Downloaded from geology.gsapubs.org on November 5, 2012

Geology

Submarine landslide triggered by volcanic eruption recorded by in situ hydrophone

W.W. Chadwick, Jr, R.P. Dziak, J.H. Haxel, R.W. Embley and H. Matsumoto

Geology 2012;40;51-54
doi: 10.1130/G32495.1

Email alerting services click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe click www.gsapubs.org/subscriptions/ to subscribe to Geology

Permission request click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

© 2012 Geological Society of America

THE
GEOLOGICAL
SOCIETY
OF AMERICA

Submarine landslide triggered by volcanic eruption recorded by in situ hydrophone

W.W. Chadwick, Jr.[1]*, R.P. Dziak[1], J.H. Haxel[1], R.W. Embley[2], and H. Matsumoto[1]
[1]Hatfield Marine Science Center, Oregon State University, Newport, Oregon 97365, USA
[2]Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Newport, Oregon 97365, USA

ABSTRACT

NW Rota-1 is a submarine volcano in the Mariana volcanic arc that is notable as the site where underwater explosive eruptions were first witnessed in A.D. 2004. After years of continuous low-level eruptive activity, a major landslide occurred at NW Rota-1 in August 2009, triggered by an unusually large eruption that produced 10 times the acoustic energy of the background level of activity. An anomalous earthquake swarm preceded the eruption, suggesting that the sequence started with a magmatic intrusion and associated faulting beneath the volcano. We quantify the size and extent of the landslide using bathymetric resurveys and interpret the timing of events using data from an in situ hydrophone. This is the first instrumental documentation of an earthquake-eruption-landslide sequence at a submarine volcano, and illustrates the close interaction between magmatic activity and mass wasting events in the growth of undersea arc volcanoes.

INTRODUCTION

NW Rota-1 volcano is a symmetrical cone of basaltic andesite composition with a summit depth of 517 m, located in the Mariana arc ~100 km north of Guam, and is the first site where submarine eruptions were directly observed in 2004 (Embley et al., 2006). Even more remarkable is that it has remained persistently active since, a conclusion supported by nearly annual visits with remotely operated vehicles (Embley et al., 2007; Chadwick et al., 2008a, 2009, 2010) and two years of continuous hydrophone monitoring at the volcano between 2008 and 2010 (Dziak et al., 2009).

Dive observations since 2004 have shown that the volcano's nearly continuous Strombolian eruptive activity is characterized by explosive bursts with a low mass eruption rate every few minutes, bursts that are primarily driven by magmatic gases (Chadwick et al., 2008a). The eruptive vent is located just south of the summit on a steep and unstable south-facing slope, which leads to cyclic buildup and collapse of fragmental lava and pyroclasts over the vent (Deardorff et al., 2011). Deep ash-laden turbidity plumes were found repeatedly above the lower flanks of the volcano, apparently formed by these frequent small collapse events (Walker et al., 2008). However, the landslide that occurred in 2009 was at least an order of magnitude larger than these earlier events.

LANDSLIDE

We have quantified the cumulative impact of both constructional and destructive processes over time at NW Rota-1 by repeated mapping of the volcano with multibeam sonar following the methods of Chadwick et al. (2008b). Depth changes between bathymetric surveys collected in February 2003 and April 2009 (before the landslide) show the cumulative deposition from the low-level Strombolian eruptions at the summit and remobilization of that material downslope (Fig. 1A). Over this 6 yr period, the thickness of these deposits was as much as 47 m, they extended downslope 4 km from the vent to

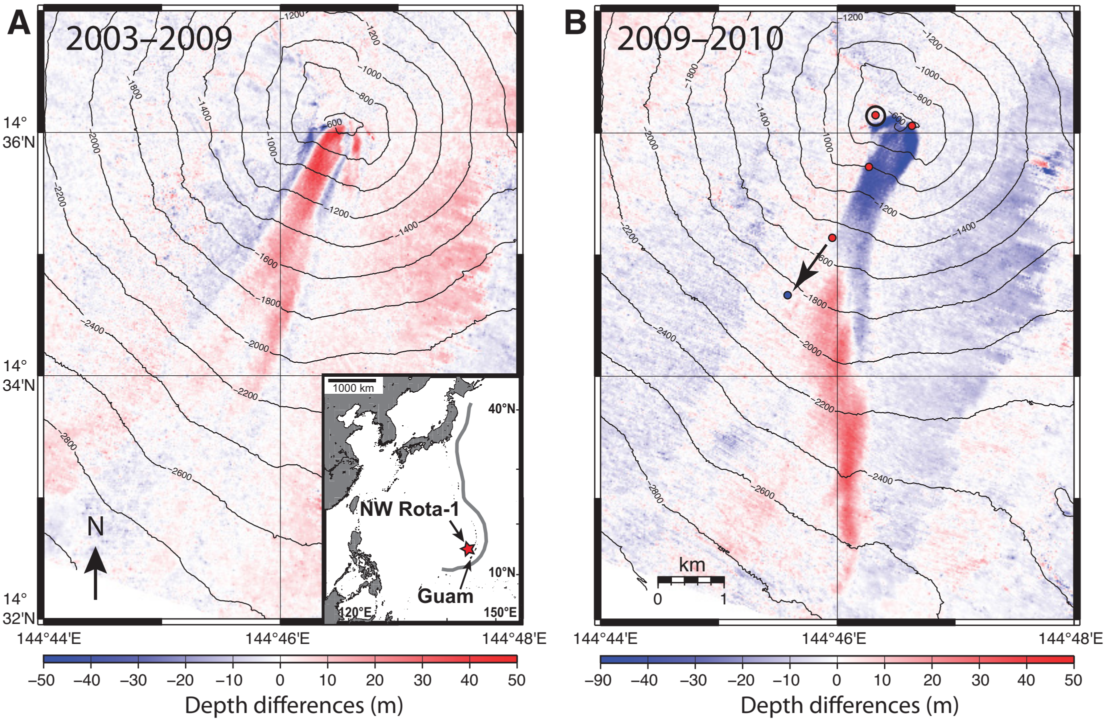

Figure 1. Maps of NW Rota-1 volcano showing depth changes between bathymetric surveys (inset shows location). A: February 2003–April 2009, during a period of volcanic construction (both surveys collected with R/V *Thompson*'s EM300 multibeam sonar). B: April 2009–March 2010, including the landslide in August 2009 (the March 2010 survey used R/V *Kilo Moana*'s EM122 sonar system). Red areas are positive depth changes (material deposited), and blue colors show negative depth changes (material removed). Areas of small apparent depth changes outside center of map are artifacts and are omitted from volume calculations. Red dots in B show locations of instrument moorings deployed in April 2009. Landslide destroyed three of the four moorings and only the hydrophone survived (circle); the acoustic release of the deepest mooring moved 1 km downslope (blue dot). Depth contours are at 200 m spacing.

---

*E-mail: bill.chadwick@noaa.gov.

Geology, January 2012; v. 40; no. 1; p. 51–54; doi:10.1130/G32495.1; 3 figures.

depths of at least 2200 m, and their cumulative volume was 34×10^6 m^3.

To investigate how these small collapse events were related to eruptive activity, we deployed four instrumental moorings in early 2009 to monitor the volcano's activity over the next year (Fig. 1B). These included a hydrophone and a fluid sampler moored above the summit, and two moorings with turbidity, temperature, and current sensors located downslope of the eruptive vent. However, when we returned in March 2010, we discovered that a major landslide had occurred and three of the four moorings had been destroyed. Of those three, the only thing that survived was the acoustic release from the deepest mooring, which had been moved 1 km downslope and was buried in sediment (Fig. 1B). Only the hydrophone mooring survived, because it was located above the slide headwall.

The size and extent of the landslide are revealed by depth changes between bathymetric surveys in April 2009 and March 2010 (Fig. 1B). The landslide removed material from the summit and upper slope to a distance of 3.5 km from the summit and deposited it on the lower flanks of the volcano, out to a distance of 8 km and to depths of at least 2800 m. The maximum negative depth change was –90 m near the slide headwall where the former summit ridge retreated ~100 m northward. The maximum thickness of the slide deposit is 42 m and its volume is 53×10^6 m^3. Figure 1 shows that the zone where material accumulated before the slide is similar to the area where material was removed during the 2009 landslide, although the volume removed is 50% larger.

We can put the NW Rota-1 landslide into context by comparing it with others documented at Monowai, another persistently active submarine volcano in the Kermadec volcanic arc. Repeated mapping there documented two major landslides over a 9 yr period (Chadwick et al., 2008b; Wright et al., 2008). The thicknesses and volumes of the landslides at Monowai (48–70 m and 40–85 × 10^6 m^3) are very similar to those from NW Rota-1, suggesting that this size of event may be typical at young active submarine arc volcanoes. This conclusion is supported by analogue experiments conducted to investigate the modes of sector collapse on volcanoes, showing that shallow, narrow collapses are a common mode of failure from fragmental loading at the summit of steep-sided cones (Acocella, 2005). Thus, this type of event may be characteristic of how pyroclastic materials that are deposited by submarine eruptions are periodically redistributed to the lower flanks of the volcano. This also suggests that the rates of eruptive output and collapse events at submarine arc volcanoes are intimately linked.

TRIGGERING ERUPTION

The in situ hydrophone that survived the landslide at NW Rota-1 recorded the event, and thus provides detailed information about its character and timing. The acoustic record between February 2009 and March 2010 shows that the cyclic, low-level Strombolian eruptive activity that had been seen previously at the volcano (Chadwick et al., 2008a, 2009, 2010; Dziak et al., 2009) was more or less continuous throughout the year (vertical stripes in Fig. 2A). However, an unusually large signal in mid-August that lasted for nearly 4 days stands out in the record (Fig. 2B); this broadband signal starts with an abrupt onset at 23:25 on 12 August (all Greenwich Mean Time), gradually builds in amplitude over the first 12 h, and continues until 18:30 on 16 August, when it ends with a rapid decrease in amplitude over 2–3 h. The 4 day signal is remarkably continuous and sustained with the highest energy density at frequencies below 10 Hz and peak amplitudes >155 dB (relative to, re 1 μPa^2/Hz) below 1 Hz (50 dB above ambient in Fig. 2D). Embedded in the middle of this 4 day signal are two distinct pulses of even larger amplitude, each lasting 2–4 h over a 10 h period between 10:27 and 20:10 on 14 August. These pulses are distinguished by their unusually high amplitudes (>200 dB) at very low frequencies (>0.5 Hz) (Fig. 2C).

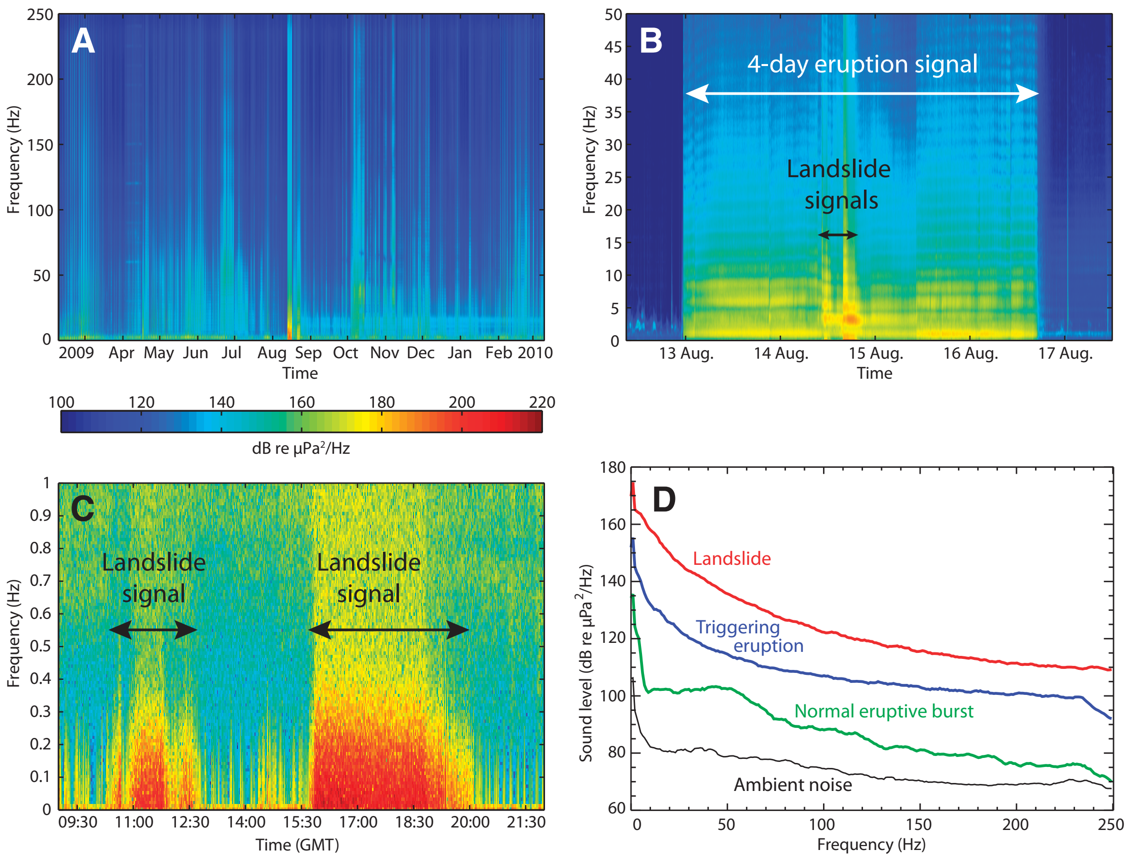

Figure 2. Data from in situ hydrophone at NW Rota-1. A: A year-long spectrogram showing sound amplitude (colors) in decibels (relative to, re μPa^2/Hz) as function of frequency versus time, from February 2009 to March 2010. Vertical stripes are more or less continuous low-level Strombolian eruptive activity. Note the unusually large signal in middle of record (expanded in B). B: Detail of large acoustic signal in August 2009, interpreted as unusually large eruption lasting nearly 4 days, that triggered the landslide (high-amplitude pulses near the center of record, expanded in C). C: Detail of landslide pulses showing unusually large amplitudes at frequencies <1 Hz. D: Frequency power spectral density curves comparing relative amplitudes of various acoustic signals in decibels. Each curve is ~20 dB (or roughly 10 times) louder than the one below. All plots corrected for instrument response, but not for distance from vent (~400 m for all curves).

We interpret that the large 4 day signal was an intense continuous explosive eruption, and the higher amplitude pulses in the middle of this signal represent the landslide. The abrupt start and end of the 4 day signal and its broadband frequency content are similar to the normal low-level Strombolian bursts observed in previous years (Chadwick et al., 2008a, 2009, 2010; Dziak et al., 2009), except that the signal is much longer and about an order of magnitude higher in acoustic amplitude (Fig. 2D). Physical evidence for such an eruption includes a deposit of fresh, frothy tephra with very low crystallinity (consistent with rapid rise, degassing, and explosive ejection) sampled from the summit ridge of NW Rota-1 in March 2010, an area beyond the reach of the normal low-level Strombolian bursts (Deardorff and Cashman, 2010; Deardorff et al., 2011).

The acoustic signal produced by the landslide was as much as 10 times the amplitude of the eruption signal (Fig. 2D). Its extreme low-frequency component is the most diagnostic of a landslide source, likely produced by the failure of large landslide blocks (from massive lava outcrops at the summit) and their subsequent movement and disintegration as they avalanched downslope. This low-frequency acoustic signal is especially remarkable because the preamplifier on the hydrophone is designed to strongly attenuate such signals (Fox et al., 2001). This high energy at low frequencies is similar to seismic signals observed during the December 2002 submarine landslide at Stromboli volcano, Italy (La Rocca et al., 2004; Pino et al., 2004), and smaller submarine collapses documented on Kilauea Volcano, Hawaii (Caplan-Auerbach et al., 2001). The durations of the landslide signals at NW Rota-1 (minutes to hours) are also consistent with the recordings at Stromboli and Kilauea (Caplan-Auerbach et al., 2001; La Rocca et al., 2004). However, the multiple pulses and their long overall duration indicate that the NW Rota-1 landslide was not a single event, but instead involved an extended sequence of retrogressive failures.

Knowing the time that the landslide occurred on 14 August 2009, we have looked for any associated tsunami signals in tide gauge data from the island of Guam (a distance of 129 km), and from nearby tsunami buoys (at distances of 800–1400 km; Meinig et al., 2005), but no unusual waves were detected. In contrast, the 2002 landslide at Stromboli generated a destructive tsunami, even though its volume (10–20 × 10^6 m^3) was less than half that of the landslide at NW Rota-1. This is apparently because the slide at Stromboli initiated at very shallow depths (0–350 m) on the flank of the island, and was more impulsive, with a duration of only 20 min (Bonaccorso et al., 2003; La Rocca et al., 2004; Chiocci et al., 2008). Landslide-generated tsunamis tend to have limited far-field effects since they have relatively small source areas, faster radial dissipation, and may take place as multiple failures over time instead of single large events (Okal and Synolakis, 2004; Masson et al., 2006).

These eruption and landslide signals were by far the largest acoustic events recorded during the two years of continuous hydrophone monitoring at NW Rota-1 (Dziak et al., 2009). The timing of the two signals strongly suggests that the eruption triggered the landslide, probably from the rapid deposition and oversteepening of pyroclastic debris on the unstable and already heavily loaded upper south slope of the volcano.

PRE-ERUPTION EARTHQUAKE SWARM

An unusually large sequence of earthquakes was detected near NW Rota-1 volcano by the global seismic network (International Seismological Centre, 2011) starting on 17 April 2009 (Fig. 3A). This swarm consisted of 58 events in 4 days (53 within the first 24 h) all with similar magnitudes ranging from m_b 3.3 to 4.5 and at depths of 0–40 km (International Seismological Centre, 2011), much shallower than typical for this location over the Mariana subduction zone (commonly >150 km; Stern et al., 2003). The temporal clustering of these events was also highly unusual as it was the highest monthly total of earthquakes in the vicinity of NW Rota-1 since at least 2003 (58 versus <10; International Seismological Centre, 2011). Over the next 4 months, 11 more globally detected earthquakes (m_b 3.6–4.5) occurred, the last on 5 August, just a week before the eruption and landslide. These characteristics, and the fact that the swarm did not follow a mainshock-aftershock pattern (Fig. 3B), suggest that the earthquakes were likely caused by magmatic intrusion rather than tectonic faulting.

The earthquake swarm at NW Rota-1 was also recorded by the in situ hydrophone moored at the summit of the volcano; the hydrophone detected ~10 times as many events (Fig. 3B). Acoustic T waves from local earthquakes are easily distinguished from eruption sounds and distant regional earthquakes by their impulsive onsets, short durations, rapid signal decay rate, and higher frequency content (Dziak and Fox, 1999; Bohnenstiehl et al., 2002). The hydrophone recorded more than 513 local earthquakes between 15 and 21 April; the peak event rate was 36/h on 17 April (Fig. 3B). During this peak, a continuous broadband acoustic signal (<50 Hz) appeared in the record and lasted for ~24 h; we interpret that the signal was produced by a high rate of small earthquakes, too numerous to be picked out as discrete events. Similar continuous low-level broadband seismoacoustic energy has been observed during other magmatic intrusions in volcanic settings (Brandsdottir and Einarsson, 1979; Dziak and Fox, 1999). The mean location of the earthquake epicenters is ~25 km northwest of NW Rota-1 (International Seismological Centre, 2011) (Fig. 3A). A similar earthquake swarm occurred near NW Rota-1 in 1997 that consisted of 64 events with magnitudes of m_b 3.7–4.9, ~64% of which occurred within the first two days, also interpreted as having a magmatic source (Heeszel et al., 2008).

The interpretation that the 2009 earthquakes were caused by magmatic intrusion centered on or near the volcano is also consistent with the fact that at least one of the earthquakes had a highly non-double-couple focal mechanism (Shuler et al., 2010) (Fig. 3A), similar to some earthquakes documented at other active volcanoes (Ekström, 1994; Shuler and Ekström, 2009). A mechanism proposed to explain such anomalous earthquakes is slip on curved ring faults due to magma withdrawal from a deep reservoir during upward intrusion (Shuler and Ekström, 2009).

CONCLUSIONS

This is the first time that an intrusion-eruption-landslide sequence of events has been doc-

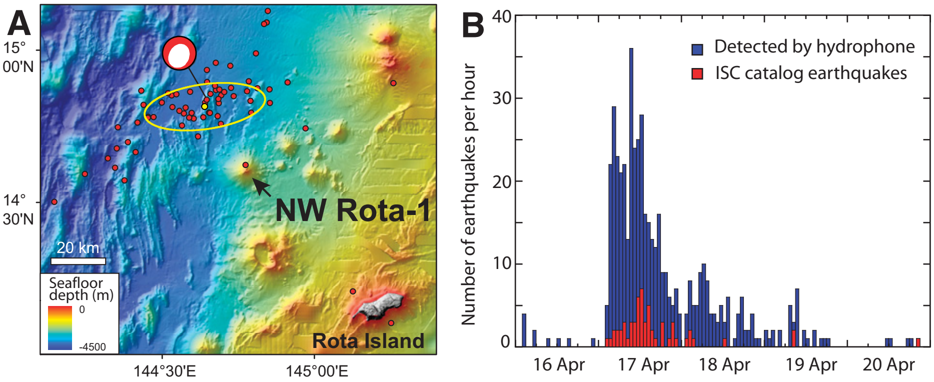

Figure 3. Pre-eruption earthquake swarm. A: Bathymetric map showing NW Rota-1 volcano and earthquake epicenters during 2009 (red dots), average swarm location and error (yellow dot and ellipse), and a non-double-couple focal mechanism from International Seismological Center (ISC) online bulletin (2011). B: Rate of earthquakes detected 16–21 April 2009 by in situ hydrophone (blue) compared to ISC data (red).

umented at a submarine volcano. The unusual swarm of earthquakes that began in April 2009 was distinctly magmatic in character and was apparently caused by faulting related to magmatic intrusion beneath or near the volcano. This intrusion, in turn, led to an extraordinary eruption that started on 12 August 2009 and lasted nearly 4 days, with acoustic energy 10 times larger than typical activity at the volcano. In the middle of this eruption, a major landslide was triggered on 14 August, probably from volcanic loading. This slide moved lava and pyroclastic material that had accumulated at the summit and on the upper slopes of the volcano during the previous decade down to the lower slopes in a matter of hours, but did not create a detectable tsunami. This sequence of events clearly shows that the dynamics of eruptions and landslides are closely linked in the growth and evolution of submarine arc volcanoes.

ACKNOWLEDGMENTS

This work was funded by National Science Foundation grant OCE-0751776; additional support was provided by the National Oceanic and Atmospheric Administration's Ocean Exploration and Vents Programs. The crews of R/V *Thompson*, R/V *Kilo Moana*, and ROV *Jason* provided outstanding logistical support for this research. Susan Merle processed the multibeam sonar data in Figure 1. Discussions with Del Bohnenstiehl, Ashley Shuler, Frank Trusdell, Jim Dixon, Kanoa Koyanagi, Marie Eble, Mick Spillane, and Vasily Titov were very helpful. Reviews by Jackie Caplan-Auerbach, Maya Tolstoy, and an anonymous reviewer improved the manuscript. This is Pacific Marine Environmental Laboratory contribution 3716.

REFERENCES CITED

Acocella, V., 2005, Modes of sector collapse of volcanic cones: Insights from analogue experiments: Journal of Geophysical Research, v. 110, B02205, doi:10.1029/2004JB003166.

Bohnenstiehl, D.R., Tolstoy, M., Dziak, R.P., Fox, C.G., and Smith, D.K., 2002, Aftershocks in the mid-ocean ridge environment: An analysis using hydroacoustic data: Tectonophysics, v. 354, p. 49–70, doi:10.1016/S0040-1951(02)00289-5.

Bonaccorso, A., Calvari, S., Garfì, G., Lodato, L., and Patanè, D., 2003, Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations: Geophysical Research Letters, v. 30, 1941, doi:10.1029/2003GL017702.

Brandsdottir, B., and Einarsson, P., 1979, Seismic activity associated with the September 1977 deflation of the Krafla central volcano in northeastern Iceland: Journal of Volcanology and Geothermal Research, v. 6, p. 197–212, doi:10.1016/0377-0273(79)90001-5.

Caplan-Auerbach, J., Fox, C.G., and Duennebier, F.K., 2001, Hydroacoustic detection of submarine landslides on Kilauea Volcano: Geophysical Research Letters, v. 28, p. 1811–1813, doi:10.1029/2000GL012545.

Chadwick, W.W., Jr., Cashman, K.V., Embley, R.W., Matsumoto, H., Dziak, R.P., de Ronde, C.E.J., Lau, T.-K., Deardorff, N., and Merle, S.G., 2008a, Direct video and hydrophone observations of submarine explosive eruptions at NW Rota-1 Volcano, Mariana Arc: Journal of Geophysical Research, v. 113, B08S10, doi:10.1029/2007JB005215.

Chadwick, W.W., Jr., Wright, I.C., Schwarz-Schampera, U., Hyvernaud, O., Reymond, D., and De Ronde, C.E.J., 2008b, Cyclic eruptions and sector collapses at Monowai submarine volcano, Kermadec arc: 1998–2007: Geochemistry Geophysics Geosystems, v. 9, Q10014, doi:10.1029/2008GC002113.

Chadwick, W.W., Jr., and 14 others, 2009, Continuous, long-term, cyclic, varied eruptive activity observed at NW Rota-1 submarine volcano, Mariana Arc: Eos (Transactions, American Geophysical Union), v. 90, abs. V44B–03.

Chadwick, W.W., Jr., Dziak, R.P., Embley, R.W., Tunnicliffe, V., Sherrin, J., Cashman, K.V., and Deardorff, N., 2010, Submarine landslide triggered by eruption recorded by in-situ hydrophone at NW Rota-1 submarine volcano, Mariana Arc: American Geophysical Union, 2010 Fall Meeting, San Francisco, California, abs. T11E–06.

Chiocci, F.L., Romagnoli, C., Tommasi, P., and Bosman, A., 2008, The Stromboli 2002 tsunamigenic submarine slide: Characteristics and possible failure mechanism: Journal of Geophysical Research, v. 113, B10102, doi:10.1029/2007JB005172.

Deardorff, N., and Cashman, K.V., 2010, Post-eruptive magma mixing: Recycling in volcanic vents: American Geophysical Union, 2010 Fall Meeting, San Francisco, California, abs. V43C–2391.

Deardorff, N.D., Cashman, K.V., and Chadwick, W.W., Jr., 2011, Observations of eruptive plumes and pyroclastic deposits from submarine explosive eruptions at NW Rota-1, Mariana Arc: Journal of Volcanology and Geothermal Research, v. 202, p. 47–59, doi:10.1016/j.jvolgeores.2011.01.003.

Dziak, R.P., and Fox, C.G., 1999, The January 1998 earthquake swarm at Axial Volcano, Juan de Fuca Ridge: Hydroacoustic evidence of seafloor volcanic activity: Geophysical Research Letters, v. 26, p. 3429–3432, doi:10.1029/1999GL002332.

Dziak, R.P., Embley, R.W., Baker, E.T., Chadwick, W.W., Jr., Resing, J.A., Matsumoto, H., Haxel, J.H., Walker, S.L., and Bohnenstiehl, D.R., 2009, Long-term explosion records from two erupting submarine volcanoes in the Mariana and Tonga island-arcs: Eos (Transactions, American Geophysical Union), v. 90, abs.V44B–02.

Ekström, G., 1994, Anomalous earthquakes on volcano ring-fault structures: Earth and Planetary Science Letters, v. 128, p. 707–712, doi:10.1016/0012-821X(94)90184-8.

Embley, R.W., and 16 others, 2006, Long-term eruptive activity at a submarine arc volcano: Nature, v. 441, p. 494–497, doi:10.1038/nature04762.

Embley, R.W., Baker, E.T., Butterfield, D.A., Chadwick, W.W., Jr., Lupton, J.E., Resing, J.A., De Ronde, C.E.J., Nakamura, K., Tunnicliffe, V., Dower, J., and Merle, S.G., 2007, Exploring the submarine ring of fire: Mariana Arc–Western Pacific: Oceanography, v. 20, p. 69–80.

Fox, C.G., Matsumoto, H., and Lau, T.-K.A., 2001, Monitoring Pacific Ocean seismicity from an autonomous hydrophone array: Journal of Geophysical Research, v. 106, p. 4183–4206, doi:10.1029/2000JB900404.

Heeszel, D.S., Wiens, D.A., Shore, P.J., Shiobara, H., and Sugioka, H., 2008, Earthquake evidence for along-arc extension in the Mariana Islands: Geochemistry Geophysics Geosystems, v. 9, Q12X03, doi:10.1029/2008GC002186.

International Seismological Centre, 2011, On-Line Bulletin: Thatcham, U.K., International Seismological Centre, http://www.isc.ac.uk (accessed April 2011).

La Rocca, M., Galluzzo, D., Saccorotti, G., Tinti, S., Cimini, G.B., and Del Pezzo, E., 2004, Seismic signals associated with landslides and with a tsunami at Stromboli Volcano, Italy: Seismological Society of America Bulletin, v. 94, p. 1850–1867, doi:10.1785/012003238.

Masson, D.G., Harbitz, C.B., Wynn, R.B., Pedersen, G., and Lovholt, F., 2006, Submarine landslides: Processes, triggers, and hazard prediction: Royal Society of London Philosophical Transactions, ser. A, v. 364, p. 2009–2039, doi:10.1098/rsta.2006.1810.

Meinig, C., Stalin, S.E., Nakamura, A.I., González, F., and Milburn, H.B., 2005, Technology developments in real-time tsunami measuring, monitoring and forecasting: Oceans, 2005: Proceedings of MTS/IEEE, v. 2, p. 1673–1679, doi:10.1109/OCEANS.2005.1639996.

Okal, E.A., and Synolakis, C.E., 2004, Source discriminants for near-field tsunamis: Geophysical Journal International, v. 158, p. 899–912, doi:10.1111/j.1365-246X.2004.02347.x.

Pino, N.A., Ripepe, M., and Cimini, G.B., 2004, The Stromboli Volcano landslides of December 2002: A seismological description: Geophysical Research Letters, v. 31, L02605, doi:10.1029/2003GL018385.

Shuler, A., and Ekström, G., 2009, Anomalous earthquakes associated with Nyiragongo Volcano: Observations and potential mechanisms: Journal of Volcanology and Geothermal Research, v. 181, p. 219–230, doi:10.1016/j.jvolgeores.2009.01.011.

Shuler, A.E., Ekström, G., and Nettles, M., 2010, Global observation of vertical-CLVD earthquakes associated with active volcanoes: American Geophysical Union 2010 Fall Meeting, San Francisco, California, abs. V32B–07.

Stern, R.J., Fouch, M.J., and Klemperer, S.L., 2003, An overview of the Izu-Bonin-Mariana subduction factory, *in* Eiler, J., ed., Inside the subduction factory: American Geophysical Union Geophysical Monograph 138, p. 175–222, doi:10.1029/138GM10.

Walker, S.L., Baker, E.T., Resing, J.A., Chadwick, W.W., Jr., Lebon, G.T., Lupton, J.E., and Merle, S.G., 2008, Eruption-fed particle plumes and volcaniclastic deposits at a submarine volcano: NW-Rota-1, Mariana Arc: Journal of Geophysical Research, v. 113, B08S11, doi:10.1029/2007JB005441.

Wright, I.C., Chadwick, W.W., Jr., De Ronde, C.E.J., Reymond, D., Hyvernaud, O., Gennerich, H.-H., Stoffers, P., Mackay, K., Dunkin, M., and Bannister, S.C., 2008, Collapse and reconstruction of Monowai submarine volcano, Kermadec arc, 1998–2004: Journal of Geophysical Research, v. 113, B08S03, doi:10.1029/2007JB005138.

Manuscript received 25 May 2011
Revised manuscript received 18 August 2011
Manuscript accepted 23 August 2011

Printed in USA