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Key Points:

- Submarine landslides occurred frequently during the West Mata eruption
- Submarine landslide speed can be estimated from hydroacoustic data

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Hydroacoustic investigation of submarine landslides at West Mata volcano, Lau Basin

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Abstract Submarine landslides are an important process in volcano growth yet are rarely observed and poorly understood. We show that landslides occur frequently in association with the eruption of West Mata volcano in the NE Lau Basin. These events are identifiable in hydroacoustic data recorded between ~5 and 20 km from the volcano and may be recognized in spectrograms by the weak and strong powers at specific frequencies generated by multipathing of sound waves. The summation of direct and surface-reflected arrivals causes interference patterns in the spectrum that change with time as the landslide propagates. Observed frequencies are consistent with propagation down the volcano's north flank in an area known to have experienced mass wasting in the past. These data allow us to estimate the distance traveled by West Mata landslides and show that they travel at average speeds of ~10–25 m/s.

1. Introduction

The development of a volcanic edifice is a balance between growth processes, notably eruption and intrusion, and processes of erosion and collapse [e.g., *McGuire*, 1996; *Carracedo*, 1999; *De Vries and Francis*, 1997]. Because eruptions often generate fragmental material and material that is easily altered, mass wasting is a frequent and important part of volcano evolution [*López and Williams*, 1993; *Reid et al.*, 2001]. Furthermore, mass wasting can be a significant hazard in volcanic environments, playing a role in eruption dynamics, tsunamigenesis, and debris flow generation.

As with most volcanic studies, research into volcanic landslides has taken place primarily on subaerial volcanoes. Bathymetric mapping and repeated surveys confirm that mass wasting plays an important role in the evolution of submarine volcanoes as well [*Holcomb and Searle*, 1991; *Hampton et al.*, 1996; *Krastel et al.*, 2001; *Oehler et al.*, 2008]. Slide deposits mantle the flanks and surrounding seafloor of many ocean island and submarine volcanoes, from slumps of surficial clastic material to massive failures of the primary edifice [*Moore et al.*, 1989; *Chadwick et al.*, 2008a, 2008b; *Wright et al.*, 2008; *Chadwick et al.*, 2012; *Watts et al.*, 2012]. Little information exists, however, on how frequently such events occur, how they are triggered, or how rapidly they move.

Most investigations of submarine landslides have focused on identifying past events in the bathymetric record [*Moore et al.*, 1989; *Watts and Masson*, 1995; *Mitchell et al.*, 2002; *Oehler et al.*, 2008]. Landslides, however, generate hydroacoustic signals that can be detected either by hydrophones or, if the signal couples into the ground, by seismometers. In 1998, dozens of small landsides occurring on the submarine flank of Kilauea volcano were recorded by a hydrophone deployed on the summit of Lo`ihi volcano [*Caplan-Auerbach et al.*, 2001]. These signals have a distinct hydroacoustic character, initiating with a low-frequency rumble that is accompanied by a prolonged (tens of seconds to minutes) broadband coda. Landslides on Kilauea were recorded only when lava was actively flowing into the ocean, suggesting that these events were triggered by loading of new material at the top of an unstable flank [*Caplan-Auerbach et al.*, 2001]. A major landslide at NW Rota-1 volcano (Marianas) was recorded by a hydrophone, as was a precursory increase in eruption intensity [*Chadwick et al.*, 2012]. That slide destroyed several instruments on the volcano's flanks and was clearly visible in before-and-after bathymetric mapping of the area.

Where hydroacoustic data are unavailable, seismic data can help identify large events: T-phases generated by a large landslide and eruptive activity on Monowai volcano in the Kermadec arc were recorded by seismometers throughout Polynesia [*Chadwick et al.*, 2008b; *Wright et al.*, 2008]. In 1998 an earthquake-induced landslide in Papua New Guinea was recorded by both hydrophones and seismometers in the Pacific

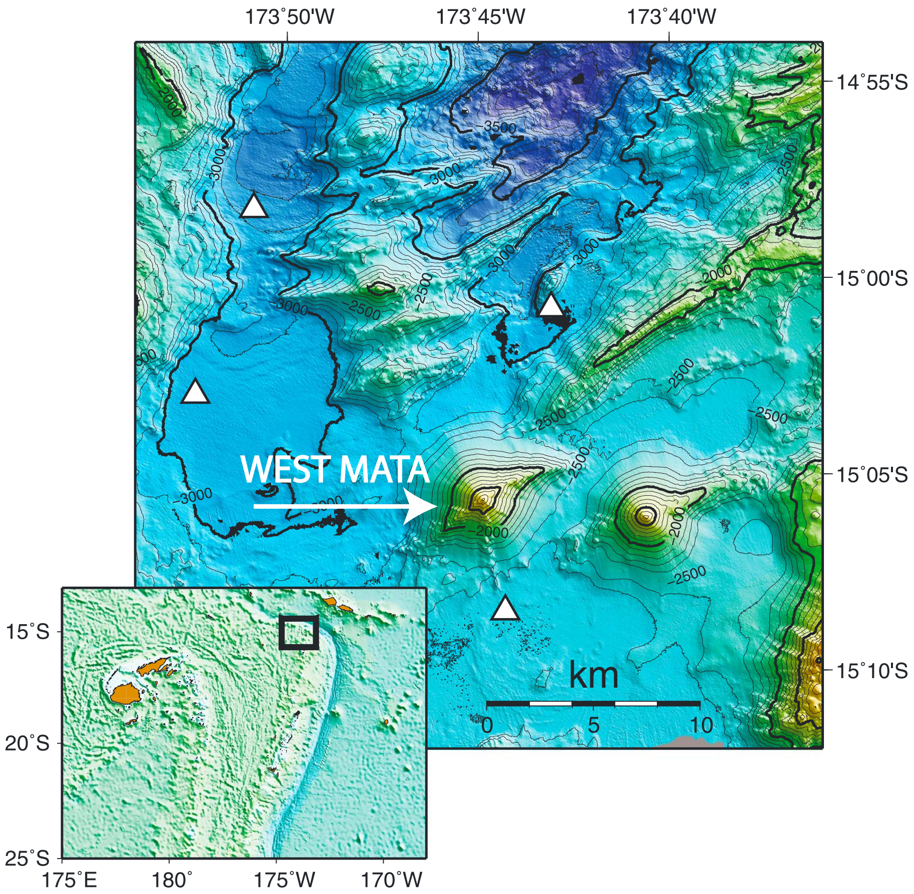

Figure 1. Map of West Mata volcano and its location in the Lau Basin (inset). Solid triangles represent the locations of moored hydrophones deployed near West Mata and the Northern Mata volcanoes from December 2009 to May 2010. Figures 3 and 4 represent data and models for the northern hydrophone. Sounds from slides on the north side of the volcano are largely blocked by the edifice; hence, signals are only weakly recorded on the southern hydrophone.

region [*Okal*, 2003]. Those signals allowed researchers to identify the slide and explain how a relatively small earthquake generated a massive and deadly tsunami. On land, seismic data were of critical importance in quantifying and describing the failure of Mount St. Helens in its 1980 eruption [*Kanamori and Given*, 1982; *Brodsky et al.*, 2003].

In this paper we present new data from a hydroacoustic study of West Mata submarine volcano in the NE Lau Basin during a period of continuous eruptive activity [*Resing et al.*, 2011; *Dziak et al.*, 2013]. We show that small submarine landslides are easily detectable in the hydroacoustic record, and we use interference patterns associated with surface reflections to constrain where the events took place and how far and rapidly they propagated. Identification of landslide signals allows us to determine the frequency of such events and to examine landslide size distributions.

2. Geologic Setting

West Mata volcano is an active submarine volcano located near the northern end of the Tonga arc in the NE Lau Basin (Figure 1). An observation of high levels of particulate material in the water column led to the discovery of an ongoing eruption at West Mata, later directly observed during a cruise with a remotely operated vehicle (ROV) in 2009 [*Walker et al.*, 2009; *Resing et al.*, 2011]. With its summit at 1200 m below sea level, West Mata is the deepest eruption ever observed [*Resing et al.*, 2011]. Evidence from hydroacoustic data suggests that the eruption ended in early 2011 [*Dziak et al.*, 2013], confirmed by ROV dives in September 2012 [*Embley et al.*, 2012].

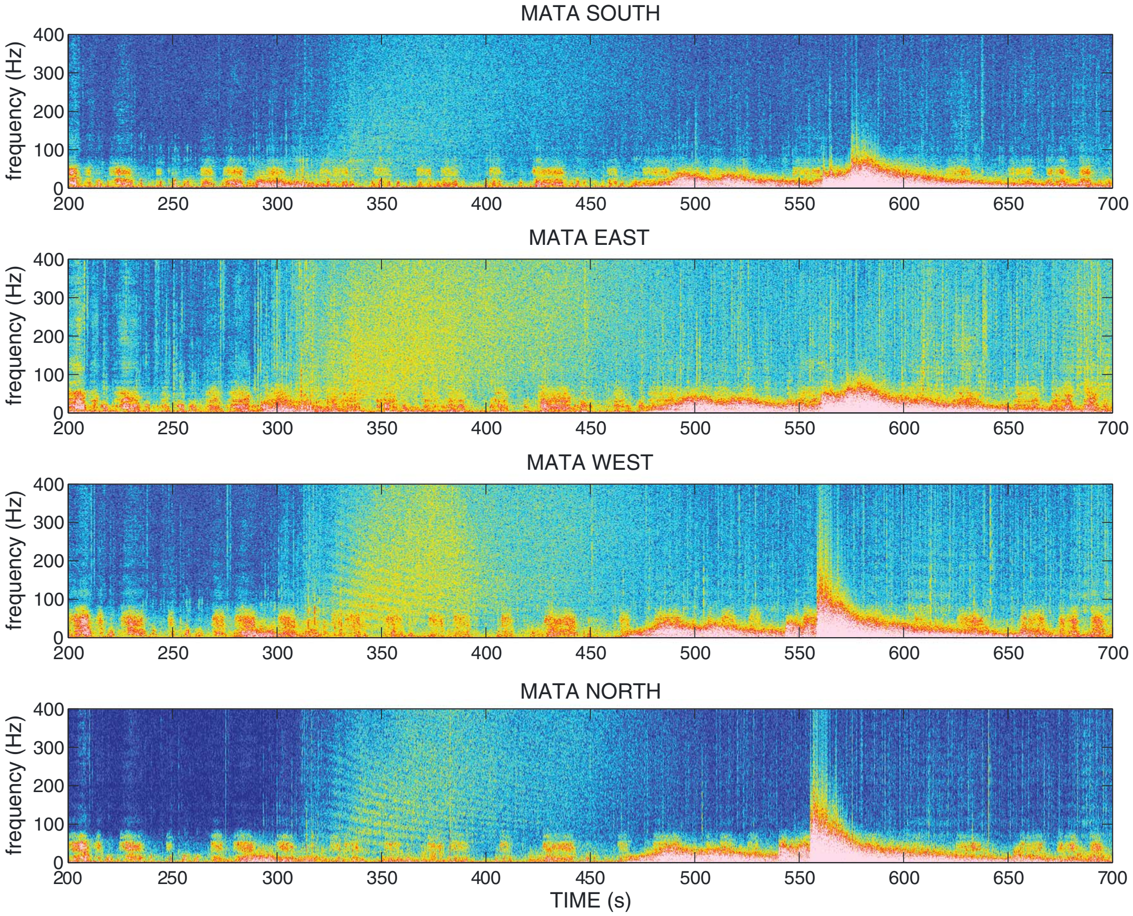

Figure 2. Spectrograms for a 700 s period at all four hydrophones. The low-frequency (<50 Hz) signals are thought to be degassing explosions associated with the West Mata eruption. The very low frequency signals between ~470 and 600 s are regional earthquakes. The signal between 300 and 450 s is a landslide, identified by its broadband spectrum and changing frequency content. The horizontal frequency bands visible in the background at each station (notably between 600 and 650 s) are a consequence of interference between direct arrivals and surface reflections. The changing spacing of these fringes during the landslide is evidence of a moving source.

The 2009 ROV observations show that the West Mata eruption comprised a variety of behaviors including explosive bubble bursts, lava fountaining, diffuse degassing, and slow lava extrusion [*Clague et al.*, 2011; *Resing et al.*, 2011]. The explosions generate significant quantities of scoria and lava fragments, which may account for the smooth appearance of its north and south flanks. Bottom photographs confirm that much of the edifice is mantled in clastic debris resting at the angle of repose [*Clague et al.*, 2011].

That landslides are a frequent occurrence at West Mata is clear from repeated bathymetric surveys. Bathymetric difference mapping by both *Clague et al.* [2011] and *Embley et al.* [2012] shows that over periods of years, material is added to or removed from the volcano's flanks. In particular, depth differences >30 m were identified on the flank NNW of the summit for the time period between 1996 and 2010 [*Clague et al.*, 2011] and to the west of the summit between 2009 and 2011 [*Embley et al.*, 2012]. *Embley et al.* [2012] also identified a clearly landslide-induced loss of up to 60 m of material on the southern flank between December 2010 and November 2011, with redeposition farther downslope.

3. Hydroacoustic Data

In December 2009, a network of four moored hydrophones was deployed in the region surrounding West Mata and the northern Mata volcanoes (Figure 1). Three of the instruments were suspended at depths within the acoustic low-velocity zone known as the Sound Fixing and Ranging channel; an error during deployment resulted in the southern hydrophone being moored at only 230 m depth. Data from the network were

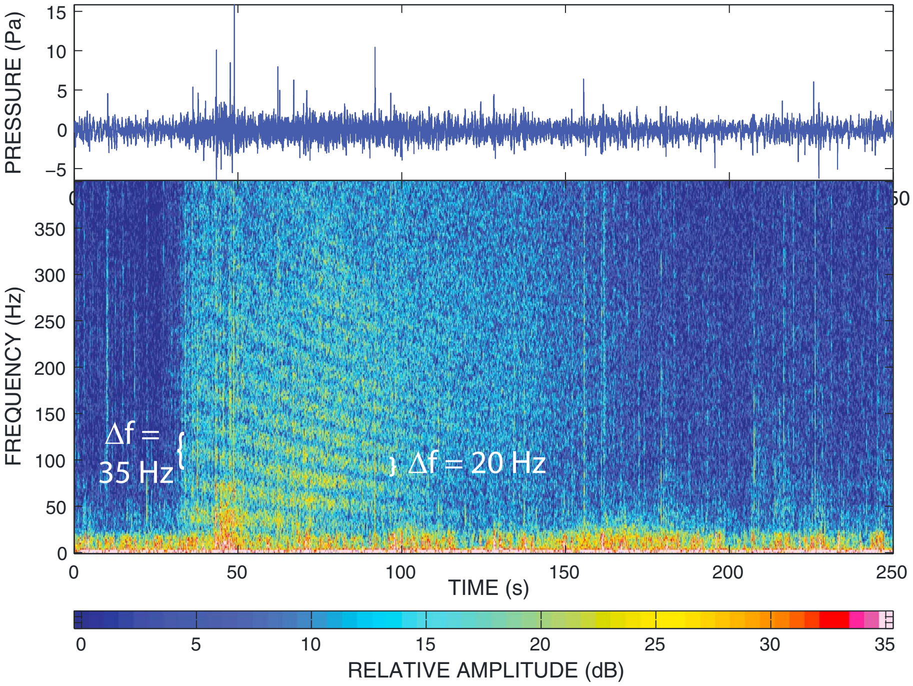

Figure 3. (top) Time series and (bottom) spectrogram for a West Mata landslide recorded on 1 January 2010 on the northern hydrophone. The spectral bands result from constructive and destructive interference of direct and surface-reflected arrivals, a phenomenon known as a Lloyd's Mirror. The spacing between spectral minima is noted: interference bands are at ~35 Hz at the beginning of the landslide and ~20 Hz near the end. Because the spacing between frequency bands depends on the time difference between direct and reflected arrivals, a change in spacing indicates a moving source. The frequencies observed are consistent with a source propagating from 1430 m to 1800 m down West Mata's north flank.

continuously recorded at 1000 Hz from December 2009 until May 2010. The southern instrument was redeployed in May 2010, and it operated until August 2012.

Data from the hydrophones reveal a variety of signals believed to be associated with the West Mata eruption. These include discrete sounds identified as lava bubble bursts, prolonged explosion and degassing events, and acoustic tremor [*Dziak et al.*, 2009, 2010; *Mack et al.*, 2012]. Most of the signals exhibit spectral banding, in which frequencies are stronger and weaker at periodic intervals (Figure 2). This pattern was shown by *Matsumoto et al.* [2011] to result from interference of direct and surface-reflected waves, an effect known as a Lloyd's Mirror [*Jensen et al.*, 2011]. In a Lloyd's Mirror, direct and surface-reflected arrivals are simultaneously recorded at a receiver. However, the surface reflection has traveled a distance dx more than the direct arrival. Because the reflected waves are inverted by the surface interaction, if the distance dx is an integral number of half wavelengths $n\lambda/2$, the two arrivals will constructively interfere. If dx is an integral number of whole wavelengths, the summation of waves causes destructive interference. Thus, wave amplitude, and thus signal power, is diminished when $\mathrm{dx} = n\lambda$. The traveltime difference dt between the two waves is $\mathrm{dt} = \mathrm{dx}/v = n\lambda/v$. And because λ/v denotes frequency f, we can see that destructive interference occurs for $f = n/\mathrm{dt}$, frequencies that are integrally related to the inverse of traveltime. The first quiescent frequency occurs for $n = 1$, with additional destructive bands for higher integer values of n. These interference bands were recorded by all of the hydrophones in association with West Mata eruption signals.

4. West Mata Landslides

Also recorded by the hydroacoustic network were dozens of landslides, identifiable by their spectra and signal durations. Like landslides recorded on Kilauea volcano [*Caplan-Auerbach et al.*, 2001], West Mata landslide signals typically begin with a low-frequency (<50 Hz) signal of variable duration with a broadband coda that often lasts for several minutes (Figure 2). West Mata signals were recorded by all four stations,

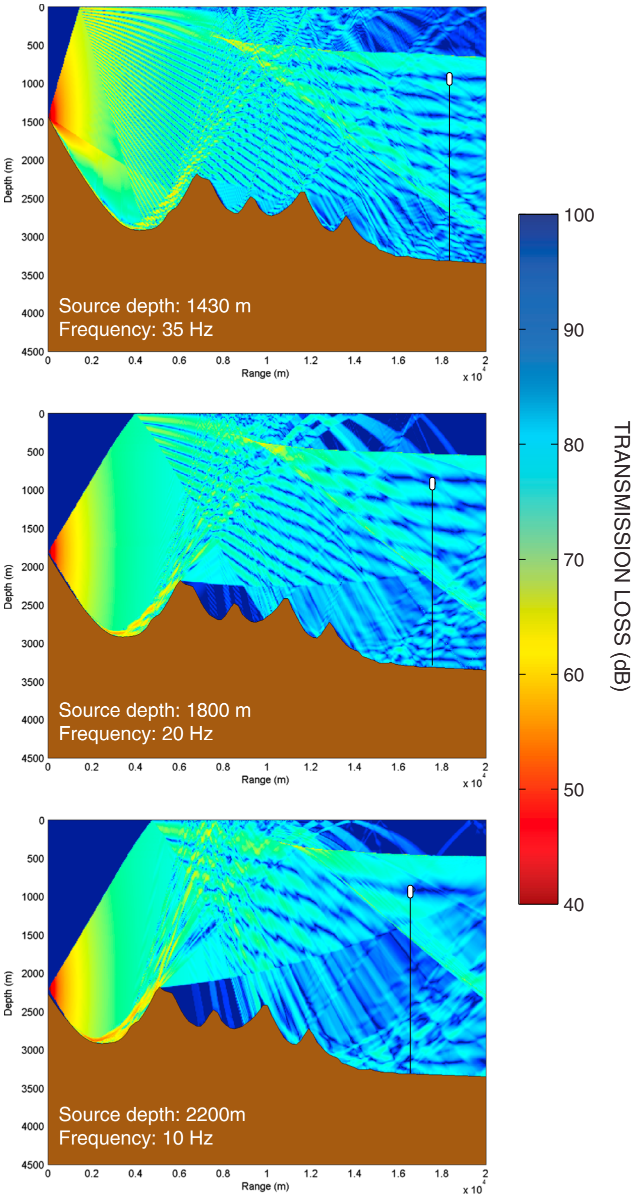

Figure 4. Transmission loss (in dB) estimates for the acoustic wavefield generated by sources of different frequency at three different locations along the proposed landslide path. From top to bottom the images represent sources at 1430 m, 1800 m, and 2200 m with frequencies of 35, 20, and 10 Hz, respectively. The profile represents bathymetry between the West Mata summit and the northern hydrophone also shown in the images. These frequencies, and their integer multiples, interfere destructively at the hydrophone site, as shown by the high (blue) transmission loss. This modeling confirms that interference bands for a sound source propagating between the summit and the northern hydrophone would become more closely spaced, as observed in West Mata landslides.

arriving first at the southern station. This suggests that the signals come from West Mata rather than another regional source.

Unlike other West Mata signals the Lloyd's Mirror interference pattern associated with landslide signals changes with time (Figure 3). In nearly all cases the frequency bands recorded at the north and west hydrophones move closer together as the slide progresses. This shows that for these events, the timing between direct and reflected arrivals increases with time, requiring that either the source or receiver be moving. As we know the receiver to be fixed, and since this phenomenon is observed on multiple hydrophones, this observation strongly supports our contention that these signals come from a moving source such as a landslide. We anticipated that slides moving to the north would show a reverse pattern on the southern hydrophone, with frequency bands getting closer in time. However, no interference patterns were observed on the southern hydrophone at all. Modeling of acoustic rays shows that very little energy from a slide on the north side of West Mata is recorded at the southern station, consistent with the low amplitude arrival in Figure 2.

The timing between direct and reflected arrivals is a function of the source-receiver distance and the path that sound waves take as they travel. Thus, sources from different locations will exhibit different interference band spacing. These patterns, however, are nonunique; at source-receiver distances $>$ 10 km the spacing of interference bands is largely a function of source depth rather than location. However, while we cannot be certain about where a specific West Mata landslide initiated, we do know where such events have happened in the past. Repeat bathymetric surveys have demonstrated that material is frequently added to the northern flank of the volcano, from the summit area at a depth of ~1200 m to the volcano's base at ~2500 m [*Clague et al.*, 2011; *Embley et al.*, 2012]. Assuming that this was the most commonly traveled landslide path, we modeled acoustic propagation between the hydrophones and sources located along this path at 200 m depth increments. Modeling was performed using the acoustic propagation code Bellhop [*Porter*, 2011] with a standard ocean velocity model. Ideally, we would be able to use the observed interference patterns to locate the landslide source, but inverting the source location requires three-dimensional acoustic modeling which is beyond the scope of this study.

We first calculated the path and traveltimes for eigenrays (rays that connect source to receiver) between each of the potential source locations along the assumed landslide path and the northern hydrophone. There are between 3 and 35 eigenrays for each of the modeled source locations. Some rays travel directly through the water column while others undergo one or more surface or seafloor reflections. Surface-reflected waves undergo a 180° phase shift while those reflected off of the seafloor remain in phase. Calculating the frequencies at which waves will interfere destructively requires evaluating all traveltime differences for waves that arrive perfectly out of phase. The number of possible combinations of arrival times makes this problem difficult.

An alternate method is to calculate the strength of a wave of a specific frequency as it arrives at the receiver. Bellhop [*Porter*, 2011] allows the user to calculate transmission loss as a function of signal frequency and location (Figure 4). We performed this analysis for a range of source depths and frequencies, observing which frequencies were strengthened or diminished at the receiver site. If a given source shows a sound strength minimum at fundamental frequency f it would also have minima at integer values nf, so only the lowest such frequency needs to be identified. Our goal with coherence modeling is simply to show that interference bands are predicted to move closer together as the landslide propagates downslope and to determine whether the observed interference band spacing is consistent with a West Mata landslide source.

Transmission loss was calculated for frequencies of 5–50 Hz, at 5 Hz increments. The results for maximum transmission loss are shown in Figure 4 for sources at 1430 m, 1800, and 2200 m, respectively. The greatest transmission loss recorded at the northern hydrophone (plotted) for each source location is associated with frequencies of 35, 20, and 10 Hz, confirming that interference occurs at progressively smaller frequency intervals as the source propagates down the volcano's north slope. The frequency values are consistent with those observed in the hydroacoustic data, confirming that downslope motion from the summit area to near the base of the volcano is a plausible explanation for the observed frequency changes.

The durations of landslide acoustic signals were observed to vary from a few tens of seconds to a few hundreds of seconds. While all slides have broadband spectra, the interference band frequencies also vary between slides, suggesting that events initiate at a range of locations and depths. Assuming that signal duration represents the time it takes for material to propagate along the proposed landslide path, we can use interference frequencies to estimate the distance traveled, the length, and the speed of the slide. We use the slide shown in Figure 3 as a test case for this procedure. Interference frequencies for that slide, as recorded on the northern hydrophone, begin at ~35 Hz and decrease to ~20 Hz. Based on Bellhop transmission loss modeling (Figure 4) and assuming a source on the northern flank of West Mata, these frequencies suggest a slide that initiated just below the summit and traveled to a depth of ~1800 m, a slant distance of ~850 m. The portion of the signal showing strong interference banding lasts 75 s, suggesting an average downslope velocity of 11 m/s. Similar analysis of other West Mata signals suggests average speeds up to 25 m/s. Because these values span the landslide's entire path, from acceleration to a maximum speed to its final deceleration, we stress that these are only average velocities, and the maximum speed of West Mata landslides is likely considerably higher.

Speeds for submarine landslides have been estimated to fall directly within this range; the turbidity current that broke communication cables in the North Atlantic in 1929 was estimated to have moved at speeds between 6 and 25 m/s [*Heezen and Ewing*, 1952; *Locat and Lee*, 2002], and the massive Storegga slide has a modeled velocity of up to 60 m/s [*De Blasio et al.*, 2005; *Masson et al.*, 2006]. Landslide speed is largely a function of slope angle, and the north flank of West Mata is steep, at 30–40° [*Clague et al.*, 2011], suggesting that our speed estimates are plausible.

Some West Mata landslides show interference signals only on certain stations while others exhibit purely broadband signals with no interference bands at all. In most cases interference bands are not observed on the southern hydrophone and signals generally appear weaker on that instrument. This is consistent with ROV observations showing that the eruptive vents were located just north of the summit and bathymetric data suggesting that most landslides occurred on the north flank of West Mata. Modeling in Bellhop shows that signals from West Mata's north slope are only weakly recorded in the south. Some slides, however, show no interference banding on any of the four stations. We interpret that these events represent failure and slide motion over a large area (>100 m in extent). In this situation sound waves coming from the head and toe of the slide could travel sufficiently different paths that the hydrophone would record destructive interference from one part of the source and constructive interference from the other. Events without interference patterns may therefore represent the largest landslides.

5. Conclusions

Landslides occurred frequently on West Mata volcano during its ongoing eruption in 2009–2010 and played an important role in the growth and evolution of its edifice. These events are easily identifiable in the hydroacoustic record and can be distinguished from other signals associated with eruptions or seismic activity. Patterns of constructive and destructive interference caused by signal multipaths can be used to confirm that these signals represent a moving sound source. Modeling of interference signals, combined with the observation that such signals are absent on certain stations, allows us to confirm that landslide locations and propagation paths were most likely on the north slope of the volcano, downslope from the active eruptive vents. Our results suggest that even small landslides move rapidly (~10–25 m/s) on West Mata's steep slopes. Larger landslides do not exhibit spectral banding suggesting that they represent a large source region where sounds travel a range of different paths.

Acknowledgments

Following AGU policy, all digital hydrophone data used in this study are available via the NOAA/PMEL Acoustics Program website to any interested parties upon email request. This manuscript is PMEL contribution number 4201.

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