot be established; for example, instruments deployed at greater depth operated

successfully. At site 25, an early release of the instrument package was inferred after only the anchor was found.

While there were some data losses due to noisy environments or technical issues, the PLUME land instruments had data return rates that compare well with those of other land-based experiments. As with the land stations, data losses were experienced for some OBS components, but in general the quality of the long-period vertical-component OBS recordings rivals that of the PLUME land stations. Given that the OBSs operated in an extreme environment, the OBS deployments should be considered highly successful. Examples of data are given in the electronic supplement to this *Eos* issue (http://www.agu.org/eos_elec/). Data analyses are still ongoing, but initial results are anticipated to appear in the peer-reviewed literature later this year.

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Supplementary material to “Probing the Hawaiian Hot Spot With New Broadband Ocean Bottom Instruments”

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Data Return and an Example

This supplement provides an example of data collected for the Hawaiian PLUME project. Because the OBSs were not buried, it was expected that ambient noise conditions would substantially restrict analyses at short periods (about 1 s and less), especially on the horizontal components. At longer periods, the horizontal components are much noisier than the vertical, but enough earthquakes can be analyzed to obtain consistent and reliable data sets to determine component orientation relative to geographic north, as well as receiver functions and shear-wave splitting measurements. The majority of the vertical components have high signal-to-noise ratios at periods between 100 and 10 s that are comparable with those for land stations.

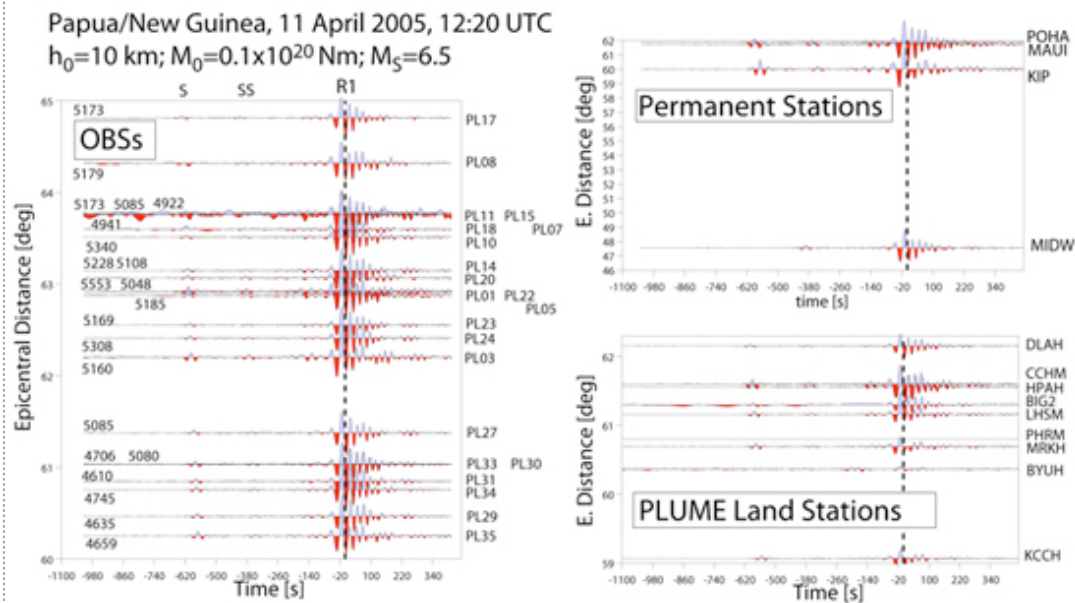


Fig. S1. Example of vertical-component data from a moderately large shallow earthquake. The water depth for each OBS is given on the left of the seismogram. For comparison, the data at permanent observatory instruments are also shown. The data were low-pass filtered with a -40-dB roll-off between 40 and 50 mHz and aligned on 50-s Rayleigh wave arrival times predicted by reference model PREM [Dziewonski and Anderson, 1981]. The data from the land stations were obtained from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC).

Figure S1 shows example records from a moderately large earthquake, filtered to analyze Rayleigh waves. The waveforms are very coherent across the OBS network, and the record quality is virtually the same as that of PLUME land stations. In fact, waveforms are compatible with those at various permanent observatory instruments of the Global Seismographic Network (GSN), GEOFON, and GEOSCOPE. This data example is fairly typical of the records obtained for PLUME, which has facilitated the assemblage of a database that is comparable in size with that of regional experiments on land.

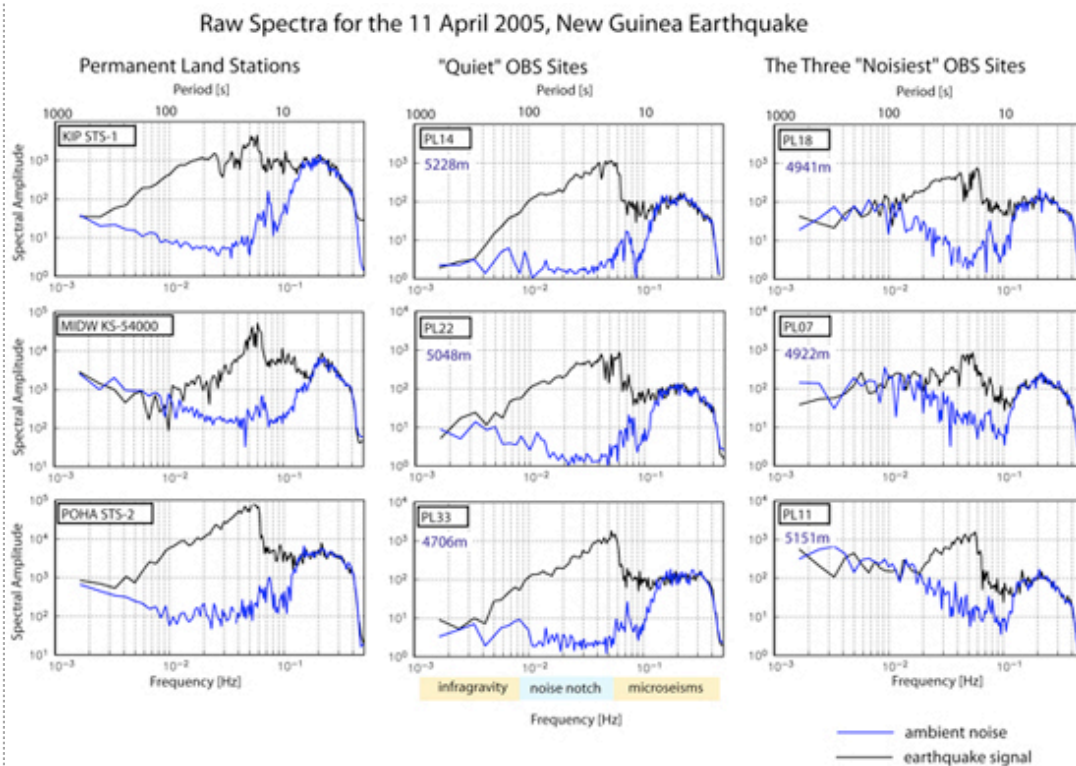


Fig. S2. Vertical-component spectra of 20-min-long segments before and during the earthquake shown in Figure S1. A large gap between the spectra signifies a high signal-to-noise ratio, hence a “quiet” station. For the purposes of earthquake seismology, this approach is more revealing than assembling the standard ambient noise plots, such as those published in the Federation of Digital Seismograph Networks (FDSN) station book. The water depth at each OBS station is given below its name. Colored bars beneath the middle panel mark the two noise bands, the microseism band above 0.05 Hz as well as the infragravity band below 0.01 Hz. The range in between is known as the noise notch.

Many OBSs have excellent signal-to-noise ratios between the infragravity and the microseism bands, often termed the noise notch (Figure S2). Near the infragravity end, some instruments remarkably surpass the quality of the Geotech/Teledyne KS-54000 borehole seismometer that is installed at GSN station MIDW. In fact, some of the better OBS spectra are compatible with land-observatory records on a Wielandt–Streckeisen STS-2. The quality does not quite match that of the very-broadband Wielandt–Streckeisen STS-1 at station KIP, which is one of the best very-long-period stations worldwide as far as vertical signal-to-noise levels are concerned. Also shown are the three OBSs with the lowest signal-to-noise levels. Though the band of useful signal is limited to frequencies above 0.02 Hz, these records still contain enough signal for useful analyses. The strength of the infragravity noise appears to fluctuate greatly among sites, but a simple dependence on water depth is not immediately apparent.

The Hawaiian PLUME project produced a very rich dataset of unprecedented quality for a seafloor network and provided an opportunity to observe ultra-low-frequency seismic signals. We recorded the 28 March 2005 aftershock ($M_0=111 \times 10^{20}$ Nm; $M_S=8.2$) of the great 26 December 2004 Sumatra–Andaman earthquake [Laske *et al.*, 2007]. At the quiet GSN site KIP, normal mode ${}_0S_4$ ($f \approx 0.647$ mHz) stands out clearly above the noise floor on the STS-2 recording. Due to the stronger infragravity noise on the ocean floor, this mode could not be expected to be seen on the OBSs. However, at least five OBSs recorded ${}_0S_8$ ($f \approx 1.413$ mHz) above the noise. PLUME may have been the first seafloor experiment to observe ultra-low-frequency normal modes on unburied seismometers.

PLUME also recorded numerous local earthquakes that lie outside the detection range of the

land-based network of the USGS Hawaiian Volcano Observatory (HVO). The off-shore events can be found across the entire OBS network, if the data are high-pass filtered above about 5 Hz [Anchieta *et al.*, 2007]. The seismicity patterns are currently being analyzed.

The initial assessment of the DPG data is also very favorable. In many cases, signal-to-noise levels on the DPGs are compatible with those on the vertical seismometer components. Some two-station surface wave dispersion curves obtained from DPG records are internally more consistent than from the corresponding seismometer records.

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