

THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Dziak, R.P., D.R. Bohnenstiehl, and D.K. Smith. 2012. Hydroacoustic monitoring of oceanic spreading centers: Past, present, and future. *Oceanography* 25(1):116–127, <http://dx.doi.org/10.5670/oceanog.2012.10>.

DOI

<http://dx.doi.org/10.5670/oceanog.2012.10>

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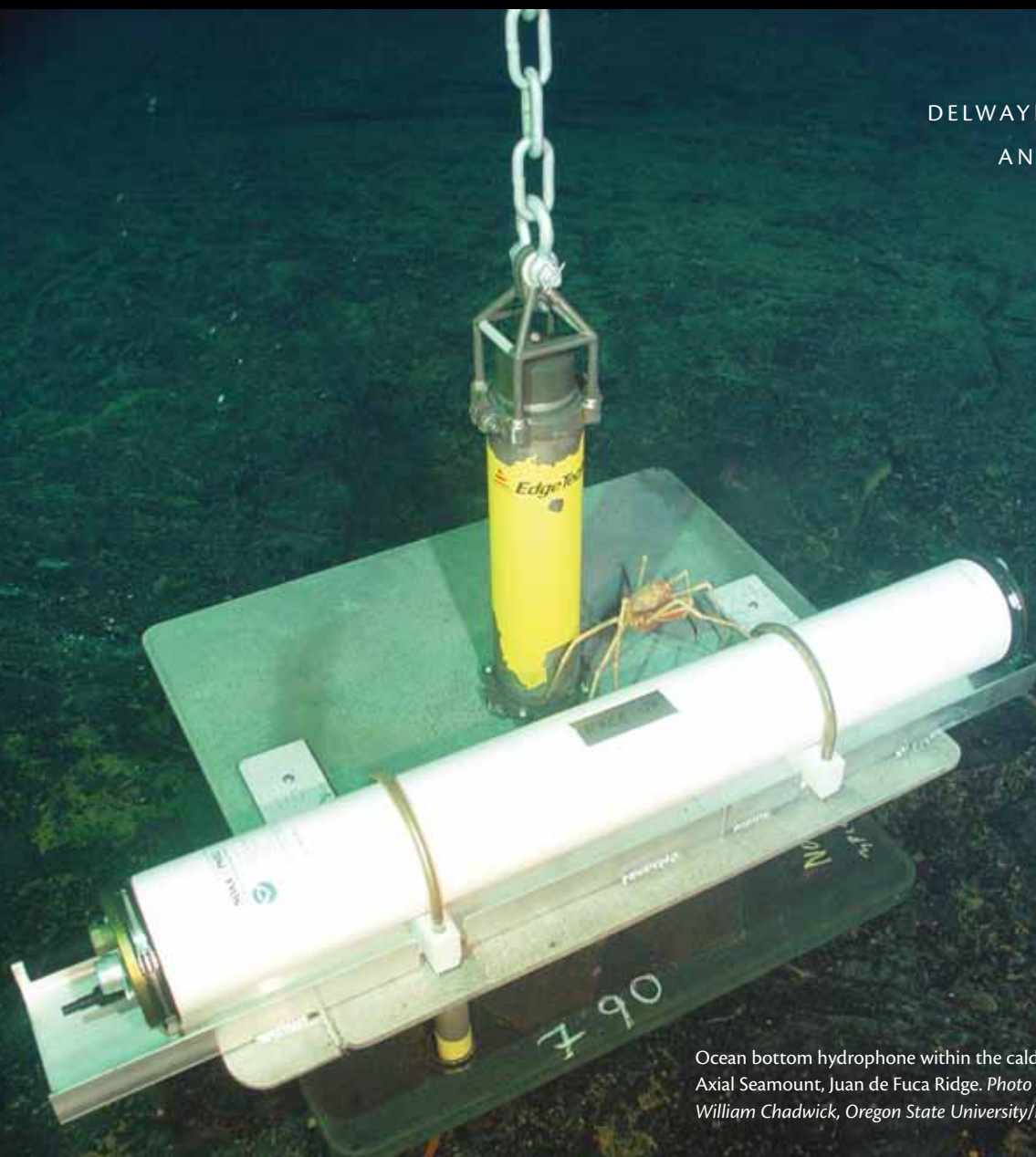
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HYDROACOUSTIC MONITORING OF OCEANIC SPREADING CENTERS

Past, Present, and Future

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Ocean bottom hydrophone within the caldera of Axial Seamount, Juan de Fuca Ridge. Photo courtesy of William Chadwick, Oregon State University/NOAA

ABSTRACT. Mid-ocean ridge volcanism and extensional faulting are the fundamental processes that lead to the creation and rifting of oceanic crust, yet these events go largely undetected in the deep ocean. Currently, the only means available to observe seafloor-spreading events in real time is via the remote detection of the seismicity generated during faulting or intrusion of magma into brittle oceanic crust. Hydrophones moored in the ocean provide an effective means for detecting these small-magnitude earthquakes, and the use of this technology during the last two decades has facilitated the real-time detection of mid-ocean ridge seafloor eruptions and confirmation of subseafloor microbial ecosystems. As technology evolves and mid-ocean ridge studies move into a new era, we anticipate an expanding network of seismo-acoustic sensors integrated into seafloor fiber-optic cabled observatories, satellite-telemetered surface buoys, and autonomous vehicle platforms.

INTRODUCTION

New seafloor is magmatically emplaced, cooled, and then faulted within the mid-ocean ridge (MOR) system, forming one of the most active and longest belts of seismicity on the planet (Figure 1). Detection of MOR magma intrusion and rifting events is critical to our understanding of the global pace of volcanism and the ephemeral physical and chemical impacts these events have on the ocean and seafloor ecosystems. MOR magmatic and tectonic activity, however, typically has no expression at the sea surface, and therefore our only means of identifying these events is via remote detection of small-magnitude (typically $M < 4$) earthquakes caused by intrusion of magma and faulting of brittle oceanic crust. One of the most effective means of detecting small-magnitude, deep-ocean seismicity is to record an earthquake's hydroacoustic phase, or "T-phase," that enters and propagates within the ocean's sound channel.

This article discusses the hydro-acoustic monitoring methods used to study mid-ocean ridges from the

first discovery of seismically generated acoustic phases in the 1920s up to the present, and speculates upon future applications of these techniques. The spreading rate of an MOR largely determines the character of seismicity it produces. Fast-spreading ridges exhibit significant magmatic activity; however, the earthquakes tend to be small and more difficult to detect regionally (Figure 1). At slow-spreading ridges, fault processes dominate, exemplified by more frequent, large-magnitude earthquakes but sporadic magmatic activity. MOR volcanism can be detected by (1) earthquakes caused from magma intrusion through oceanic crust and/or faulting resulting from the intrusion, (2) volcanic tremor produced by flow of either magma or hydrothermal fluid through oceanic crust, or (3) violent

magmatic explosions from degassing. All three volcano-acoustic sources can be useful for remote detection of volcanism on MORs because of their unique signal characteristics and because they are the loudest natural sounds recorded in the ocean.

Because of the combined dependence of ocean sound speed on pressure and temperature, much of the global ocean exhibits a low-velocity region known as the SOund Fixing And Ranging (SOFAR) channel (Figure 2). The channel's axis lies $\sim 1,000$ m below the sea surface in equatorial regions, becoming progressively shallower and then disappearing near the poles in response to the changing temperature structure of the water column. Seismically generated acoustic energy may become trapped in the SOFAR channel, where it propagates laterally in range (r) via a series of upward- and downward-turning refractions and has little interaction with the seafloor or sea surface. The attenuation due to geometric spreading is cylindrical ($\sim 1/r$) for SOFAR guided waves, making transmission significantly more efficient relative to solid Earth phases that undergo spherical spreading loss ($\sim 1/r^2$) and allowing acoustic phases to propagate thousands of kilometers with little energy loss.

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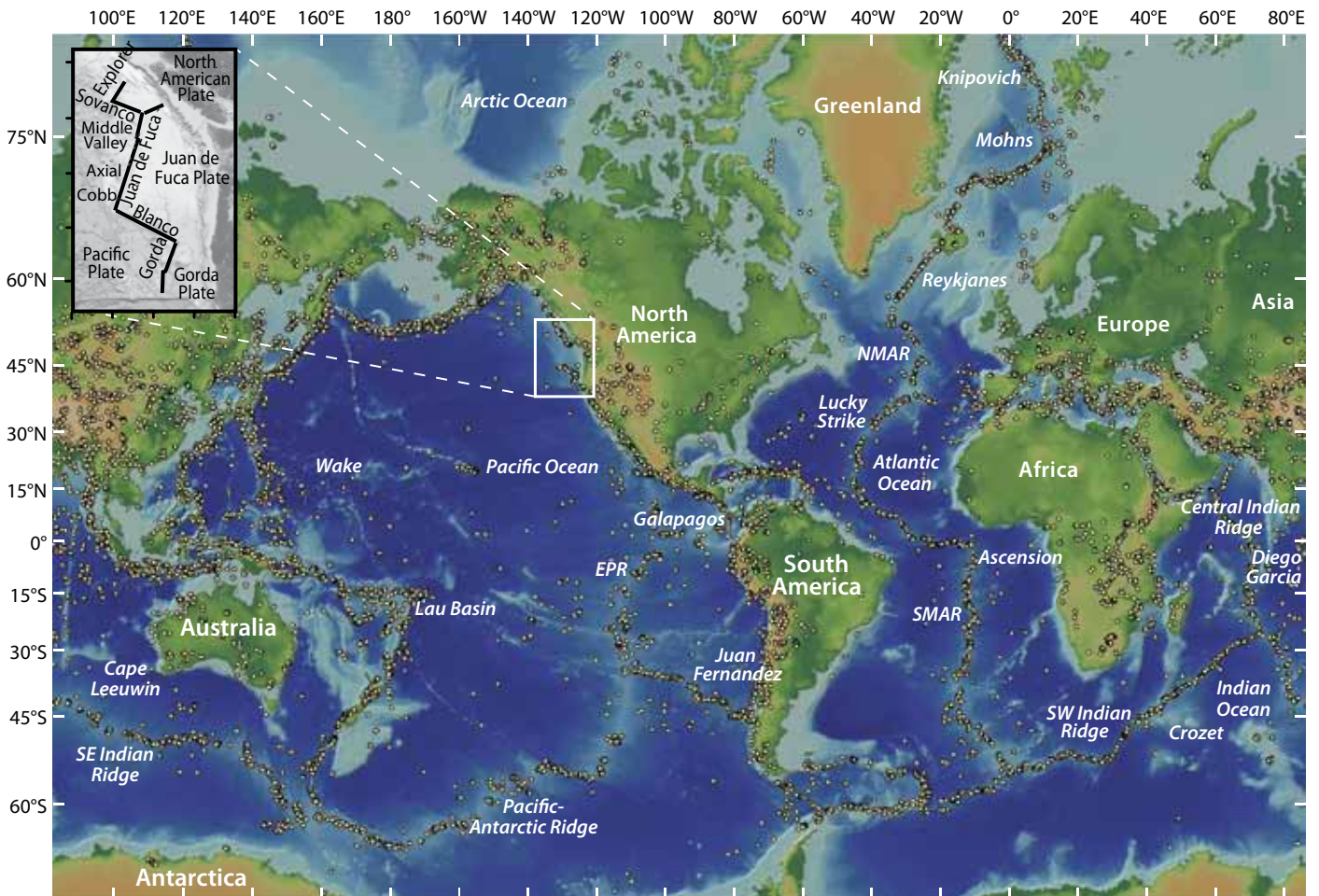


Figure 1. Global map of seismicity from the National Earthquake Information Center catalog, $M \geq 4.5$, 1976–2009. Mid-ocean ridges and oceanic transforms are defined by narrow bands of shallow hypocenter earthquakes. Spreading centers and approximate full spreading rates:

- East Pacific Rise (EPR), $\sim 110\text{--}140 \text{ mm yr}^{-1}$
- Pacific-Antarctic Ridge, 65 mm yr^{-1}
- Galápagos Spreading Center, $\sim 45\text{--}60 \text{ mm yr}^{-1}$
- Northern Mid-Atlantic Ridge (NMAR), 25 mm yr^{-1}
- Southern Mid-Atlantic Ridge (SMAR), $\sim 30 \text{ mm yr}^{-1}$
- Central Indian Ridge, $\sim 35 \text{ mm yr}^{-1}$
- Southwest Indian Ridge, $\sim 15 \text{ mm yr}^{-1}$
- Southeast Indian Ridge, $\sim 70 \text{ mm yr}^{-1}$
- Mohns Ridges, $\sim 15\text{--}20 \text{ mm yr}^{-1}$
- Reykjanes Ridge, $\sim 20 \text{ mm yr}^{-1}$
- Juan de Fuca and Gorda Ridges (inset), $\sim 60 \text{ mm yr}^{-1}$

Earthquake data from <http://earthquake.usgs.gov/eqcenter>.

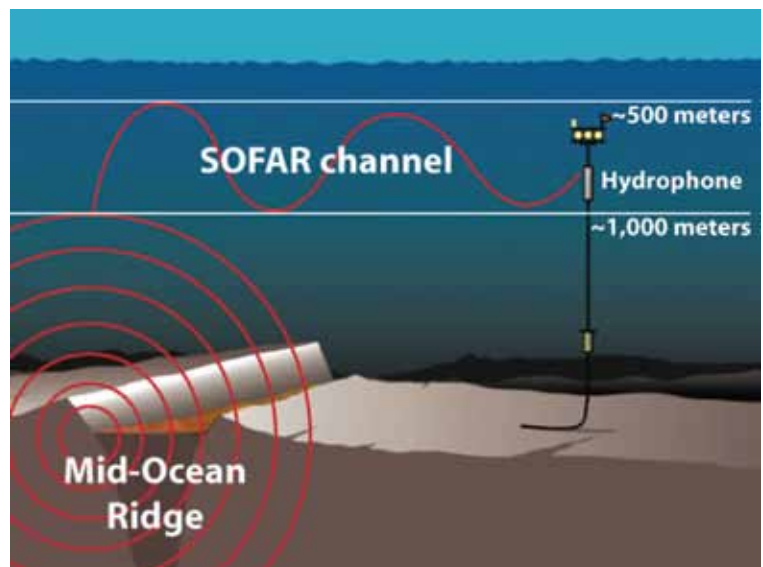


Figure 2. Diagram showing how a hydrophone deployed in the ocean sound channel is used to record acoustic waves from seismic and volcanic activity originating at a mid-ocean ridge. Red circles represent hydroacoustic wave fronts produced by seafloor seismic events that eventually become trapped and laterally propagate along the sound channel. A float keeps the hydrophone moored vertically in the water column. The entire mooring package can be retrieved via acoustic release near the seafloor.

HISTORICAL HYDROACOUSTIC MONITORING (PRE-1990)

The Discovery of *T*-phases

The first published report of a teleseismic *T*-phase wavetrain is attributed to Jagger (1930), who described a high-frequency arrival recorded on Hawai'i Volcano Observatory seismometers within the coda of a large 1927 Alaskan earthquake (Okal, 2008). Several years later, Collins (1936) noted that the seismogram of a Caribbean earthquake featured a third arrival following the primary (P) and secondary (S) phases recorded on short-period channels. Linehan (1940) first coined the term "*T*-phase" when he identified this third or "tertiary" arriving phase in the West Indian region, although he could only speculate as to its source.

The effort to develop antisubmarine warfare techniques during World War II brought considerable progress in hydroacoustics. Ewing et al. (1946) were the first to suggest that underwater sounds recorded during an ocean acoustic experiment were generated by submarine volcanic activity, and they proposed that a network of sound channel hydrophones could be used to monitor seafloor volcanism. Ewing and Worzel (1948) provided the theoretical basis for this phenomenon by describing the basics of long-range propagation in the ocean sound channel. Two years later, Tolstoy and Ewing (1950) provided the first identification of *T*-phases as the water-borne phases of an earthquake source resulting from the conversion of seismic energy to acoustic energy at the seafloor-ocean interface. The first detection of *T*-phases from MOR earthquakes was reported by Bath (1954), who used a land-based seismic network to

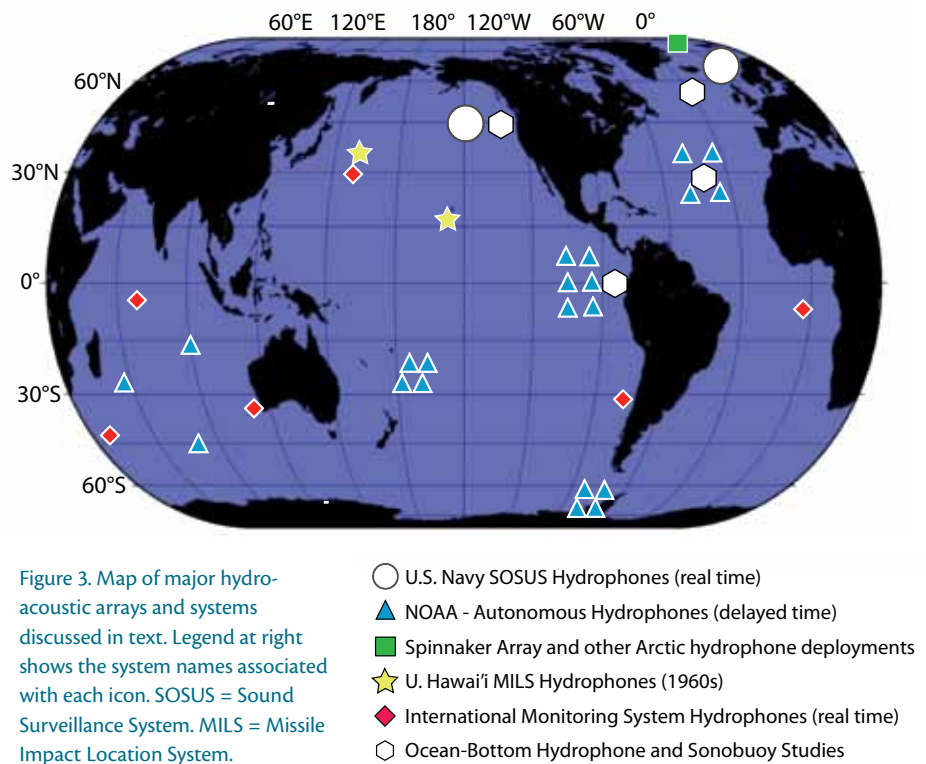
detect earthquakes from the Mohns and Knipovich Ridges, establishing the existence of long-range acoustic propagation in the Arctic, despite the sound channel being surface limited there.

The Hawai'i *T*-phase Group (1960s to Early 1970s)

The study of *T*-phases and the effectiveness of hydroacoustic methods for volcano monitoring were advanced in the 1960s by use of a Pacific-wide network of sound channel hydrophones, the Air Force's Missile Impact Location System (MILS; Figure 3), whose data were analyzed by researchers at the Hawai'i Institute of Geophysics. Johnson et al. (1963) introduced the concept of down-continental-slope conversion for the generation of *T*-phases by subduction earthquakes. A potential generation mechanism for mid-ocean ridge and

abyssal *T*-phases was later introduced by Johnson et al. (1968), who proposed the coupling of acoustic energy into the sound channel via sea surface scattering directly above the earthquake epicenter.

Northrop et al. (1968) and Northrop (1970) presented analysis of MILS hydrophone records of *T*-phases from the Gorda Ridge, a spreading center in the Northeast Pacific Ocean. These studies focused on the discrepancy between seismic and *T*-phase locations of ridge earthquakes (with *T*-phase locations being more accurate). Hammond and Walker (1991) used MILS data to show that the Juan de Fuca Ridge produced 58 *T*-phase events during a two-year period in the mid-1960s, all of which were located either at areas of vigorous hydrothermal venting or volcanic edifices near the spreading axis. Moreover, Walker and Hammond



(1998) showed that of the 644 *T*-phase Gorda Ridge events detected, nearly all occurred in discreet swarms centered on the ridge axis, and the swarms remained confined to individual ridge segments.

or slip on graben faults. Sonobuoy experiments also were performed along the Mid-Atlantic Ridge (MAR) at 36.5°–37°N (Reid and Macdonald, 1973; Spindel et al., 1974), the Galápagos

sonobuoys was air deployed to record acoustic arrivals and refine earthquake locations. These data showed the earthquakes were centered on a volcanic complex on the Reykjanes rift axis. Subsequent side-scan and submersible surveys showed the earthquake source region was an area of high acoustic backscatter and relatively recent lava flows.

A hydrophone array suspended through the Arctic sea ice was used to record the *T*-phases generated by 32 mid-Arctic Ridge earthquakes (Keenan and Dyer, 1984). The sea surface ice scattered the earthquake acoustic rays, enabling long range *T*-phase propagation despite the absence of a sound channel in the polar ocean. Keenan and Merriam (1991) provided further spectral analysis of Arctic *T*-phases and their long-range propagation characteristics, as well as giving estimates of their acoustic magnitudes. The earthquake locations published in these studies indicate the events were near the Spitzbergen Fracture Zone (transform fault) and not the Gakkel Ridge, which was not discernible from the bathymetry available at the time.

“ DETECTION OF [MID-OCEAN RIDGE] MAGMA INTRUSION AND RIFTING EVENTS IS CRITICAL TO OUR UNDERSTANDING OF THE GLOBAL PACE OF VOLCANISM AND THE EPHEMERAL PHYSICAL AND CHEMICAL IMPACTS THESE EVENTS HAVE ON THE OCEAN AND SEAFLOOR ECOSYSTEMS. ”

Global Mid-Ocean Ridge Hydroacoustic Observations (1960s to Early 1990s)

There was increasing awareness that ocean *T*-phases were being recorded at coastal and island seismic stations. Cooke (1967) reported that *T*-phases were recorded by seismometers in New Zealand from earthquakes occurring on the Pacific-Antarctic Ridge. Bath and Shahidi (1971) again reported *T*-phases from earthquakes on the Mohns and Knipovich Ridges, showing acoustic rays propagated by sea surface and seafloor reflections. Sonobuoys were first employed during this time as an inexpensive method to detect mid-ocean ridge seismicity at the sea surface. Reid et al. (1973) used sonobuoys to detect multiple large earthquake swarms along the Guaymas basin rift in the Gulf of California. They attributed these swarms to either magma movement

Rift (MacDonald and Mudie, 1974), and the Nansen Ridge in the Arctic Basin (Kristoffersen et al., 1982).

Brocher (1983) recorded *T*-phases from MAR (31.6°N) earthquakes on seafloor seismometers off Nova Scotia. A total of 16 *T*-phase events were detected over 30 hours, indicating the swarm was possibly of volcanic origin. Toomey et al. (1985) used an array of ocean-bottom hydrophones (OBHs) to record microearthquakes from the MAR at 23°N. During three weeks of monitoring, they detected an average of 15 earthquakes per day, interpreted to reflect the extensional brittle failure of the crust.

In May 1989, an earthquake swarm of 45 teleseismic events ($M = 4-5.5$) was detected from the Reykjanes Ridge, 500 km southwest of Iceland. The swarm was interpreted as a seafloor eruption (Crane et al., 1997), and an array of

RECENT PAST AND PRESENT DAY HYDROACOUSTIC MONITORING (1990–2010)

The US Navy Sound Surveillance System

Following the end of the Cold War, the US Navy sought environmental applications for many military assets and developed a dual-use program to share technology with civilian researchers. Two projects were initiated to use the Navy's networks of bottom-mounted hydrophones, referred to as the Sound Surveillance System (SOSUS), one in

the Atlantic (Nishimura and Conlon, 1994) and one in the Northeast Pacific (Fox and Hammond, 1994; Figure 3). The Atlantic effort focused on cetacean research; however, one notable exception was the use of northern Atlantic SOSUS arrays to detect a submarine eruption on the Mohns Ridge (Blackman et al., 2000). *T*-phase earthquake swarms concentrated at various locations along a 50–70 km length of the ridge, which Blackman et al. (2000) interpreted as representing focused eruptions at a few discrete areas rather than the intrusion and propagation of a magma dike.

In 1991, the National Oceanic and Atmospheric Administration

(NOAA) Pacific Marine Environmental Laboratory’s *T*-phase monitoring project began the first systematic effort to use hydrophone data to produce a continuous catalog of mid-ocean ridge seismicity by screening SOSUS data for earthquakes from the Juan de Fuca and Gorda Ridges. Availability of SOSUS to the civilian research community enabled real-time detection of *T*-phases from seafloor earthquakes, reducing the detection threshold of seismicity by almost two orders of magnitude (Fox et al., 1994). The excellent array geometry of the SOSUS network relative to Northeast Pacific spreading centers, combined with the existence of a well-defined velocity

model of the ocean, yielded significant improvements in the accuracy of derived earthquake locations (Slack et al., 1999).

This much enhanced earthquake detection capability led to the first real-time observations of a seafloor spreading event on the Juan de Fuca Ridge (Fox et al., 1995). Nearly 700 earthquakes were tracked during a 23-day period following the intrusion of a magma dike 60 km along the rift axis of the CoAxial ridge segment (Dziak et al., 1995; Figure 4). The remote detection of this volcanic episode resulted in several in situ multidisciplinary studies that led to the discovery of a hydrothermal plume, a still cooling lava flow,

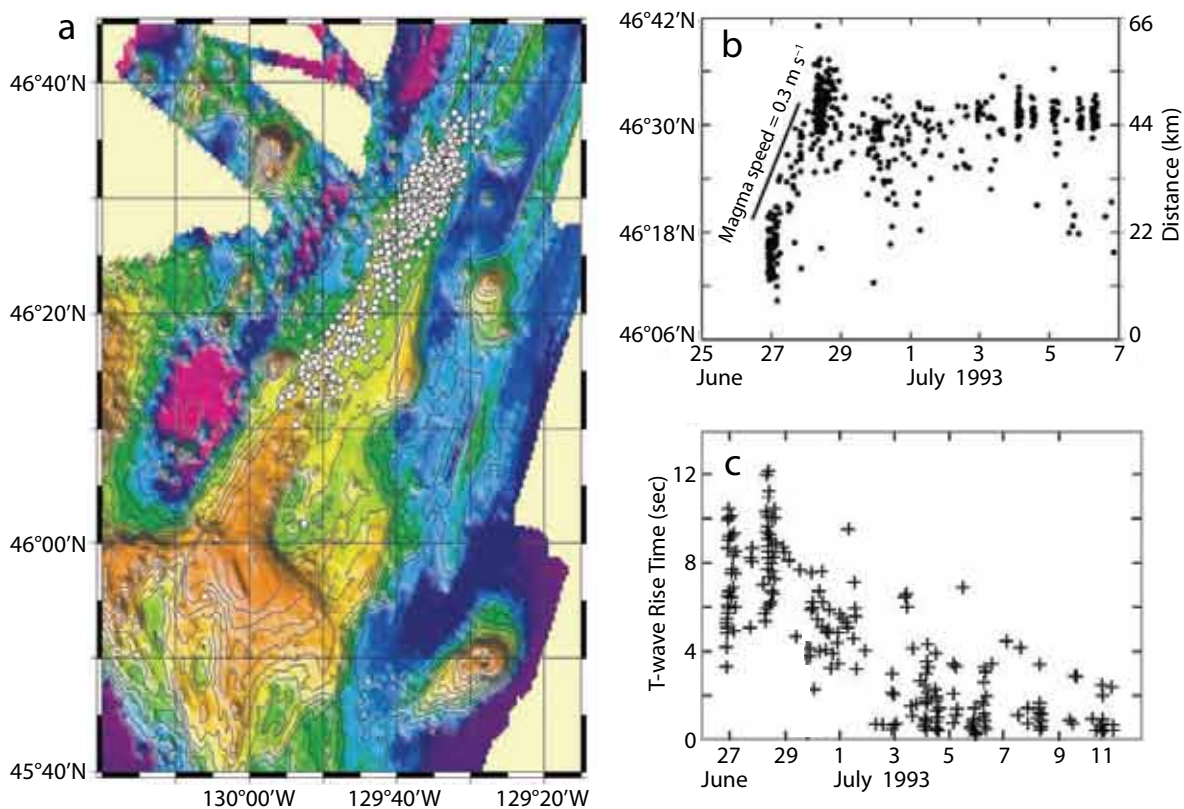


Figure 4. (a) Bathymetric map of the CoAxial segment of the Juan de Fuca Ridge. Circles show earthquake locations recorded during a 23-day period. (b) Along-segment position of earthquake locations vs. time during the swarm. (c) *T*-wave rise time vs. time during the swarm. Events show a decrease in rise time consistent with shoaling of earthquakes as the magma approaches the seafloor, erupting fresh lava along the northern part of the segment. Reproduced from Dziak et al. (1995)

and microbial communities living in a subseafloor ecosystem (e.g., Baker et al., 1995; Embley et al., 1995; Holden et al., 1998). Estimates of relative earthquake depths were also obtained using the *T*-phase rise time, defined as the time between the onset of the signal and its amplitude peak (Schreiner et al., 1995).

amounts of hydrothermal fluid during MOR spreading events.

The SOSUS earthquake locations also have been used in several studies of Northeast Pacific transform faults. Dziak et al. (1996) presented evidence of earthquake and volcanic-tremor activity from an extensional basin within the western

Autonomous Portable Hydrophones

Early successes using SOSUS facilitated the development of moored autonomous underwater hydrophone systems (AUHs) that could be used to monitor global ridge segments. In this design, the hydrophone sensor and instrument package are suspended within the SOFAR channel using a seafloor tether and foam flotation (Figure 2). These instruments have been deployed successfully along mid-ocean ridge spreading centers in the Atlantic (Smith et al., 2002, 2003; Goslin et al., 2005; Simao, 2010), eastern Pacific (Fox et al., 2001), and Indian (Royer et al., 2009) Oceans, as well as along the back-arc spreading systems of the western Pacific (Dziak et al., 2005) and Antarctic Peninsula (Dziak et al., 2010). A typical deployment consists of only six to seven instruments that can monitor more than 2,000 km along axis and provide a record of earthquakes with $M > 2.5$ –3.

On the fast-spreading East Pacific Rise (EPR), seismicity was observed to concentrate along active transform faults, with the exception of a few swarm sites on the ridge axis (Fox et al., 2001). The likely volcanic nature of these EPR swarms was confirmed in 2006 when an in situ seismic array observed an eruption as it occurred (Tolstoy et al., 2006). Thousands of events were recorded by the seismometers, whereas only 23 *T*-phase events were detected by the regional hydrophone array (Dziak et al., 2009).

In contrast to the EPR, hydrophone-recorded seismicity on the slow-spreading MAR is common along both the rift axis and its transform offsets (Smith et al., 2002). Smith et al. (2003) showed ridge-crest seismicity correlates

“GIVEN THE EXPECTED IMPROVEMENTS IN GLOBAL, DEEP-OCEAN MONITORING TECHNOLOGIES DURING THE NEXT CENTURY, WE FORESEE A TIME WHEN EVEN A SEGMENT-SCALE MAGMATIC OR SEAFLOOR SPREADING EVENT WILL BE DETECTED AS IT HAPPENS ANYWHERE IN THE DEEP OCEAN.”

Two other major eruptive episodes have been documented using SOSUS, one at the northern Gorda Ridge in 1996 (Fox and Dziak, 1998) and another at Axial Volcano in 1998 (Dziak and Fox, 1999). In addition, three dike injection/seafloor spreading episodes were detected at Endeavour Segment in 1999, 2000, and 2005 (Bohnenstiehl et al., 2004b; Hooft et al., 2010). Prolonged, intrusion-style earthquake swarms also were observed at the Gorda Ridge (Jackson segment) and Middle Valley segment in 2001, and the northern Gorda Ridge segment in 2008. Using this *T*-phase earthquake record, Dziak et al. (2007) were able to infer that a rapid intrusion of magma within a rift zone typically leads to seafloor eruptions and expulsion of massive

Blanco Transform. Subsequent submersible dives in the basin confirmed the presence of recently formed constructional pillow lava mounds as well as diffuse venting. Dziak et al. (2003) showed that an M_w 6.2 earthquake on the western Blanco Transform caused precursory and coseismic temperature changes at hydrothermal vent sites on the southern Juan de Fuca Ridge, ~ 39 km distant from the main shock. Merle et al. (2008) described the detection of a 2008 earthquake sequence on SOSUS that began within the Juan de Fuca Plate. After a week, the earthquakes moved to the eastern Blanco Transform and ended 30 days later with a seafloor-spreading event on the northern Gorda Ridge.

with axial thermal structure, where regions of low and high numbers of events correspond to thinner (hotter) and thicker (colder) lithosphere. Bohnenstiehl et al. (2002, 2003) and Dziak et al. (2004a) used hydrophone seismicity at the MAR to quantify the completeness level of the hydrophone earthquake catalog (magnitude ≥ 2.5) and the temporal distribution of ridge-crest aftershock sequences. Location comparisons again demonstrated significant improvements relative to more distant land-based seismic monitoring (Bohnenstiehl and Tolstoy, 2003; Pan and Dziewonski, 2005).

Dziak et al. (2004b) showed that a 2001 earthquake swarm at Lucky Strike Seamount (MAR at 37°N) was likely caused by magma intrusion. Subsequent submersible observations confirmed increased venting and microbial activity at the summit. Goslin et al. (2005) documented several large earthquake sequences along the Reykjanes Ridge south of Iceland. These sequences exhibited spatio-temporal patterns consistent with involvement of magmatic or hydrothermal processes. Escartín et al. (2008) showed that high rates of hydroacoustic seismicity at the northern MAR correlate with the locations of detachment faults that bring lower crust and upper mantle rocks to the seafloor and are typically associated with hydrothermal activity. Simao et al. (2010) showed that *T*-phase earthquakes along the MAR north and south of the Azores tend to cluster on mantle Bouguer gravity anomaly maxima. Most of these clusters seemed to be caused by magma intrusion and propagation along the ridge axis. An array of eight hydrophones is currently deployed along the equatorial MAR.

The results of this monitoring effort are expected to provide new insight into volcano-tectonic processes along this poorly understood section of the ridge.

Royer et al. (2008) located more than 2,000 *T*-phase earthquakes during a 16-month deployment of autonomous hydrophones in the Indian Ocean. Southeast Indian Ridge seismicity occurs predominantly along transform faults, the Southwest Indian Ridge exhibits some periodicity in earthquake activity between adjacent ridge segments, and two large tectono-volcanic earthquake swarms were observed along the Central Indian Ridge near the triple junction.

Autonomous hydrophone arrays also have been deployed at two back-arc spreading centers, the Bransfield Strait in Antarctica (Dziak et al., 2010) and the Lau Basin in the western Pacific (Bohnenstiehl et al., 2010). The Bransfield Strait array detected 3,900 earthquakes during a two-year deployment, including eight earthquake swarms located on the 400 km long central rift zone. Only five months of the Lau Basin data have been analyzed to date; however, preliminary results indicate many of the 26,900 earthquakes detected so far are focused on the main transform (Peggy Ridge) and the large (~ 50 km) overlapping spreading center in the region.

Additional Cabled and Deployed Hydroacoustic Arrays

Sohn and Hildebrand (2001) used the Spinnaker hydrophone array (Figure 3) in the Arctic Ocean to detect tectonic earthquakes from the Gakkel Ridge and further established the effectiveness of using of *T*-phases in the Arctic for long-range earthquake detection beneath the ice canopy. Schlindwein

et al. (2005) deployed seismometers on an Arctic iceflow to record the acoustic phases of volcanic explosions from the Gakkel Ridge. During 11 days, a total of 200 explosions were located at a large volcanic center, and a recent lava flow was discovered in 1999 (Edwards et al., 2001).

OHBs also have been used to study ridge-crest seismicity. Kong et al. (1992) employed seven OBHs to detect micro-earthquakes over a three-week period from the TAG segment of the MAR at 26°N. The high seismicity levels at 26°N have recently been interpreted as due to slip on the local detachment fault (deMartin et al., 2007). Sohn et al. (1999) recorded microseismicity using OBHs following a large eruption at Axial Volcano on the Juan de Fuca Ridge in 1998. These local earthquakes were interpreted as either slip along the caldera rim fault or shear along the volcano's southeast flank. Haxel et al. (2010) have maintained an array of four OBHs within Axial's summit caldera since 2006. The OBHs have recorded thousands of earthquakes annually, which have steadily increased through time, consistent with geodetic observations of caldera floor uplift caused by a renewed influx of magma (Nooner and Chadwick, 2009) and leading to discovery of a summit eruption in April 2011.

During 2010, NEPTUNE Canada, a fiber-optic cabled node of deep-sea sensors deployed along the northern Juan de Fuca Ridge, became operational (Barnes and Tunnicliffe, 2008). The node's seismometers and hydrophones are deployed on and off the ridge axis. The acoustic phases of hundreds of earthquakes from the ridge and nearby transforms have been recorded to date.

International Monitoring System

During the late 1990s, a global real-time system of radionuclide, seismic, infrasound, and hydroacoustic sensors was constructed to support a Comprehensive Nuclear Test Ban. This infrastructure is collectively known as the International Monitoring System (IMS; Figure 3). The hydroacoustic component consists of five island-based seismic stations and six cabled hydrophone installations at Diego Garcia, Cape Luewin, and Crozet Island in the Indian Ocean; Juan Fernandez and Wake Islands in the Pacific; and Ascension Island in the Atlantic. Each hydrophone station hosts a set of three sound-channel moored sensors deployed as a small-aperture (~ 2 km) horizontal array, allowing the direction of incoming acoustic energy to

be determined and therefore enhancing the location capabilities afforded by the relatively sparse network.

Hanson and Bowman (2005) used *T*-phases recorded on the IMS stations in the Indian Ocean to locate 1,146 earthquakes from the Central and Southeast Indian Ridges during a 10-month period in 2003. The Indian Ocean *T*-phase seismicity clustered at ridge-transform intersections, with several gaps in earthquake activity occurring within ridge segments. Other projects have used *T*-phase seismicity to study the diffuse nature of the plate boundary system along the Indian Ocean spreading centers and the organization of transform faults within the basin (e.g., Bohnenstiehl et al., 2004b; Yun et al., 2009).

THE FUTURE OF MID-OCEAN RIDGE MONITORING

It is interesting to speculate upon what developments will occur in deep-ocean acoustic monitoring. Recent improvements in autonomous underwater vehicle (AUV) technology will lead to the next significant advancement in hydroacoustic monitoring. A recent example occurred when an ocean glider capable of satellite data transmission was flown around an erupting volcano with a hydrophone in its payload (Matsumoto et al., 2011). One can envision a constellation of gliders or autonomous floats (e.g., Simons et al., 2009) circling large regions of the world's MORs, screening acoustic signals for volcano-tectonic seismicity and reporting on the latest eruption or seafloor spreading event.

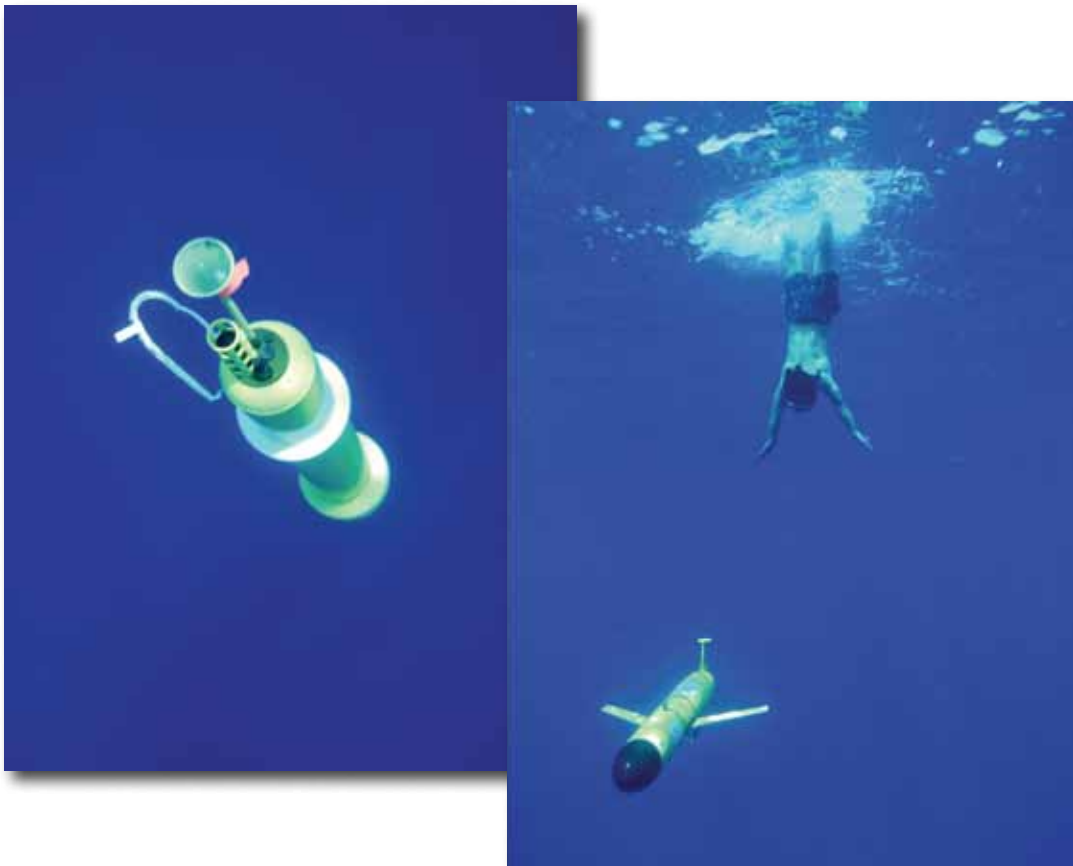


Figure 5. (Left) Image of quasi-Eulerian autonomous hydrophone (Que-phone) float. The Que-phone self controls buoyancy and can perform several ascent/descent cycles to survey the ocean sound field from seafloor to sea surface. (Right) Image of an ocean glider (Webb Research Inc.) with a hydrophone and recording package mounted on the platform (Matsumoto et al., 2011). The glider is capable of a more structured survey methodology and can vertically and laterally survey the water column over a several tens of square kilometers. Haru Matsumoto is shown for scale.

Within the next few years, the US Regional Scale Nodes, a counterpart to the NEPTUNE Canada initiative, will instrument portions of the Juan de Fuca Ridge. The Axial Volcano node will include an array of seafloor seismometers and at least one hydrophone moored in the water column. These systems will enable real-time, in situ, seismo-acoustic monitoring of ridge-crest volcanic activity, albeit a spatially limited view of Northeast Pacific spreading center dynamics.


Ocean glider and AUV technology will continue to improve in both physical maneuverability and the quality and amount of data collected (Figure 5). Perhaps future developments will allow for deployment of a shoal of platforms with multiple hydrophones, which can beamform and localize acoustic sources while at sea. The instruments will then transmit their findings in real time back to shore-based researchers via satellite. Undoubtedly, future military assets will improve on the capability of the current SOSUS hydrophone system, and we optimistically envision a future military-civilian, dual-use program where the latest technology will be available to the ocean science community for deep-ocean research.

SUMMARY

Over the last 84 years since hydro-acoustic *T*-phases were first discovered, there have been profound advances in our understanding of the physical means by which *T*-phases are generated, how they propagate, the variety of volcano-tectonic settings where they are created, and the hydroacoustic technologies used to detect them. This paper focused on the acoustic phases detected

from mid-ocean ridges and how this information was used to provide insight into spreading center processes. Given the expected improvements in global, deep-ocean monitoring technologies during the next century, we foresee a time when even a segment-scale magmatic or seafloor spreading event will be detected as it happens anywhere in the deep ocean.

ACKNOWLEDGEMENTS

The authors wish to thank M. Tolstoy, J. Perrot, E. Hooft, and E. Kappel for very insightful comments that improved the manuscript. SOSUS studies discussed in this paper were supported by the NOAA Vents Program and during 2006–2009 by the National Science Foundation, Grant OCE-0623649. This paper is PMEL contribution number 3746. 

REFERENCES

- Baker, E.T., G.J. Massoth, R.A. Feely, R.W. Embley, R.E. Thomson, and B.J. Burd. 1995. Hydrothermal event plumes from the CoAxial seafloor eruption site, Juan de Fuca Ridge. *Geophysical Research Letters* 22(2):147–150, <http://dx.doi.org/10.1029/94GL02403>.
- Bath, M., and M. Shahidi. 1971. *T*-phases from Atlantic earthquakes. *Pure and Applied Geophysics* 92:74–114, <http://dx.doi.org/10.1007/BF00874995>.
- Bath, M. 1954. Study of *T*-phases recorded at the Kiruna seismograph station. *Tellus* 6(1):63–72.
- Barnes, C., and V. Tunnicliffe. 2008. Building the world's first multi-node cabled ocean observatories (Neptune Canada and VENUS, Canada): Science, realities, challenges, and opportunities. Pp. 1–8 in *Oceans 2008: MTS/IEEE Kobe Techno-Ocean*. <http://dx.doi.org/10.1109/OCEANSKOBE.2008.4531076>.
- Blackman, D.K., C.E. Nishimura, and J.A. Orcutt. 2000. Seismoacoustic recordings of a spreading episode on the Mohs Ridge. *Journal of Geophysical Research* 105(B5):10,961–10,973, <http://dx.doi.org/10.1029/2000JB900011>.
- Bohnenstiehl, D.R., R.P. Dziak, H. Matsumoto, A. Lau, M. Fowler, K.E. Cook, C.M. Scheip, K.W. Warren, J.A. Conder, and D.A. Wiens. 2010. Hydroacoustic monitoring of seismic

- and volcanic activity within the Lau Basin. *Eos, Transactions, American Geophysical Union* 90(52):Fall Meeting Abstract T11E-02.
- Bohnenstiehl, D.R., R.P. Dziak, M. Tolstoy, C. Fox, and M. Fowler. 2004. Temporal and spatial history of the 1999–2000 Endeavour Segment seismic series, Juan de Fuca Ridge. *Geochemistry Geophysics Geosystems* 5, Q09003, <http://dx.doi.org/10.1029/2004GC000735>.
- Bohnenstiehl, D.R., and M. Tolstoy. 2003. Comparison of teleseismically and hydroacoustically derived earthquake locations along the north-central Mid-Atlantic Ridge and equatorial East-Pacific Rise. *Seismological Research Letters* 74:790–801, <http://dx.doi.org/10.1785/gssrl.74.6.791>.
- Bohnenstiehl, D.R., M. Tolstoy, and E. Chapp. 2004. Breaking into the plate: A 7.6 M_w fracture-zone earthquake adjacent to the Central Indian Ridge. *Geophysical Research Letters* 31, <http://dx.doi.org/10.1029/2003GL018981>.
- Bohnenstiehl, D.R., M. Tolstoy, R.P. Dziak, C.G. Fox and D.K. Smith. 2002. Aftershock sequences in the mid-ocean ridge environment: An analysis using hydroacoustic data. *Tectonophysics* 354:49–70, [http://dx.doi.org/10.1016/S0040-1951\(02\)00289-5](http://dx.doi.org/10.1016/S0040-1951(02)00289-5).
- Brocher, T.M. 1983. *T*-phases from an earthquake swarm on the Mid-Atlantic Ridge at 31.6°N. *Marine Geophysical Researches* 6(1):39–49, <http://dx.doi.org/10.1007/BF00300397>.
- Collins, M.P. 1936. *Bulletin Number 5*. Harvard University Seismograph Station, 23 pp.
- Cooke, R.J.S. 1967. Observations of the seismic *T*-phase at Macquarie Island. *New Zealand Journal of Geology and Geophysics* 10:1,212–1,225.
- Crane, K., L. Johnson, B. Appelgate, C. Nishimura, R. Buck, C. Jones, P. Vogt, and R. Kos'yan. 1997. Volcanic and seismic swarm events on the Reykjanes Ridge and their similarities to events on Iceland: Results of a rapid response mission. *Marine Geophysical Researches* 19(4):319–338, <http://dx.doi.org/10.1023/A:1004298425881>.
- deMartin, B.J., R.A. Sohn, J.P. Canales, S.E. Humphris. 2007. Kinematics and geometry of active detachment faulting beneath the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge. *Geology* 35(8):711–714, <http://dx.doi.org/10.1130/G23718A.1>.
- Dziak, R.P., D.R. Bohnenstiehl, J.P. Cowen, E.T. Baker, K.H. Rubin, J.H. Haxel, and M.J. Fowler. 2007. Rapid dike emplacement leads to eruptions and hydrothermal plume release during seafloor spreading events. *Geology* 35(7):579–582, <http://dx.doi.org/10.1130/G23476A.1>.
- Dziak, R.P., D.R. Bohnenstiehl, H. Matsumoto, M.J. Fowler, J.H. Haxel, M. Tolstoy, and F. Waldhauser. 2009. The January 2006

- seafloor spreading event at 9°50'N, East Pacific Rise: Ridge dike intrusion and transform fault interactions from regional hydroacoustic data. *Geochemistry Geophysics Geosystems* 10, Q06T06, <http://dx.doi.org/10.1029/2009GC002388>.
- 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. 2004a. *P*- and *T*-wave detection thresholds, *P_n* velocity estimate, and detection of lower mantle and core *P*-waves on ocean sound channel hydrophones at the Mid-Atlantic Ridge. *Bulletin of the Seismological Society of America* 94:665–677, <http://dx.doi.org/10.1785/0120030156>.
- Dziak, R.P., W.W. Chadwick, C.G. Fox, and R.W. Embley. 2003. Hydrothermal temperature changes at the southern Juan de Fuca Ridge associated with the *M_w* 6.2 Blanco Transform earthquake. *Geology* 31(2):119–122, [http://dx.doi.org/10.1130/0091-7613\(2003\)031<0119:HTCATS>2.0.CO;2](http://dx.doi.org/10.1130/0091-7613(2003)031<0119:HTCATS>2.0.CO;2).
- Dziak, R.P., C.G. Fox, R.W. Embley, J.E. Lupton, G.C. Johnson, W.W. Chadwick, and R.A. Koski. 1996. Detection of and response to a probable volcanogenic *T*-wave event swarm on the western Blanco Transform Fault Zone. *Geophysical Research Letters* 23(8):873–876, <http://dx.doi.org/10.1029/96GL00240>.
- Dziak, R.P., and C.G. Fox. 1999. The January 1998 earthquake swarm at Axial Volcano, Juan de Fuca Ridge: Hydroacoustic evidence of seafloor volcanic activity. *Geophysical Research Letters* 26(23):3,429–3,432, <http://dx.doi.org/10.1029/1999GL002332>.
- Dziak, R.P., C.G. Fox, and A.E. Schreiner. 1995. The June–July seismo-acoustic event at CoAxial segment, Juan de Fuca Ridge: Evidence for lateral dike injection. *Geophysical Research Letters* 22(2):135–138, <http://dx.doi.org/10.1029/94GL01857>.
- Dziak, R.P., M. Park, W.-S. Lee, H. Matsumoto, D.R. Bohnenstiehl, and J.H. Haxel. 2010. Tectonomagmatic activity and ice dynamics in the Bransfield Strait back-arc basin, Antarctica. *Journal of Geophysical Research* 115, B01102, <http://dx.doi.org/10.1029/2009JB006295>.
- Dziak, R.P., D.K. Smith, D.R. Bohnenstiehl, C.G. Fox, D. Desbruyeres, H. Matsumoto, M. Tolstoy, and D.J. Fornari. 2004b. Evidence of a recent magma dike intrusion at the slow spreading Lucky Strike segment, Mid-Atlantic Ridge. *Journal of Geophysical Research* 109, B12102, <http://dx.doi.org/10.1029/2004JB003141>.
- Edwards, M.H., G.J. Kurras, M. Tolstoy, D.R. Bohnenstiehl, B.J. Coakley, and J.R. Cochran. 2001. Evidence of recent volcanic activity on the ultraslow-spreading Gakkel Ridge. *Nature* 409:808–812: <http://dx.doi.org/10.1038/35057258>.
- Embley, R.W., W.W. Chadwick Jr., I.R. Jonasson, D.A. Butterfield, and E.T. Baker. 1995. Initial results of a rapid response to the 1993 CoAxial event: Relationships between hydrothermal and volcanic processes. *Geophysical Research Letters* 22(2): 143–146, <http://dx.doi.org/10.1029/94GL02281>.
- Escartín, J., D.K. Smith, J. Cann, H. Schouten, C.H. Langmuir, and S. Escrig. 2008. Central role of detachment faults in accretion of slow-spreading lithosphere. *Nature* 455:790–794, <http://dx.doi.org/10.1038/nature07333>.
- Ewing, W.M., G.P. Woollard, V.C. Vine, and J.L. Worzel. 1946. Recent results in submarine geophysics. *Geology Society of America* 40:53–58, [http://dx.doi.org/10.1130/0016-7606\(1946\)57\[909:RRISG\]2.0.CO;2](http://dx.doi.org/10.1130/0016-7606(1946)57[909:RRISG]2.0.CO;2).
- Ewing, W.M., and J.L. Worzel. 1948. *Long-Range Sound Transmission*. Geological Society of America Memoir 27(3), 39 pp.
- Fox, C.G., and R.P. Dziak. 1998. Hydroacoustic detection of volcanic activity on the Gorda Ridge, February–March 1996. *Deep Sea Research Part II* 45(12):2,513–2,530, [http://dx.doi.org/10.1016/S0967-0645\(98\)00081-2](http://dx.doi.org/10.1016/S0967-0645(98)00081-2).
- Fox, C.G., R.P. Dziak, H. Matsumoto, and A.E. Schreiner. 1994. Potential for monitoring low-level seismicity on the Juan de Fuca Ridge using military hydrophone arrays. *Marine Technology Society Journal* 27(4):22–30.
- Fox, C.G., and S.R. Hammond. 1994. The VENTS Program *T*-phase project and NOAA's role in ocean environmental research. *Marine Technology Society Journal* 27(4):70–74.
- Fox, C.G., H. Matsumoto, and T.-K. Lau. 2001. Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. *Journal of Geophysical Research* 106:4,183–4,206, <http://dx.doi.org/10.1029/2000JB900404>.
- Fox, C.G., W.E. Radford, R.P. Dziak, T.-K. Lau, H. Matsumoto, and A.E. Schreiner. 1995. Acoustic detection of a seafloor spreading episode on the Juan de Fuca Ridge using military hydrophone arrays. *Geophysical Research Letters* 22(2):131–134, <http://dx.doi.org/10.1029/94GL02059>.
- Goslin, J., N. Lourenzo, R.P. Dziak, D.R. Bohnenstiehl, J. Haxel, and J. Luis. 2005. Long-term seismicity of the Reykjanes Rift (North Atlantic) recorded by a regional hydrophone array. *Geophysical Journal International* 162(2):516–524, <http://dx.doi.org/10.1111/j.1365-246X.2005.02678.x>.
- Hammond, S.R., and D.A. Walker. 1991. Ridge event detection: *T*-phase signals from the Juan de Fuca spreading center. *Marine Geophysical Researches* 13:331–348, <http://dx.doi.org/10.1007/BF00366282>.
- Hanson, J.A., and J.R. Bowman. 2005. Indian Ocean Ridge seismicity observed with a permanent hydroacoustic network. *Geophysical Research Letters* 32, L06301, <http://dx.doi.org/10.1029/2004GL021931>.
- Haxel, J.H., R.P. Dziak, H. Matsumoto, M.J. Fowler, and W.W. Chadwick Jr. 2011. A time history of micro-seismicity leading to volcanic eruption at Axial Volcano, Juan de Fuca Ridge. *Eos, Transactions, American Geophysical Union*, Fall Meeting Abstract V14C-06.
- Holden, J.F., M. Summit, and J.A. Baross. 1998. Thermophilic and hyperthermophilic microorganisms in 3–30°C hydrothermal fluids following a deep-sea volcanic eruption. *FEMS Microbiology Ecology* 25:33–41, <http://dx.doi.org/10.1111/j.1574-6941.1998.tb00458.x>.
- Hooft, E.E.E., H. Patel, W. Wilcock, K. Becker, D. Butterfield, E. Davis, R. Dziak, K. Inderbitzen, M. Lilley, P. McGill, and others. 2010. A seismic swarm and regional hydrothermal and hydrologic perturbations: The northern Endeavour Segment, February 2005. *Geochemistry Geophysics Geosystems* 11, Q12015, <http://dx.doi.org/10.1029/2010GC003264>.
- Jagger, T.A. 1930. How the seismograph works. *The Volcano Letter* 268:1–4.
- Johnson, R.H., R.A. Norris, and F.K. Duennebie. 1968. Abyssally generated *T*-phases. Pp. 70–78 in *The Crust and Upper Mantle of the Pacific Area*. L. Knopoff, C.L. Drake, and P.J. Hart, eds, American Geophysical Union Monograph Series Volume 12, Washington, DC, <http://dx.doi.org/10.1029/GM012p0070>.
- Johnson, R.H., J. Northrop, and R. Epply. 1963. Sources of Pacific *T*-phases. *Journal of Geophysical Research* 68:4,251–4,261.
- Keenan, R.E., and I. Dyer. 1984. Noise from Arctic Ocean earthquakes. *Journal of the Acoustical Society of America* 75(3):819–825, <http://dx.doi.org/10.1121/1.390591>.
- Keenan, R.E., and L.R.L. Merriam. 1991. Arctic abyssal *T* phases: Coupling seismic energy to the ocean sound channel via under-ice scattering. *Journal of the Acoustical Society of America* 89(3):1,128–1,133, <http://dx.doi.org/10.1121/1.400648>.
- Kristoffersen, Y., E.S. Husebye, H. Bungum, and S. Gregersen. 1982. Seismic investigations of the Nansen Ridge during the FRAM I experiment. *Tectonophysics* 82(1):57–68, [http://dx.doi.org/10.1016/0040-1951\(82\)90088-9](http://dx.doi.org/10.1016/0040-1951(82)90088-9).
- Kong, L.S.L., S.C. Solomon, and G.M. Purdy. 1992. Microearthquake characteristics of a mid-ocean ridge along-axis high. *Journal of Geophysical Research* 97(B2):1,659–1,685, <http://dx.doi.org/10.1029/91JB02566>.
- Linehan, J. 1940. Earthquakes in the West Indian region. *Eos, Transactions, American Geophysical Union* 21:229–232.

- Macdonald, K.C., and J.D. Mudie. 1974. Microearthquakes on the Galapagos spreading centre and the seismicity of fast-spreading ridges. *Geophysical Journal International* 36(2):245–257, <http://dx.doi.org/10.1111/j.1365-246X.1974.tb03636.x>.
- Matsumoto, H., J. H. Haxel., R.P. Dziak, D.R. Bohnenstiehl, and R.W. Embley. 2011. Mapping the sound field of an erupting submarine volcano using an acoustic glider. *Journal of the Acoustical Society of America* 129(3):94–99, <http://dx.doi.org/10.1121/1.3547720>.
- Merle, S.M., R.P. Dziak, R.W. Embley, W.W. Chadwick Jr., J.E. Lupton, D.R. Bohnenstiehl, J. Braunmiller, R. Greene, and M. Fowler. 2008. Preliminary analysis of multibeam, subbottom, and water column data collected from the Juan de Fuca and Gorda Ridge earthquake swarm sites, March–April 2008. *Eos, Transactions, American Geophysical Union* 88: Fall Meeting Abstract T23B–2025.
- Nishimura, C.E., and D. Conlon. 1994. IUSS dual use: Monitoring whales and earthquakes using SOSUS. *Marine Technology Society Journal* 27(4):13–21.
- Nooner, S.L., and W.W. Chadwick Jr. 2009. Volcanic inflation measured in the caldera of Axial Seamount: Implications for magma supply and future eruptions. *Geochemistry Geophysics Geosystems* 10, Q02002, <http://dx.doi.org/10.1029/2008GC002315>.
- Northrop, J. 1970. Accuracy of earthquake epicenters on the Gorda ridge. *Bulletin of the Seismological Society of America* 60(1):265–267.
- Northrop, J., H.W. Menard, and F.K. Duennebieber. 1968. Seismic and bathymetric evidence of a fracture zone on the Gorda Ridge. *Science* 161:688–690, <http://dx.doi.org/10.1126/science.161.3842.688>.
- Okal, E.A. 2008. The generation of *T* waves by earthquakes. *Advances in Geophysics* 49:1–65, [http://dx.doi.org/10.1016/S0065-2687\(07\)49001-X](http://dx.doi.org/10.1016/S0065-2687(07)49001-X).
- Pan, J., and A.M. Dziewonski. 2005. Comparison of mid-oceanic earthquake epicentral differences of travel time, centroid locations, and those determined by autonomous underwater hydrophone arrays. *Journal of Geophysical Research* 110, B07302, <http://dx.doi.org/10.1029/2003JB002785>.
- Reid, I., and K. Macdonald. 1973. Microearthquake study of the Mid-Atlantic Ridge near 37°N using sonobuoys. *Nature* 246:88–90, <http://dx.doi.org/10.1038/246088a0>.
- Reid, I., M. Reichle, J. Brune, and H. Bradner. 1973. Microearthquake studies using sonobuoys: Preliminary results from the Gulf of California. *Geophysical Journal International* 34(3):365–379, <http://dx.doi.org/10.1111/j.1365-246X.1973.tb02401.x>.
- Royer, J-Y, R.P. Dziak, M. Delatre, C. Brachet, J.H. Haxel, H. Matsumoto, J. Goslin, V. Brandon, D.R. Bohnenstiehl, C. Guinet, and F. Samaran. 2008. Preliminary results from an hydroacoustic experiment in the Indian Ocean. *Eos, Transactions, American Geophysical Union* 88:Fall Meeting Supplement Abstract T51B–1883.
- Schindwein, V., C. Muller, and W. Jokat. 2005. Seismoacoustic evidence for volcanic activity on the ultra-slow spreading Gakkel Ridge, Arctic Ocean. *Geophysical Research Letters* 32, L18306, <http://dx.doi.org/10.1029/2005GL023767>.
- Schreiner, A.E., C.G. Fox, and R.P. Dziak. 1995. Spectra and magnitudes of *T*-waves from the 1993 earthquake swarm on the Juan de Fuca Ridge. *Geophysical Research Letters* 22(2):139–142, <http://dx.doi.org/10.1029/94GL01912>.
- Simao, J., J. Escartín, J. Goslin, M. Haxel, M. Cannat, and R. Dziak. 2010. Regional seismicity of the Mid-Atlantic Ridge: Observations from an autonomous hydrophone array. *Geophysics Journal International* 183(3):1,559–1,578, <http://dx.doi.org/10.1111/j.1365-246X.2010.04815.x>.
- Simons, F.J., G. Nolet, P. Georgief, J.M. Babcock, L.A. Regier, and R.E. Davis. 2009. On the potential of recording earthquakes for global seismic tomography by low-cost autonomous instruments in the oceans. *Journal of Geophysical Research* 114, B05307, <http://dx.doi.org/10.1029/2008JB006088>.
- Slack, P.D., C.G. Fox, and R.P. Dziak. 1999. *P*-wave detection thresholds, *Pn* velocity estimates, and *T* wave location uncertainty from oceanic hydrophones. *Journal of Geophysical Research* 104:13,061–13,072, <http://dx.doi.org/10.1029/1999JB900112>.
- Sohn, R.A., W.C. Crawford, and S.C. Webb. 1999. Local seismicity following the 1998 eruption of Axial Volcano. *Geophysical Research Letters* 26(23):3,433–3,436, <http://dx.doi.org/10.1029/1999GL900505>.
- Sohn, R.A., and J.A. Hildebrand. 2001. Hydroacoustic earthquake detection in the Arctic Basin with the Spinnaker Array. *Bulletin of the Seismological Society of America* 91(3):572–579, <http://dx.doi.org/10.1785/0120000099>.
- Smith, D.K., J. Escartín, M. Cannat, M. Tolstoy, C.G. Fox, D.R. Bohnenstiehl, and S. Bazin. 2003. Spatial and temporal distribution of seismicity along the northern Mid-Atlantic Ridge (15°–35°N). *Journal of Geophysical Research* 108(B3), 2167, <http://dx.doi.org/10.1029/2002JB001964>.
- Smith, D.K., M. Tolstoy, C.G. Fox, D.R. Bohnenstiehl, H. Matsumoto, and M.J. Fowler. 2002. Hydroacoustic monitoring of seismicity at the slow-spreading Mid-Atlantic Ridge. *Geophysical Research Letters* 29(11), 1518, <http://dx.doi.org/10.1029/2001GL013912>.
- Spindel, R.C., S.B. Davis, K.C. Macdonald, R.P. Porter, and J.D. Phillips. 1974. Microearthquake survey of the median valley of the Mid-Atlantic Ridge at 36°30'N. *Nature* 248:577–579, <http://dx.doi.org/10.1038/248577a0>.
- Tolstoy, I., and M. Ewing. 1950. The *T*-phase of shallow-focus earthquakes. *Bulletin of the Seismological Society of America* 40:25–51.
- Tolstoy, M., J.P. Cowen, E.T. Baker, D.J. Fornari, K.H. Rubin, T.M. Shank, F. Walderhauser, D.R. Bohnenstiehl, D.W. Forsythe, and R.C. Holmes. 2006. A sea-floor spreading event captured by seismometers. *Science* 314(587):1,920–1,922, <http://dx.doi.org/10.1126/science.1133950>.
- Toomey, D., S.C. Solomon, G.M. Purdy, and M.H. Murray. 1985. Microearthquakes beneath the median valley of the mid-Atlantic Ridge near 23°N: Hypocenters and focal mechanisms. *Journal of Geophysical Research* 90(B7):5,443–5,458, <http://dx.doi.org/10.1029/JB090iB07p05443>.
- Walker, D.A., and S.R. Hammond. 1998. Historical Gorda Ridge *T*-phase swarms: Relationships to ridge structure and the tectonic and volcanic state of the ridge during 1964–1966. *Deep Sea Research Part II* 45:2,531–2,545, [http://dx.doi.org/10.1016/S0967-0645\(98\)00082-4](http://dx.doi.org/10.1016/S0967-0645(98)00082-4).
- Yun, S., S. Ni, M. Park, and W.S. Lee. 2009. Southeast Indian Ocean-Ridge earthquake sequences from cross-correlation analysis of hydroacoustic data. *Geophysical Journal International* 179:401–407, <http://dx.doi.org/10.1111/j.1365-246X.2009.04292.x>.