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A Tale of Two Eruptions

HOW DATA FROM AXIAL SEAMOUNT LED TO A DISCOVERY ON THE EAST PACIFIC RISE

By Maya Tolstoy, William S.D. Wilcock, Yen Joe Tan, and Felix Waldhauser

ABSTRACT. Mid-ocean ridge volcanism generates two-thirds of the surface of our planet and plays an important role in chemical exchange with the overlying ocean, yet little is known about the dynamic processes involved in mid-ocean ridge eruptions. This is largely due to the costs and challenges of deploying long-term instrumentation on the seafloor, particularly those that transmit data to shore in real time and would allow the scientific community to respond to and coalesce around a particular event. The 2015 eruption at Axial Seamount, which lies along the Juan de Fuca Ridge in the Northeast Pacific Ocean, resulted in the first in situ, real-time geophysical data collected during a mid-ocean ridge eruption. The results provided insights into the caldera fault structure and response to a seafloor-spreading episode, and also confirmed the origin of seismically recorded impulsive signals that are associated with fresh lava erupting onto the seafloor. This confirmation of a seismic signal associated with erupting lava led to revisiting data from an eruption almost a decade earlier and a fundamental new view of seafloor spreading at fast-spreading ridges thousands of kilometers from Axial Seamount. This example illustrates the point that even though cabled observatories are necessarily bound to a specific location, their results can have significant implications for understanding systems that are quite different, in far reaches of the globe.

Fresh lava from a 2006 East Pacific Rise eruption overlying lava from an older seafloor eruption. *Photo credit: Dan Fornari/Woods Hole Oceanographic Institution/NSF*

Real-time, open-access geophysical data collected from the deep-sea floor have long held great promise for understanding dynamic seafloor processes, in particular, mid-ocean ridge eruptions. The benefits of streaming data live to the science community include the ability to respond quickly to events of interest, the ability to monitor instrument status, and the collective engagement of the interested community. While the benefits of having access to real-time data are obvious to scientists studying a particular site, it is perhaps less obvious how these data can also benefit understanding of seafloor processes far away in analogous settings.

In April 2015, a seafloor eruption at Axial Seamount was captured live on geophysical instruments attached to the Ocean Observatories Initiative (OOI) Cabled Array (Wilcock et al., 2018, in this issue, and references therein). The eruption came just months after live-streaming seismic data had become openly available, and two days after conclusion of a workshop that discussed science at Axial Seamount. Community engagement was high, as an eruption was forecast to be imminent. The ability to geophysically observe a seafloor eruption live for the first time generated substantial excitement, and different signals were discussed, analyzed, and shared rapidly through emails as new data were received. Although a formal discussion platform did not exist, the email list grew and generated a dynamic collective discussion that brought multiple perspectives to interpreting the event unfolding at Axial Seamount. This was the real-time event the community had been preparing for.

One observation of a waterborne impulsive signal was discussed at length and interpreted to be associated with lava erupting onto the seafloor (Wilcock et al., 2016). Such signals had previously been hypothesized as being associated with seafloor eruptions (e.g., Caplan-Auerbach and Duennebier, 2001; Schlindwein and Riedel, 2010), but not clearly demonstrated as such in the field. The timing of the multiple water bounce arrivals (Figure 1) on multiple instruments allowed rapid estimation of the source locations. Initial locations were soon confirmed to be associated with new lava flows (Chadwick et al., 2016). The exact cause of these signals is yet to be determined (Tan et al., 2016; Wilcock et al., 2016), but they could be related to steam explosions (Perfit et al. 2003; Chadwick et al., 2016), pillow implosions or degassing (Caplan-Auerbach and Duennebier, 2001; Schlindwein and Riedel, 2010), other lava-seawater interactions, or a mix of causes (Figure 2). Regardless of the cause, these signals provide a newly ground truthed way to establish the timing of lava reaching the seafloor, a critical factor in understanding eruption dynamics.

As a result of this observation, data from the only previous in situ seismically observed seafloor eruption, at 9°50'N on the East Pacific Rise (Tolstoy et al., 2006), were revisited. These data were limited to three ocean bottom seismometers, in part because two-thirds of the original array was buried in the lava flow. However, a number of the recovered instruments also had hard drive issues unrelated to the eruption that were not known until after recovery, illustrating another important limitation of non-real-time data. Therefore, analysis of available earthquake data was quite limited. The eruption period was dominated by many small impulsive seismic events that were not consistent with earthquake travel times between instruments, and thus were thought to perhaps be isolated small events happening very near individual instruments.

On reexamining the East Pacific Rise data, it was clear these signals were not small local earthquakes, but instead impulsive signals similar to those observed during Axial Seamount's eruption. When these waterborne arrivals were revisited, their locations correlated remarkably well with the previously mapped lava flows (Soule et al., 2007; Tan et al., 2016), addressing a long-standing debate about the timing of that eruption, and providing a whole new insight into how mid-ocean ridges erupt. The results showed that the majority of the lava erupted within a matter of days in January 2006; flows could even be tracked moving down the flanks of the ridge axis. Most interesting was the timing of the eruption with respect to the largest earthquakes, which suggested that the East Pacific Rise erupted largely in response to the rupture of the plate rather than in response to buildup of magma pressure (Tan et al., 2016). This is in contrast to what is expected at most volcanoes, where magma pressure is solely driving the seismic and eruptive activity, and different to what was observed at Axial Seamount in 2015.

Of particular note when comparing the geophysical signals leading up to and during both eruptions is the difference in timing of the magmatic tremor. At Axial Seamount, six hours of tremor (inferred to be magma movement) preceded the seismic crisis that led to the eruption (Wilcock et al., 2016). At the East Pacific

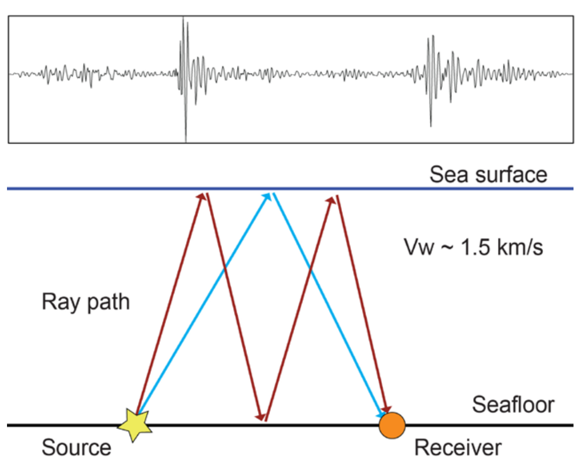

FIGURE 1. Illustration of ray paths taken by the first two arrivals of the waterborne impulsive signal observed to be associated with lava eruption, with an example waveform show at the top. The blue ray is the first arrival and the red ray is the second arrival. At Axial Seamount, more than two arrivals were often observed associated with a single event (Wilcock et al., 2016). With good knowledge of the regional water depth, the velocity of sound in water, and signal arrival times, the events could be accurately located using multiple instruments.

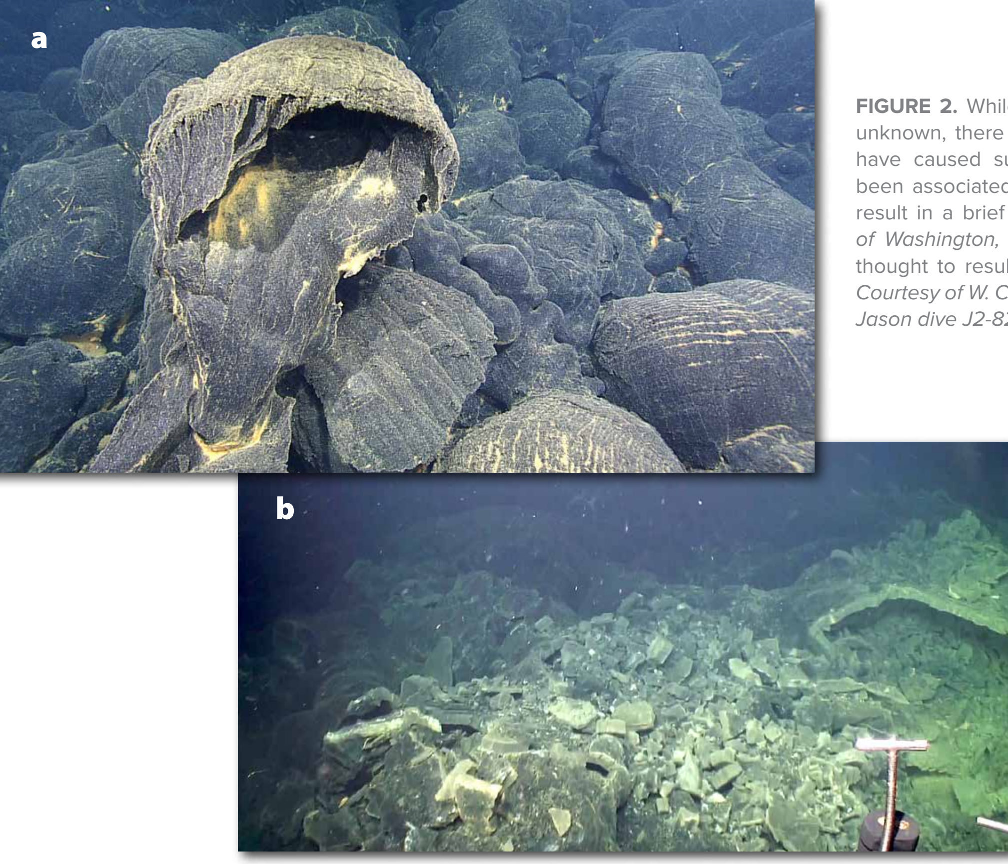

FIGURE 2. While the exact source of the impulsive signals is still unknown, there are multiple examples of lava features that might have caused such signals. (a) A drained pillow that may have been associated with degassing or other phenomenon that might result in a brief acoustic source. *Courtesy of D. Kelley, University of Washington, NSF/OOI-ROPOS dive R1863 (TN326).* (b) Rubble thought to result from a steam explosion (Chadwick et al., 2016). *Courtesy of W. Chadwick, NOAA-PMEL and Oregon State University, Jason dive J2-822 (TN327).*

Rise, however, approximately one hour of tremor (long-period events) followed the initiation of the seismic crisis. The tremor at the East Pacific Rise appeared within tens of minutes following the largest earthquakes recorded at the site in a decade (Dziak et al., 2009), and ended 36 minutes prior to lava first reaching the seafloor (Tan et al., 2016). This timing is consistent with the tremor resulting from magma response to failure of the plate boundary. This contrast in relative timing of the tremor to the seismic crisis implies that at Axial Seamount, magma pressure played a key role in the timing of the eruption, whereas at the East Pacific Rise, the buildup of tectonic stress due to plate pull led to rupture of the plate boundary. It is possible that magma pressure may also have contributed to initiation of the eruption at the East Pacific Rise, but the timing of the eruption is interpreted as largely responding to the rupture.

Comparison of the seafloor eruptions shows that they represent two end members: Axial Seamount displays classic ring-fault caldera dynamics (Wilcock et al., 2016), while the East Pacific Rise demonstrates that mid-ocean ridge eruptions can result from a "tear" in the seafloor (Tan et al., 2016). While the East Pacific Rise at 9°50'N is viewed as a "typical" fast-spreading ridge, Axial Seamount by contrast is a feature of the Cobb-Eickelberg hotspot that interacts with the intermediate-spreading Juan de Fuca Ridge. This fundamental difference between ridge-based hotspot volcanism and non-hotspot-influenced mid-ocean ridge magmatism remains to be demonstrated elsewhere and at other spreading rates. However, it provides an exciting template to test these two models, both in further eruptions at Axial Seamount and eruptions elsewhere on the deep seafloor.

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AUTHORS

Maya Tolstoy (tolstoy@ldeo.columbia.edu) is Professor, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA. **William S.D. Wilcock** is Jerome M. Paros Endowed Chair in Sensor Networks, School of Oceanography, University of Washington, Seattle, WA, USA. **Yen Joe Tan** is a graduate student and **Felix Waldhauser** is Professor, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA.

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