exhibit the highest rates of nitrogen fixation. Interestingly, most nitrogen fixation by cryptogams takes place in regions where bacterial nitrogen fixation associated with plants is low.

Perhaps the most important message arising from this study is that terrestrial cryptogamic covers need to be considered when constructing carbon and nitrogen budgets on local to global scales. The direct effects of carbon uptake and nitrogen fixation on the organisms themselves, as well as the downstream effects on soils and plant productivity and biomass, and thus carbon sequestration and albedo[7], all need to be taken into account. Moreover, given that these budgets influence climate, the contribution from these often-ignored terrestrial communities needs to be included in climate models.

Elbert and colleagues[3] show that terrestrial cryptogamic covers play a significant but hitherto overlooked role in global carbon and nitrogen cycles. The study also shows that there are large geographic areas where we need to learn more about how these organisms contribute to carbon and nutrient cycles. Given that cryptogams are sensitive to both climatic and anthropogenic disturbance, it is important that their roles in terrestrial biogeochemical cycles receive more focused attention. ❒

Jayne Belnap is at the US Geological Survey, Southwest Biological Science Center in Moab, 2290 S. West Resource Blvd, Moab, Utah 84532, USA. e-mail: jayne_belnap@usgs.gov

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SUBMARINE VOLCANISM

Hot, cracking rocks deep down

Most volcanism on Earth takes place under water, yet little is known about submarine eruptions. Monitoring of two volcanic seamounts beneath the Pacific Ocean reveals the pulsed nature of their eruption cycles.

Neil Mitchell

Submarine volcanoes produce observable effects at the sea surface, such as floating pumice and plumes of gas, but only if they erupt in shallow water. Most submarine eruptions have been relatively harmless — there have been few catastrophes at sea when vessels ventured too close to unseen, submerged erupting volcanoes, and only some minor landslides, tsunamis and submarine cable damages have occurred. However, submarine eruptions are still important. Our knowledge of volcanic processes largely comes from several decades of scientific observations of volcanoes erupting into the atmosphere. Yet, measured by volume, about 85% of Earth's volcanism occurs beneath the ocean[1]. Four studies[2–5] in *Nature Geoscience* now provide unprecedented details of eruptions that occurred at two submarine volcanoes at opposite ends of the Pacific Ocean in 2011.

Submarine volcanism differs from volcanism on land in many respects[6]. Ambient pressure increases by 1 bar for every 10 m increase in depth. In the deep ocean, the resulting vast pressure at the sea floor opposes the tendency for volatiles, such as carbon dioxide and water, to exsolve from lava, making eruptions less explosive. Water is much more viscous and dense than air, so the momentum resulting from an explosive emission is easily absorbed by ambient water. Lava is cooled more rapidly, owing to the greater heat capacity of water and the greater thermal conductivity of water and steam compared with air.

Until recently, our approach to studying submarine volcanism has relied heavily on a combination of forensics — studying the products of eruptions long after the events — and analogue experiments[7]. Direct observations of submarine eruptions have been scarce, as they are hard to predict and occur in remote locations where it is challenging to take measurements.

The difficulty of detecting remote oceanic eruptions has been addressed, to some degree, by hydrophone arrays deployed in the Pacific and Atlantic oceans. An ocean layer with a low acoustic velocity causes sound waves to refract into the layer, meaning that earthquake signals can travel over long distances, as if trapped in a giant fibre-optic cable. Much smaller earthquakes can therefore be detected underwater than on land. Thus, hydrophone arrays provide a means for identifying active eruptions.

Watts *et al.*[2] used a hydrophone array to detect an eruption at Monowai volcano, in the Kermadec Arc, southwestern Pacific Ocean, in May and June 2011. Fortuitously, they had surveyed the topography of the submarine volcano immediately before it had erupted. They returned two weeks later to find that, in some areas of the sea bed, large amounts of erupted material had accumulated, whereas material elsewhere had been lost by landsliding. Of particular note, a 79-m-tall steep cone, with sloped sides of 60° or more, was found to top the summit of the volcano. The time taken to erupt the lava was deduced from the hydrophone data, and provides accurate estimates of the eruption rate. The results indicate unusually intensive activity, but in keeping with rates determined at other volcanic ocean islands where edifices have grown over a wide range of periods[1]. The Monowai volcanic eruption occurred in a water depth of only about 100 m, allowing relatively explosive activity[2].

By contrast, a more effusive eruption was recorded in April 2011 at Axial Seamount in the northeast Pacific (Fig. 1), beneath more than 1500 m of water, and is described by three studies[3–5] in *Nature Geoscience*. Chadwick *et al.*[3] used accurate sensors of hydrostatic pressure to record the movements of the sea floor in the run-up to the eruption. They document a gradual rise of the sea floor by nearly 20 cm over a period of several months, followed by an abrupt uplift of 7 cm in less than an hour before the eruption onset. The movements indicate that a magma reservoir beneath the surface initially filled gradually, until one or more dykes abruptly intruded from the reservoir into the upper crust. Subsequently, the sea floor subsided by more than 2 m as the magma was evacuated from the reservoir over a period of six days.

During this inflation and deflation sequence, two hydrophones recorded water-borne signals of micro-earthquakes. Comparing the pressure sensor data with these measurements, Dziak *et al.*[4] show that the frequency of earthquake swarms increased during the year before the eruption. They attribute this to increasing stress and cracking in the rocks surrounding the magma reservoir, as magma continued to charge the reservoir and increase its pressure. The sudden uplift of the volcano-crater floor immediately before the eruption[6] was itself preceded by a swarm of micro-earthquakes over 2 hours. The seismicity might have been associated with the migration of magma dykes out from the reservoir towards the sea floor. If so, the data constrain the rate of propagation of the dykes to 16–21 cm per second, rates comparable with those of dykes around volcanoes on land. The seismic data also contain strong tremors before and after the start of the eruption that could have been caused by magma oscillating or surging within the magma reservoir or dykes.

Finally, Caress *et al.*[5] report changes in seafloor topography caused by the eruption of lava at Axial Seamount at metre-scale resolution. The sea floor was surveyed repeatedly using a robotic submersible equipped with a multiple-beam echo-sounder to measure the topography. Mapping lava flows in these rugged terrains is challenging because the topographic signature of the new lava is difficult to discriminate from the existing volcanic relief. Even on land, it can often be difficult to map different lava flows without geochemical or other information because different flow textures can arise in the same eruption. However, a comparison of the seafloor topography at Axial Seamount before and after the eruption reveals the new lava in exceptional detail and shows that it is more than 10 m thick in places. Interestingly, some parts of the flows seem to have erupted from pre-existing fissures and have followed pre-existing lava channels. The lava flows terminate in lobes that inflated during the eruption as the lava continued to flow towards the flow fronts in a similar fashion to that observed on land at volcanoes like Kīlauea, Hawai'i.

Flow fronts on land exhibit statistical fractals — a self-similarity in their geometry — that reflect the lava viscosity and sequence of emplacement[8]. Viscous 'a'ā-type lavas tend to form smoother, rounded fronts than less-viscous pāhoehoe lava, which develops more indented, crenelated fronts formed when lava breaks through the inflated frontal lobes and continues to flow. The lava flows at Axial Seamount seem, superficially, to have intermediate geometrical complexity. In contrast, submarine lava flows around Pico Island, Azores, are more pāhoehoe-like due to a more complicated branching sequence[9].

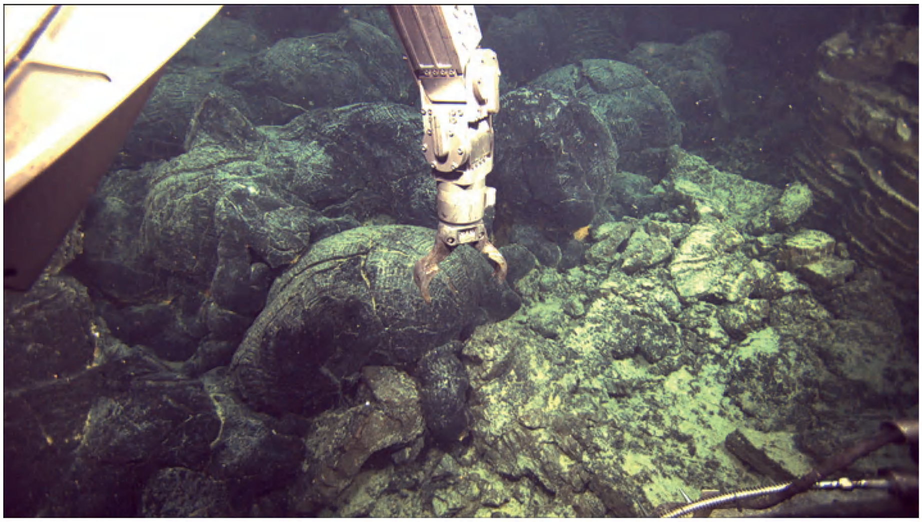

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Figure 1 | Lavas erupted at Axial Seamount. The manipulator arm of a remotely operated vehicle prepares to sample lava flows erupted in April 2011. Four studies[2–5] in *Nature Geoscience* document two different submarine eruptions that occurred in the Pacific Ocean in 2011. The studies detail the rapid growth and collapse, and the cycle of inflation and deflation, of submarine volcanoes, and highlight the dynamic nature of the erupted lava flows.

Even with these developments, there are still gaps in our knowledge compared with our understanding of volcanic eruptions on land. The relationship between viscosity of lava and temperature is highly nonlinear[10], and the growth and ultimate morphology of lava fields critically depends on the toughness of an outer visco-elastic layer that develops as the lava cools[11]. Although infrared remote-sensing and direct temperature measurements can provide valuable information about lava flows on land, detailed thermal observations of submarine lava flows are unlikely to be possible any time soon.

Nevertheless, a number of developments in the pipeline offer tremendous potential for monitoring submarine volcanism in the years ahead. The hydrophone arrays now routinely report data from the Atlantic and Pacific oceans[12], and should provide us with increasing knowledge of volcanic swarms that can alert scientists to impending eruptions. Rapid distribution of the hydroacoustic data to scientists at sea is now possible, thanks to improved satellite internet connections. This could potentially enable shipboard scientists to respond rapidly to survey new eruption sites. Cabled observatories installed off the coast of the western USA will include seafloor instruments on Axial Seamount, and the Canadian NEPTUNE (NorthEast Pacific Time-Series Undersea Network Experiments) cabled observatories will also include seafloor instruments on the nearby Endeavour Ridge. A wider range of measurements will be vital to the continued development and validation of models for submarine volcanic processes.

These four studies[2–5] highlight the pulsed nature and rapid growth and collapse of submarine volcanoes during eruptions. Future developments will allow scientists to tease out, in even more detail, the dynamic adjustment of the sea floor during voluminous lava flowage, and their similarities and differences with their counterparts on land. ❐

Neil Mitchell is in the School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, UK.
e-mail: neil.mitchell@manchester.ac.uk

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