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Seismic and acoustic signals detected at Loʻihi Seamount by the Hawaiʻi Undersea Geo-Observatory

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[1] **Abstract:** The Hawaiʻi Undersea Geo-Observatory (HUGO) is an ocean bottom observatory located on the summit of Loʻihi seamount, Hawaiʻi. An electro-optical cable connects the HUGO junction box to a shore station on the Big Island of Hawaiʻi, thereby enabling the first real-time monitoring of a submarine volcano. HUGO was active for 3 months in 1998, collecting nearly continuous, real-time data on a high-rate hydrophone. Signals detected during that time include local as well as teleseismic earthquakes, *T* phases from Pacific-wide earthquakes, landslides on the submarine flank of Kilauea, and eruption sounds from the current Kilauea eruption. The data do not indicate a Loʻihi eruption during the time that HUGO was active. The variety and quality of signals detected by the HUGO hydrophone confirms that a real-time observatory can serve a valuable role in studies of oceanic acoustics, local and teleseismic earthquakes, and submarine eruption mechanics.

1. Introduction

[2] Study of undersea volcanic systems began decades ago, on both mid-ocean ridges and intraplate volcanoes [e.g., *Johnson*, 1973; *Bal-* *lard et al.*, 1981; *Francheteau et al.*, 1981]. The logistics of performing long-term monitoring in such an environment are challenging and can be achieved in one of several ways: by a series of visits to the volcano, through the use of

autonomous ocean bottom systems, by remote systems such as seismometers or hydrophone arrays, or by permanent observatories. Repeated submersible visits are costly and provide a poorly sampled view of the volcano's behavior. Autonomous data collection systems, such as ocean bottom seismometers, provide a continuous view of activity but are limited by power and storage capacity and must be routinely replaced. Moreover, changes in the behavior of the volcano are only determined after the system is retrieved and the data processed, thus providing no information useful for rapid response. Delayed reception of data also means that any faults in the equipment cannot be discovered until retrieval. Distant monitoring systems have been effective in detecting submarine eruptive activity [Fox et al., 1995; Dziak and Fox, 1999; Fox et al., 2001], but only a few types of data, such as seismic and acoustic signals, can be detected remotely.

[3] An alternative to the methods described above is the real-time submarine observatory, capable of supplying continual power to experiments and transmitting data to a shore facility for analysis. Ocean observatories such as the New Millennium Observatory, deployed on Axial seamount in 1999, deliver data via an acoustic link to a surface buoy and then via satellite to shore. Other observatories such as LEO-15 (Long-Term Ecosystem Observatory) in New Jersey, the Real-Time Deep Seafloor Observatory off of Hatsushima, Japan, and the Hawaii-2 Observatory transmit data and power to a shore station through undersea communications cables. Plans are underway to monitor the entire Juan de Fuca plate with the NEPTUNE observatory, which will be connected by cable to shore stations on the North American west coast.

[4] The deep-ocean observatory HUGO, the Hawai'i Undersea Geo-Observatory, is the subject of this paper. HUGO was designed for long-term, real-time monitoring of Lo'ihi submarine volcano and the surrounding ocean. HUGO is composed of a junction box positioned on Lo'ihi's summit at 1200-m water depth, a 47-km electro-optical cable for data and power transmission, and a shore station on Hawai'i Island. A variety of experiments may be plugged into the system, and data are immediately sent to the shore station for processing. The system was designed to allow installation and repair of experiments via submersible or remote operated vehicle (ROV). A description of HUGO's technical details may be found in the work of Duennebier et al. [2001].

[5] Lo'ihi seamount, located 35 km south of Hawai'i island with its summit ~1000 m below the ocean surface (Figure 1), has been studied in detail by means of oceanographic surveys and autonomous data collection systems. More than 50 submersible dives on the volcano have yielded a wealth of data on the geology, chemistry, and biology of Lo'ihi [e.g., Malahoff, 1987; Garcia et al., 1998; Hilton et al., 1998]. An autonomous ocean bottom observatory (OBO) deployed in 1991 contained a seismometer, pressure sensor, and thermistor for monitoring of hydrothermal vent temperatures. Data from the OBO show a number of features suggestive of an eruption, including increased seismicity and changes in both hydrothermal vent temperature and summit elevation [Malahoff, 1993]. Unfortunately, the potential eruption was not recognized until the data were returned to shore, too late to organize a thorough investigation of the event. In 1986, five ocean bottom seismometers were deployed on Lo'ihi ihi in response to an earthquake swarm [Bryan and Cooper, 1995]. By the time the network was launched, however, the swarm had largely diminished. An ocean bottom seismometer was deployed during a 1996 earthquake
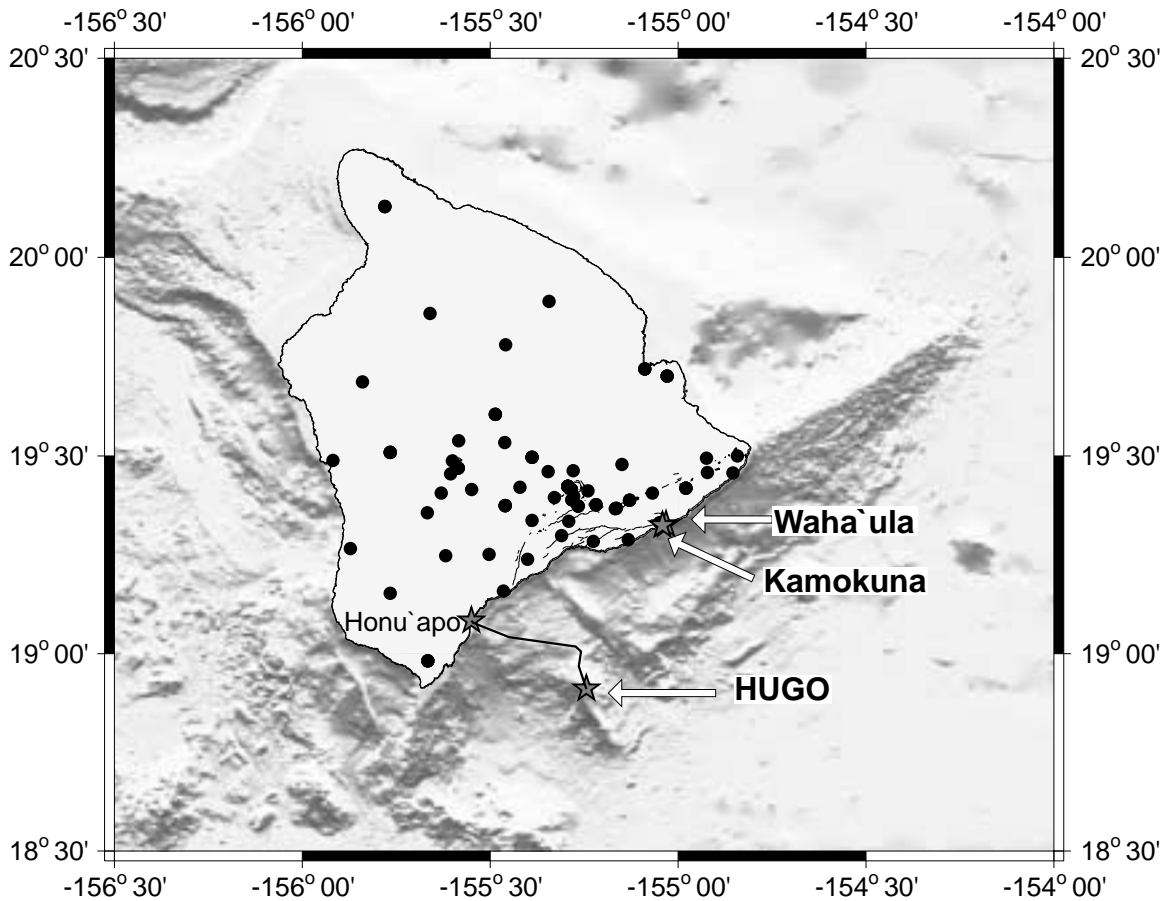
Figure 1. Location of the Hawai'i Undersea Geo-Observatory (HUGO) junction box with respect to the island of Hawai'i. HUGO sits on the summit of Lo'ihi seamount, ~35 km south of the Big Island of Hawai'i. The electro-optical cable follows the route shown between Lo'ihi and the shore station at Honu'apo. Black circles represent the locations of the seismic network operated by the Hawai'i Volcano Observatory. Stars at the Kilauea coast represent the Wahaùla and Kamokuna ocean entries, the sites where lava entered the ocean during the period when HUGO was active.

swarm, but it also caught only the tail end of activity [*Caplan-Auerbach and Duennebier*, 2001]. Thus, although a number of projects have successfully used autonomous data collection systems to study Lo'ihi, all have been compromised by delays in instrument deployment and data analysis.

[6] In this paper we present the results of three months of data collection from a high-rate hydrophone connected to the HUGO junction box. The HUGO system is described, as well as the chronology of its installation and repair. We discuss the many kinds of signals detected by the HUGO hydrophone, of local, regional, and Pacific-wide events and investigate the benefits of a real-time observatory on Lo'ihi. Many events were recorded only at HUGO and cannot be located or thoroughly characterized. The purpose of this paper is to describe these events as much as possible and to provide justification for future use of similar systems.

2. Geologic Setting

[7] Loʻihi seamount is the youngest volcano in the Hawaiian chain and is the only known member of that group still in the submarine phase of activity. Loʻihi probably formed on the submarine flanks of Mauna Loa and Kilauea volcanoes and as a result sits on a base that slopes from ∼2000- to ∼5000-m depth. The highest point on Loʻihi's summit is currently 976 m below sea level. Well-defined rift zones to the north and south of the summit suggest that Loʻihi grows in a manner similar to that of other Hawaiian volcanoes; eruptions are probably most common at the summit and along the rift zones. Loʻihi's summit platform includes three pit craters and a number of arcuate normal faults (Figure 2), suggesting that it may be in the process of caldera formation.

[8] Loʻihi was first identified as an active volcano in the early 1970s when a massive earthquake swarm was located beneath its flanks [Klein, 1982]. Since that time, eight additional earthquake swarms have been recorded at Loʻihi, and at least one eruption has been documented [Garcia et al., 1998]. Loʻihi has been extensively mapped and visited via submersible, and a number of geochemical and hydrothermal studies have been performed to investigate the volcano's eruptive behavior [e.g., Moore et al., 1982; Garcia et al., 1998; Hilton et al., 1998]. Petrologic studies also indicate that Loʻihi is currently undergoing a transition into the tholeiitic and most active stage of development [Garcia et al., 1998; Hilton et al., 1998]. All of these features make Loʻihi an ideal place for submarine volcanic studies. It is nearshore, very active, and its fundamental behavior has been studied and documented.

[9] The HUGO junction box is situated on a flat plain in the southeastern region of the summit platform in a region known as the Thousand Fingers Field (Figure 2). Although a number of rocky outcrops surround the HUGO site, the seafloor beneath the junction box consists of volcaniclastic mud at least 1.5 m deep into which the junction box has settled to a depth of ∼20 cm.

3. The HUGO System

[10] The initial experiment package deployed with the junction box consisted of a high-rate hydrophone, a three-component seismometer, and a pressure sensor. Power transmission and data return are achieved over a 47-km electro-optical cable linking the junction box with a shore station in Honuʻapo on Hawaiʻi island (Figure 1). Eventually, >100 experiments could be deployed over Loʻihi's summit, each sampled at 2000 Hz and allotted an average of 10 W of power. The junction box was designed for a lifetime of at least 10 years. More detail on the HUGO design is contained in the work of Duennebier et al. [2001].

[11] Installation of HUGO began on October 11, 1997, when the junction box and initial experiment packages were lowered to Loʻihi's summit. Because landslides are common on the submarine flanks of Hawaiian volcanoes, the cable was laid perpendicular to contours wherever possible (Figure 1). Data from the hydrophone and seismometer were recorded throughout the installation but recording was discontinued when the cable was brought to shore and until the fiber optic link could be completed on October 19. Unfortunately, adhesive at the seismometer's optical connector failed, and the instrument connector flooded 3 days after recording began. The hydrophone was active until October 29 when its fiber optic termination also flooded. The pressure sensor remained operative until November 7 when the shunt regulator to the junction box failed because of a similar connector flaw.
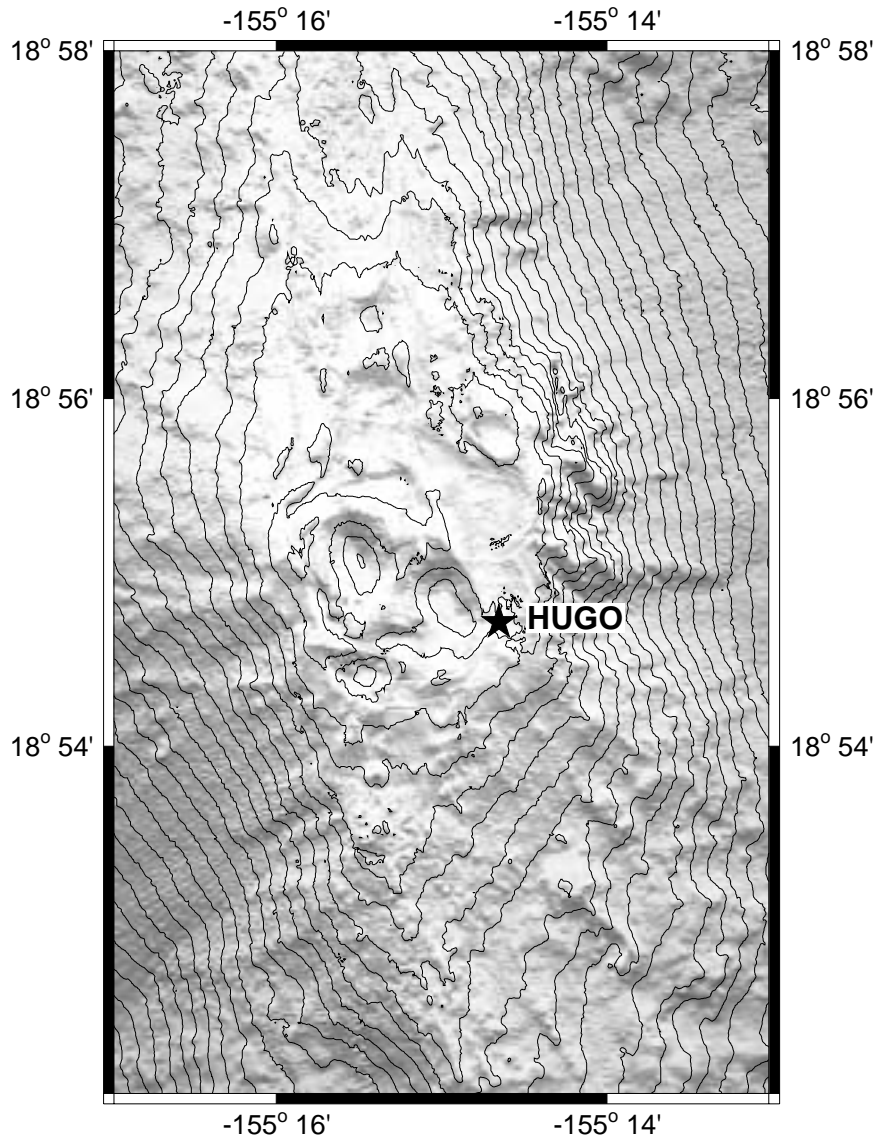
Figure 2. Location of HUGO on Loʻihi's summit. HUGO sits in a region known as the "Thousand Fingers Field," on the southeast side of the summit platform. The three pit craters on Loʻihi's summit region are also visible. Bathymetry courtesy J. R. Smith and T. Duennebier, 1997.

[12] The faulty connectors were replaced on a series of submersible dives in January 1998. Power consumption was sufficiently low to permit disconnection of the shunt regulator and its faulty connector and operate the junction box without regulation. A new hydrophone was successfully deployed, and the system was brought back on line on January 17, with continuous data recording beginning on January 27.

[13] Data collection continued until April 26, 1998, when an electrical short circuit in the main fiber optic cable terminated operations. A survey of the first few kilometers of cable on

Lo'ihi shows that the cable is suspended in places over large fractures, and it is likely that sharp rock on the edge of one of these fractures wore through the cable's polyethylene coating, resulting in the short circuit. That the fault lay in the cable, not in the junction box, was confirmed in October 1998, when a battery package was plugged directly into the junction box during a submersible dive, bringing the system back on line for ~8 hours. Over 6 GB of hydrophone data were recorded during the 3 months of operation, representing a nearly continuous record of acoustic and seismic signals detected at Lo'ihi.

4. Data Collection

[14] Data from the high-rate hydrophone were initially sampled at 64 kHz and were resampled before archiving at 16-bit resolution. The hydrophone had a flat response from 10 s to ~20 kHz. High-frequency data were occasionally recorded at sample rates up to 16 kHz and archived on digital audio tape (DAT). In general, however, owing to constraints on data storage as well as our particular interest in low-frequency signals, the data were resampled at 512 Hz. A 1.6-Hz highpass filter was employed to reduce oceanic microseism noise. HUGO ceased operation before an antialiasing filter had been added; however, data recorded at 16 kHz confirm that only a few types of events carry energy at frequencies >200 Hz where they would be affected by aliasing.

[15] Volcanic and seismic signals were detected continuously throughout the time that HUGO was active. At times, the low-frequency rumbling and explosion signals from Kilauea were of sufficient amplitude to render identification of small T phases and local earthquakes impossible. Anthropogenic signals such as air guns and ship noise are also common in the HUGO records and often dominate the signal.

4.1. Earthquakes

[16] Although the seismometer initially deployed with HUGO failed, we were able to use the hydrophone to detect seismic waves. While hydrophones may be most commonly associated with detection of T phases, the seismic phase that travels through water, they are also effective at detection of seismic body waves. Identification of body waves is useful because these phases yield information about the earthquake's hypocenter, whereas the timing of T phases yields the location for P-to-T or S-to-T conversion at the seafloor.

[17] One of the strongest benefits of HUGO is that it extends the dimensions of the Hawaiian Volcano Observatory (HVO) seismic network to better constrain locations of Lo'ihi and offshore Kilauea earthquakes. Deep earthquakes thought to be associated with the ascent of magma from the hot spot [Klein et al., 1987] often have offshore epicenters and could be better located with sensors farther offshore. Nine earthquake swarms have been located on Lo'ihi since it was recognized as an active volcano [Caplan-Auerbach and Duennebier, 2001]. Because Lo'ihi sits well outside of the HVO seismic network, the locations of these earthquakes are poorly resolved. The use of autonomous ocean bottom seismometers in 1986 [Bryan and Cooper, 1995] and 1996 [Caplan-Auerbach and Duennebier, 2001] demonstrate the improvement in hypocentral locations. To that end we examine the effects of HUGO data on constraining the location of earthquakes below Hawai'i island and Lo'ihi.

[18] Because HUGO had only a single receiver, we were unable to locate any of the events using HUGO data alone and therefore depend on the HVO network to calculate hypocenters. During the 3-month deployment of HUGO, 81 Hawai'i earthquakes were detected on the HUGO hydrophone, examples of which are
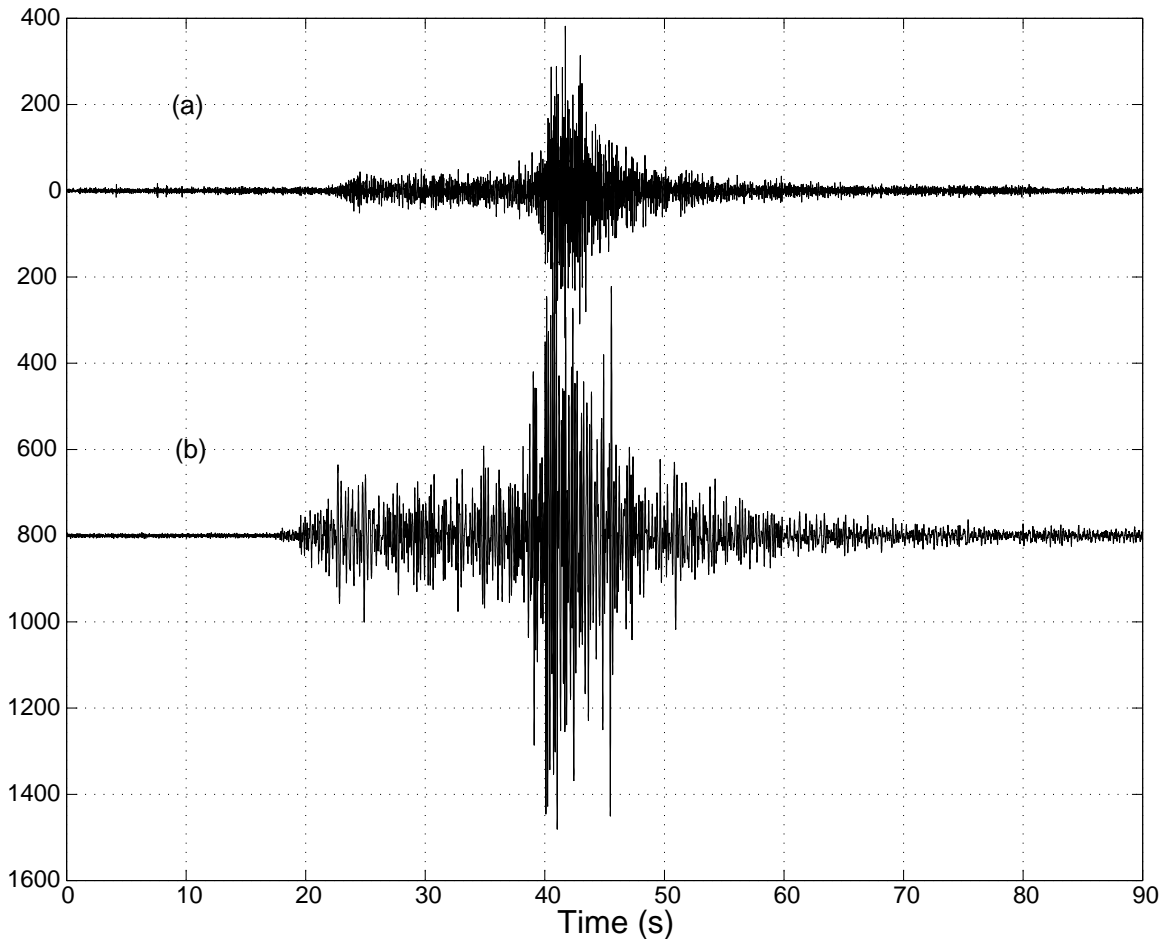
Figure 3. Two Kilauea earthquakes, as detected by the HUGO hydrophone: (a) *M*2.2 event on Kilauea's lower southwest rift zone, March 18, 1998. (b) *M*4.4 event on Kilauea's upper east rift zone, April 5, 1998.

shown in Figure 3. Of these events, 66 were located by the HVO land-based network. Timing of *P* waves from HUGO records was possible for 34 of the 66 events. The fact that timing was not always possible for HUGO-detected earthquakes is largely due to the presence of other acoustic signals such as volcanic noise from Kilauea or ship noise. Furthermore, some noise in the frequency band for local events (5–30 Hz) may be aliased from high-frequency volcanic, meteorologic, and biologic signals. Fifteen earthquakes detected by HUGO did not trigger the HVO network and therefore cannot be located. We interpret

some of these events as Loʻihi earthquakes because we are unable to distinguish between the onset of body and surface waves. Other events that did not trigger the land-based network show a several second gap between body and surface waves, consistent with earthquakes below Hawaiʻi island.

[19] Epicenters for five South Hawaiʻi earthquakes, calculated using HYPOINVERSE [*Klein*, 1989], are shown in Figure 4. Initial epicenters, determined using data from the HVO network only, are plotted as white circles with dashed 95% confidence error ellipses.
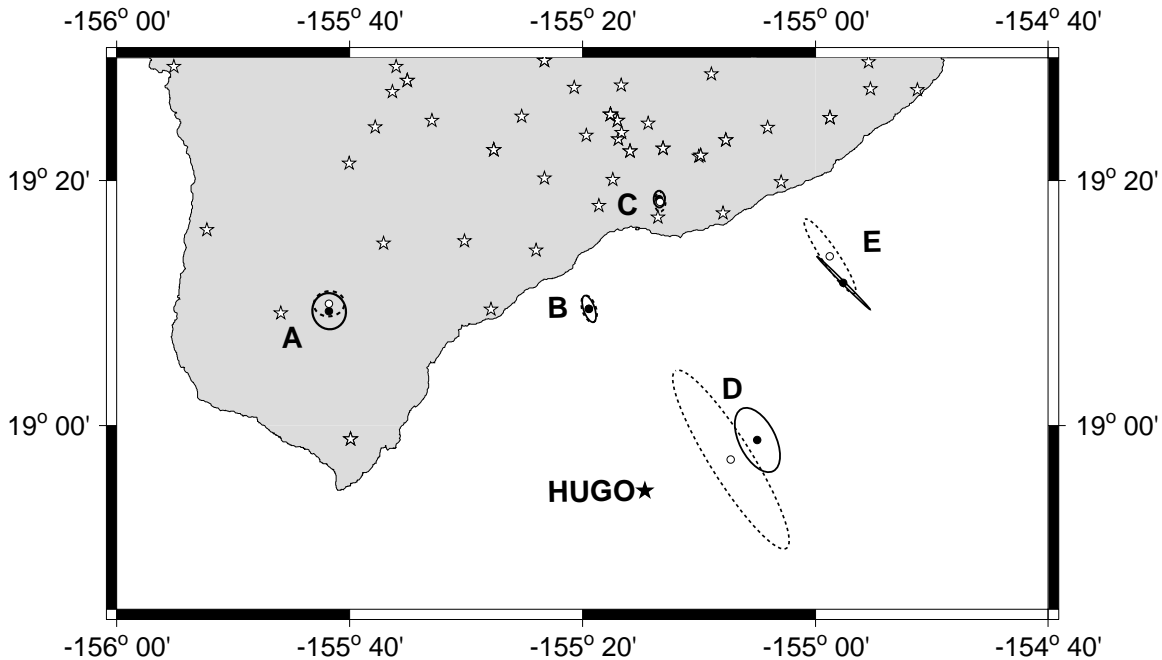
Figure 4. Initial and relocated epicentral locations for several Hawaiʻi earthquakes during the time that HUGO was operational. Initial locations, made using HVO stations only, are indicated by black circles with dashed error ellipses. Relocated epicenters include data from HUGO records and are symbolized by a white circle and solid error ellipses. The HUGO site is represented by a black star. White stars represent the positions of seismic stations in the Hawaiian Volcano Observatory (HVO) network. Error ellipses show the 95% confidence region for earthquake epicenters assuming 0.20 s uncertainty in arrival times.

Events relocated with the addition of HUGO data are shown in black with solid error ellipses. Errors are calculated assuming a standard timing uncertainty of 0.20 s. For events D and E the addition of HUGO data has the effect of extending the network geometry such that the events lie inside of the expanded array, resulting in a more tightly constrained epicenter. In contrast, events A, B, and C lie inside the original array geometry, are already well located, and are not significantly affected by the addition of the HUGO data. We therefore conclude that hypocentral locations for earthquakes southeast of the HVO land-based array can be significantly improved with the addition of data from sensors positioned on Loʻihi. Focal depths, in particular, can only be constrained with data from an offshore sensor [*Caplan-Auerbach and Duennebier*, 2001].

[20] The small number of Loʻihi earthquakes detected by HUGO is a consequence of the relative seismic quiescence of the volcano since 1996. Between 1986, when the HVO earthquake cataloguing system reached its current status, and 1996, the number of earthquakes located on Loʻihi averaged 2–10 per month. Since a massive earthquake swarm shook Loʻihi in 1996, only ~25 quakes in the Loʻihi area have been detected by the HVO network, and most of those events have hypocenters between Loʻihi and the Big Island of Hawaiʻi.

[21] Teleseismic earthquakes were also detected on the HUGO hydrophone, including the
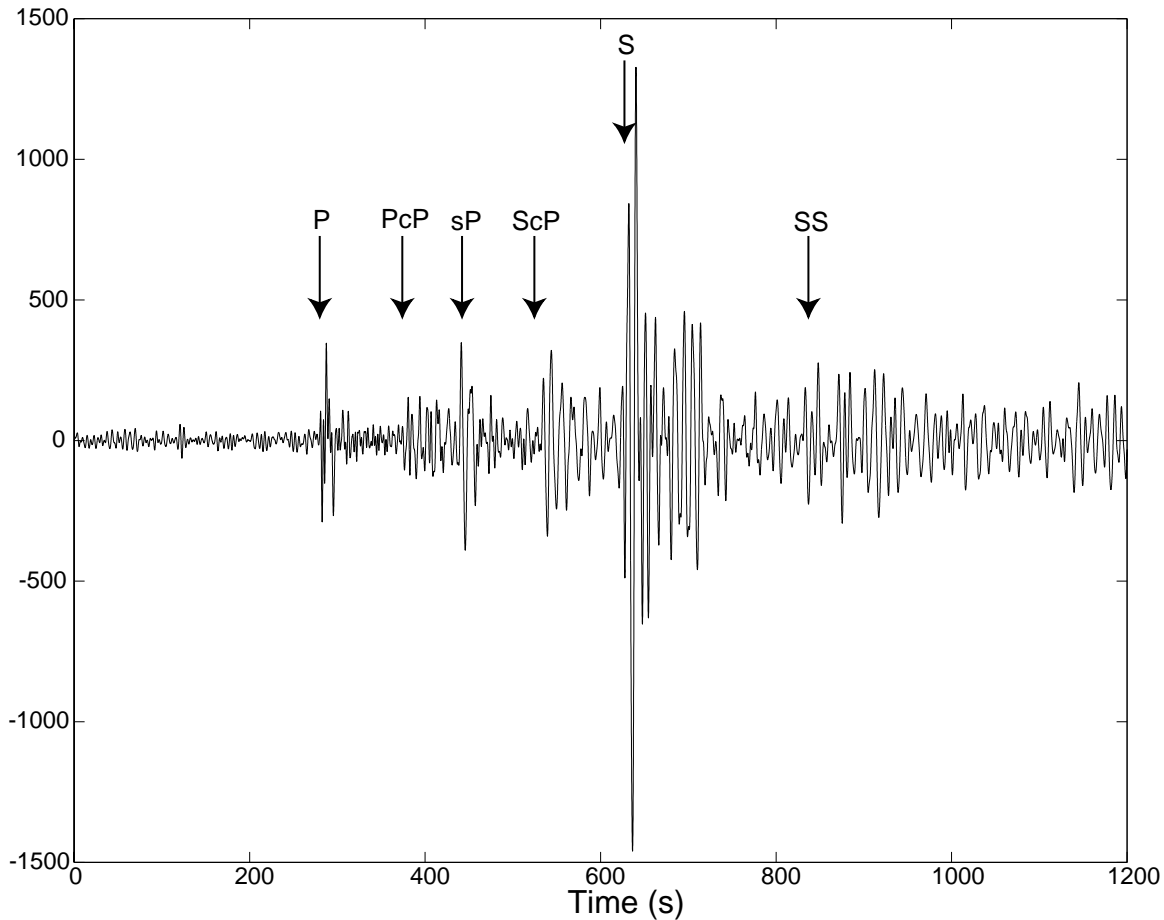
Figure 5. Body waves from a *M*7.2 earthquake in the Fiji islands, March 29, 1998, bandpass filtered between 0.04 and 0.1 Hz, as detected by the HUGO hydrophone.

March 25, 1998, *M*8.1 Balleny islands earthquake and the March 29, 1998, *M*7.2 Fiji earthquake (Figure 5). Surface waves for smaller (∼*M*6) events were sometimes detected whereas body waves were not. Signals with peak frequencies between 0.1 and 1 Hz are often not detectable over the strong microseism signal characteristic of oceanic environments [*Webb*, 1998].

4.2. T Phases

[22] The summit of Lo'ihi is located in nearly isovelocity water ∼200 m below the SOFAR channel axis, making it an excellent environ-

ment for the detection of *T* phases (water-borne seismic waves) from Pacific-wide earthquakes (Figure 6). Although the presence of a single receiver on Lo'ihi is not sufficient to locate *T* phases, HUGO records can be used to supplement other hydrophone networks.

[23] *T* phase sources have been located throughout the Pacific by the equatorial hydrophone array operated by National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL) (Figure 6), The *T* phase sources shown in Figure 6 are those calculated from the PMEL data. As a result, the locations have associated
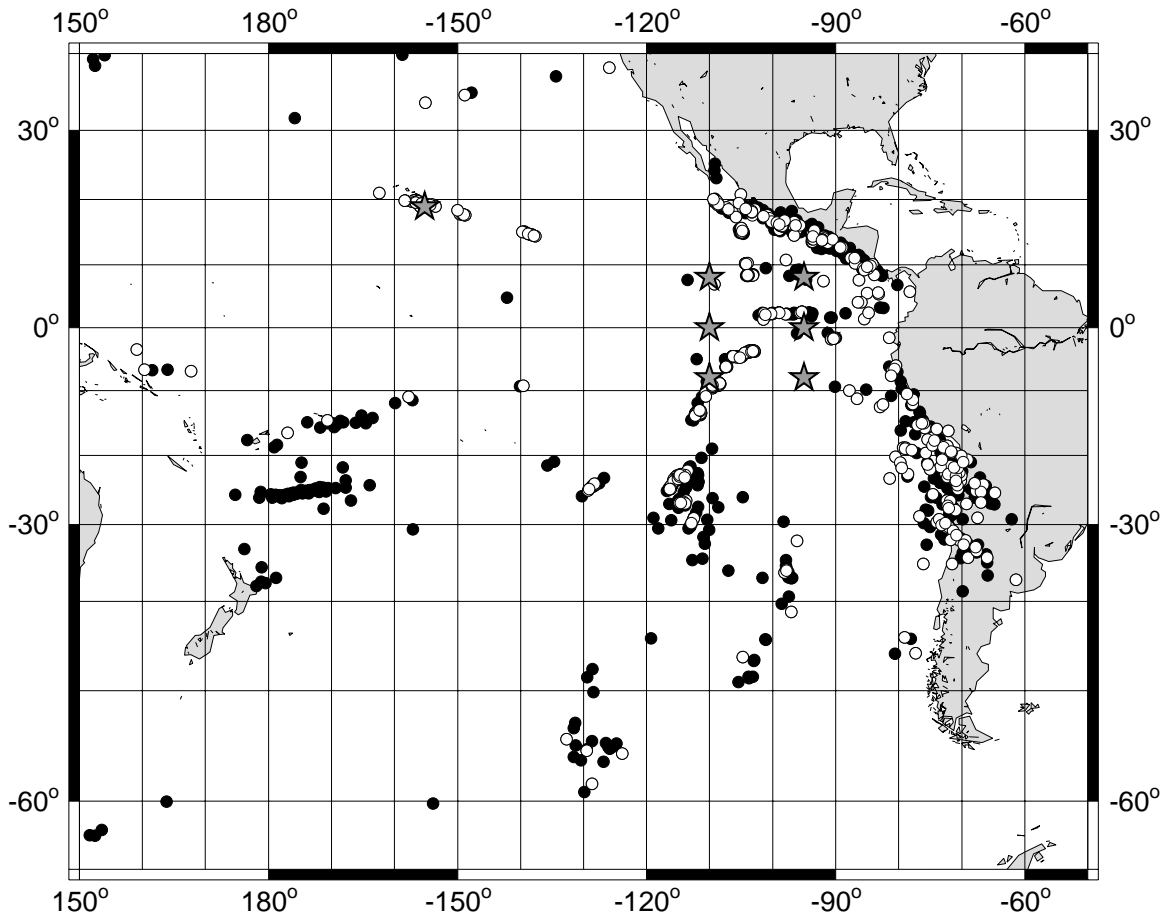
Figure 6. *T* phase sources detected by the Pacific Marine Environmental Laboratory (PMEL) equatorial hydrophone array (black circles) and also by HUGO (white circles) for the period in which HUGO was operational. The stars symbolize the locations of HUGO and the PMEL hydrophone array. Locations are based on PMEL data and do not include HUGO arrivals. As a result, location uncertainties increase with distance in a direction radial to the network.

uncertainties that increase with distance from the equatorial network and are oriented radial to the array [*Fox et al.*, 2001]. A sensor suspended above Lo'ihi effectively extends the array geometry and could help constrain *T* phase sources in the central Pacific. The PMEL network shares HUGO's view of the east and south Pacific, from California to Fiji, as evidenced by the fact that of 458 *T* phases detected by HUGO, 442 could be correlated with events detected by PMEL. During this time period, however, the PMEL hydrophones

detected over 1800 events. HUGO's detection capacity is limited by local bathymetry; the sensor sits on the bottom where it detects only downgoing rays, and Hawai'i island blocks signal from the east and north. Suspension of a hydrophone above Lo'ihi would probably increase its sensitivity to *T* phases. In contrast, PMEL sensors are able to detect both upgoing and downgoing rays and have a totally unobstructed view of the surrounding region. Finally, some *T* phases at HUGO may be drowned out by volcanic signals.

4.3. Acoustic Signals

[24] The most common signal recorded by the HUGO hydrophone was a sharp acoustic pulse sounding very much like an explosion. Recordings of explosions from a submarine eruption on the Juan de Fuca ridge confirm that such an interpretation is reasonable [*Fox et al.*, 1995; *Schreiner et al.*, 1995]. Explosive events were nearly continuous during the time that HUGO was active, occurring hundreds to thousands of times per day. Our initial interpretation of the explosions was that they resulted from lava-water contacts from a Loʻihi eruption. This interpretation was inspired by the results of a 1996 sonobuoy survey that located similar explosive signals on the northeastern part of Loʻihi's summit [*Duennebier et al.*, 1997]. Because of the limitation of a single receiver, we were unable to determine a source location for the explosive events until October 1998, when HUGO was brought temporarily back on line with a battery pack. At that time we deployed two sonobuoys north of the junction box and recorded the same events on both the sonobuoys and on the HUGO hydrophone. A series of progressive sonobuoy deployments confirmed that the source of the explosive events was in fact the Kilauea ocean entry, the site where lava from the current eruption enters the ocean ∼40 km north of HUGO. We therefore interpret the source of these events as explosions at the ocean entries near Wahaʻula and Kamokuna (Figure 1).

[25] Although their frequency content varies from <10 Hz to several kHz, most of these acoustic events share a similar pattern in time series (Figure 7). The first pulse is followed 0.75 s later by a second signal, and by a third pulse ∼2 s after the first. The second arrival is noticeably more dispersed in time and lower in frequency than the first arrival. The triplicate nature of the events is independent of frequency content; both high- (>50 Hz) and low- (<50 Hz) frequency explosions display the three-pulsed signal (Figure 7). This frequency independence, combined with the fact that the time difference between pulses is virtually identical over the course of months, suggests that the triplicate waveform results from propagation rather than source effects. This hypothesis is confirmed by the fact that explosive events can be correlated between HUGO records and data collected the PMEL equatorial hydrophone array [*Caplan-Auerbach et al.*, 2001]. Waveforms of explosive events detected by the PMEL array do not display triplicate character. Data from an air gun survey performed over the Kilauea south-flank during February 1998 and two-dimensional ray tracing indicate that no direct arrivals are possible along this line and that rays must undergo at least one reflection en route to Loʻihi. The high-frequency (>1000 Hz) content of many explosive events requires that they be water-borne, rather than crustal, arrivals. We can therefore rule out the possibility that the pulses represent conversions from different crustal phases.

[26] Our inability to locate events based only on HUGO signals means that we cannot determine whether all of the explosive events have their source at Kilauea or whether some come from Loʻihi itself. To investigate the possibility that Loʻihi may also have been erupting at the time HUGO was active, we looked at data from times when lava from the Kilauea eruption was not flowing into the ocean. During these pauses, virtually no volcanic signals were detected on the HUGO hydrophone, supporting the hypothesis that the majority of explosive signals come from Kilauea.

[27] The mechanism that produces the explosive events is not yet known. Some events, however, display nearly identical waveforms (Figure 8), suggesting that they share a common source mechanism and location. In other cases, events with different spectral character-
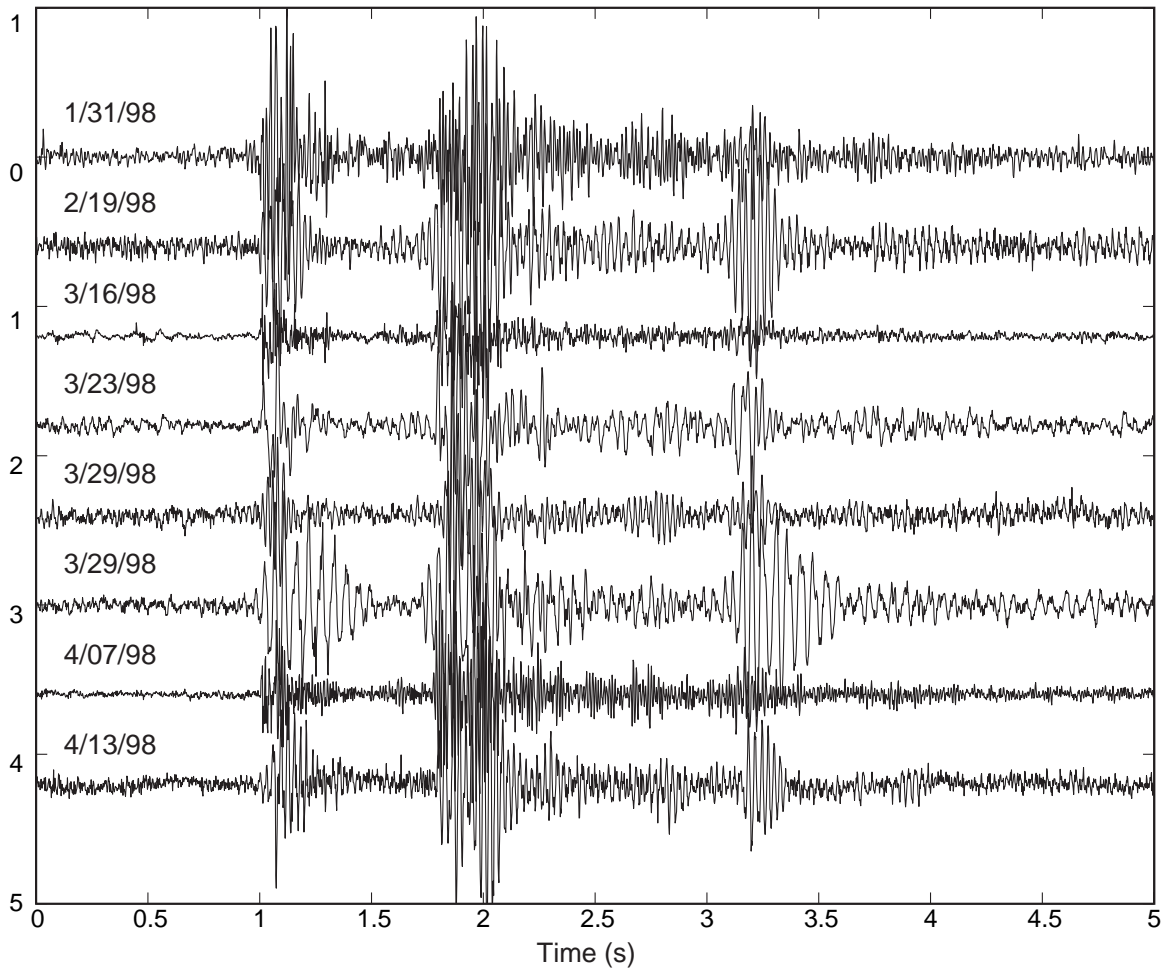
Figure 7. Nine different Kilauea explosive events, detected at the HUGO hydrophone between January 31, 1998, and April 13, 1998. Although their frequency content varies, each shows the same three pulses in time series. This suggests that the triplicate nature of the waveform results from path effects rather than the source mechanism. The third main pulse has not been identified in two-dimensional ray tracing and may result from a side echo.

istics are closely spaced in time, indicating different sources or a source changing in time. Some insight into the processes generating these signals may be gained by comparing HUGO records with observations made by scuba divers who visited the active ocean entry in 1973 and 1989 [*Moore et al.*, 1973; *Tribble*, 1991]. In some instances, divers described explosions that recurred at a single position along a submarine lava stream. These explosions, produced by the combustion of hydrogen

gas, generated a bubble of lava 0.5–1 m in diameter [*Tribble*, 1991]. The sound produced by these explosions was audible to the divers, implying a source frequency >20 Hz. We believe that the explosions detected at HUGO result from processes similar to those observed on these SCUBA dives.

[28] Divers also described a "rumbling" that could be felt when they touched the offshore lava tube [*Tribble*, 1991]. This signal may be
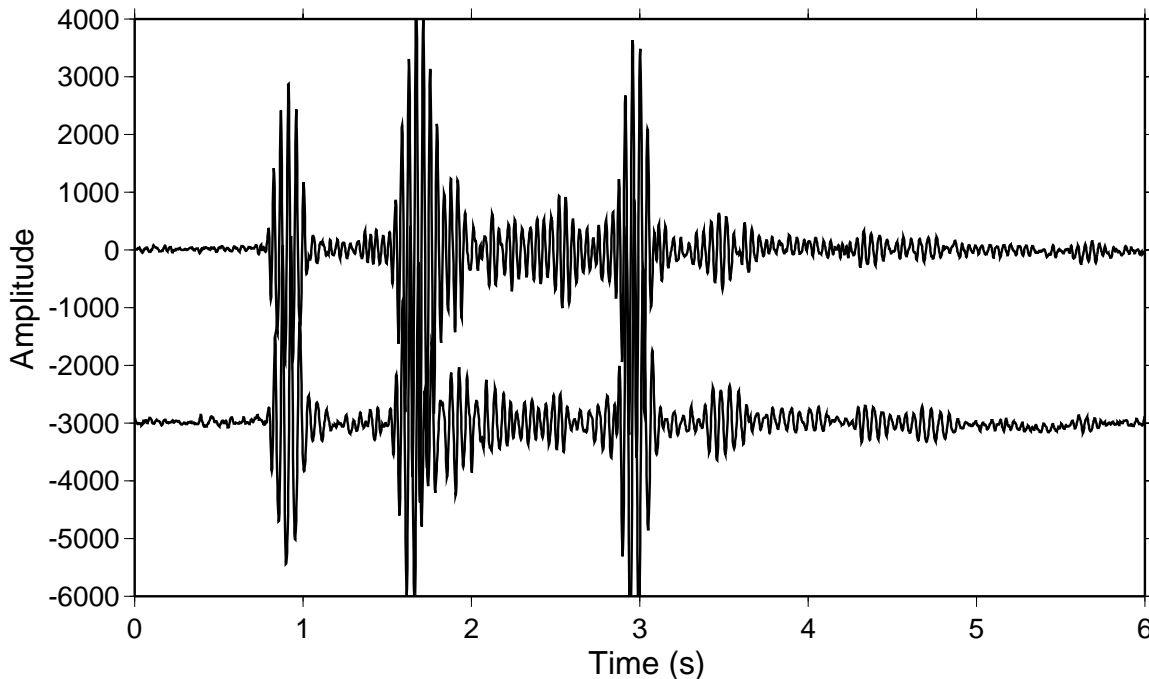
Figure 8. Two explosive events detected by HUGO on March 29, 1998. The two events occurred minutes apart and have nearly identical waveforms, suggesting a common location and source mechanism.

similar to a low-frequency (<20 Hz) rumble commonly detected by the HUGO hydrophone (Figure 9). This signal occurred periodically throughout the recording period and was commonly accompanied by high-frequency explosive signals. This rumble sometimes comes in short (10–60 s) pulses of activity, while at other times it is continuous for tens of minutes. Although there is no clear pattern to the occurrence of the explosive signals or low-frequency rumble, the latter signal often ceases for some time after events dubbed "roars," interpreted as submarine landslides (Figure 9).

4.4. Roar Events

[29] Perhaps the most intriguing signals detected by the HUGO hydrophone are prolonged roaring noises believed to be associated with landsliding on Kilauea's submarine south flank. This interpretation is supported by the fact that the largest of these events coincide

with observed subaerial collapses of the lava shelf at the Kilauea ocean entry. During the 3 months that HUGO was active, HVO reported two major bench collapses and a host of minor ones (C. Heliker, personal communication, 1998). Each of these events coincides with a large roar event in HUGO records.

[30] Roars share a common spectral character. The initial part of the roar generally consists of a low-frequency (<50 Hz) rumble, accompanied by, and eventually replaced by, a broadband hiss (Figure 9). The low-frequency portion has the greatest amplitude and lasts ~20–30 s. The hiss involves signal up to several kHz and may last anywhere from 1 to 30 min. Commonly, a roar event coincides with the end of a prolonged period of low-frequency rumble. In many instances following a roar, the signals detected by HUGO are dominated by isolated explosions (Figure 9). In a few cases, the roar has no low-frequency
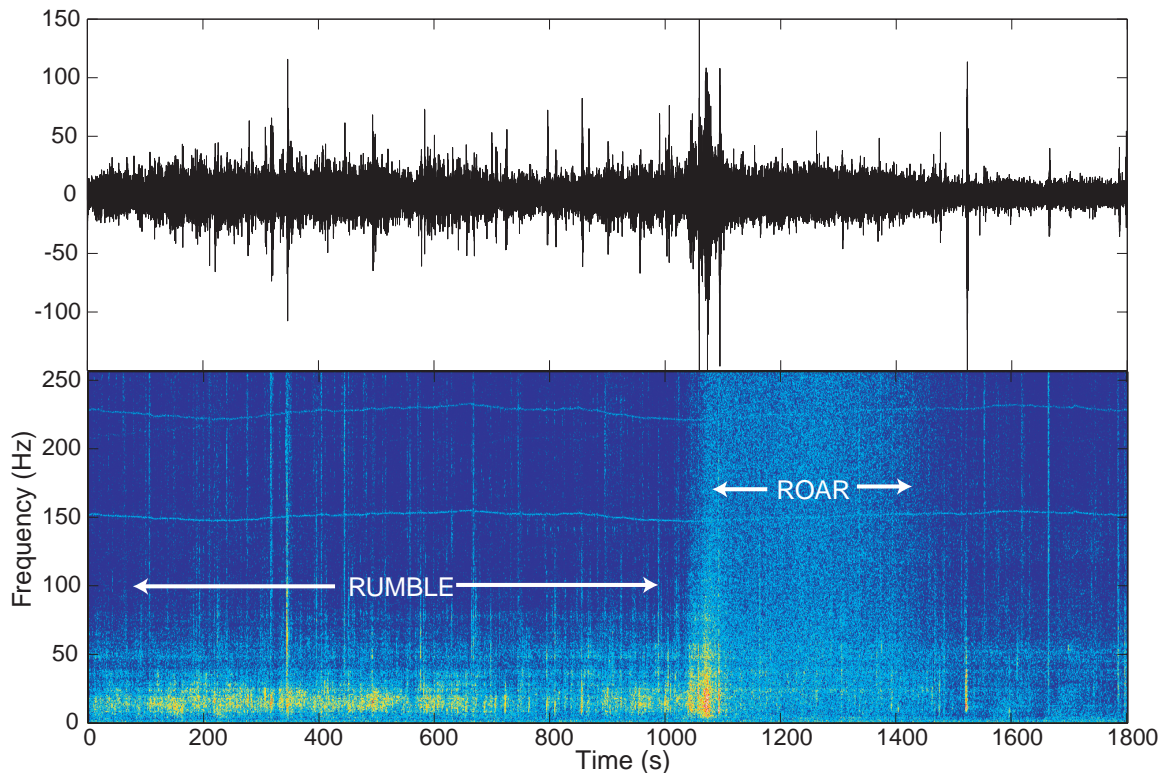
Figure 9. Typical Kilauea rumble and roar events, March 21, 1998. The first 1000 s of the time series are characterized by pulses of low-frequency rumbling. The low-frequency signal ends after the "roar" event initiating at 1040 s. Because roars bear similarity to bench collapses and because they include a wide range of frequencies, we attribute them to landsliding on Kilauea's southflank. The low-frequency portion probably relates to the sliding of large rocks, while the hissing noise represents the downslope motion of talus. The fact that low-frequency activity ceases after the roar suggests that its source may be destroyed in the roar event.

component and consists only of a prolonged broadband hiss.

[31] A likely interpretation of the roar signal is that the initial low-frequency signal results from the failure of large blocks, while the hissing represents the downslope motion of hyaloclastic debris. The fact that many roars coincide with the end of low-frequency rumbling suggests that the landslide destroys the source of the rumble. Similar rumbling has been identified in hydroacoustic records of other submarine eruptions and is believed to be associated with magma movement and perhaps harmonic tremor [*Fox et al.*, 1995; *Fox*

and Dziak, 1998]. Consequently, we speculate that the rumbling noise is generated by the motion of lava in an offshore tube or lava stream and that roars signify the destruction of one of these tubes by mass wasting. Once the tube is destroyed, an open source of lava is exposed to the ocean, accounting for the observed increase in explosive events that often follows a roar. Many roars are immediately preceded by a large explosion that may act as a trigger to the destruction of the tube and the generation of a small landslide. The fact that some roars have no low-frequency component suggests that some slides are composed only of talus.

[32] We note that in many cases, the low-frequency rumble continues uninterrupted through the roar event. However, during the time that HUGO was active, lava from the Kilauea eruption flowed into the ocean at two sites: Wahaùla and Kamokuna (Figure 1). The sites are only ~1 km apart, and we are unable to differentiate between signals generated at the two ocean entries. Thus an offshore lava tube at one entry may continue while the tube at the other entry is destroyed by a landslide.

[33] Roars are detected frequently, on the order of 3–10 times per day. Although we can correlate some large roars with observed bench collapses, many more roars are detected by the HUGO hydrophone than can be documented by the HVO records of subaerial collapse at the ocean entry. These events may be attributed to small landslides on the submarine flank of Kilauea's east rift zone. Such slides were observed by scuba divers at the active ocean entry [*Moore et al.*, 1973; *Tribble*, 1991]. Divers reported that the submarine slope was at the angle of repose, and any motion by divers triggered small landslides. Other slides were observed approximately once an hour with no obvious triggering mechanism [*Tribble*, 1991]. Seismic reflection profiles [*Hills et al.*, 1999], confirm that the submarine south flank is largely composed of unstable volcanic debris. It has also been noted [*Moore and Chadwick*, 1995] that the offshore morphology changes dramatically once the rift zone goes submarine at the Puna Ridge; beyond Puna, there is little to no hyaloclastic sedimentation to blanket the flank. No roars were observed during the several days when no lava was flowing into the ocean, suggesting that the weight of new rock at the ocean entry helps initiate mass wasting.

5. Was Loʻihi Erupting in 1998?

[34] Our initial belief, upon hearing the large number of explosive signals detected by the HUGO hydrophone, was that Loʻihi was probably erupting in early 1998. We now believe that the triplicate waveform of the most of the explosive events requires that the source of the signal be Kilauea. The fact that the hydrophone detected little to no signal when Kilauea was in a pause supports this view. However, it is not certain that all of the explosive events in early 1998 came from Kilauea, since a few events do not exhibit the triplicate waveform. Additionally, the roar events could not be located, and we attribute their source to the Kilauea ocean entry largely owing to the correlation of bench collapses and with roars and the strong correlation of roars with triplicate events. It is possible that some of the roars came from Loʻihi landslides. In any case, the amplitude and clarity of the Kilauea signals confirms that noises from a Loʻihi eruption would be easily detected by a system such as HUGO.

6. Conclusions

[35] Despite the fact that its active lifetime was cut short by a fault in the power cable, HUGO yielded a large quantity of high-quality data demonstrating that a permanent observatory at Loʻihi can be of significant value in studies of Hawaiʻi volcanic systems and Pacific-wide seismicity. The HUGO hydrophone was able to detect events with power spectral peaks ranging from 0.01 to 15,000 Hz. Hydroacoustic data from the Kilauea ocean entry could prove useful in examining shallow submarine eruption mechanics. Further analysis and close observation of the landslides at Kilauea's ocean entry may also lend insights into the formation of that volcano's submarine south flank. In spite of the fact that the seismic sensor package did not operate, many local and teleseismic earthquakes were recorded by the hydrophone. Locations for local offshore earthquakes improved upon addition of data from the HUGO sensor. Information about HUGO may be obtained at http://www.soest.hawaii.edu/HUGO/hugo.html and

sounds recorded by the HUGO hydrophone may be heard at http://www.soest.hawaii.edu/~fred/sounds/sounds.html.

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