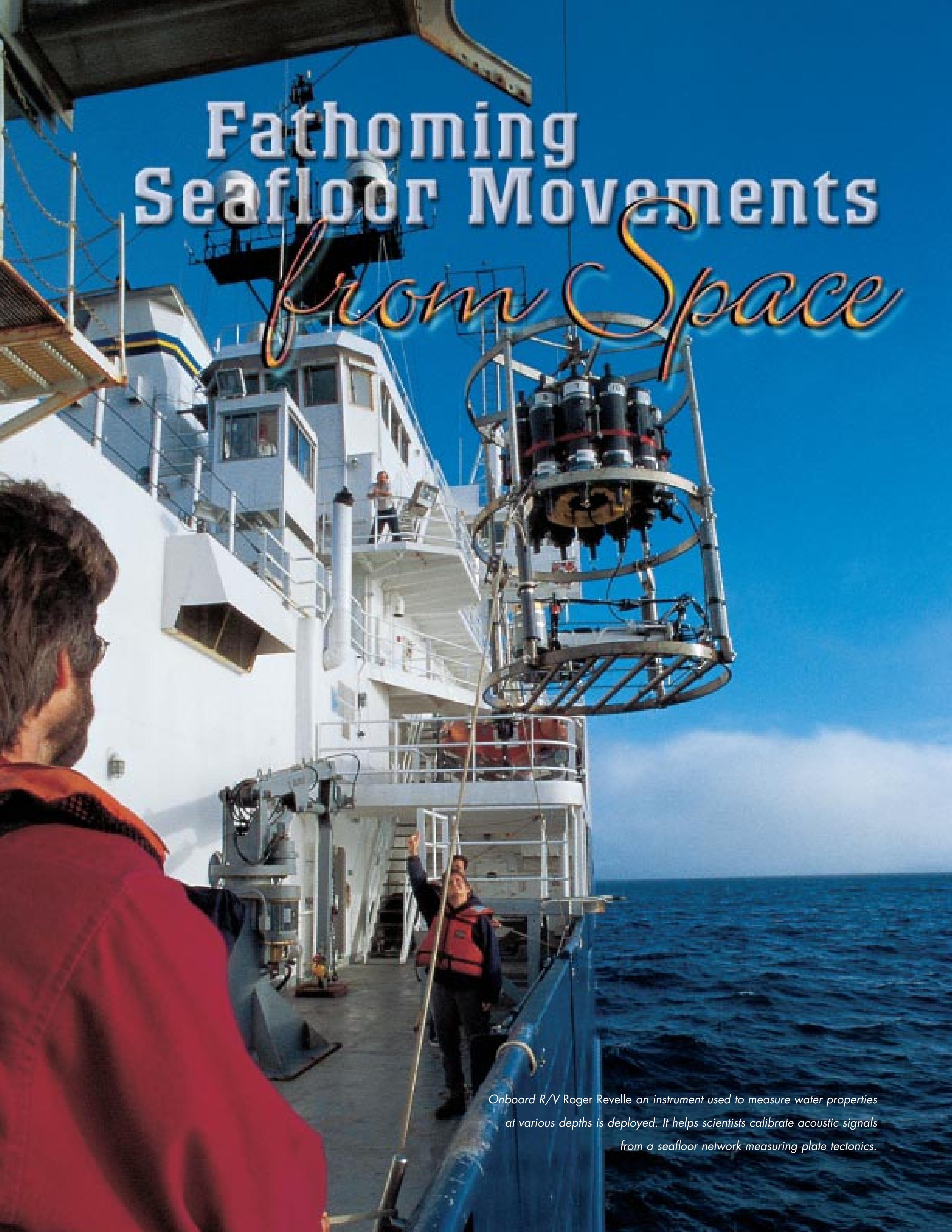
Fathoming Seafloor Movements *from Space*



Onboard R/V Roger Revelle *an instrument used to measure water properties at various depths is deployed. It helps scientists calibrate acoustic signals from a seafloor network measuring plate tectonics.*

Scripps Researchers Achieve Earth Science Milestone

BY CHUCK COLGAN

Above, *Chief scientist Fred Spiess.* **Right,** *Global Positioning Satellite antenna on R/V Roger Revelle.*

Just after the most recent rainsquall passes and the last sun rays vanish into an endless ocean horizon, Scripps research vessel *Roger Revelle* comes a halt some 200 miles (320 km) off the Washington/Oregon coastline.

On deck, a late-August wind stiffens as about a dozen scientists, students, and technicians don jackets and safety vests and divide into small groups. Old hands guide new as the groups begin setting up and calibrating a variety of sophisticated instruments—some to be deployed into the deep sea and others to be mounted on the ship.

Chief scientist onboard is Dr. Fred Spiess, one of Scripps's most prominent geophysics professors, who at age 80 is overseeing an operation that is about to measure the motions of tectonic plates beneath the oceans with greater accuracy than ever before. Spiess and colleagues hope to verify a method that will yield new details about the dynamics of Earth's crust on a global scale, including information on seismic strain and earthquake potential.

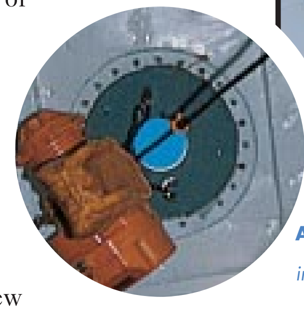
By combining measurements from instruments on the seafloor and in space, Spiess and his research collaborators are taking advantage of two diverse technologies, which, Spiess admits, "is not a big deal in theory, but a very big deal in engineering and costs."

TRACKING PLATE TECTONICS

The past decade has seen a revolution in how movements of Earth's crust are studied. The Global Positioning Satellite (GPS) system, best known as a means for airline pilots, sailors, and hikers to determine their locations, has given scientists a new tool. By marking fixed locations on land and using GPS to monitor the distances between the positions, the scientists can determine if and where the Earth's surface is moving to within an accuracy of a half inch over distances of hundreds of miles.

This GPS information reveals minute details of the crust's stretching and folding far more accurately and over larger areas than traditional survey techniques. GPS has become a cornerstone for the study of crustal deformation, and GPS monitoring networks have been set up along many major earthquake faults. However, GPS radio signals do not pass through water, which covers nearly three-quarters of Earth's surface and virtually 90 percent of all major tectonic plate boundaries. GPS is useful in the oceans only where there are islands on which to anchor GPS instruments.

Measurements of seafloor plate tectonics were first made by oceanographers conducting geomagnetic surveys in the 1950s. They discovered the process of seafloor spreading, where new crust is created along volcanic ridges, slowly moving the tectonic plates apart. They could chart plate motions over geologic time scales of thousands and millions of years, but couldn't survey the seafloor with the same detail as on land. To penetrate the oceans to study the earth below would require completely new technologies.



Above, *Nicole Olivares, a UCSD student, uses a survey instrument to position the GPS antennas with the acoustic transducer that is lowered through a hole (left) to extend beneath the ship's hull (bottom, opposite page).*

In the 1960s, Spiess and other researchers pioneered the use of acoustic instruments called transponders for seafloor navigation. Transponders are electronic devices that respond to sound signals in ways that allow the distances between them and the acoustic source to be determined. By placing a network of transponders on the seafloor, the scientists could precisely guide instruments towed from a ship through the survey site. Over the years, in Spiess's lab, more precise transponders and the mathematics to support them were developed, and at-sea experiments verified their increased accuracy.

John Hildebrand makes final calibrations on an acoustic transponder before it is lowered to the deep seafloor.

"In the future we foresee the possibility of establishing 30 or so ocean observatories consisting of geophysical and oceano-

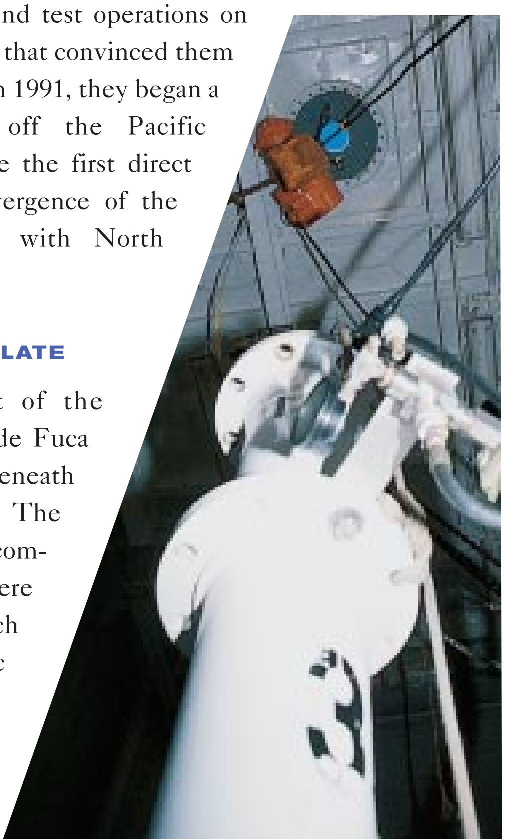
Every day at sea is an adventure for Fred Spiess as he oversees deployment of the acoustic network and the data collection. **Lower left**, *He checks bathymetry charts with his co-investigators David Chadwell (center) and John Hildebrand (right).*

In the late 1980s, Spiess and John Hildebrand, a professor of geophysics at the Marine Physical Laboratory, devised a strategy to combine seafloor transponders with GPS measurements. They conducted a series of development and test operations on the seafloor off San Diego that convinced them that the idea was viable. In 1991, they began a series of expeditions off the Pacific Northwest Coast to make the first direct observations of the convergence of the Pacific Ocean seafloor with North America.

THE JUAN DE FUCA PLATE

Over eons, a segment of the seafloor called the Juan de Fuca Plate has been plunging beneath the North America Plate. The Juan de Fuca Plate is completely submerged, so there are no islands from which to study its tectonic motions.

The Juan de Fuca Plate extends north from southern Oregon to Vancouver Island, British Columbia, offshore about 250 miles (400 km). Its western border is a nearly 300-mile-long (480-km) ridge, which in simplified terms is a fault, or rift, in the seafloor more than a mile below the sea surface. Its eastern border is a subduction zone, where the Juan de Fuca Plate slowly crashes into and under the Pacific Northwest, forming the Cascade Mountain Range and a line of active volcanoes in Oregon and Washington. This slow-motion collision also carries with it the potential for earthquakes on a grand scale. Spiess and Hildebrand's goal was to install a series of acoustic networks at strategic locations along the Juan de Fuca Plate and to use GPS to tie the seafloor data to extremely accurate satellite positioning. The alignment of the instruments



David Chadwell (left) and Dave Jacobson (right) carry the transponder to the winch. ***Below,*** *John Hildebrand runs the winch while Tammy Baiz handles the cables and lines.*

and the data processing were extremely complex.

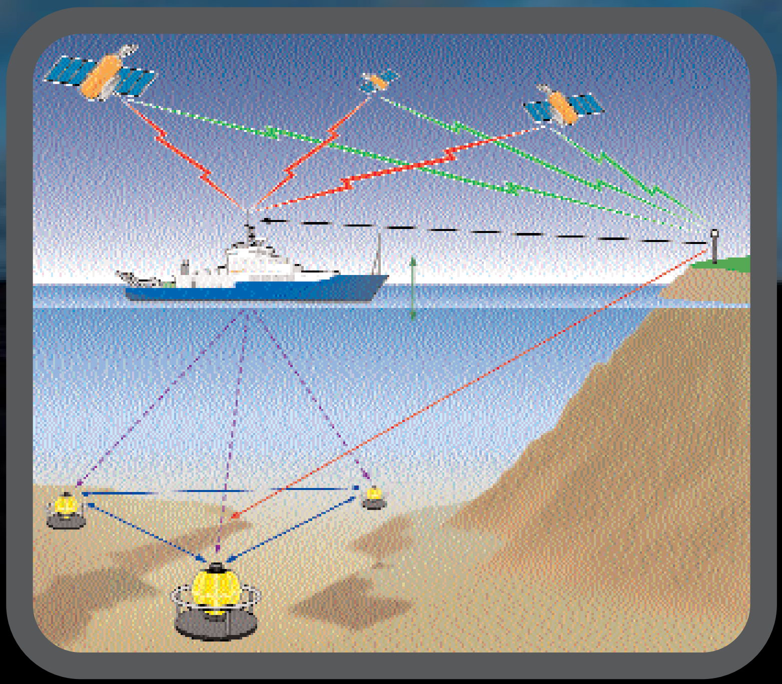
Installing the network involves deploying three or more precision transponders on the seafloor about two miles (3-4 km) apart around a three-mile (4-5 km) diameter circle. At the surface, three well-separated GPS antennas are mounted atop tall towers on the ship, and an acoustic transducer is attached to the bottom of the ship to send signals to the transponders below. A laser survey instrument is used to precisely fix the locations of the antennas and the transducer relative to each other. On shore, one or more GPS receivers at known reference points complete the system.

The ship is positioned above the center of the seafloor array. By correlating the land-based and shipboard GPS signals, the exact location of the transducer is determined at the split second that it transmits to the transponders below. The signal is received by each transponder and then retransmitted to the ship. Using elaborate mathematical models that average together several thousand signals, it is possible to determine the position of the seafloor transponders, relative to themselves and the shore stations, to within a fraction of an inch.

Because ship time is expensive, the researchers were limited to one cruise about every other year beginning in 1991. The early trips were mostly engineering efforts, which led to more sophisticated instrument designs and advanced number-crunching techniques. At four sites on the more recent expeditions, Spiess and Hildebrand installed transponder networks that can be switched on when the ship is in place and ready to collect data.

In 1997 Spiess and Hildebrand added a third member to their team, David Chadwell, who received his doctoral degree in the relatively new field of satellite geodesy. Chadwell saw a tremendous challenge in transferring techniques for terrestrial geophysics to the seafloor.

GPS/Acoustic Network—Transponders on the seafloor communicate together and with the ship. Antennas onboard receive signals from Global Positioning Satellites and from receiving stations on land. Vector components of the signals determine location of the seafloor array relative to known points ashore. **Left,** *At night a transponder is deployed (top) and a weather balloon is launched (bottom).*



"With water covering almost all spreading centers and most subducting plate edges, only seafloor monitoring gives us a way to observe the strain patterns at these sites and to improve our understanding of the global dynamics of the crust," Chadwell said.

THE EXPEDITION

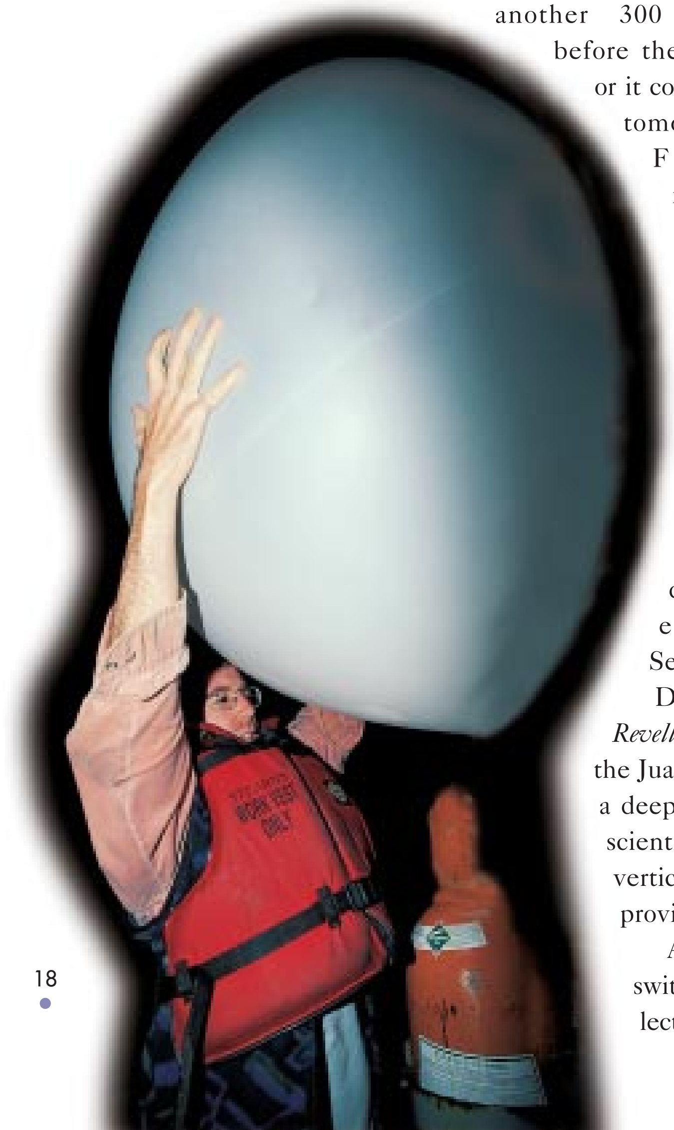
Onboard R/V *Roger Revelle*, the evening meal is finished and a science meeting is being held in the ship's library.

The group gathers around a conference table, with a stack of bathymetry maps depicting the Juan de Fuca Ridge, which is a mile below them. It is a narrow, volcanic caldera framed on either side by ridges about 400 feet (120 m) high. The ridge is punctuated by small, underwater volcanoes and rocked by minor earthquakes.

Hildebrand leads a discussion of the region's seismology and earthquake history. Generally, the spread of Juan de Fuca's motions over geologic time proceeds at a rate comparable to the growth of fingernails, but in the process strains build up that can trigger major earthquakes. He points out that although earthquakes

in the Pacific Northwest region of North America are few and relatively small, there is potential for large-scale earthquakes, the last of which occurred in January 1700. "There are written accounts of a tsunami destroying villages in Japan, and at places along its Northwest Coast you can find tree stumps that once grew on land but are now submerged in saltwater marshes," Hildebrand said. "According to written accounts and geological evidence, the earthquake must have been a magnitude of 8 to 9."

Hildebrand reports a cycle of large-scale earthquakes occurring about every 600 years in the Cascadia region in the Pacific Northwest, so it could be another 300 years before the next, or it could be tomorrow. For now, he says, the Juan de Fuca is "saving up energy for a big one." And unlike 1700, today the Pacific Northwest is dotted with heavily populated cities such as Portland, Seattle, and Vancouver.



During the two-week expedition, R/V *Roger Revelle* travels to the four instrumented sites on the Juan de Fuca Plate. New for these experiments is a deep-sea video camera system, which will allow the scientists to remotely determine the exact horizontal and vertical orientation of the transponders on the seafloor, providing the most accurate measurements to date.

At each site, the transponder network is remotely switched on and the ship's computers continually collect data for two to three days.

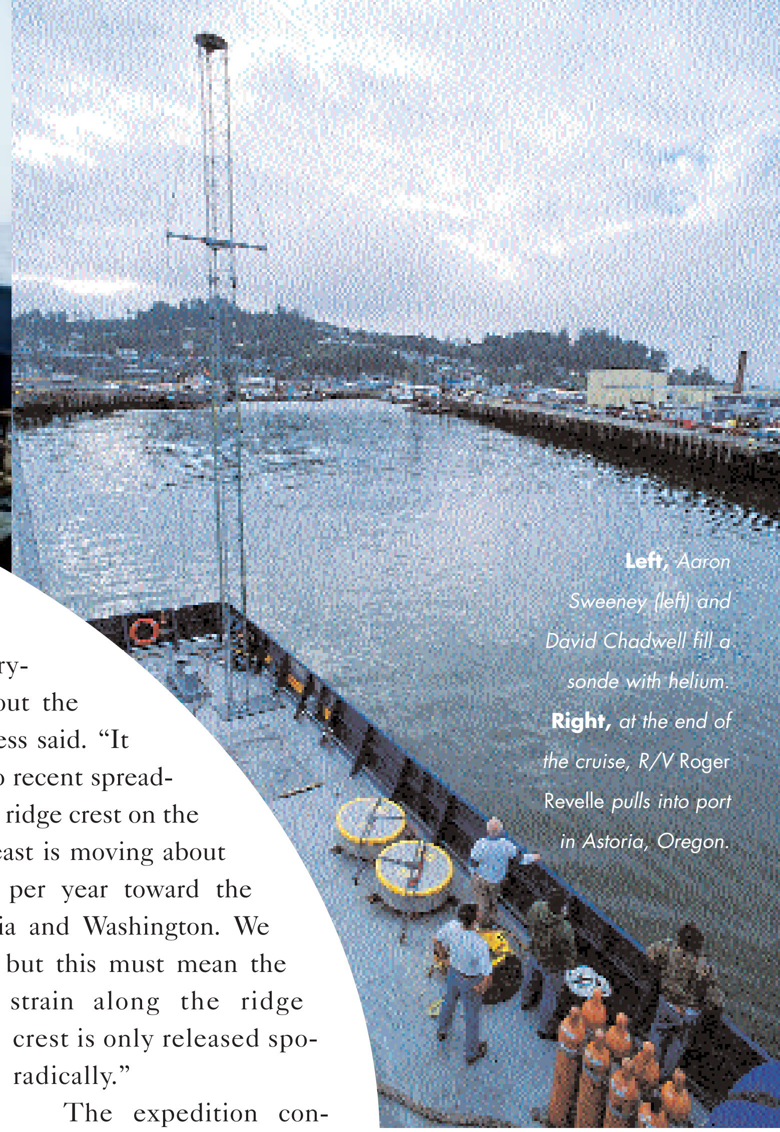
Tammy Baiz: Resident Technician

Perhaps the most unusual job on R/V *Roger Revelle* is that of a resident technician. Part scientist, part mechanic, part diplomat, and all sailor, it requires just the right person. Meet Tammy Baiz.

As resident technician, Tammy is the link between the ship crew and the scientists. Her primary responsibility is the mission of each science party. This might be dredging rocks from the seafloor one week or taking water samples around the clock the next, all the while overseeing every scientific activity on deck and instructing beginners in at-sea safety and procedures.

A Kentucky native, Tammy did not see the ocean until she was a teenager, yet she had always wanted to be an oceanographer. Pursuing her dream, she received a B.A. in marine biology from Occidental College in Los Angeles. However, prior to obtaining her degree, Tammy realized she was more interested in the hands-on aspects of ocean science. After graduation, she became a marine biology instructor and shipboard lab technician at the Orange County Marine Institute in Dana Point, California.

In 1995, Tammy joined Scripps's Shipboard Technical Support Group, spending about half of each year at sea and the other half preparing for the next cruise. Being away means she misses daily contact with family and friends, but Tammy has managed to get around this by marrying another resident technician with the Scripps fleet, Shad Baiz. They both love life at sea, and the variety of each expedition.



Left, *Aaron Sweeney (left) and David Chadwell fill a sonde with helium.* **Right,** *at the end of the cruise, R/V* Roger Revelle *pulls into port in Astoria, Oregon.*

Work begins early and continues around the clock. In the computer room, three people at a time on four-hour watches monitor the incoming signals. Every two hours, the team cycles a water-sampling device from the ocean surface to the seafloor so that the physical properties of the water can be taken into account when calculating the acoustic signal travel times. Every six hours, a weather balloon, or sonde, is launched from the deck into the upper atmosphere so that the effects of water vapor on the GPS signals can be substantiated. Literally millions of measurements are taken each day to answer these questions: How fast is the plate moving and where is it headed?

"We're in the process of trying to answer questions about the Juan de Fuca right now," Spiess said. "It appears that there has been no recent spreading on the southern part of the ridge crest on the west, yet the seafloor to the east is moving about 4.5 centimeters (1.8 inches) per year toward the northeast off British Columbia and Washington. We don't know the implications, but this must mean the strain along the ridge crest is only released sporadically."

The expedition concludes as R/V *Roger Revelle* pulls into port on a foggy morning in Astoria, Oregon, along the Columbia River. The science group works intensively all day to disassemble and pack up its instruments and computers.

The wrap-up is difficult, but the urgency is over. The scientists have their numbers and data that prove they can monitor crustal motion on the seafloor within GPS accuracy. There's a satisfaction, Hildebrand said, in "doing something that no one else has the capability to do."

The work is far from done, however. Hildebrand will be using the system to study the seafloor southeast of the big island of Hawaii, and Chadwell is taking it to South America to monitor subduction of the Nazca Plate off Peru. And someday there may be more permanent installation strategies for continuous monitoring elsewhere.

"In the future, we foresee the possibility of establishing 30 or so ocean observatories consisting of geophysical and oceanographic seafloor instruments, with moored buoys at the surface to provide real-time telemetry links to shore by way of satellites," Chadwell said. "That would bring us much closer to our goal of understanding crustal dynamics on a global scale."