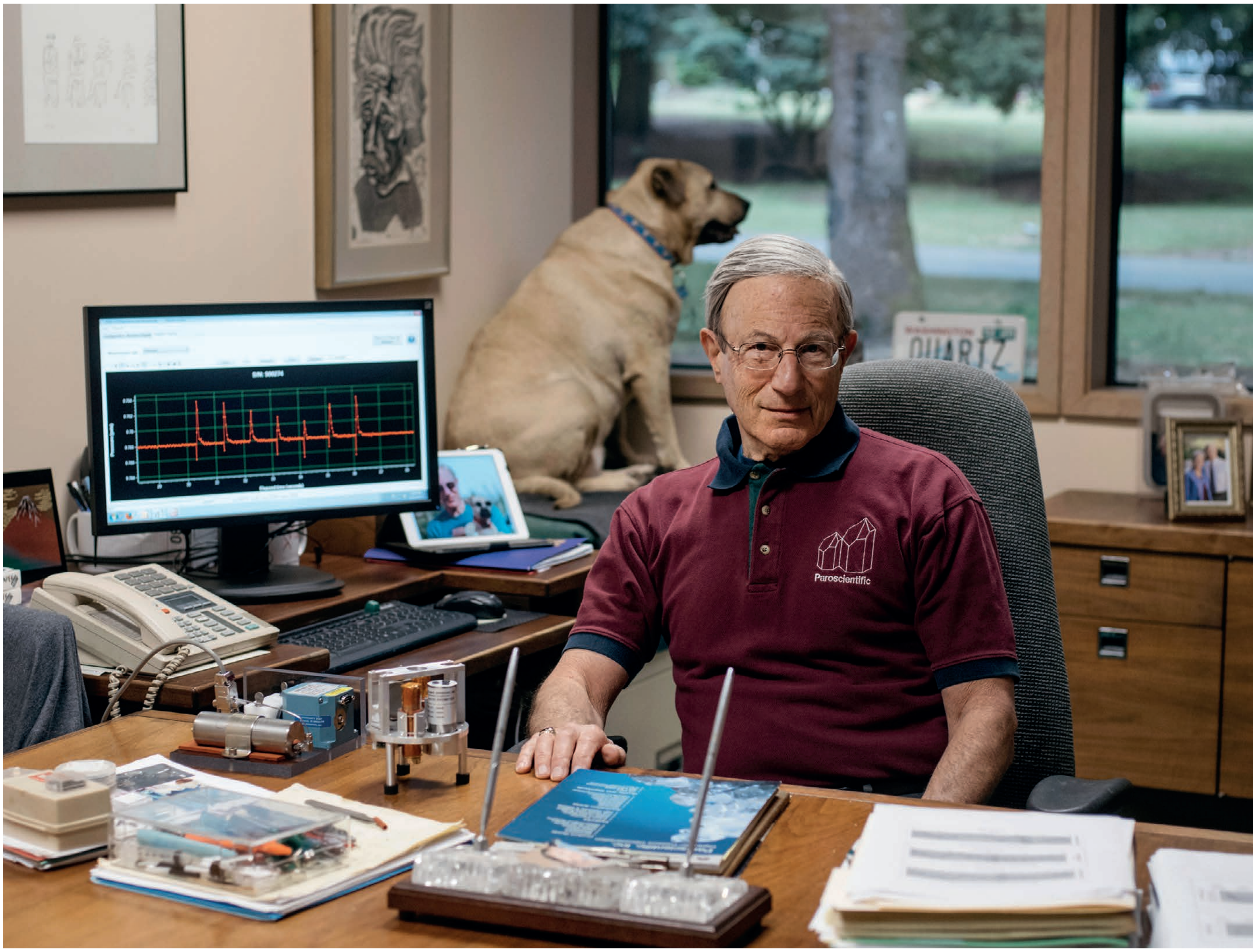


Inventor Jerry Paros has developed quartz sensors that are helping researchers to detect movements of the sea floor to within about 1 centimetre.

Quake quest

Networks of precision sea-floor sensors could help coastal nations to prepare for the next giant earthquake.

BY ALEXANDRA WITZE

Jerry Paros is worried about the geological time bomb ticking away just off the coast near his home in Washington state. But unlike the millions of people who fear the earthquake and tsunami that will one day rock that region, Paros is doing something about it. His company made millions of dollars building exquisitely precise quartz sensors for oil, gas and other industry applications. Now he wants to use them to save the world from natural disasters.

At the Redmond headquarters of his company, Paroscientific, the 79-year-old inventor picks up a volleyball-sized metallic rack from a table, lifts it to shoulder height and then lowers it. Inside the contraption, sensors pick up the tiny change in atmospheric pressure as the device travels up and down. "Here, I'll give you a very expensive doorbell," he says, opening and shutting the office door to change the air pressure yet again. In the air, Paros's instrument can register such delicate shifts in pressure. But the ultimate destination of this device is offshore, a few kilometres below the waves, where it will sense the weight of the water above it to detect changes in the depth of the sea floor.

IAN C. BATES FOR *NATURE*

Paros wants his ultra-precise gauges to be the heart of an early-warning system designed to detect when an earthquake shifts the sea floor, unleashing a tsunami. He has donated US$2 million to the University of Washington and collaborated with its researchers to test the sensors off the coastline of the Pacific Northwest.

Many other coastal nations, including Japan and Chile, are working to monitor the movements of the ocean bottom, an effort known as sea-floor geodesy. They are racing to install sensors because geological faults in these regions produce the most powerful earthquakes on the planet — and some of the most devastating disasters. In 2004, a subsea quake off Indonesia triggered a tsunami that killed nearly a quarter of a million people.

Geophysicists have long struggled to get a handle on the behaviour of offshore faults, but sensors such as the one created by Paros are giving them their first opportunity to spy on geodetic movements of the 70% of Earth's crust that is covered by water, making it inaccessible to standard tools. These networks could reveal which parts of undersea faults are slipping harmlessly and which parts might be storing energy for the next big quake.

"It will help us answer the big question of where are those zones," says Emily Roland, an oceanographer at the University of Washington in Seattle, who works with Paros. "It's the thing that we've been missing."

SLEEPING GIANT

When Paros first moved to the Pacific Northwest in 1970, few recognized the region's risk for giant earthquakes. The largest shock in the region's recorded history was a magnitude-7.1 jolt that struck Olympia, Washington, in 1949. But by the late 1980s, researchers started to uncover signs that the entire coastline from northern California to southern British Columbia in Canada can experience magnitude-9 earthquakes and giant tsunamis. The source of danger lies about 50 kilometres offshore, where one patch of Earth's outer shell dives beneath another. Called the Cascadia subduction zone, this junction is 1,000 kilometres long and is part of the 'ring of fire', a series of similar features that encircle the Pacific Ocean. Subduction zones produce the biggest earthquakes ever measured, including the record-setting magnitude-9.5 quake in Chile in 1960. In 1700, Cascadia ruptured in an estimated magnitude-9 quake, releasing a tsunami that annihilated villages along the Cascadian coast and raced across the Pacific Ocean, drowning people in Japan as well.

Seismologists aren't sure when the next big one might strike Cascadia. It could be tomorrow, or it could be centuries from now. At other subduction zones, scientists monitor geological activity and assess the risk of future big quakes by listening to the patterns of smaller ones. Cascadia, however, is "eerily quiet", says Kelin Wang, a seismologist at the Geological Survey of Canada in Sidney, British Columbia. It experiences very few of the small quakes that might otherwise illuminate how the two tectonic plates are moving against one another. That makes Cascadia something of a sleeping giant — and a dangerous one, with major cities such as Portland and Seattle at risk.

On land, engineers can use measurements from the Global Positioning System (GPS) to track the more subtle signs of geological unrest — including the ground uplifting around a volcano before it erupts, or rocks sliding along major geological faults, such as the San Andreas fault in California. But making these measurements on the sea floor is difficult and expensive. Only in the past few years has sea-floor geodesy started to catch up with its land-based counterpart, thanks to new tools and innovative ways to deploy them in the ocean (see 'Underwater threat').

"We've kind of exhausted the information from land-based observations."

From New Zealand and Japan to Chile, geophysicists are working to understand the long-term geological risk and to develop ways to alert coastal communities about earthquakes and tsunamis that have already begun. Much of the work is based on government-funded networks of sea-floor sensors. Other networks have private support, from funders such as Paros. Six of his quartz pressure sensors currently rest on the sea floor off Oregon, monitoring which parts of Cascadia are creeping along slowly and which parts are locked in place.

From GPS measurements on land, geophysicists have developed two competing models for Cascadia (G. M. Schmalzle *et al. Geochem. Geophys. Geosyst.* **15,** 1515–1532; 2014). In one, the descending tectonic plate is moving very slowly beneath the upper plate, releasing strain as it creeps along. In the other, the two plates are locked together, allowing the dangerous build-up of strain.

TAKE THE STRAIN

Using only land-based instruments, there is no way to tell which of the models is correct — if either. "We just don't know to what degree it's locked," says Wang. "That's why we need offshore measurements. We've kind of exhausted the information from land-based observations."

From time to time, oceanographers have peppered Cascadia's sea floor with monitoring instruments. A team led by the University of Washington and the Scripps Institution of Oceanography in La Jolla, California, has been working to create a system that can measure movements of the sea floor over time and identify the nature of the threat. Key to that work is Paros's quartz sensor.

Fifty years ago, Paroscientific began developing quartz sensors to measure physical factors such as acceleration, pressure changes and temperature. The sensors rely on the piezoelectric qualities of quartz — it generates an electrical charge when squeezed. When sent down to the sea floor, a Paroscientific pressure sensor measures the changing pressure of the water column above it. After correcting for factors such as waves and tides, oceanographers can detect up or down movements of the sea floor to within about 1 centimetre.

Paroscientific is one of many companies that manufacture oceanographic pressure sensors. But Paros himself is an unusual mix: an entrepreneur-turned-amateur-scientist, who now hobnobs with many of the region's leading geophysicists. "Jerry likes interacting with the engineers and technically minded scientists," says William Wilcock, a marine geophysicist at the University of Washington. "He really does push the community forward with his single-minded desire to get this done."

As early as 1983, Paroscientific sensors were sent out into the Pacific as part of the US National Oceanic and Atmospheric Administration's tsunami-observing system. In 2006, shaken by the devastation of the Indian Ocean tsunami two years earlier, Paros gave $1 million to the University of Washington to stimulate research in sensor networks. That money, plus another $1 million in 2012, helped university researchers to design and test new generations of ocean-bottom pressure sensors (G. Sasagawa and M. A. Zumberge *IEEE J. Ocean. Eng.* **38,** 447–454; 2013).

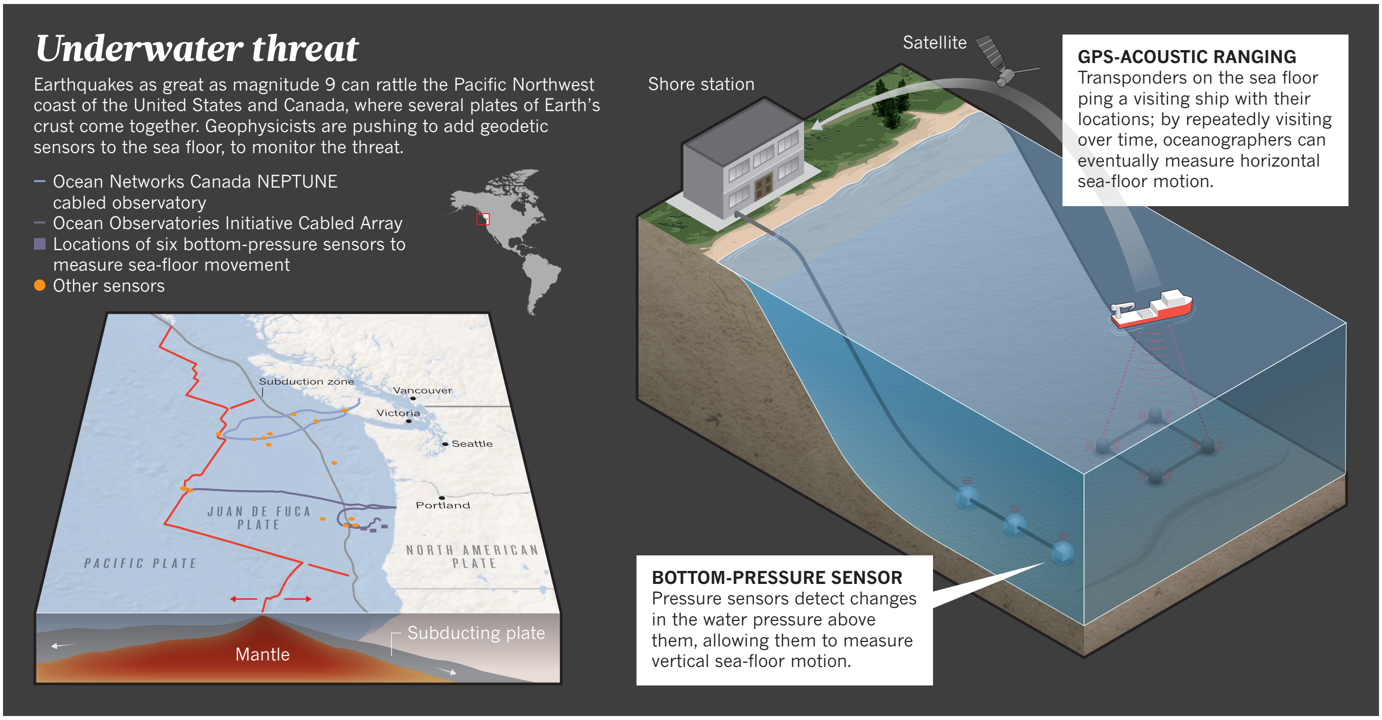
The latest ocean-bottom gauges developed by the Scripps–Washington team are arranged in a rough line from near the Oregon coast all the way to the subduction zone. They rest there quietly, taking the pulse of the water above them. Researchers can compare those data to their models of how Cascadia is slipping. "Within a decade, we will know if the fault is locked," says Wilcock, who helps to lead the effort.

But even the best pressure sensors can reveal only one aspect of sea-floor motion — up and down. They cannot detect horizontal shifts. For that, researchers must turn to a different technique, which involves two or more transponders that sit 2–3 kilometres apart on the sea floor. Every year or so, scientists visit the transponder locations by ship, and ping acoustic signals to the devices. By measuring the time it takes for the signals to travel through the water, the researchers can tell whether the transponders have shifted relative to one another since the last visit, and hence whether the sea floor has moved horizontally.

THE SOUND OF MOVEMENT

This type of sea-floor acoustic ranging is used around the world. The GEOMAR Helmholtz Centre for Ocean Research in Kiel, Germany, installed such a network along the subduction zone off Chile in late 2015, to monitor earthquake threats there. Japan's coast guard spends months every year collecting data at dozens of sites off the country's coastline. And by using autonomous vehicles called wave gliders to gather data, rather than using ships, the studies can be done at a fraction of the cost, says David Chadwell, a geophysicist at Scripps. "It's been a transformation," says Chadwell, who has been testing the wave gliders off Oregon and hopes soon to bring them into wider use.

To understand Cascadia's true danger, geophysicists need to deploy many types of tool, including seismometers as well as geodetic instruments, both offshore and on land. But geophysicists debate where to place these sensors and how many of each type would be ideal. The



SOURCES: WILLIAM WILCOCK/UNIV. WASHINGTON; R. BÜRGMANN & D. CHADWELL *ANNU. REV. EARTH PLANET. SCI.* **42**, 509–534 (2014).

disagreements sometimes come down to a split between those pursing basic research and those focusing on developing early-warning systems for earthquakes and tsunamis. The University of Washington researchers hope that their network can serve both groups. "We need to, and can, make these scientific instruments serve multiple purposes, advancing scientific understanding as well as monitoring for hazards," says seismologist Heidi Houston, who is also at the University of Washington but not part of the sensor-network effort.

In early April, during a damp couple of days on the University of Washington campus, leading researchers gathered to brainstorm about the best way to monitor Cascadia's danger. After two days of talks, the attendees broke into small groups to design their ideal network. Each group got a large printout of a Cascadia coastal map, a bunch of coloured pens and an exhortation to dream big. "Who's ready to draw?" asked Wilcock as he shepherded the groups into breakout rooms.

Some groups envisioned lines of sea-floor geodetic arrays off the coast, with wave gliders passing to collect data. Studded among them were seismometers to measure ongoing earthquake activity, and tsunami-alert buoys to warn of any dangerous waves. Other groups sketched powered cables laid across the sea floor, festooned with scientific instruments. Instead of using gliders or buoys to transmit data, these arrays would send their information back to shore directly through the cable.

> *"The problem with tsunamis that happen every 300 years is that you can't get much traction with officials."*

Two basic observatories already exist in Cascadia. The Ocean Observatories Initiative Cabled Array operates a 900-kilometre-long cable that runs from the coast of Oregon out to an underwater volcano and back again. On the northern side of the border, Ocean Networks Canada has a similar-length cable looping out to the subduction zone. Both carry geodetic and seismic instruments at several nodes along their length.

The cables dreamed up at the workshop would be a massive expansion of those. They would more closely resemble a $100-million Japanese sea-floor observatory called DONET-2, completed last year in the Nankai trough, part of a subduction zone near the cities of Osaka and Kobe. Its backbone cable runs for 500 kilometres and has 29 separate observatories studded along it, says Katsuyoshi Kawaguchi, the deputy director of the observatory at the Japan Agency for Marine-Earth Science and Technology in Yokosuka.

A second, even more ambitious project is under way in Japan to string 150 observatories along 5,700 kilometres of powered cable. The $320-million S-NET project is being installed in stages offshore, south of Hokkaido. The first segments began operating in May 2016, and the deepest-water section is being installed in the next few months. Each of the observatories includes Paroscientific pressure sensors at a cost of roughly $50,000 per package.

Data from both Japanese observatories feed into the nationwide early-warning system for earthquakes and tsunamis, which was radically beefed up after the 2011 Tohoku earthquake killed nearly 16,000 people. That event also sent a tsunami into the Fukushima nuclear power plant, triggering a reactor accident and a nationwide energy crisis.

One day, Paros would like to see his sensors peppering the sea floor off Cascadia as part of a broad monitoring network for natural hazards. "The problem with tsunamis that happen every 300 years is that you can't get much traction with local officials," he says as he drives around Seattle in a sensible car, his Ford Five Hundred, with personalized plates reading QUARTZ. And so he goes out among the scientists, working to get his pressure gauges into as many oceans as he can. Last week, University of Washington engineers deployed a new set of sensors on a small cabled sea-floor observatory off Monterey, California; it will remain there for a number of months for testing.

"I've been doing this Sisyphus thing, rolling the boulder up the hill, for so long," Paros says. "I just want to plant the seeds to show this is feasible, with the hope the government will recognize that this is an important public-safety issue." ■ SEE EDITORIAL P.451

Alexandra Witze *writes for* Nature *from landlocked Boulder, Colorado.*