SCIENCE, SEAMOUNTS
AND SOCIETY

In reviewing the distribution and formation of seamounts, **Tony Watts** highlights the societal implications of these abundant oceanic features and the urgent need for more seafloor mapping

It has been more than one hundred years since the publication of Sir John Murray's 'bathymetrical chart' of the world's ocean basins. Compiled from lead-line surveys during expeditions such as *Challenger* and *Michael Sars*, the coloured contour map revealed for the first time the nature of Earth's surface beneath the oceans and the outline of the continental margins, the Mid-Atlantic Ridge and the intervening abyssal plains (Fig. 1). Profiles showed, however, that apart from the prominence of a few widely scattered islands such as the Azores, the seafloor of the oceans was smooth and featureless—a view that persisted for about the next four decades.

The development of new technologies during World War II dramatically altered this view. Arguably the most important was the Precision Depth Recorder (PDR), which used a hull-mounted acoustic transducer/receiver to continuously measure two-way reflection time and hence depth. The Princeton academic, Harry Hess, who had been given command of the troop-carrying ship USS *Cape Johnston*, for example, used a PDR to chart 160 flat-topped bathymetric features in the Pacific Ocean, rising up to 4.5 km above the seafloor. He named them guyots, in honour of the Swiss born geographer and Princeton Professor, Arnold H. Guyot. Hess (*Amer. J. Science* 1946), and considered them as volcanic oceanic islands that had been wave trimmed prior to subsidence below sea level.

After more than three centuries of discovery on sailing ships, we know there are 1,770 ocean islands (all but one was

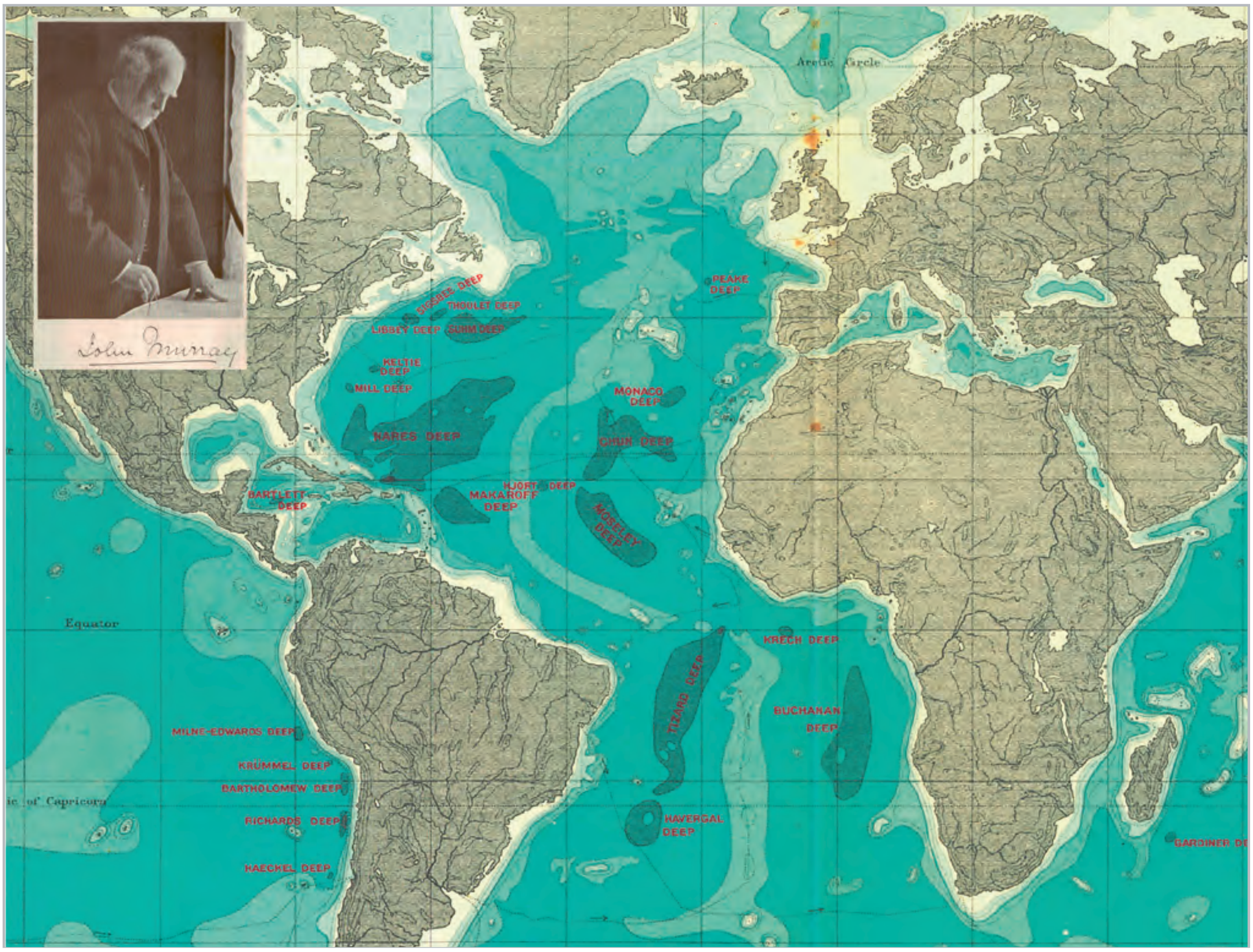

Fig 1: Sir John Murray and his 'bathymetrical chart' of the Atlantic, western Indian and eastern Pacific oceans published in 1912. Constructed from ~3,200 soundings made with pre-stressed hemp rope and lead weights on British and other survey ships. Abyssal plains ('deeps') correspond to depths >3,000 fathoms (5,486 m). Chart produced by John G. Bartholomew, cartographer to the King

discovered by 1840). 47 are active volcanoes. Approximately 439 are atolls (Goldberg, *Atoll Research Bulletin* 2016), which Charles Darwin hypothesized in 1842 comprise coral reefs that had grown upwards on the summit of volcanoes as they subsided below sea level.

While we now attribute the subsidence of guyots and atolls to sinking of the oceanic plate as it ages and cools, their spatial distribution raises questions about the origin of volcanic activity on Earth. The Smithsonian Global Volcano Program (SGVP), for example, lists 1,535 volcanoes that have been active since the Holocene, the large majority of which are associated with compressional plate boundaries, where one plate is underthrust by another (e.g. the circum-Pacific) and extensional plate boundaries, where the plates are moving apart (e.g. East Africa). Yet, the large majority of guyots and atolls are located in the interior of plates, far from plate boundaries (Fig. 2b).

Here I show that when 'seamounts' are added into the mix, most of which are also volcanic in origin (Fig. 3), the spatial extent of magmatic activity on Earth changes even more dramatically. Indeed, the distribution raises important scientific questions about Earth's 'magmatic pulse' and the origin of intra-plate volcanism, as well as societal questions about the role that seafloor volcanoes play in navigation, fisheries and geohazards.

What is a seamount?

In his 1964 book, *Marine Geology of the Pacific*, Bill Menard defined a seamount as:

"a more or less isolated elevation of the sea floor with a circular or elliptical plan, at least 1 km of relief, comparatively steep slopes and relatively small summit area"

Menard estimated there were about 2,000 seamounts greater than 1 km high in the ocean basins. Satellite-derived gravity and ship PDR data, however, show there are >14,500 seamounts higher than 1 km. A large concentration is found in the western Pacific Ocean (Figs 2, 4). Some of these seamounts are growing up on the seafloor and may become islands, while others were once islands that are now sinking.

An important technological development in the late 1980s was the introduction of multibeam swath bathymetry systems. These had an advantage over PDRs in that rather than determining water depth immediately beneath a ship's hull, they insonified a broad swath of the seafloor, up to 2.5 times the water depth. Such systems ▶

revealed the morphology of seamounts, guyots, atolls and ocean islands in unprecedented detail, for example those along the Hawaiian-Emperor seamount chain in the central Pacific Ocean (Fig. 5). Other islands to have had their submarine slopes swath mapped include the Canary and Cape Verde in the Atlantic Ocean, and La Reunion and Kerguelen in the Indian Ocean. However, the number of swath surveys carried out to date is limited and only about 10-12% of the seafloor has been insonified.

Seamount dynamics

While we still do not know how many seamounts are growing and sinking, field observations suggest they are important to fully understanding Earth history and environmental change. Field sample and scientific drill data suggest that there have been bursts of volcanism in the oceans, for example the 90 to 100 -million-year 'event' that created many of the seamounts and oceanic plateaus in the central Pacific Ocean (e.g. Shatsky Rise, Hess Rise, Mid-Pacific Mountains). There may have been other such volcanic events in the Pacific Ocean, peaking in the Eocene and Late Jurassic. Once formed seamounts are susceptible to modification by large-scale sector collapse, as manifest by scalloped coastlines, submarine debris flows and the emplacement of large blocks on the seafloor. Such processes operate on time scales on the order of hundreds of thousands of years as seen, for example, in the Icod and La Orotava landslides on the north flank of Tenerife in the Canary Islands.

In historical times, seamounts show surprising variability on scales that greatly exceed their terrestrial counterparts. The number of historically active volcanoes in the SGVP data set is 538, about 35% of the total number of volcanoes younger than Holocene. If a similar percentage of seamounts higher than 1 km are active, then we might expect upwards of about 5,000 historically active volcanoes on the ocean floor. We know, however, only a few (~12) from floating pumice and discoloured water, Remotely Operated Vehicle (ROV) observations, and repeat swath bathymetry surveys.

One of the best-surveyed active

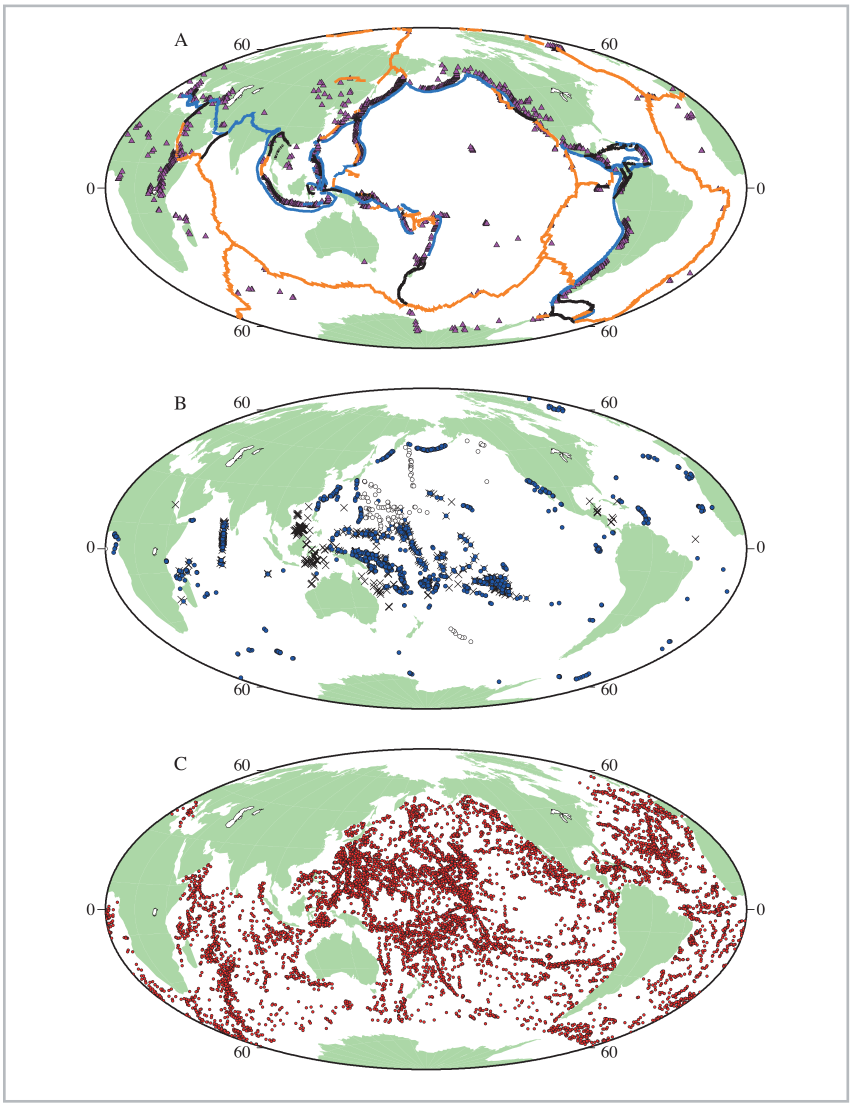

Fig 2: a) Holocene-Recent volcanoes (filled purple triangles, from https://volcano.si.edu/), compared to boundaries of major plates (blue, subduction zones; orange, mid-ocean ridges; black, transform/ strike-slip faults). b) Ocean islands (filled blue circles), atolls (×). Guyots (unfilled circles, distribution incomplete) were once islands. c) Seamounts (filled red circles) with height above seafloor > 1,344 m, the height of Ben Nevis, the UK's highest mountain. (Data sources: Nunn, 1994; Goldberg, 2016; Smoot & King, 1997; Caplan-Auerback et al., 2000; Hillier & Watts, 2007)

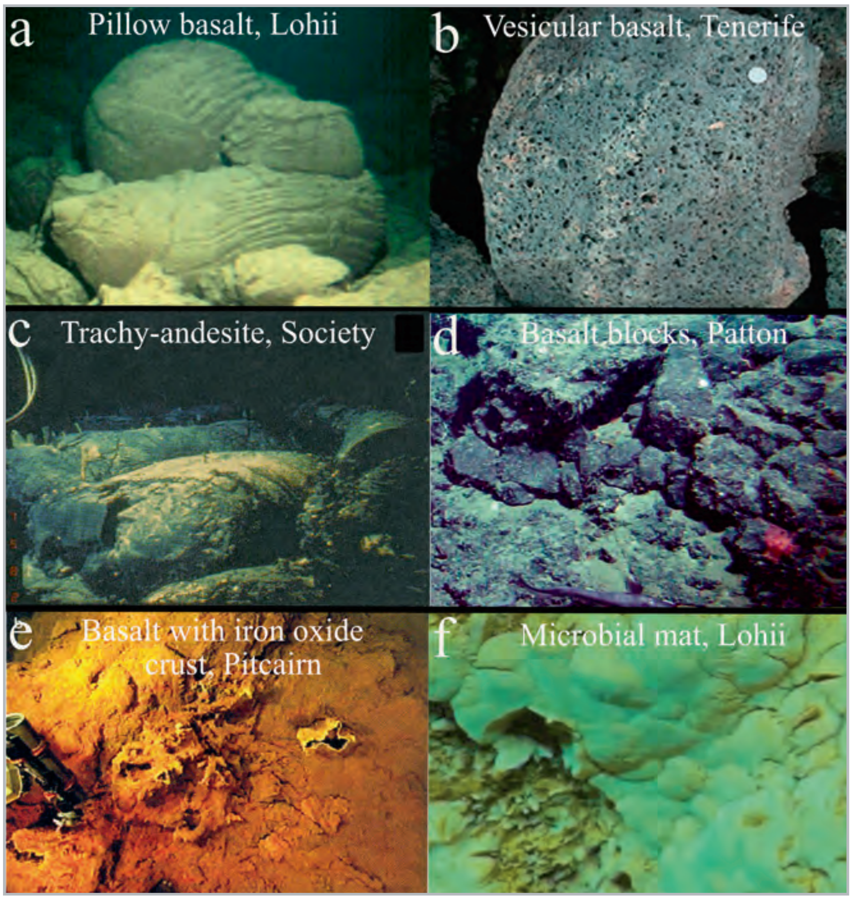

Fig. 3: The flanks of intra-plate oceanic islands and seamounts comprise mainly basaltic rocks that are geochemically distinct from basalts sampled at mid-ocean ridges and islands arcs. Products of seawater-Fe-Mg reactions (e,f) are an important source of microbial life. (a, A. Malahoff, U.Hawaii, 1980; c, Binard et al. & e, Scholten et al., both in: Ocean Hotspots. Hekinian et al. (eds) 2004 ©Springer; d, Public domain; f, Chan et al., 2016 CC-BY 4.0. c,e are exempt from CC licence, reprinted by permission from SpringerNature SNCSC).

submarine volcanoes is Monowai in the Tonga-Kermadec arc, southwest Pacific Ocean. The volcano (Fig. 6) was swath surveyed in 1998, 2004, 2007, 2011 and 2013. Large differences, up to several tens of metres, were measured between the surveys. During the 32-day-long cruise of M/V *SONNE* in 2011, the volcano was surveyed twice. Seismic data recorded on Rarotonga (Cook Islands) revealed that the volcano erupted during May 17-22, 2011 and surveys with swath bathymetry before and after the eruption showed dramatic differences: the seafloor depth on the cone summit shallowed by up to 70 m and deepened by up to 18 m.

The seismic events recorded on Rarotonga were generated by the rapid emplacement of volcanic rock onto the seafloor. They originated as hydroacoustic waves that had become trapped in the SOund Fixing And Ranging (SOFAR) channel, the low velocity sound layer in the ocean that transmits whale calls. When these waves, known as *T*-waves, impact an ocean island they convert to body waves and, depending on noise levels, may be recorded on a seismic station on an ocean island.

Another recorder of *T*-waves are the hydrophone stations maintained by the Consortium for Test-Ban Treaty Organization (CTBTO). Three hydrophones are deployed on tethers in the SOFAR channel so a *T*-wave generated by an active submarine volcano will, if it is not obstructed, have a unique back azimuth when it arrives at a station. Explosive activity at Monowai, for example, has a back azimuth of 243.8° at a station located south of Juan Fernandez Island in the eastern Pacific Ocean (Fig. 7) and provide a means to continually monitor the submarine volcanic centre. Remarkably, the T-waves are able to transmit across the south Pacific Ocean despite possible bathymetric obstructions on the Louisville Ridge, East Pacific Rise and Chile Ridge. A recent study of these data by Dirk Metz (Oxford University) reveals that Monowai has erupted some 82 times over a 3.5-year period, making it arguably the most active volcano on Earth.

Origin of seamounts

Away from island arcs, many seamounts form distinct lines that progressively increase in age away from an active volcano and can be explained by absolute motion of a tectonic plate over a fixed mantle hotspot. The 7,000-km-long Hawaiian-Emperor seamount chain in the central Pacific Ocean is arguably the best-known example of ▶

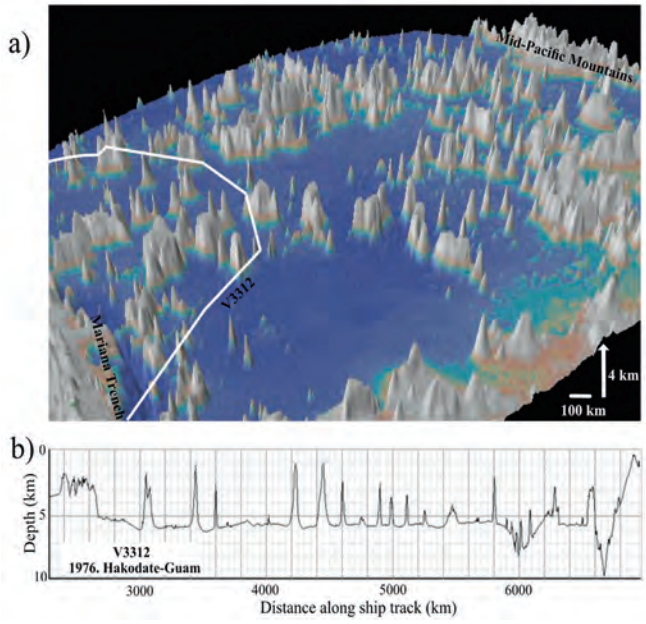

Fig 4:* *Western Pacific Ocean seafloor bathymetry, between the Mariana Trench and the Mid-Pacific Mountains. a) Perspective view to NE (gridded data set from Ryan et al., G3 2009; GeoMapApp, http://www.geomapapp.org/; Marine Geoscience Data System, www.marine-geo.org). Vertical exaggeration ×25. Scale approximate. White line illustrates the ship track of R/V Vema cruise V3312. b) PDR bathymetry profile along the Vema ship track.

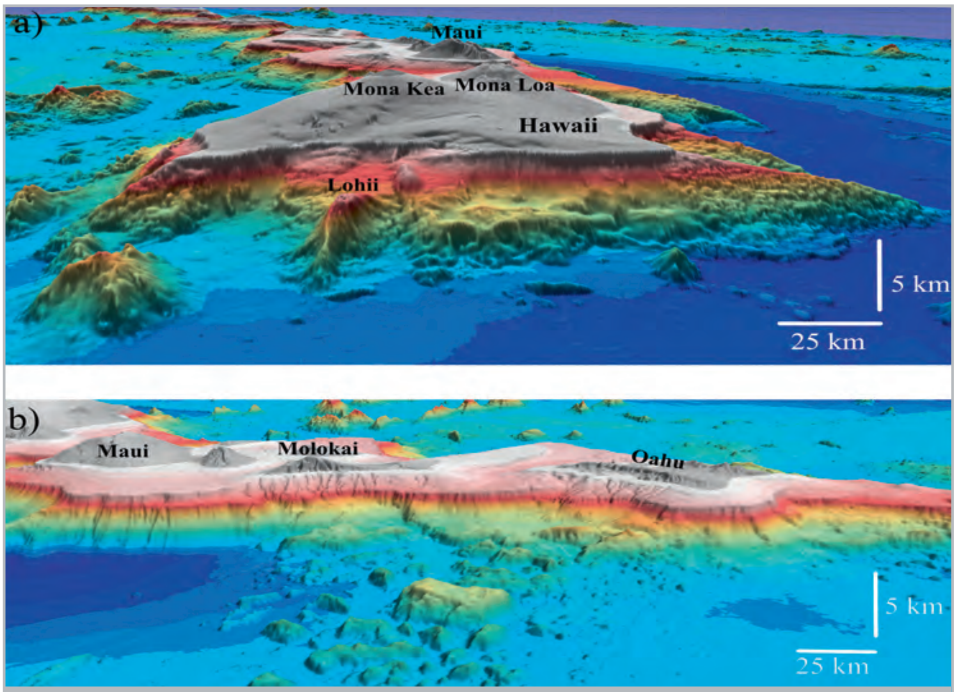

Fig 5: Submarine flanks of the Hawaiian Islands (perspective views). a) SE flank of Hawaii. b) N flank of Maui, Molokai and Oahu. 4x Vert. exagg. (Data: Ryan et al., 2009; http://www.geomapapp.org/; www.marine-geo.org)

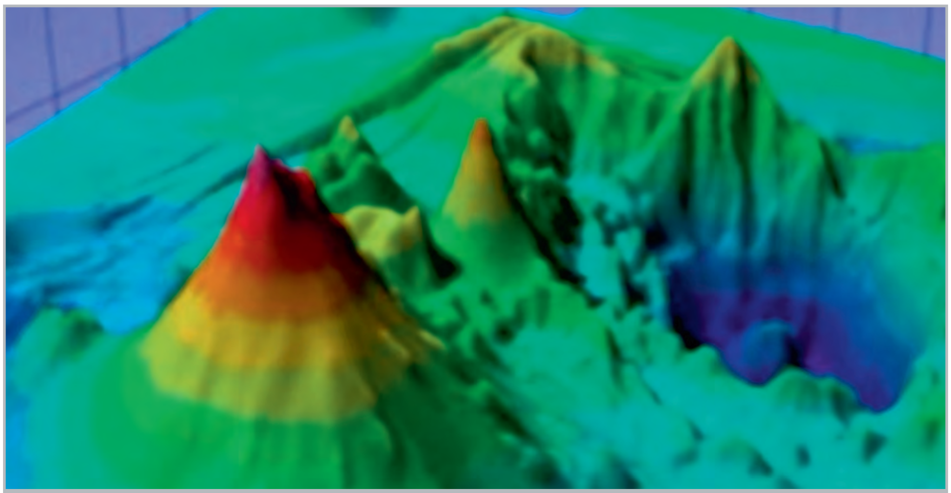

Fig. 6: Monowai in the Tonga-Kermadec island arc (perspective view, towards NW), SW Pacific Ocean. A ~1,000-m-high, 10-12-km-wide stratovolcanic cone with parasitic cones and a flanking ~500-m-deep, 7-10-km-wide caldera with ring faults and a central mound. (Data: SONNE Cruise 215; https://www.bodc.ac.uk/.)

▶ such a hotspot track. Seamounts increase in age from ~20 ka at the young end of the chain, through ~50 Ma at the Hawaiian-Emperor 'bend', to ~80 Ma at the old end of the chain. The young end comprises ocean islands that are superimposed on a broad topographic swell ~1.5 km in height, which gravity and seismic data suggest is supported by a deep mantle plume, while the old end is characterized by guyots and an absence of a swell.

A fixed hotspot origin for the seamount chain is supported by palaeomagnetic data that show the Hawaiian ridge, up to the 'bend', formed at or near the present-day latitude of the Hawaiian hotspot. But, palaeomagnetic data show that the Emperor Seamounts, beyond the 'bend', formed at a latitude up to 15° north of the current location of the hotspot. John Tarduno (University of Rochester) and colleagues have interpreted this as evidence that during 50 to 80 Ma, the Hawaiian hotspot was not fixed with respect to the deep mantle and had migrated south while the plate moved north.

While palaeomagnetic data suggest the Louisville Ridge, a seamount chain with a ~50 Ma 'bend' in the southwest Pacific Ocean, may also have formed at a fixed mantle hotspot, other volcanic lines are more difficult to explain. Some show an age progression, yet form close to a mid-ocean ridge (e.g. the Lamont Seamounts close to the East Pacific Rise) and have been attributed to a 'mini hotspot' at the ridge. Others (e.g. the Puka Puka Seamounts, south-central Pacific) show no evidence of an age progression and have been attributed to magmatically filled tension cracks generated by stresses set up in the Pacific Plate by processes such as a slab pull, convective instabilities and mantle dynamics.

Most difficult to explain are the numerous isolated seamounts that litter the seafloor (Fig. 2c). Some occur in regions of plate flexure at trench-outer rises (e.g. the 'petit spot' volcanoes in

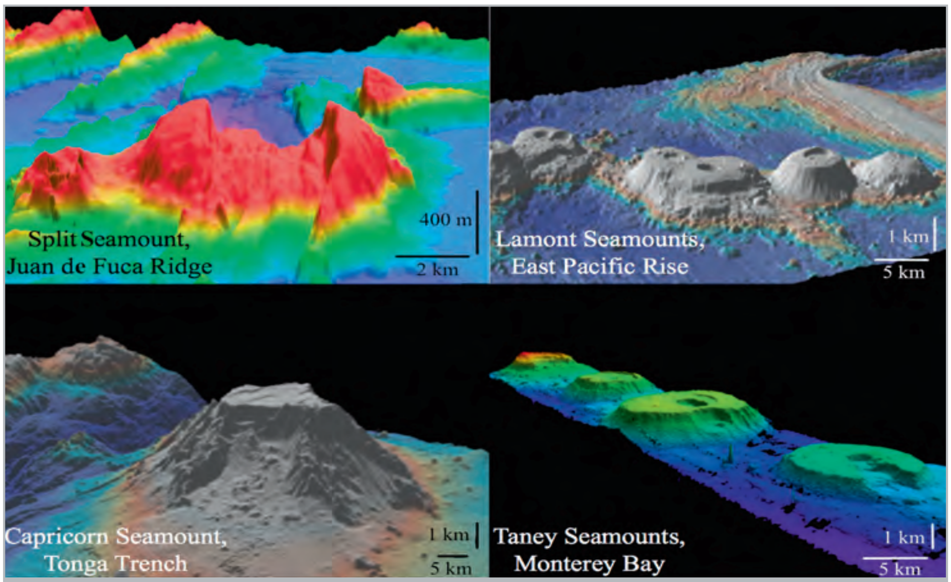

Fig. 8: Isolated seamounts and short seamount chains (Pacific Ocean, perspective views). Data: Carbotte et al., 2006; Coumans et al., 2015; Ryan et al., 2009; http://www.geomapapp.org/; www.marine-geo.org; Split image courtesy of Bill Ryan). Vert. exagg. from ×2 (Taney) to ×5 (Split). Scales approx. Capricorn's flat top tilts toward Tonga Trench. Sector collapses on Capricorn, Taney and Lamont seamounts. Summit craters on Lamont and Taney seamounts.

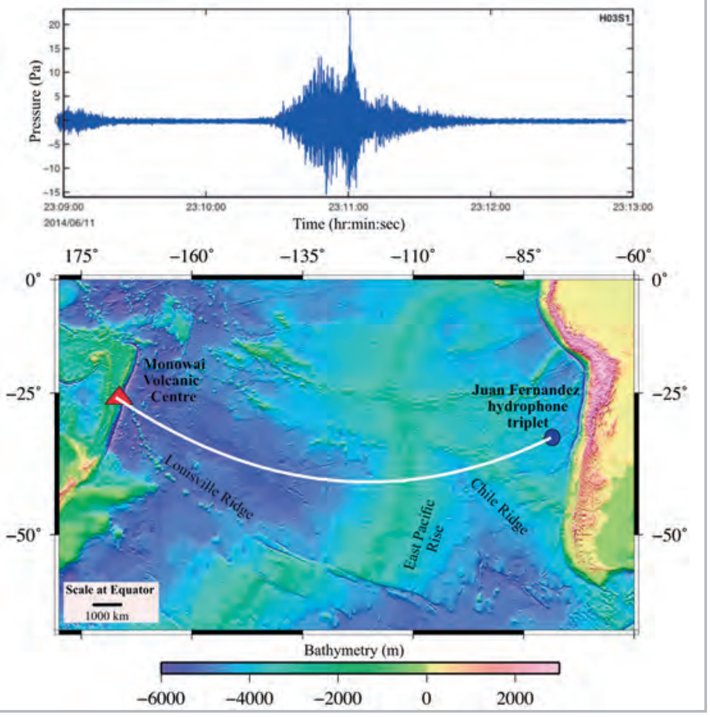

Fig. 7: Typical T-wave generated by volcanic activity at Monowai in the Tonga-Kermadec arc and recorded at hydrophone stations south of Juan Fernandez Island, eastern Pacific Ocean. (data replotted from Metz et al., 2018).

Fig. 9: USS San Francisco in Guam (Jan 2005). The submarine collided with an uncharted seamount while travelling at 33 knots between Guam and Brisbane. One sailor was killed, 115 were injured. (Credit: US Navy photo by Photographer 039, Mate 2nd Class Mark Allen Leonesio [Public domain])

the western Pacific), submarine volcanic loads (e.g. the 'North and South Arch' volcanics of the Hawaiian Islands) and along transform faults and 'leaky' fracture zones, where plate-bending stresses may be high enough to cause faulting. Others are too widely scattered and show no obvious link to regions of loading and flexure. The occurrence of so many scattered seamounts implies an extensive melt source in or below the oceanic crust and lithosphere. The observation by Nicholas Schmerr (NASA Goddard) and colleagues of seismic precursors to underside reflections from the crust between an earthquake and a receiver that suggest an age-independent discontinuity (the Gutenberg discontinuity) at about 65±10 km depth is therefore an exciting development, especially as it might reflect an ocean-wide, thin zone of partial melt.

Seamounts and society

While the origin of seamounts, especially the isolated ones, remains a scientific enigma, they are significant in a number of ways that impact society. Seamounts have steep slopes (up to ~25°) and rise abruptly above the regional seafloor depth, so are potential hazards for navigation. This was illustrated in a tragic accident in 2005. The USS *San Francisco*, a nuclear attack submarine, collided with an uncharted seamount at 160 m depth, between Pikelot and Lamotrek atolls in the western Pacific Ocean (Fig. 9). Four minutes prior to the collision, the seafloor depth was measured at 2,000 m.

Seamounts also act as seismicity moderators, tsunami wave scatterers, oceanographic "dip sticks" and biodiversity "hotspots". Seamounts carried by plate motions towards a trench, for example, are potential asperities on a subduction zone megathrust and may either inhibit or promote seismic activity. Furthermore, if intact when subducted into a trench, seamounts may disrupt the forearc (the region between the trench and arc) and cause submarine landslides. And seamounts may diffract earthquake-generated tsunami waves, which may, in turn, focus the waves more along one segment of coastline than another. Finally, seamounts may be sites of a tidal-induced ocean turbulence, which aids in bringing nutrients from the flank of a seamount to its summit. Indeed, some of our favourite fish and their predators are found on the summits of seamounts and seamounts have been targeted by the fishing industry, although not always with a positive outcome for their coral habitats, as for example in the Graveyard Seamounts, east of New Zealand (Fig. 10).

Limits of exploration

The lack of field data limits our exploration of seamounts. The number of scientific research cruises with PDRs onboard increased rapidly following World War II, but has been in a steady decline since the early 1970s. Single-beam bathymetry ship-track coverage is therefore limited, especially in the south Pacific Ocean, south of latitude 26° S (Fig. 11, Despite their large surface area, seafloor the size of the UK, Germany and France has been sampled by the equivalent of just 8, 8 and 5 ship tracks, respectively. Seafloor equivalent to entire countries (e.g. Greece, Bulgaria and Poland) has barely been sampled at all). Multibeam swath bathymetry coverage is even sparser. Imagine the difficulty in determining the geology of a country the size of France from just a few transects of geophysical data!

The challenge becomes even clearer when we consider the number of seamounts that might exist in the

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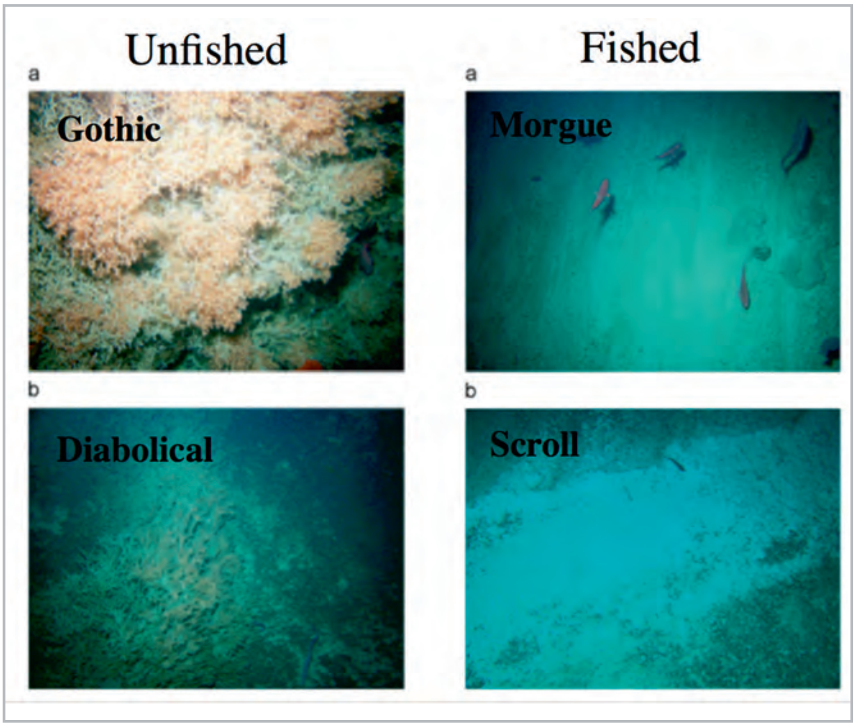

Fig. 10: Unfished and fished seamounts in the Graveyard Seamounts, east of New Zealand. Unfished seamounts have extensive cold-water corals that support a diverse array of invertebrates. Corals are removed from fished seamounts by bottom trawlers that leave their marks in the pelagic drape. (Images reproduced from Clark & Rowden, Deep-Sea Res.2009 © Elsevier)

▶ world's oceans. Satellite-derived gravity data have found most, if not all large seamounts, but few of the small ones, while ship PDRs have found some large seamounts (ships tend to avoid the largest seamounts!) and many of the small ones (Fig. 12). If we assume that satellites have found *all* the seamounts with heights between say 2 and 9 km, then the relationship between the number and height of seamounts in this height range can be extrapolated into the domain of the smaller, yet still significant seamounts, taking into account the relationship found in the ship data. When we do this, we find that there may be upwards of ~30,000 seamounts in the height range of 1 to 2 km that still remain to be discovered!

So, what might Sir John Murray and the other great bathymetric chart makers of the last century, such as Heezen and Tharp, Uchipi and Emery, and Fisher and Mammerickx, have made of this challenge? Surely, they would have wanted the ocean floor to be mapped in its entirety? Walter Smith and Karen Marks (Laboratory for Satellite Altimetry, National Oceanic and Atmospheric Administration; NOAA) estimate that it will take about 200 ship years (e.g. 20 ships for 10 years) to completely swath map the world's ocean basins and their margins. Incidents such as the loss of flight MH370 and the 2004 and 2005 Java-Sumatra megathrust earthquakes suggest that we should start soon in order to build a global database that can be used as a reference to compare with new data, so enabling changes in seafloor depth to be detected. The challenge will require international collaboration and will take time and cost money (Mayer *et al. Geosciences* 2018).

> “WHAT MIGHT SIR JOHN MURRAY AND THE OTHER GREAT BATHYMETRIC CHART MAKERS OF THE LAST CENTURY, SUCH AS HEEZEN AND THARP, UCHIPI AND EMERY, AND FISHER AND MAMMERICKX, HAVE MADE OF THIS CHALLENGE? SURELY, THEY WOULD HAVE WANTED THE OCEAN FLOOR TO BE MAPPED IN ITS ENTIRETY?”

We could begin now, however, by encouraging academic research ships with onboard swath systems to record data not only in their survey regions, but during transits to and from a focus site. Such efforts could be enhanced by public engagement using 'ships of opportunity', for example cruise ships, Navy vessels and 'megayachts'. Only then might we be able to put to rest the well-known cliché that we know the surfaces of the Moon, Mars and Venus better than we know the surface of our own planet.

—Full figure captions are available online

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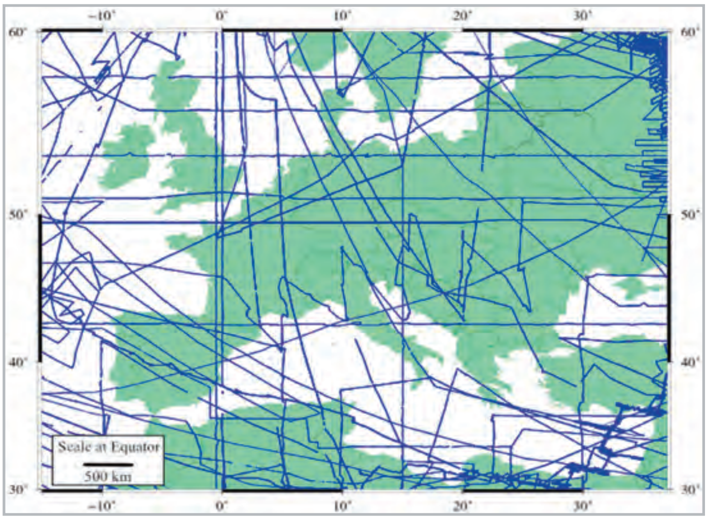

Fig. 11: All available single-beam bathymetry, gravity and magnetic ship-track data in part of the central Pacific Ocean (-165° to -113° longitude and -56° to -26° latitude) superimposed at the same scale on a map of Europe (blue lines, ship tracks; grey lines, national boundaries). (Data from http://www.geomapapp.org/)

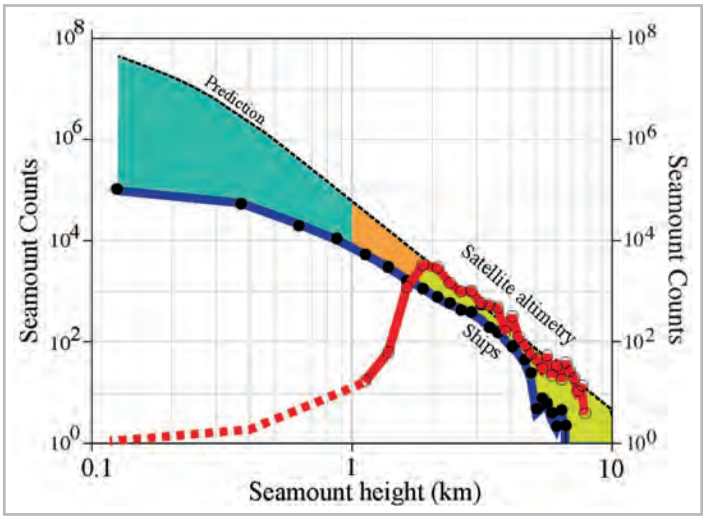

Fig. 12: No. of seamounts vs. seamount height above regional seafloor depth. Satellite data (red line) reveal nearly all the large seamounts, while surface ship data (blue line) reveal most small seamounts. Orange/green shaded region suggests many seamounts are undiscovered, tens of thousands of which may have heights up to 1-2 km. (Data replotted from Hillier & Watts, 2007)

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