Hydroacoustic Records and Numerical Models of the Source Mechanisms from the First Historical Eruption of Anatahan Volcano, Mariana Islands

M. Park*, R.P. Dziak**, H. Matsumoto***

* Korea Ocean Research & Development Institute, Ansan P.O. Box 29, South Korea
** Oregon State University/NOAA, Hatfield Marine Science Center, Newport, OR 97365, U.S.A.
*** Oregon State University/NOAA, Hatfield Marine Science Center, Newport, OR 97365, U.S.A.

Summary

Anatahan Volcano in the Commonwealth of the Northern Mariana Islands (CNMI) erupted for the first time in recorded history on 10 May 2003. The underwater acoustic records of earthquakes, explosions, and tremor produced during the eruption were recorded on a sound-channel hydrophone deployed in February 2003. Acoustic propagation models show the seismic to acoustic conversion at Anatahan is particularly efficient, aided by the slope of the seamount toward the hydrophone. The hydrophone records confirm the onset of earthquake activity at 01:53Z on 10 May as well as the onset (at ~06:20Z) of continuous, low-frequency (5-40 Hz) acoustic energy that is likely volcanic tremor related to magma intrusion. The hydrophone recorded a total of 458 earthquakes associated with the eruption. To predict the character of acoustic signals generated from Anatahan, we developed a moment-tensor representation of a volcano-seismic source that is governed by the geometry of the source and the physical properties of the magma. A buried magmatic pipe model was adopted, and numerically modeling source parameters such as the pipe radius and magma viscosity enable us to grasp the inward nature of Anatahan Volcano.

1. Introduction

In February 2003, an array of 5 hydrophones were deployed along the active island- and back-arc of the Mariana Islands (Figure 1) and moored within the ocean sound channel. The hydrophones (1-110 Hz bandpass) were designed to record the hydroacoustic tertiary phase or *T*-wave of oceanic earthquakes and estimate the acoustic location of these earthquakes from throughout the Commonwealth of the Northern Mariana Islands (CNMI). Since acoustic *T*-waves obey cylindrical spreading (r^{-1}) energy loss as opposed to the spherical spreading (r^{-2}) of solid-earth seismic *P*-waves, sound channel hydrophones can often detect smaller and therefore more numerous earthquakes than land-based seismic networks (Fox et al., 1994). Seismic coverage in the Pacific ocean basin is sparse because permanent installations are restricted largely to islands, thereby limiting our understanding of seismicity and volcanic activity in the deep-ocean and significant portions of the Earth (Kanamori, 1988).

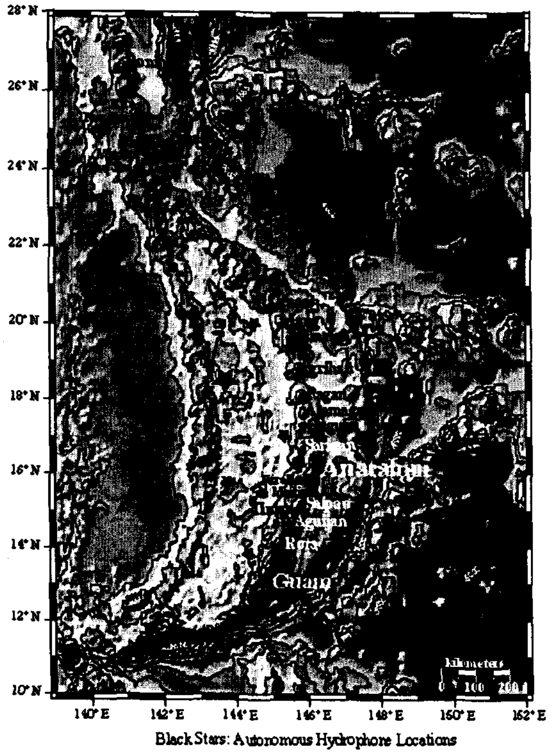


Figure 1. Bathymetry of the Commonwealth of the Northern Mariana Islands with the locations of the major islands labeled. Red circle shows the location of Anatahan Island. Black stars show location of five hydrophones deployed in February and recovered in September 2003, large star indicates hydrophone that recorded data.

On 10 May 2003 at 07:30Z, the first documented eruption of Anatahan Volcano (in the center of the CNMI) occurred in historical time (Wiens et al., 2004). Anatahan is a composite volcano that erupts primarily dacitic lavas, and also has the largest caldera of all the volcanoes in the CNMI, indicating that explosive eruptions were always a possibility (BGVN, 2003). Unfortunately, only the hydrophone located at 18°16.8'N ; 143°45.7'E recorded throughout the eruption of Anatahan. The data from this one hydrophone, however, provides critical information on the onset of earthquake and volcanic tremor activity related to the eruption and on the efficiency of seismic to acoustic wave conversion for earthquakes occurring within this subaerial/submarine volcano. In addition, a numerical model of the eruption activity recorded on the hydrophone provides constraints on the volcano source geometry and physical properties of the magma.

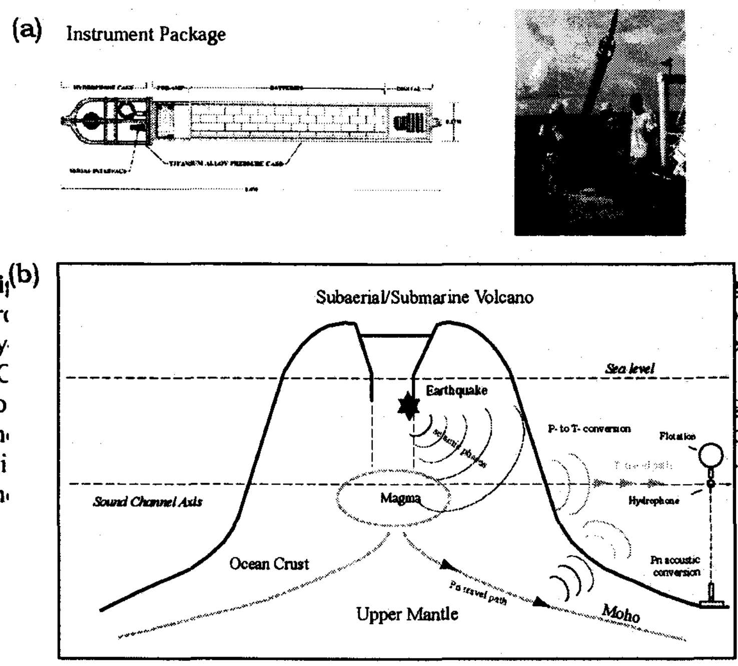
2. Instrument Description

A schematic diagram of the autonomous hydrophone instrument and mooring is shown in Figure 2. The hydrophone instrument package includes a single ceramic hydrophone, a filter/amplifier stage, accurate clock, and processor modified from off-the-shelf hardware (Figure 2a). The instrument records at 16-bit data resolution at 250 Hz (1-110 Hz bandpass) for periods of up to 2.5 years.

3. Seismo-acoustic Propagation

A schematic diagram of the probable seismic and acoustic propagation is also shown in Figure 2b. Although Anatahan is a subaerial volcano, the vast majority of the volcanic edifice is submarine. For example, the floor of the caldera was estimated at 68 m above sea level before the eruption, but had subsided to nearly sea level by 20 May (BGVN, 2003). Therefore many of the earthquakes related to the eruption and the ascent of magma beneath the caldera are below sea level, and much of their seismic energy will be able to project downward, and laterally, out of the volcanic edifice and into the water column. The depth of the ocean-sound channel in this region is ~800 m (Davis et al, 1986), and earthquakes that produce seismic raypaths with take-off angles that are horizontal or near to horizontal (Figure 2b) will have the most enhanced seismic to acoustic conversion process as rays will refract directly into the sound channel as they exit the volcanic edifice and propagate into the water column. Thus multiple seafloor-sea surface reflections are not needed to obtain a horizontal raypath to enter the sound channel (Talandier and Okal, 1998), and therefore much more of the signal's energy is preserved.

In addition to the seismo-acoustic phases that exit the volcano edifice and propagate directly into the sound channel, earthquakes from within Anatahan also generate seismic phases that propagate along the Moho discontinuity (*Pn*) and convert to an acoustic phase directly beneath the hydrophone (Dziak et al., 2004). These phases propagate at *P*-wave seismic speeds for the majority of the path to the hydrophone and thus arrive 7-8 minutes before the *T*-wave arrival at the hydrophone 300 km (Figure 2b and Figure 3). These *Pn* arrivals are readily identifiable since they are much lower frequency (<3 Hz) than the *T*-waves (3-50 Hz).



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4. Hydrophone Records of Eruption Seismicity

Figure 3 shows spectrograms (frequency-time) diagrams of the hydrophone data during the onset of the Anatahan eruption from 0100Z to 1800Z on 10 May 2003. The apparent optimal seismic to acoustic conversion properties of Anatahan volcano should mean the hydrophone detected much of

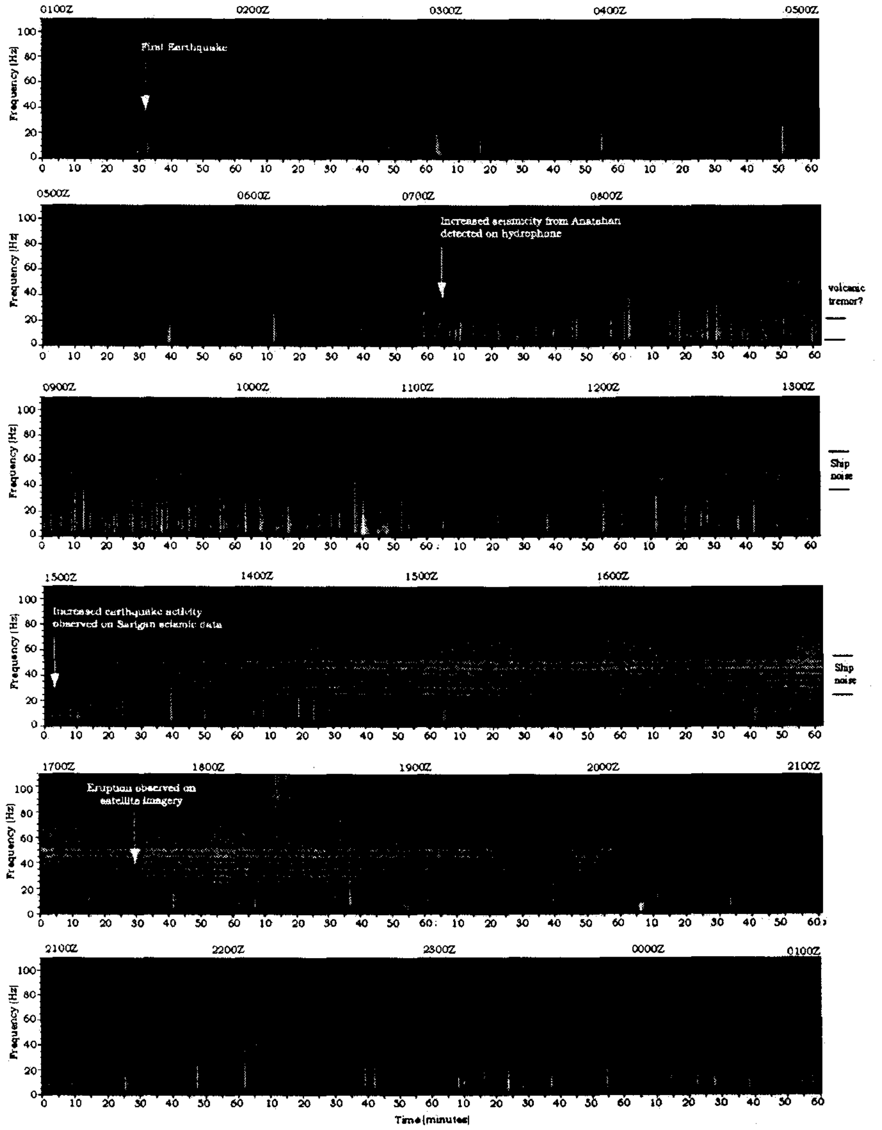

Figure 3. Spectrograms (0-100 Hz) of hydrophone data in increments of an hour during the onset of the Anatahan eruption. Seismicity from Anatahan can be seen as the impulsive, short-duration signals with peak acoustic energy in the range of 3-40 Hz. The peak in seismicity observed on the hydrophone occurs some 8-12 hours before eruption activity was observed on seismic or satellite observing systems.

the small magnitude seismicity associated with the 10 May eruption. This seems to be the case since seismicity detected by a broadband IRIS/PASSCAL seismograph installed on Anatahan just 4 days prior to the eruption (Wiens et al., 2004) was also detected by the hydrophone despite the hydrophone being ~300 km from the volcano. The seismograph recorded no signs that an eruption was imminent. The hydrophone does record infrequent seismicity in the days preceding the eruption. Since it is, however, not possible to locate earthquakes nor derive a back-azimuth to the earthquake signal source with this one hydrophone, the origin of the hydrophone recorded seismicity preceding the eruption remains ambiguous.

A total of 458 earthquakes were recorded on the hydrophone during the eruption. The hydrophone records show the same general increase in seismicity leading up to the eruption as recorded by the broadband seismometer, as well as a clear record of the first large event at 0236Z and the increase of seismicity at 0620Z (Wiens et al., 2004). Strangely, the hydrophone seems to record significantly more earthquakes than the seismometer on Anatahan Island that again could be a result of the efficient seismic to acoustic conversion.

5. Volcanic Tremor

A broadband, continuous tremor-like energy accompanies the onset of increased seismicity at 0620Z on 10 May during the Anatahan eruption. Intrusion tremor observed at Krafla Volcano in Iceland is very similar to the tremor observed here, with a broad spectrum and predominant frequencies >3 Hz [Brandsdottir and Einarsson, 1992]. Intrusions of magma dikes at Krafla generally are accompanied by tremor mixed with swarms of small earthquakes. Intrusion tremor and earthquakes usually stop when the magma reaches the surface and the dike stops propagating. There is clear broadband energy present on the hydrophone from 3 Hz up to at least 30 Hz (Fig. 3)

6. Seismo-Acoustic Wave Field Modeling

A model representation of the seismo-acoustic wave field provides a natural framework for modeling *T*-waves, and makes clear well known features of the *T*-wave signal packet such as the generally weak dispersion and the concentration of energy near the sound channel axis as well as providing insights into the *T*-wave source mechanisms. We present a model of the volcanogenic seismicity recorded on the hydrophone from Anatahan based on previously developed models of mode scattering (Park and Odom, 1999) and seismo-acoustic excitation mechanisms (Park et al., 2001).

7. Conclusion

An autonomous hydrophone moored in the sound channel ~300 km from Anatahan Island clearly recorded the seismicity and tremor associated with the 10 May 2003 explosive eruption. Increased earthquake activity is observed on the hydrophone beginning at ~0630Z on 10 May, roughly 8 and 12 hrs before the eruption was detected on seismograph and satellite monitoring systems, respectively. Approximately 458 earthquakes were detected on the hydrophone during the onset of the eruption at Anatahan Volcano.

The earthquakes are accompanied by continuous, low-frequency (5-15 Hz) energy that is similar to volcanic (intrusion) tremor that has been observed at other oceanic volcanoes worldwide. The

Volcanogenic T-wave signals recorded by the hydrophone are best modeled with a buried magma pipe source mechanism using mode scattering theory.

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References

Brandsdottir, B and P. Einarsson. Volcanic tremor and low-frequency earthquakes in Iceland, in *IAVCEI Proceedings in Volcanology*, P. Gasparini, R. Scarpa, and K. Aki, Eds., Springer-Verlag, Berlin, Germany, 212-222, 1992.

Bulletin of the Global Volcanism Network, v:28, 5, May 2003.

Davis, T.M., K.A. Countryman, and M.J. Carron, Tailored acoustic products utilizing the NAVOCEANO GDEM (a generalized digital environmental model), in *Proceedings, 36th Naval Symposium on Underwater Acoustics*, Naval Ocean Systems Center, San Diego, CA, 1986.

Dziak, R.P., D. R. Bohnenstiehl, H. Matsumoto, C. G. Fox, D. K. Smith, M. Tolstoy, T-K Lau, J. H. Haxel, and M. J. Fowler, P- and T-wave detection thresholds, Pn velocity estimate, and detection of lower mantle and core P-waves on ocean sound-channel hydrophones at the Mid-Atlantic Ridge, *Bull. Seism. Soc. Am.*, in press, 2004.

Fox, C. G., R. P. Dziak, H. Matsumoto and A. E. Schreiner, Potential for monitoring low-level seismicity on the Juan de Fuca Ridge using military hydrophone arrays, *Mar. Tech. Soc. J.*, 27(4), 22-30, 1994.

Park, M. and R. Odom, 1999, The effect of stochastic rough interfaces on coupled-mode elastic waves. *Geophys. J. Int.*, 136, 123-143.

Park, M., R. Odom, and D.J. Soukup, 2001, Modal scattering: a key to understanding oceanic T-waves. *Geophys. Res. Lett.*, 28(17), 3401-3404.

Talandier, J., and E.A. Okal. On the mechanism of conversion of seismic waves to and from T-waves in the vicinity of island shores. Bull Seism. Soc. Am., 88, 621, 1998.

Wiens, D.A., P.J. Shore, A. Sauter, D.R. Hilton, T. Fisher, J.T. Camacho, Observing the historic eruption of northern Mariana Islands volcano, Eos Transactions, America Geophysical Union, 85, No. 1, 2-4, 6 January, 2004.