

## Ears in the Ocean

### Hydrophones reveal a whole lot of previously undetected seafloor shaking going on

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If you sought to delve into the forces that drive and shape the face of the earth and that distinguish it from all other planets in our solar system, you would shine a spotlight on the mid-ocean ridges.

This 75,000-kilometer (45,000-mile)-long volcanic mountain chain bisects the seafloor and wraps around the entire globe. It is the site where magma continuously erupts to create new crust. As the crust spreads out on both sides of the ridges, it paves the surface of the planet and sets in motion the tectonic forces that cause continents to rip apart and collide, and oceans to open and close.

This planetary extravaganza, full of fury and sound, is accompanied by a constant drumbeat of earthquakes and volcanic eruptions. But the oceans act like a great blue curtain, completely shrouding our view and muting the sound.

About 80 percent of all volcanic and earthquake activity on Earth occurs on the seafloor, but it is like those proverbial trees that fall in forests when nobody's there. If we could eavesdrop on all that seismic activity, we could glean a great deal of information about the workings of our planet.

To do that, earth scientists have employed instruments that record seismic waves generated by earthquakes and volcanoes. (See "Listening Closely to 'See'

into the Earth," page 16.) But these studies have suffered from two primary limitations. The instruments have been installed in land-based networks, which cover broad areas over long time periods but can detect only large-magnitude earthquakes in the oceans. Experiments using ocean-bottom seismometers can detect seafloor earthquakes with precision, but they are best-suited to monitor small areas.

But now, the ending of the Cold War has given earth scientists an unprecedented opportunity to take advantage of a tool created to wage that war—a project launched by the U.S. Navy in the 1950s that went by the code name Jezebel.

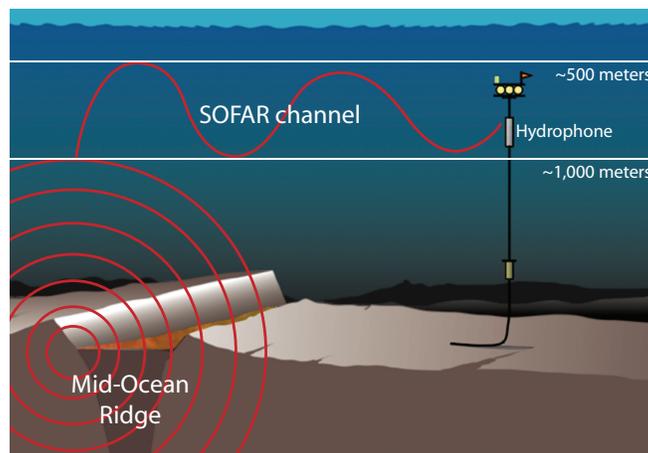
#### SOFAR, so good

The roots of Jezebel actually began at Woods Hole Oceanographic Institution during World War II when two scien-

tists, Maurice Ewing and J. Lamar Worzel, began to conduct basic research on acoustics in the ocean—seeking any advantages that would help the Navy detect enemy submarines or mines, or help U.S. subs avoid detection. In a critical experiment, they detonated 1 pound of TNT under water near the Bahamas and detected the sound 2,000 miles away near West Africa.

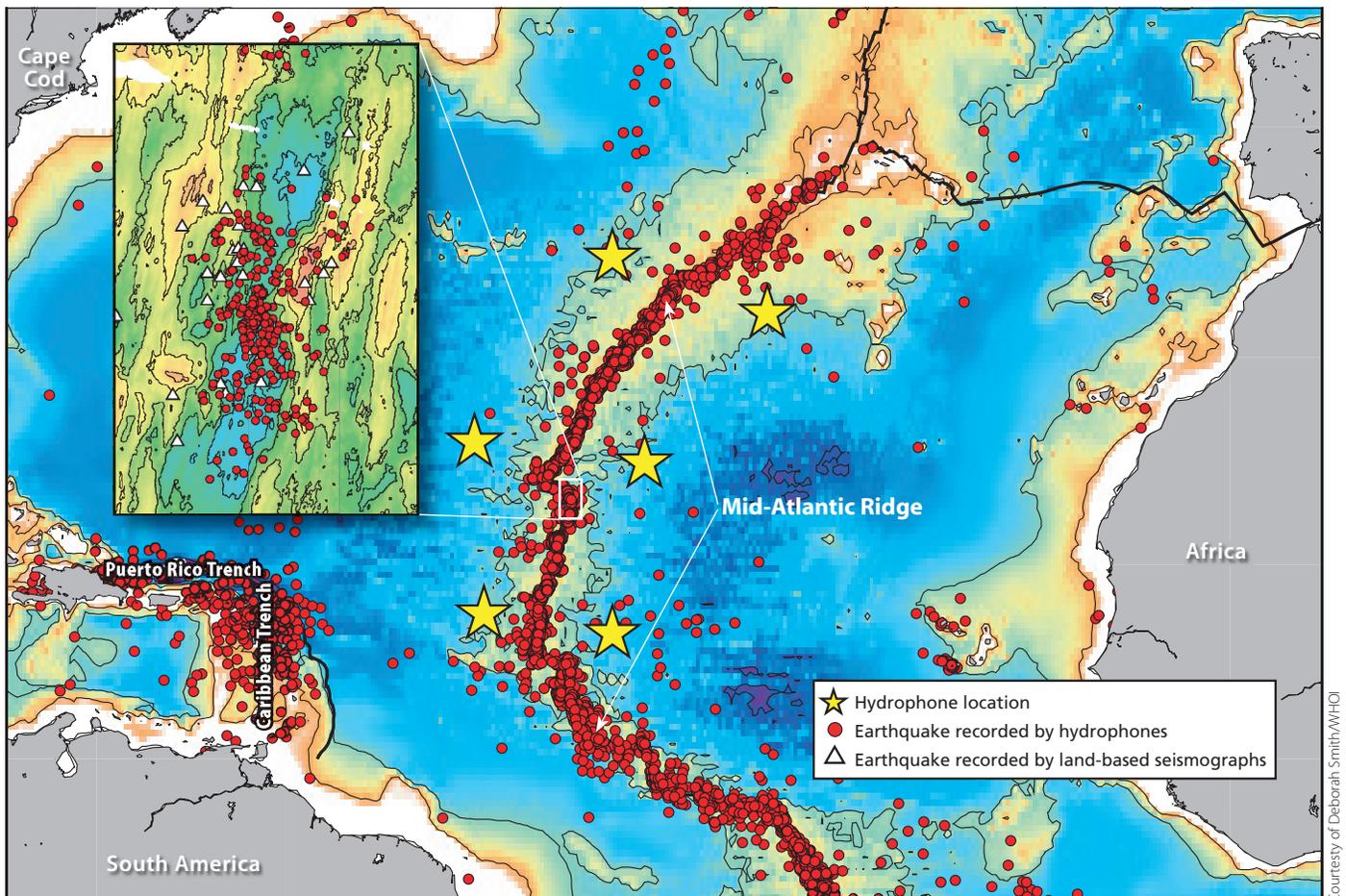
The test confirmed Ewing's theory that low-frequency sound waves were less easily scattered or absorbed by water and could travel far without losing energy. The key, however, was the discovery of a layer of water in the ocean that acted like a pipeline to channel low-frequency sound and transmit it over vast distances. This sound pipeline, called the SOFAR (Sound Fixing and Ranging) channel, was independently discovered by Russian scientist Leonid Brekhovshkikh, working simultaneously with underwater explosions in the Sea of Japan.

The key to the SOFAR channel is that sound energy, traveling in waves, speeds up in waters where temperatures are warmer (near the surface) or where pressure is higher (at depths). But in between lies the SOFAR channel, which is bounded by water layers where sound velocities increase. The boundaries act like a ceiling and floor: When sound energy enters the channel from below, it slows down. When it hits the ceiling, it does not keep going, but rather it is refracted back downward. Then it hits the floor, and it is refracted back upward.



*New hydrophone arrays have been developed to detect and monitor previously "unheard" volcanic and earthquake activity in the oceans. They are deployed in the SOFAR channel, a layer of water in the ocean that channels sound waves generated by seismic events and allows them to be transmitted and detected thousands of miles away.*

Jack Cook/WHOI Graphic Services



Courtesy of Deborah Smith/WHOI

An array of six hydrophones (yellow stars) recorded 7,785 seismic events (red dots) between 1999 and 2002, mostly along the Mid-Atlantic Ridge and the Puerto Rico and Caribbean Trenches. A close-up of one portion of the ridge reveals that land-based seismographs recorded far fewer seafloor seismic events (white triangles) over a much longer period (26 years).

In this way, sound is efficiently channeled horizontally with minimal loss of signal over thousands of kilometers.

The Navy immediately saw the value of the SOFAR channel, launching Jezebel, which later became the Sound Surveillance System, or SOSUS. It deployed a network of underwater microphones, called hydrophones, connected by undersea cables to onshore facilities. The hydrophones were installed in locations to optimally exploit the SOFAR channel. The Navy could detect radiated acoustic energy of less than a watt at ranges of several hundred kilometers—a sensitivity that often could distinguish the number of propellers a submarine had.

The fall of the Berlin Wall in 1989 marked the end of the Cold War, and in 1991, the Navy declassified SOSUS and

entertained the idea of allowing scientists to use it for basic research. Scientists at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (PMEL) in Seattle had the clever idea of using the Northeast Pacific Ocean SOSUS array to detect low-level seismic waves on the Juan de Fuca Ridge off the Pacific Northwest. The waves were generated by magmatic eruptions or rocks slipping along faults to cause earthquakes.

But since SOSUS covered only a portion of the world ocean, PMEL launched a strategy to develop moored, autonomous hydrophones that could be deployed for long durations in the SOFAR channel to monitor seismicity in more remote ocean regions. In 1996, PMEL deployed long-term hydrophones in the eastern

equatorial Pacific between 20°N and 20°S and began monitoring them successfully. That led me to ask if NOAA could deploy similar hydrophones in my neck of the woods—the North Atlantic Ocean.

With support from the National Science Foundation, our research team—myself, Christopher Fox and Haru Matsumoto of NOAA PMEL, and Maya Tolstoy of Lamont-Doherty Earth Observatory, and later Robert Dziak of NOAA PMEL and Oregon State University—deployed six autonomous hydrophones, designed and built by NOAA's PMEL, in the North Atlantic in 1999. In a sweet coincidence, we used Lamont's ship, R/V *Maurice Ewing*, named after the SOFAR channel's co-discoverer. We placed the six hydrophones on the flanks of the Mid-Atlantic Ridge between 15° and 35°N—

three on each side, each spaced about 550 nautical miles apart.

### Eavesdropping on the earth

We selected this section of the Mid-Atlantic Ridge because it has been studied intensively over many years, beginning with the famous FAMOUS (French-American Mid-Ocean Undersea Study) Project in 1974—the first expedition using human-occupied vehicles to explore a mid-ocean ridge—and more recently by the French-American Atlantic Ridge project, which extended from 15° to 40°N.

The entire length of the ridge in this region, as well as a few areas extending onto the ridge flanks, has been surveyed using multibeam sonar. This provides detailed bathymetric maps that give scientists the seafloor equivalent of the lay of the land. In addition, the area includes several sites, such as the TAG hydrothermal vent field, where detailed multidisciplinary investigations are taking place.

All of these studies provide a framework—a wide view and select close-up images of the region—on which we now can superimpose a soundtrack of seismic events. By combining these data, we can correlate the occurrences, locations, and timing of various seismic events with the seascape on which they are occurring.

We can begin to unravel, for example, a whole series of questions and cause-and-effect relationships: How frequently does magma erupt on mid-ocean ridges, and in which locations? And how do these temporal and spatial patterns influence the geological landscape, and vice versa? Where and when do different magnitudes of earthquakes occur? Can they give us clues to help us predict where and when earthquakes will likely occur on land?

### An unheard seismic symphony

The ability to attack all these questions hinges on getting good hydrophone data. In short, the array worked beautifully. Between 1999 and 2002 the Mid-Atlantic hydrophones recorded 7,785 seismic events in the study area—more than five

times as many as were recorded by seismometers on land.

The hydrophones also detected seismic events that release energy at levels 1,000 times less than events detected by land-based seismometers (down to magnitude 2.5). These events, mostly small faults moving, previously fell on the deaf ears of land-based networks, which do not detect seafloor seismic events smaller than about magnitude 4.5.

This data set provides us with an unparalleled view of the seismicity of the ridge over a broad region and over a broad range of event magnitudes. Joined by new collaborators—DelWayne Bohnenstiehl of Lamont-Doherty and Javier Escartin, Mathilde Cannat, and Sara Bazin of the Institut de Physique du Globe de Paris—we have begun to piece together temporal and spatial patterns of seismic events, which, in turn, can shed light on fundamental planet-shaping processes that occur at the ridges.

### Stripes and gaps

Initial results show areas on the ridge with intense and persistent seismic activity, which we call “stripes,” that stand in sharp contrast with areas that lack seismicity, which we call “gaps.” Our hypothesis is that the “stripes” correspond to areas where the crust is thicker, colder, and more brittle. In these places, stress builds in rocks until a threshold is reached and the rocks slip suddenly, causing earthquakes. The gaps represent areas where the crust is hotter and thinner, and stress is more easily accommodated by deformation in the rocks, perhaps producing

earthquakes too small to be detected by hydrophones. (See “Peering into the Crystal Fabric of Rocks,” page 57.)

The gaps might also turn out to correlate with the presence in the crust of a type of rock called serpentinite, which is more slippery than other crustal rocks. It slides rather than breaks, and therefore reduces the probability of earthquakes. Clues like these, discovered on the seafloor, could apply to land and aid in the quest to forecast where earthquakes are more likely to occur. (See “Earthshaking Events,” page 48.)

On a small scale, the distribution of seismicity on mid-ocean ridges has important implications for hydrothermal vents and their biological communities because magmatic eruptions initiate, maintain, and destroy them. (See “The Evolutionary Puzzle on the Seafloor,” page 76 and “Is Life Thriving Beneath the Seafloor?” page 70.)

On a larger scale, we are analyzing seismic patterns to find clues that will more precisely reveal the directions in which three of Earth’s great tectonic plates are moving. A cruise in 2005 will investigate a telltale area of high seismicity that we discovered 70 kilometers west of the Mid-Atlantic Ridge between 12.5° and 13.5°N, which we hope will reveal the location of the triple junction where the South American, North American, and African Plates all meet.

Long-term hydrophone arrays have given us our first glimpse of the robust seismic activity rumbling on the seafloor. As seismic monitoring continues and expands into other oceans, we will accumulate a treasure-trove of new information to explore the earth.



Deborah Smith grew up in the cornfields of Illinois. She now travels to the far reaches of land and sea to investigate how volcanoes are built. She has hiked through tropical plants in Hawaii and Tahiti and over the cold, barren terrain of Iceland. She has mapped underwater volcanoes along a mid-ocean ridge at the location where one can’t be farther away from land and still be on the planet: halfway between New Zealand and South America. In an effort to share the experiences of scientists with the general public, she has developed a Web site that profiles the careers of women oceanographers (<http://www.womenoceanographers.org>).