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Hydroacoustic Detection of Submarine Landslides on Kilauea Volcano

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Hydroacoustic detection of submarine landslides on Kilauea volcano

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Abstract. Landslides produced at the site where lava flows into the ocean at Kilauea volcano have been detected hydroacoustically. Up to 10 landslides per day were detected by a hydrophone on the Hawaii Undersea Geo-Observatory (HUGO), located 50 km south of the entry site. The largest of these landslides, partly subaerial events known as bench collapses, were detected by a network of hydrophones in the eastern Pacific, 5000-7000 km away from the source. The landslides display a characteristic spectral signature easily recognizable among other signals such as earthquake T-phases and anthropogenic noises. The fact that signals are detected at great distances suggests that hydroacoustic detection of landslides could be a powerful tool in tsunami monitoring and modeling efforts.

Introduction

The role of landslides in tsunamigenesis has long been recognized [*Gutenberg*, 1939; *Wilson and Torum*, 1972; *Tinti and Bortolucci*, 2000] but events such as the July, 1998 tsunami in Papua New Guinea (PNG) have recently returned the issue to the forefront of hazards research [*Synolakis et al.*, 2000]. The recent discovery of landslide headwalls on U. S. continental margins has also renewed interest in the relationship between landslides and tsunamigenesis [*Greene et al.*, 2000].

While the tsunamigenic capacity of great (M>8) earthquakes is well established, several earthquakes are associated with tsunamis far larger than predicted by their magnitude. In some cases, these tsunamis are better modeled by a landslide source [*Tappin et al.*, 2001; *Fryer and Watts*, 2000]. The anomalous tsunami magnitude associated with these events makes identifying their source an important challenge. One posible method is to examine seismic data for evidence of a single-force mechanism [*Hasegawa and Kanamori*, 1987; *Ma et al.*, 1999], although *Dahlen* [1993] demonstrated that such a single force source is not unique to landslides. *Okal* [2000] used the length and spectrum of T-phase codas to identify a potential landslide associated with the 1998 PNG tsunami. In general, however, no means has yet been developed to rapidly identify a submarine landslide using seismic or hydroacoustic data.

In this paper we report on hydroacoustic detection of landslides by two independent instruments: a high-rate hydrophone deployed as part of the Hawaii Undersea Geo-Observatory (HUGO) and the Eastern Pacific hydrophone array operated by the Pacific Marine Environmental Laboratory (PMEL). Although the PMEL network is located >5000 km from Kilauea while HUGO sits only 50 km from the landslide site, the signals can be clearly correlated between the two systems. These data, among the first hydroacoustic recordings of confirmed submarine landslides, are used to determine whether landslides display a characteristic spectral signature that may be used for landslide and tsunami monitoring over ocean basin scales.

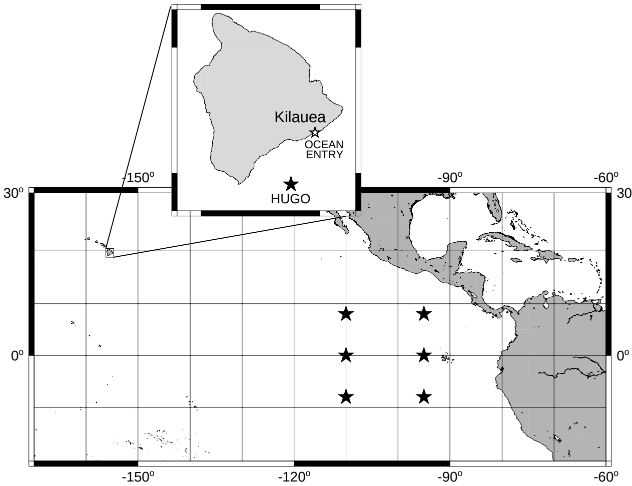

Figure 1. ocation of the HUGO and PMEL hydrophones relative to the Kilauea ocean entry. The ocean entry, the site where bench collapses occur, is marked with a white star in the inset map of Hawaii island. The inset map also shows a black star at the site of the HUGO hydrophone. Locations of PMEL hydrophones are shown in the larger map as black stars.

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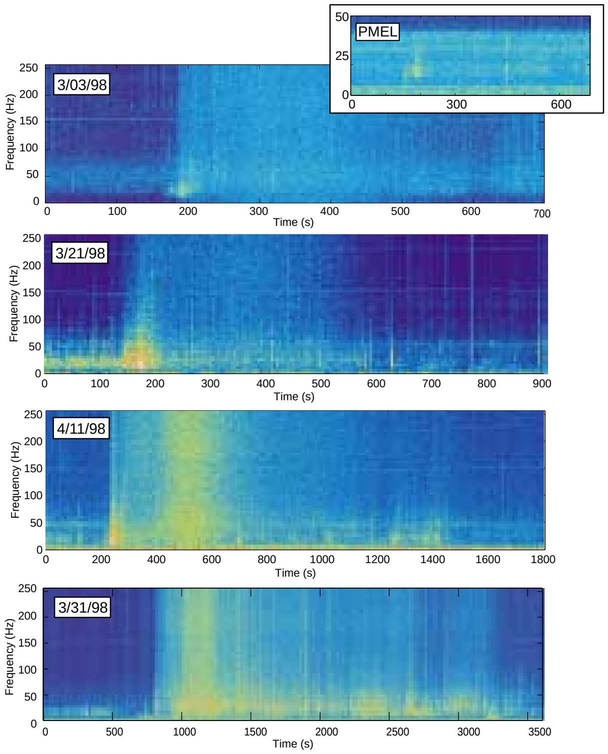

Figure 2. Spectrograms for four typical landslides, recorded by the HUGO hydrophone during March and April, 1998. The landslides are characterized by a 30-50 second low-frequency rumble accompanied by a longer-lasting broadband hiss. Although the hiss has been recorded at frequencies >2500 Hz, we present data at 512 Hz to highlight the low-frequency and broadband components. Signal durations vary (note the different time scales). Warm colors represent higher amplitudes. The inset spectrogram accompanying the 3/03/98 landslide is the 3/03/98 event as detected by one of the PMEL hydrophones, 5400 km from Kilauea. The event of 3/31/98 is a bench collapse, also shown in Figure 3.

System description

HUGO consists of a junction box positioned on the summit of Loihi seamount, and connected to a shore station on Hawaii island via a 47-km electro-optical cable (Figure 1). HUGO's high-rate hydrophone collected a continuous record of data from January 27-April 25, 1998. Data were most often stored at 512 Hz, but occasionally at rates as high as 16 kHz. HUGO sits at depth of 1200 m, just below the axis of the SOFAR channel and is therefore well-positioned to detect submarine acoustic signals.

The PMEL hydrophone array consists of six autonomous instruments suspended in the SOFAR channel over the equatorial East Pacific Rise (Figure 1). The 8-bit data recorded by the PMEL hydrophones are bandpass filtered at 1-40 Hz and sampled at 100 Hz. The PMEL array became operational in May, 1996 and, with the exception of one 7-day period in late 1998, has recorded continuously since that time [*Fox et al.*, 2000].

Landslide signal identification

The current eruption of Kilauea volcano began in January, 1983, and continues at the time of writing. In November, 1986, lava from the eruption first met the sea, and since that time has frequently entered the ocean along the southeast coast of Hawaii island. As lava enters the ocean, a delta forms atop a layer of hyaloclastites. As the weight of the delta increases, it subsides and may eventually collapse into the ocean. When the subaerial portion of the delta is involved in the landslide it is called a "bench collapse". Major collapses that may involve tens of acres of bench occur approximately 1-2 times per month during times of coastal volcanic activity [*Mattox and Mangan*, 1997].

Throughout the time that HUGO was active, landslides from the Kilauea ocean entry were detected by the hydrophone between 4 and 10 times daily [*Caplan-Auerbach and Duennebier*, 2001]. We identify these signals as landslides due to the fact that the largest events are directly correlated with bench collapses observed by Hawaiian Volcano Observatory (HVO) staff [*C. Heliker,* pers. comm., 2000]. No independent observations have been made of the smaller events, but their similarity to bench collapses strongly suggests a similar source mechanism.

The landslide events share common spectral characteristics and are easily discriminated from other acoustic events such as seismic T-phases, whale vocalizations and man-made acoustic sources (airguns or shipping noise). The majority of landslides begin with a low-frequency (<50 Hz) rumble accompanied by, and eventually replaced by, a broadband hiss (Figure 2). The hiss has a nearly flat power spectrum from 1 to 3000 Hz. Landslide duration varies from 1-2 minutes to several hours. We hypothesize that the rumble is associated with the failure of large blocks, such as the main bench or a submarine lava tube, and interpret the hiss as sliding hyaloclastic debris. In some instances, the signal has no low-frequency component and includes only the broadband hiss.

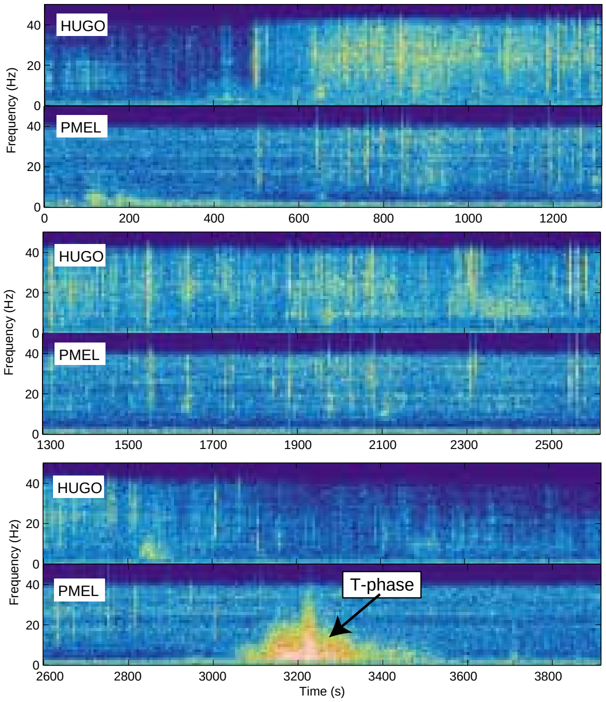

Figure 3. Bench collapse of 3/31/98 recorded at HUGO (top panels) and PMEL (bottom panels). The HUGO data have been filtered and decimated such that they are similar to PMEL recordings. Individual explosions can be correlated on the two sensors. The stronger broadband component in the HUGO data may be a consequence of aliasing during inital resampling from 64 kHz to 512 Hz. A T-phase from an unidentified teleseismic earthquake is visible in the PMEL record at 3200 seconds.

Many landslides also feature an increase in impulsive signals believed to be hydrovolcanic explosions resulting from the exposure of a lava tube [*Mattox and Mangan*, 1997].

All of the bench collapses detected by HUGO were also detected by the PMEL equatorial hydrophone array. Not only do onset times coincide (after accounting for the required travel time), but individual hydrovolcanic explosions can be correlated between HUGO and PMEL records (Figure 3). Because the PMEL recordings are bandpass filtered between 1 and 40 Hz, only the low frequency portion of the signal is recorded. These signals are easily distinguishable from earthquake T-phases which are emergent and have durations of minutes. The stronger background signal in the HUGO record may be a consequence of aliasing during resampling from 64 kHz to 512 Hz.

Comparison of HUGO and PMEL data is limited by the fact that HUGO was only operational between January 27 and April 25, 1998 and therefore only recorded a few large collapse events. However, virtually all of the bench collapses documented by HVO since the PMEL network was installed in 1996 were detected by the equatorial array. Many more collapses occurred for which initiation times are not known [*C. Heliker*, pers. comm., 2000]. These events may account for the hundreds of unidentified signals in PMEL records.

Use of hydroacoustic data for landslide monitoring

The fact that Kilauea landslides were detected >5000 km from the initiation site makes us hopeful that hydroacoustic data could be used to identify submarine landslides on ocean basin scales as part of a tsunami monitoring program. However, the fact that the observed bench collapses occur on an active volcano introduces signals that may not be found in other landslide events. Most importantly, the signals detected by PMEL are largely composed of impulsive events, believed to be hydrovolcanic explosions. Such signals are not expected to be associated with other landslides and cannot be used as a distinctive spectral characteristic. However, at least one "typical" landslide was detected by the PMEL network (Figure 2), confirming that events with no associated explosions are also detectable on ocean basin scales. Further study of the relationship between landslide volume and acoustic signature is also required. The dramatic difference in size between Kilauea bench collapses (1-10 x 10^5 m^3) and tsunamigenic events (4-10 x 10^9 m^3 for the 1998 PNG event) may result in different spectral characteristics.

The broadband hiss is a promising characteristic for hydroacoustic monitoring of landslides. Unfortunately, the current sample rate for PMEL data makes it impossible to evaluate whether the broadband signal is identifiable at large (>1000 km) source-receiver distances. Attenuation is a concern: over the 6000 km between Kilauea and the PMEL network, a 20 Hz signal is predicted to attenuate by 2 dB whereas a 200 Hz signal will lose 20 dB [*Urick*, 1967]. More data at higher sample rates must be collected before the merits of hydroacoustic landslide monitoring can be evaluated. PMEL has recently advanced its hydrophone technology to allow recording of 0-450 Hz signals at 12 bit resolution.

Conclusions

Submarine landslides and bench collapses from the Kilauea ocean entry have been detected on hydrophones located 50 km (HUGO) and >5000 km (PMEL) from the landslide site. The landslides display recognizable spectral characteristics including an initial low-frequency (<50 Hz) rumble and a broadband coda. This signal is easily distinguishable from other acoustic events, making hydroacoustic monitoring of landslides an encouraging possibility. Further data collection is required, ideally at higher sample rates, to determine whether hydroacoustic monitoring of landslides is a viable mechanism for use in tsunami monitoring at ocean basin scales.

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