COMMENT

CORBIS

SPACE Curbing Chinese space activity undermines US interests **p.444**

BRAIN Conspiracies, religions, coincidences, ghosts and patterns **p.446**

HEALTH The rise in height and lifespan during the industrial revolution **p.448**

MUSEUM Monaco exhibition showcases marine marvels **p.449**

H. NEW/REUTERS

The wave that hit Miyako City on Japan's east coast during the 11 March tsunami caught researchers by surprise.

Hidden depths

A staggering lack of undersea data hampers our understanding of earthquakes and tsunamis. Geophysicists must put more instruments offshore, says **Andrew V. Newman**.

The magnitude-9.0 Tohoku-Oki earthquake and tsunami that struck Japan on 11 March were devastating not just to the Japanese people, but also to the scientific community. Seismologists had underestimated the earthquake size by a factor of 4 or more, and the tsunami hazard by so much that the protective walls around the Fukushima nuclear power plant were overtopped.

The past 20 years have seen great strides in understanding earthquake faults and volcanoes, largely thanks to technological advances allowing a huge increase in ground-deformation measurements. Precise measurements of ground movement can provide nearly direct information about the strain energy accumulating along a fault, which can be released by a giant quake. The number of researchers interested in this field has skyrocketed.

But underwater monitoring lags behind. The tools for monitoring subtle ground movements rely largely on the Global Positioning System (GPS), and so only work when they have a clear view of the satellites they rely on. Their radio waves cannot penetrate water. This makes underwater monitoring expensive and time-consuming, so few opt for it. Instead, most of the community has been drawn to rely on cheaper, land-based tools for understanding earthquake behaviour, including that around underwater faults — where the real action happens offshore. Seismometers, which detect shaking during earthquakes, are routinely deployed on land and at sea. But ground-deformation monitors have been restricted almost entirely to land. Geophysicists are relying on the data they have rather than the data they need.

This needs to change. We must improve undersea monitoring and make it cheaper, increasing measurements of the sea floor 100-fold. By so doing, we will vastly improve both our understanding of plate-boundary dynamics and volcanic processes underwater, and our assessment of earthquake and tsunami hazards.

LOCKED AND LOADED

Earthquakes are the result of runaway release of stored strain energy from 'locked patches', where the tectonic plates get ▶



D. PARKER/SPL; EARTHSCOPE; J. WARK, VISUALS UNLIMITED/SPL

Land-based deformation monitors (left and middle) are crucial, but only help to understand above-ground stretches of faults like California's San Andreas.

stuck along faults. As the plates creep past each other, the ground deforms over these locked patches in a way that is easily modelled. So, by monitoring and quantifying regions undergoing deformation along tectonic-plate boundaries, researchers can determine the locations and sizes of locked patches. That in turn helps to determine the earthquake potential of a given fault.

Along the section of the San Andreas Fault in Parkfield, California, for example, scientists have taken measurements of ground deformation at a dozen GPS stations spaced 5–10 kilometres apart, some of which have been in place since the early 1990s. These stations mapped out the locked patch that failed in the 2004 magnitude-6.0 earthquake at Parkfield[1].

More than 90% of known tectonic-plate boundaries are underwater. Only rarely do large, coastal faults pop up above the water to places where we can more easily monitor them, as in the San Andreas Fault, the North Anatolian Fault in Turkey or numerous faults in central China. These locales are important because they yield detailed imaging opportunities. But they provide only glimpses of these faults' processes, and offer little solace to those studying the environments that create the world's largest earthquakes: subduction zones, where an oceanic plate slides beneath another plate, underwater and out of sight.

As with tectonic boundaries, many major tectonic plates are largely underwater, which makes tracking their motions difficult. The Cocos plate, for example — which collides into, and is forced under, the North American and Caribbean plates below southern Mexico and much of Central America — holds only a single island. This leads to significant uncertainty in our estimates of convergent plate velocities and direction — parameters important for assessing the long-term earthquake potential of the region.

Subduction-zone faults extend downwards from a trench on the sea floor, often hundreds of kilometres offshore (200 kilometres in the case of the Japan Trench). From here, the fault slices downwards at an angle towards and underneath land (see 'Watching the Earth move'). With land-based measurements alone, scientists can do a fair job of imaging the locking in the deeper portions, which typically lie 30–50 kilometres below the surface. This can be helpful for assessing the strain energy likely to be released by strong shaking on land. But we cannot assess the quake's tsunami potential from land measurements.

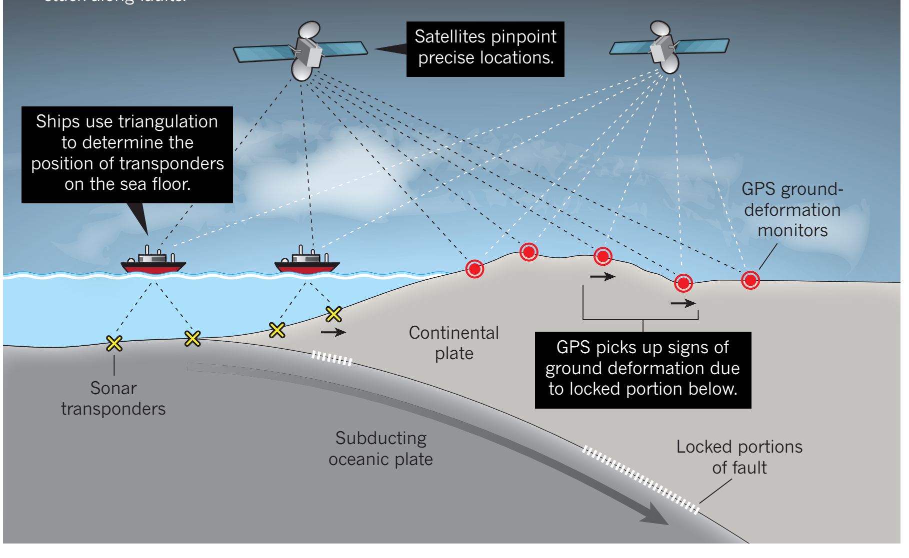
A growing body of research is now showing that large tsunamis are most easily generated by earthquake movement near the trench. In Sumatra last October, for example, a magnitude-7.8 earthquake very near the sea-floor trench created waves approximately 10 metres high, comparable to those from the quake in Chile in February that year, which was magnitude-8.8 but 20 kilometres deeper[2,3].

To get offshore ground-deformation data, scientists mostly use sonar transponders on the sea floor. Using GPS, a ship pinpoints its own location, and uses triangulation to determine the transponders' positions on the sea floor. Repeat measurements are made, years apart, to determine any changes in the transponders' locations. This works, but it is expensive. The development and deployment of a transponder may cost several hundreds of thousands of US dollars, and the use of a large ship for several days to make measurements would cost another hundred thousand. Depending on the ships used and the cost of fuel, a single determination of sea-floor deformation may cost half a million dollars.

This has kept the number of measurements to just a handful, globally. Studies off the coast of Japan before and after the Tohoku-Oki

WATCHING THE EARTH MOVE

Ships are used as intermediaries to measure sea-floor deformation, which reveals where the plate is locked — stuck along faults.

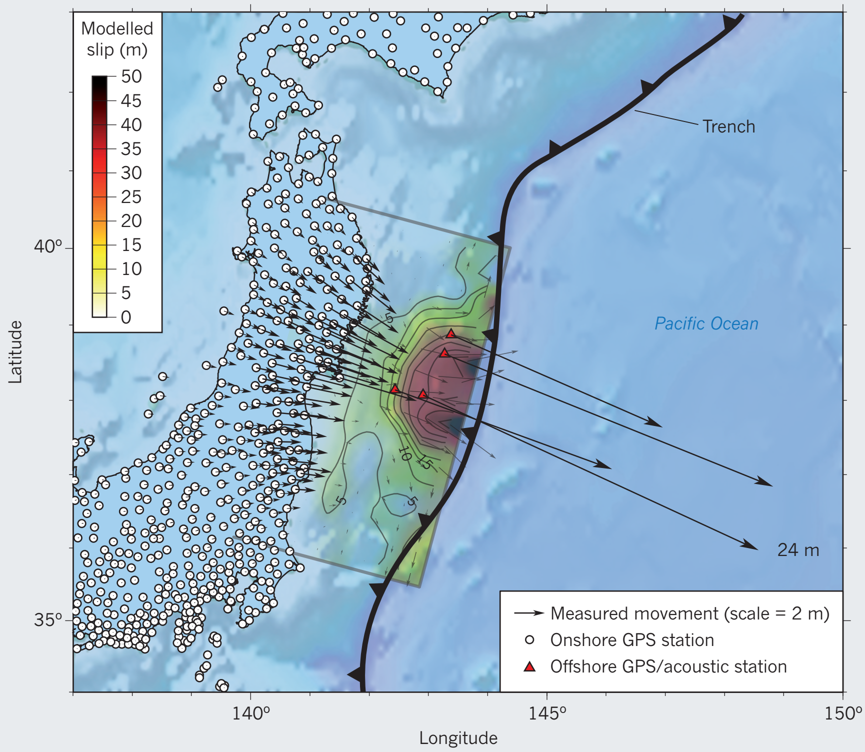


N. JONES/A. V. NEWMAN

earthquake[4], and earlier off Peru and western North America[5,6], have shown deformation in a few spots along a trench using a combination of GPS and acoustic tools. In Japan, three points were observed to be moving landwards in the 10 years prior to the earthquake: a signal indicator of strain build-up. The region with the most such build-up suddenly jumped at least 24 metres seawards as the Tohoku-Oki quake ruptured along the fault[7] (see 'Lopsided measures'). With numerous similar measurements, particularly closer to the trench and before the event, it would have been possible to map out the shallow locked area, and better estimate both the earthquake and tsunami potential.

LOPSIDED MEASURES

Most of the action during the 11 March 2011 tsunami-forming earthquake that hit Japan was offshore, but the vast majority of ground-deformation sensors are on land.



NEWMAN, A. V. *ET AL. SEISMO. RES. LETT.* **82** (2011).

SCALING UP

Geophysicists should be working with government and intergovernmental agencies to develop and test cheaper technologies for tracking continuous, long-term sea-floor strain accumulation. Autonomous systems that can run without human intervention will be much cheaper in the long run. Real-time transmission of data would be possible by hooking in to existing systems of underwater cables, such as those used by NEPTUNE Canada, the scientific observatory offshore from Vancouver Island. Or it could be achieved through satellite communication with buoys on the ocean's surface, as is currently being developed at Scripps Institution of Oceanography in San Diego, California. It is not yet clear exactly what the cost savings of these methods might be.

There will likely be trade-offs between tools capable of making many accurate measurements in a matter of weeks, versus those more suited to making one measurement a year over many years. Some instruments need not based on GPS: devices can measure changes in tilt precisely, for example, rather than changes in absolute position.

It is vital that all subduction boundaries — particularly those with the capacity for causing massive damage to nearby cities — be densely measured routinely enough to capture the extent of locking. How many sensors are needed? For an underwater volcanic system, up to a dozen instruments might be sufficient to capture magmatic unrest. To identify the offshore locking that causes big earthquakes and tsunamis in subduction zone environments, stations should ideally be installed 20–40 kilometres apart, in a grid, from the shore to over the trench. For the Japan Trench, this would mean 100–400 new sensors on top of the handful there today. For larger-scale studies of global plate dynamics, stations distributed every 5,000–15,000 kilometres would be sufficient.

It should be possible to bring instrument manufacturing and deployment costs to under US$50,000 per station within a decade, if research and development is stepped up on available and emerging technologies. It would then cost $5 million to $20 million to equip an environment like the Japan Trench. That's far less than the current spend on national, land-based scientific-grade GPS infrastructure in countries such as the United States, Japan, and New Zealand. (The western US Plate Boundary Observatory, for example, cost $100 million to install, and needs about $10 million per year in upkeep.) Put another way, the figure is less than 0.01% of the projected costs of the Japanese tsunami, which may exceed $300 billion.

Geoscientists need to overcome the 'cognitive inertia' that is holding back progress in this field. Although the community is starting to recognize the importance of offshore measures, ideas and common practices are slow to change. Scientists and engineers should prod funding agencies for significantly more support towards developing new and cheaper tools.

Because earthquakes and tsunamis do not stop at political borders, it is essential that agencies such as the United Nations Educational, Scientific and Cultural Organization and the World Bank play a part. Intergovernmental agencies should catalyse the international research community, first through funding workshops and exploratory research, and then through the deployment and upkeep of extensive sea-floor measurement systems. Wealthier countries could offer support through programmes such as the United States Agency for International Development.

We live in something of a golden age for earthquake geophysicists: there has been a burst of large quakes to study with advanced research tools in the past 20 years. Data sharing is also getting better. Scientists worldwide had access to local seismic and geodetic data within a few days of the recent Japanese quake. Globally, the seismology community can examine real-time data from sensors almost anywhere on land only a few seconds after it is recorded. It is time for underwater monitoring to catch up. ■

Andrew V. Newman *is at the School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Drive, Atlanta 30332, USA.*
anewman@gatech.edu

1. Murray, J. & Langbein, J. *Bull. Seismo. Soc. Am.* **96,** S283–S303 (2006).
2. Newman, A. V., Hayes, G., Wei, Y. & Convers, J. A. *Geophys. Res. Lett.* **38,** L05302 (2011).
3. Lorito, S., Romano, F., Atzori, S. & Tong, X. *Nature Geosci.* **4,** 173–177 (2011).
4. Sato, M. *et al. Geophys. Res. Lett.* **38,** L01312 (2011).
5. Spiess, F. N. *et al. Physics Earth Planet. Inter.* **108,** 101–112 (1998).
6. Gagnon, K., Chadwell, C. D. & Norabuena, E. *Nature* **434,** 205–208 (2005).
7. Sato, M. T. *et al. Science* 10.1126/science.1207401 (2011).