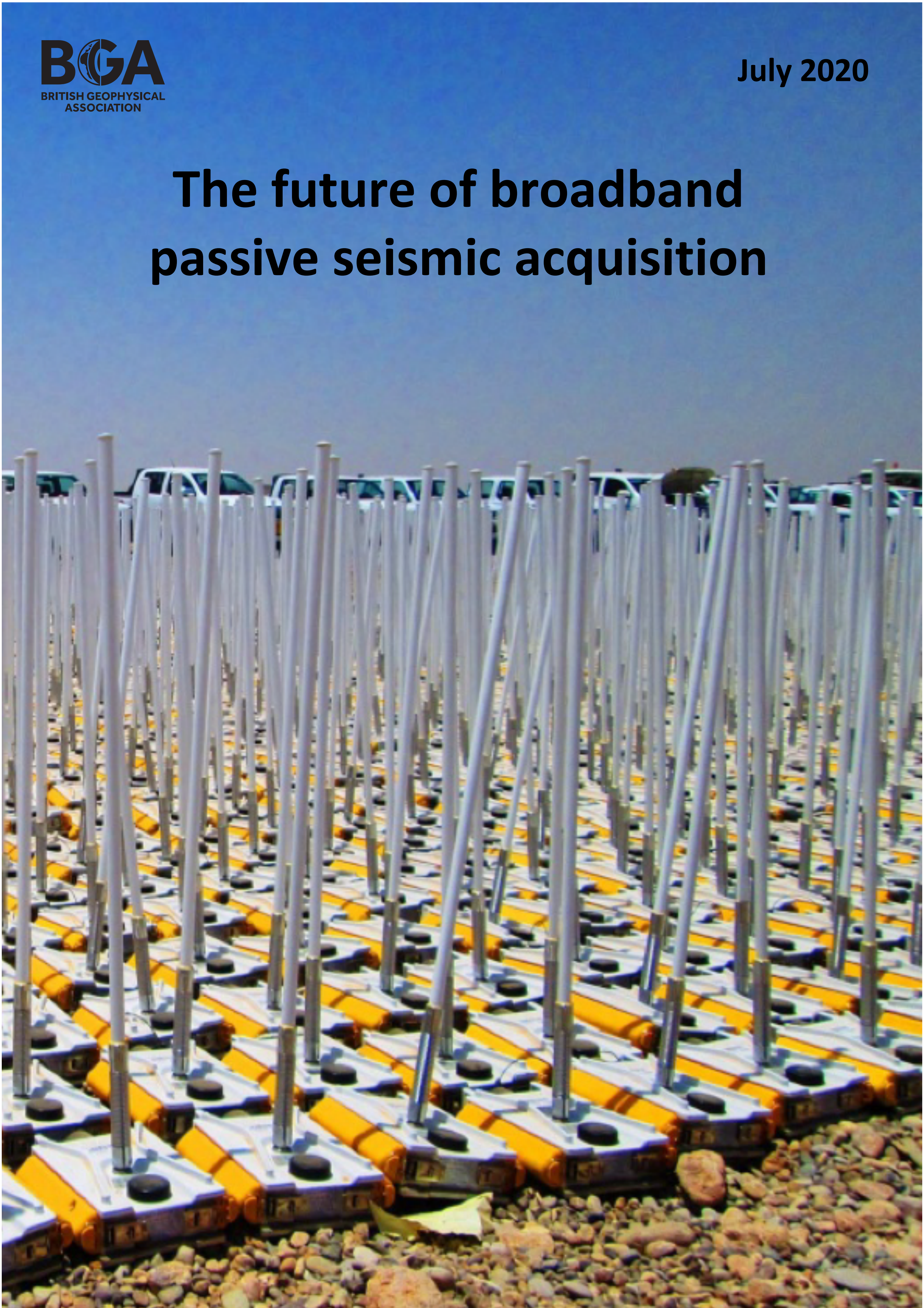
BRITISH GEOPHYSICAL ASSOCIATION

July 2020

The future of broadband passive seismic acquisition



The following authors prepared this report:

James Hammond (Editor), Birkbeck, University of London
Brian Baptie, British Geological Survey
Alex Brisbourne, British Antarctic Survey
Andrew Curtis, University of Edinburgh
Richard England, University of Leicester
Amy Gilligan, University of Aberdeen
Nicholas Harmon, National Oceanography Centre, Southampton, University of Southampton
Jess Johnson, University of East Anglia
Andy Nowacki, University of Leeds
Nick Rawlinson, University of Cambridge
Stella Pytharouli, University of Strathclyde
Karin Sigloch, University of Oxford
Jim Whiteley, British Geological Survey

This report was inspired by a number of presentations and discussions held over two meetings (Edinburgh, September 2018 and Cambridge, March 2019) sponsored by the British Geophysical Association. For full details of the meetings and a list of all participants see: https:nagedinburgh.wordpress.com.

Cover Image: Seismic nodes ready for deployment in Kurdistan. Image courtesy of Wireless Seismic, Inc.

Executive Summary

Passive seismology has long been used to study the interior of the Earth. By recording and analysing seismic waves we can monitor fault movements during earthquakes, track the evolution of volcanic eruptions and help understand and monitor human induced seismicity. We use these data to develop models of the Earth or other planets, from sedimentary basins in the shallow crust to large scale images of continental margins, ridges and subduction zones and the whole planet to help understand tectonic processes or planetary formation. **To date, the UK has played a leading role in passive seismology**. This includes making some of the first seismic recordings, using seismology to help develop plate tectonic theory and more recently, using large arrays of seismometers to understand tectonic processes.

This document concerns the future. **New emerging technology provides an opportunity for more detailed images of the subsurface on all spatial scales**. For example, new autonomous vehicles, low power ocean bottom sensors or use of trans-ocean fibre optic cables could allow us to instrument the whole ocean for the first time. New, low cost, low power land-based instruments mean that we can use dense networks of sensors. This can provide orders of magnitude improvements in resolution, thus help understand processes in more detail than before. **However, this equipment is not available to the UK academic community, which means we risk losing our place at the forefront of this field.**

Together with important blue skies discoveries, future societal grand challenges would benefit from enhanced passive seismology capacity. Examples highlighted in this report include, **future energy production** such as geothermal and hydropower and carbon capture and storage solutions, which require monitoring of seismicity for production and safety. As our vulnerability to **natural hazards** increases, a better understanding of earthquake dynamics and volcanic processes will allow us to develop better forecasting and monitoring strategies. Finally, passive seismology is now being widely used to monitor **environmental changes** such as ice sheet breakup, changes in subsurface water or tracking storms at sea.

The past and future **success of passive seismology is underpinned by the community having access to the most advanced technology**. This allows researchers to develop and execute large scale projects beyond their individual capacity. **Delivering the scientific objectives outlined in this report can be achieved through developing the capability of the NERC Geophysical Equipment Facility.** In particular, access to the following instrumentation is necessary to allow the UK to remain at the forefront of passive seismology:

1. Tens to hundreds of traditional land and ocean broad-band seismometers.
2. Thousands of low power, low cost seismic sensors (so-called seismic nodes).
3. Suitable computing resources to handle the increase in data and meta-data.

The community recognise that this may require different ways of working including closer partnerships with manufacturers and industry. We also believe that it is essential that a future facility can monitor and ideally lead development of new technologies that show potential (e.g., fibre optics, rotational sensors and subsea autonomous vehicles).

Introduction: Seismology in the UK

Seismology is the study of processes and structures in the interior of the Earth or other planetary bodies using seismic and acoustic waves. *Passive* seismology uses only waves emanating from sources of energy that occur naturally or which are induced inadvertently. Examples of passive sources include earthquakes, oceanic waves, landslides and anthropogenic activities. The UK has played a leading role in passive seismology over the last century. We have advanced the discipline in the development and manufacture of new equipment and its deployment in multi-sensor arrays to understand tectonic, volcanic and environmental processes on land and at sea. We developed methods that extend seismology beyond earthquake observation to imaging the Earth, and are at the forefront of the wave of intelligent processing algorithms used to interrogate large data sets.

Seismology is at a turning point: new disruptive technologies such as wireless communications, low power seismometers, better battery technology, optical sensors on fibre optic cables and high performance computing allow deployments of hundreds to thousands of sensors on land and sea, and potentially millions to billions of sensor points along optical cables. These advances enable new transformative processing technologies to be applied, allowing passive seismology to venture beyond imaging the solid Earth into monitoring of the natural environment. These are revealing novel dynamics and societally important phenomena in both the natural and anthropogenically altered world. To date, these new instruments have not been available to the UK community so we risk losing our leading role in this important and exciting area of Earth science and observation.

This motivated a meeting, sponsored by the British Geophysical Association, on '*The Future of Passive Seismic Acquisition*' in Edinburgh in November 2018 (Hammond et al., 2019). The meeting, with over 110 participants from UK, Europe, Canada, USA, Middle East, Africa and Japan explored the current state of the discipline and focussed on key areas for the next 10-20 years. All agreed that the UK facilities must change to respond to community need: they must provide dense networks of broadband and short period sensors in the oceans and on land, plus a platform to evaluate, acquire and make available newly developed technologies such as fibre optic sensors, rotational seismometers and autonomous vehicles to the community as these technologies develop.

The NERC Geophysical Equipment Facility meets some of these requirements, providing passive seismic equipment and data management facilities to the UK community. However, its current structure cannot host the order of magnitude increase in equipment and commensurate increase in data storage/ processing required to facilitate the next generation of observational tools. Nor is it suitably structured to test and make available novel technologies. A new model is essential.

This report summarises the areas and challenges where passive seismology can make advances that are important to science and society, and articulates suggestions for how to develop passive seismology with a facility at its core, so that the UK can lead this area well into the 21st century.

Grand Challenge 1: Technology

Subsea instrumentation: The greatest opportunity, both for developing new instrumentation and to enable novel science, is in oceanic areas. There is a desire to monitor submarine eruptions, ice sheet/glacier calving, iceberg singing, sea-level rise, ocean waves, ship traffic, whales, rainfall, as well as deeper, purely seismological targets such as processes and structures of the deep Earth. The oceanic ridges constitute the largest volcanic system in the world, dwarfing the volcanic system on land, yet are almost entirely unmonitored. Ocean bottom seismology is needed for the study of subduction zones, including low frequency sensors to detect slow earthquakes, in order to illuminate the degree of inter-tectonic plate coupling and the potential for mega-earthquakes.

While dense networks of broadband seabed instrumentation on large spatial scales remain unfeasible due to costs and logistics, floating seismometers (Figure 1) that build on the network of ~4000 sensors monitoring temperature and salinity in the oceans, or

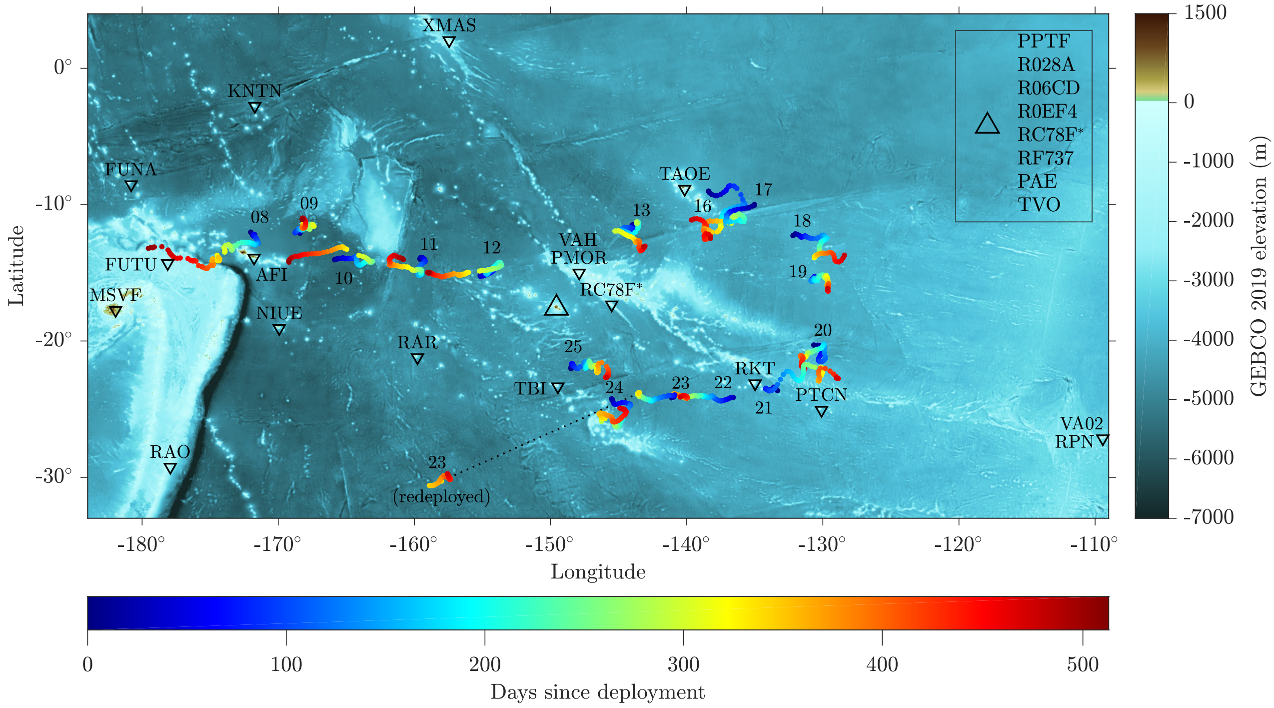


Figure 1: Top: 16 of 50 MERMAID floating seismic sensor trajectories in the South Pacific with time (coloured tracks) and location of nearby island stations (triangles). Note the extra coverage provided by the floating sensors. See www.earthscopeoceans.org for details and current status of sensors. Modified with permission from Joel D. Simon's PhD thesis, 2020. Left: Joachim Lomani (left) and Edwin Jimmy (right) aboard the R/V Alis deploying MERMAID sensors in August 2018 (Image courtesy of Frederik Simons). MERMAID was designed and built by Yann Hello (GeoAzur, Sophia Antipolis, France) with OSEAN SAS (Le Pradet, France).

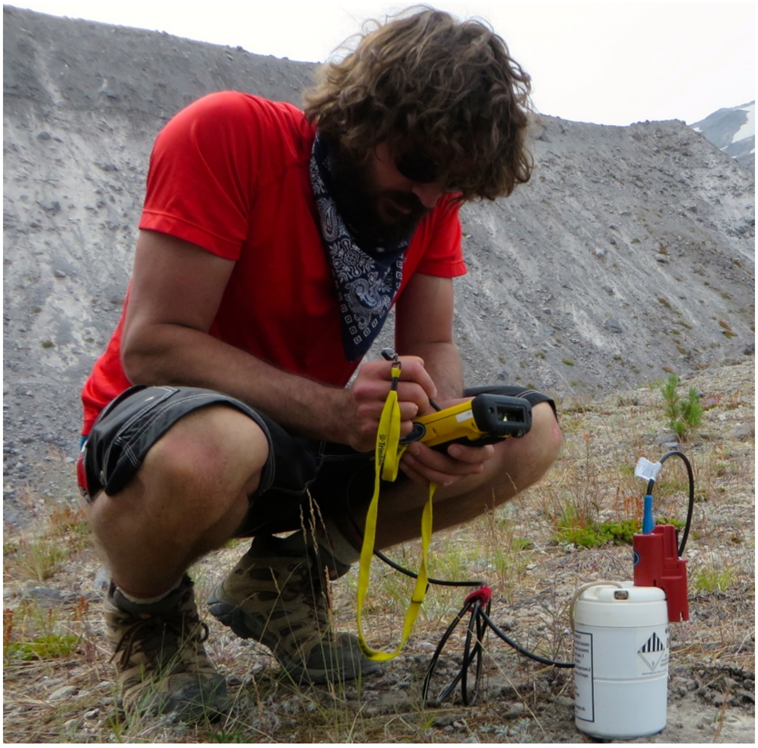


Figure 2: Nodal seismometer deployed at Mt. St. Helens (Image courtesy of Brandon Schmandt).

autonomous vehicles such as the MERMAID system (Figure 1), have been shown to produce useful data. Trans-oceanic fibre optic tele-communications cables represent a possible technology to image and monitor the oceanic and solid-Earth subsurface using laser interrogation systems that allow small vibrations along cables to be monitored and recorded. This technology exists, but it requires access to existing communications fibres for the academic community to explore as test-beds of this technology.

Land instrumentation: Deploying land instrumentation is logistically simpler than on the seabed, but many innovations are required to achieve our scientific goals. These include the requirement for low power, easy to deploy sensors to create dense networks for full wavefield imaging, for engineering geology through ground motion study, or for rapid deployment after/during earthquakes and volcanic eruptions and other natural hazards. These so-called nodal sensors (Figure 2), are already used by industry and are becoming increasingly popular for solid Earth and environmental applications. With current technology, a global array of broadband seismometers in boreholes would provide significantly better data quality, allowing global seismicity to be monitored and understood at far lower magnitudes, thus informing models of earthquake triggering and forecasting. Wells abandoned as the hydro-carbon industry gradually diminishes may therefore represent an opportunity to develop monitoring capability further. While still in the development phase, portable land based rotational sensors are available and provide data more closely related to ground-strain than ground-displacement, which are useful for a wider range of applications. Fibre optic cables present a new way of measuring seismic strain with denser spatial sampling and are now being tested and used intensively within the hydrocarbon industry. Finally, citizen science can play a role through simple seismometers or accelerometers installed on tablets and mobile phones. These provide rich data streams with the potential to significantly improve global coverage if the quality of such data can be improved and verified, and if privacy issues can be overcome.

Computing infrastructure: High volume data streams are already being produced in seismology and growing rapidly. Access to suitable data infrastructure, computing power and the automation of many standard seismic processing methods will be key for making projects feasible within the budget constraints of standard scientific grants.

Grand Challenge 2: Tectonic Processes

Plate tectonics plays a fundamental role in shaping the Earth over geological timescales. It controls the chemical budget through cycling elements from the atmospheres and oceans into the solid Earth, it focuses geothermal sources and mineral or hydrocarbon deposits, and it gives rise to natural hazards which impact society through earthquakes and volcanoes. UK science has led research in key parts of this area through projects focussed on natural laboratories: rifting in East-Africa and Iceland, mountain building in Asia, and subduction in the Caribbean among others. However, many of these processes are inherently amphibious with subduction zones and mid-ocean ridges lying beneath the oceans, so the existing largely land-based projects are limited in their scope. For example, the down-going oceanic plate, the primary source of water and volatiles, is typically submerged (e.g., Figure 3). Without direct images of this system, we cannot estimate the input of volatiles, meaning

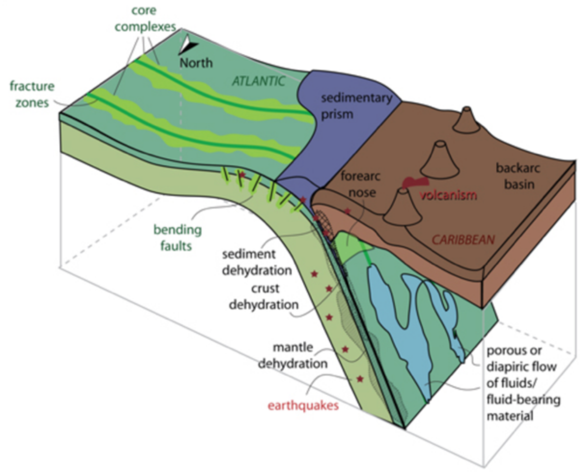


Figure 3: Recycling volatiles in the Caribbean subduction zone (see the Voila project for more information, http://www.voila.ac.uk) (Image courtesy of Saskia Goes).

correlations from geochemistry and geodynamics on what is released/stored in the volcanic arc, or carried into the deeper Earth are unconstrained. Despite this fundamental question, key information is lacking for most subduction zones.

Another example comes from studies of continental breakup and the transition to seafloor spreading. To date, most subsea

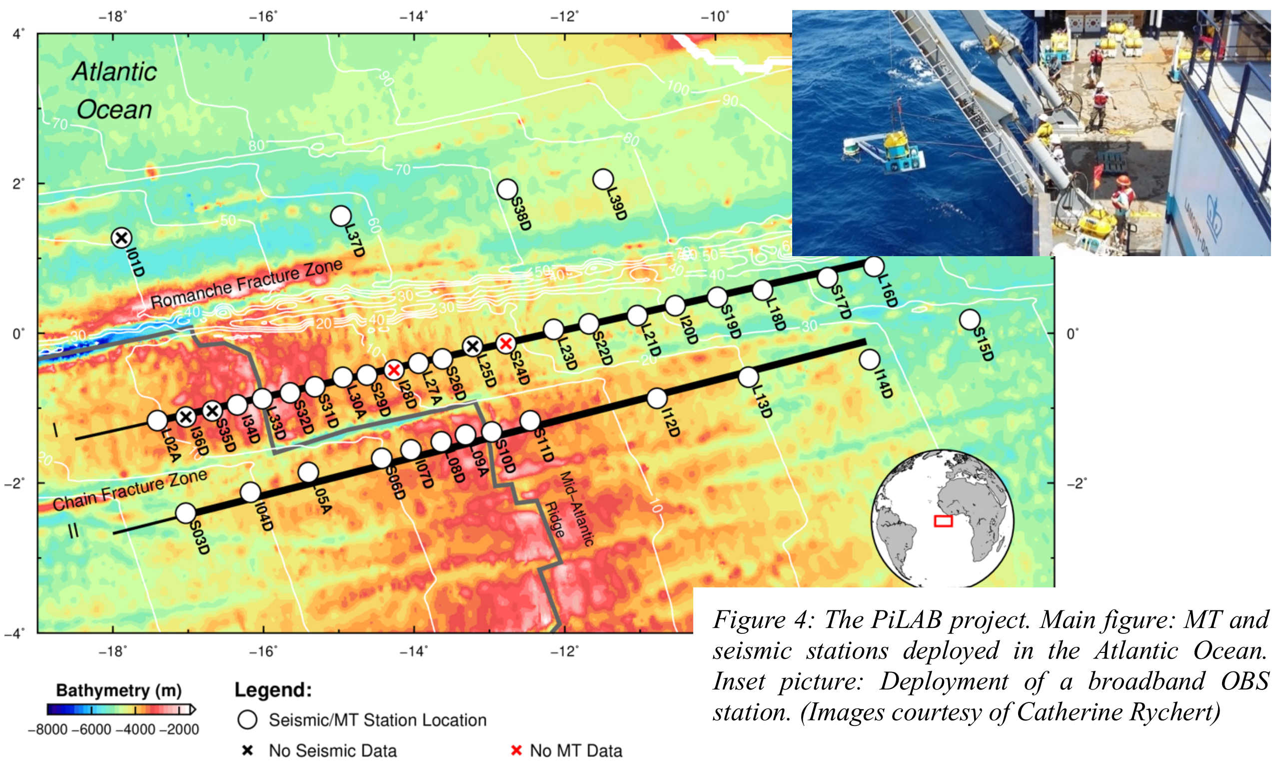


Figure 4: The PiLAB project. Main figure: MT and seismic stations deployed in the Atlantic Ocean. Inset picture: Deployment of a broadband OBS station. (Images courtesy of Catherine Rychert)

studies have relied on controlled source (explosive) seismology and large passive seismology imaging studies have been mostly confined to land in East Africa and Iceland. While logistically these areas are ideal for studying processes, they are inherently anomalous, being affected by mantle plumes which explains their sub-aerial occurrence. Developments in instrumentation make it possible for these areas to become long-term natural laboratories, helping us understand how most of the Earth's crust is formed (e.g., the PiLAB project, Figure 4). This presents us with an opportunity to study the earthquake cycle, where, unlike on land, their simple geometries, geology and tectonic forces yield quasi-predictable earthquake periodicities.

The key to understanding tectonic processes is to observe and understand structure and dynamics at a variety of scales, resolutions and timescales. This requires dense, long term networks of seismometers, combined with other subsea instrumentation like magneto-tellurics and geodetic instrumentation. Much of this technology exists, including broadband ocean bottom seismometers with emerging technologies like absolute pressure gauges capable of millimetre per year vertical motion resolution, ocean bottom acoustic geodetic systems, ocean bottom magnetotellurics and rapidly deployable, low-power terrestrial seismometers. Recent results also suggest that floating sensors (Figure 1) and telecommunic-ations cables which traverse the major oceans of the world may themselves be able to be used as seismic sensors (Figure 5). In addition, computing infrastructure is now commonly available that is capable of storing and processing the huge volumes of data now and in the future.

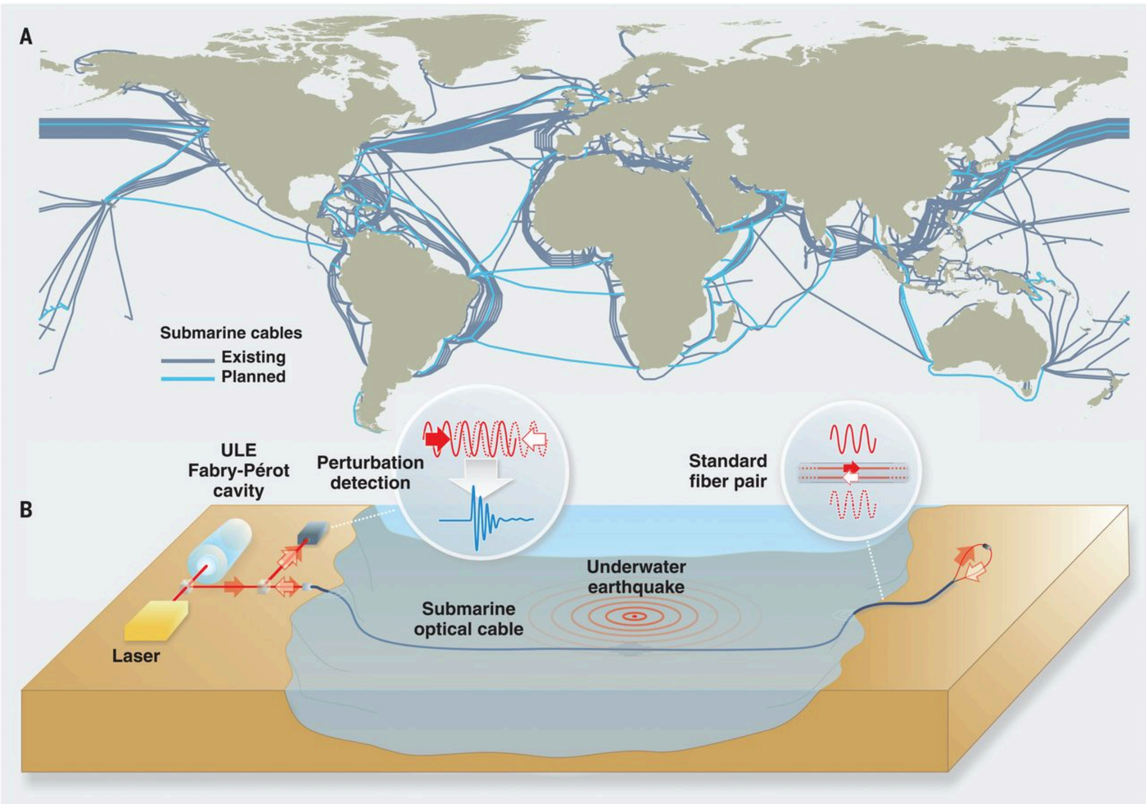


Figure 5: Current and planned subsea fibre optic cables (as of 2018) (A) and principles of using fibre optic signals to record seismic data. Image from Marra, G., Clivati, C., Luckett, R., Tampellini, A., Kronjäger, J., Wright, L., Mura, A., Levi, F., Robinson, S., Xuereb, A. and Baptie, B., 2018. Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables. Science, 361(6401), pp.486-490, doi:10.1126/science.aat4458. Reprinted with permission from AAAS.

Grand Challenge 3: Earth Resources

The development and modernisation of human society is strongly dependent on its access to Earth resources. Materials extracted from the Earth are used to build houses, cities, our transport and industrial systems, electronic devices and other technology. The Earth is also the primary supplier of energy, without which modern society could not operate and it is a storage space for the safe containment of human-generated waste. Access to and safe extraction of Earth resources is therefore a key challenge for current and future generations. Particular challenges come from human induced seismicity where geothermal energy extraction (Figure 6), hydraulic stimulation extraction (fracking) or carbon capture and storage induce fracturing of the rock mass through injection of fluids. Mining and dams also induce seismicity due to the removal or addition of mass. A better understanding of the physics of rock fracturing would have a huge benefit to these industries, reduce hazard to society and the environment, and make energy extraction safer, more cost effective and efficient.

Seismic imaging and microseismic monitoring play a key role in conventional and un-conventional (e.g. fracking) hydrocarbon extraction (Figure 6) and the extraction of geothermal energy. This allows identification of resources and local baseline seismicity rates to be established for comparison, and a better understanding of the mechanical behaviour of rocks in response to high pressure fluid injection and extraction.

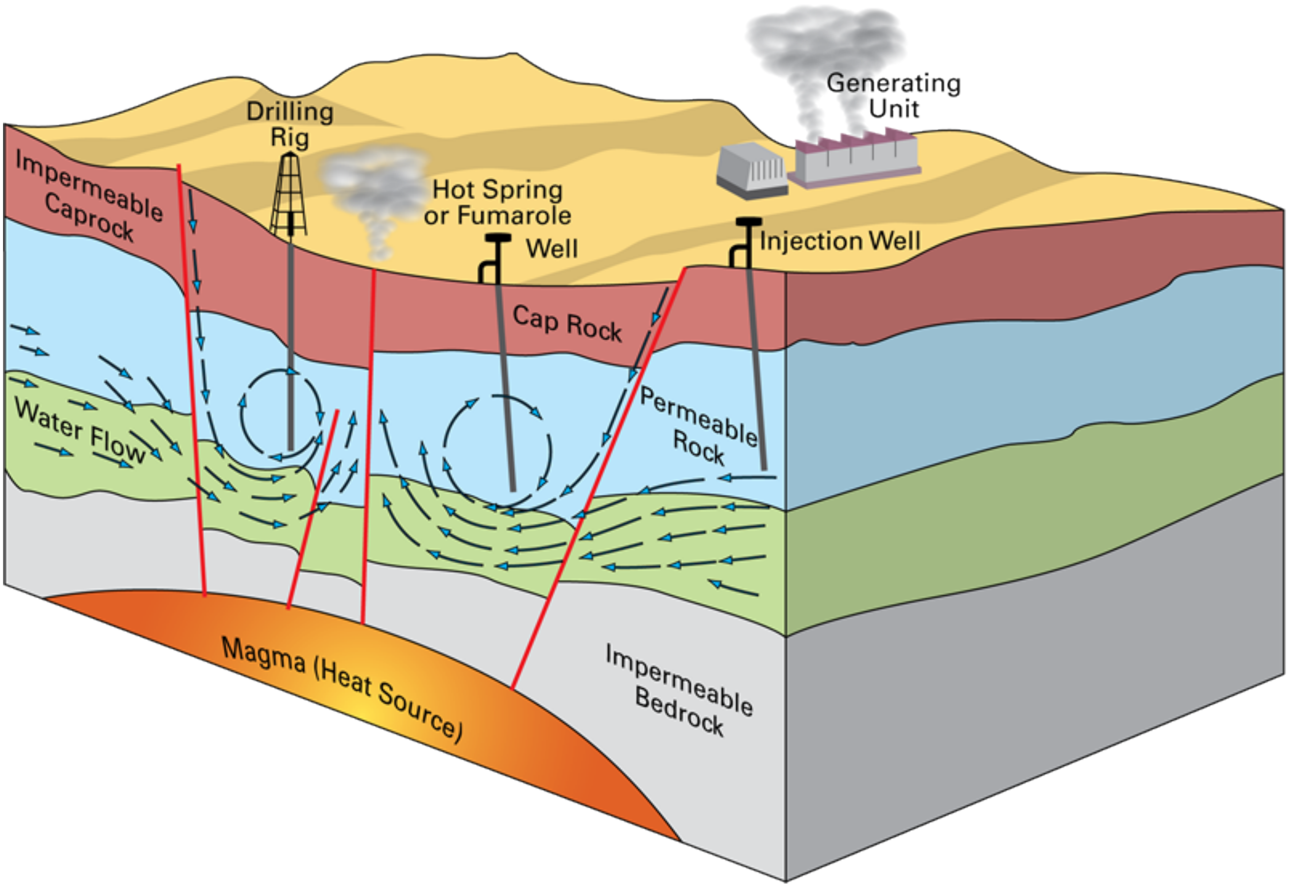


Figure 6: Simplified diagram of a geothermal plant (British Geological Survey © UKRI 2020. All Rights Reserved. Sourced: https://www.bgs.ac.uk/research/energy/geothermal/).

Traditionally, controlled source (explosive) seismology has provided images of the subsurface, driving energy production. However, new dense deployments of land and sea seismometers together with new 4D, high resolution seismic imaging and location methods that incorporate modern rock physics science can help us understand how best to exploit these systems in future.

To address these challenges, we can follow the example of the hydrocarbon industry, where dense networks of short period, low cost, low power seismic nodes are commonly used on both land (Cover Image) and on the seafloor (Figure 7). This allows much more of the full wavefield to be recorded, improving subsurface imaging to identify small anomalies and the detection and location of seismicity. Developments in fibre optic sensors can further enhance spatial coverage, and rotational sensors may replace local arrays. Monitoring efforts should combine long-term broad-band seismometers to identify important or dangerous subsurface events with shorter term dense nodal deployments to identify and characterise the event in order to design mitigating action. Finally, ocean bottom sensors or autonomous vehicles would allow us to extend this coverage underwater, enhancing micro-seismic monitoring, imaging CCS or geothermal sites and exploring deep sea mining sites in future.

Figure 7: Main picture: Automated deployment of ocean bottom nodes (Magseis Fairfield Nodal ZXPLR® system) in a deepwater setting (Image from Magseis Fairfield).

Grand Challenge 4: Natural Hazards

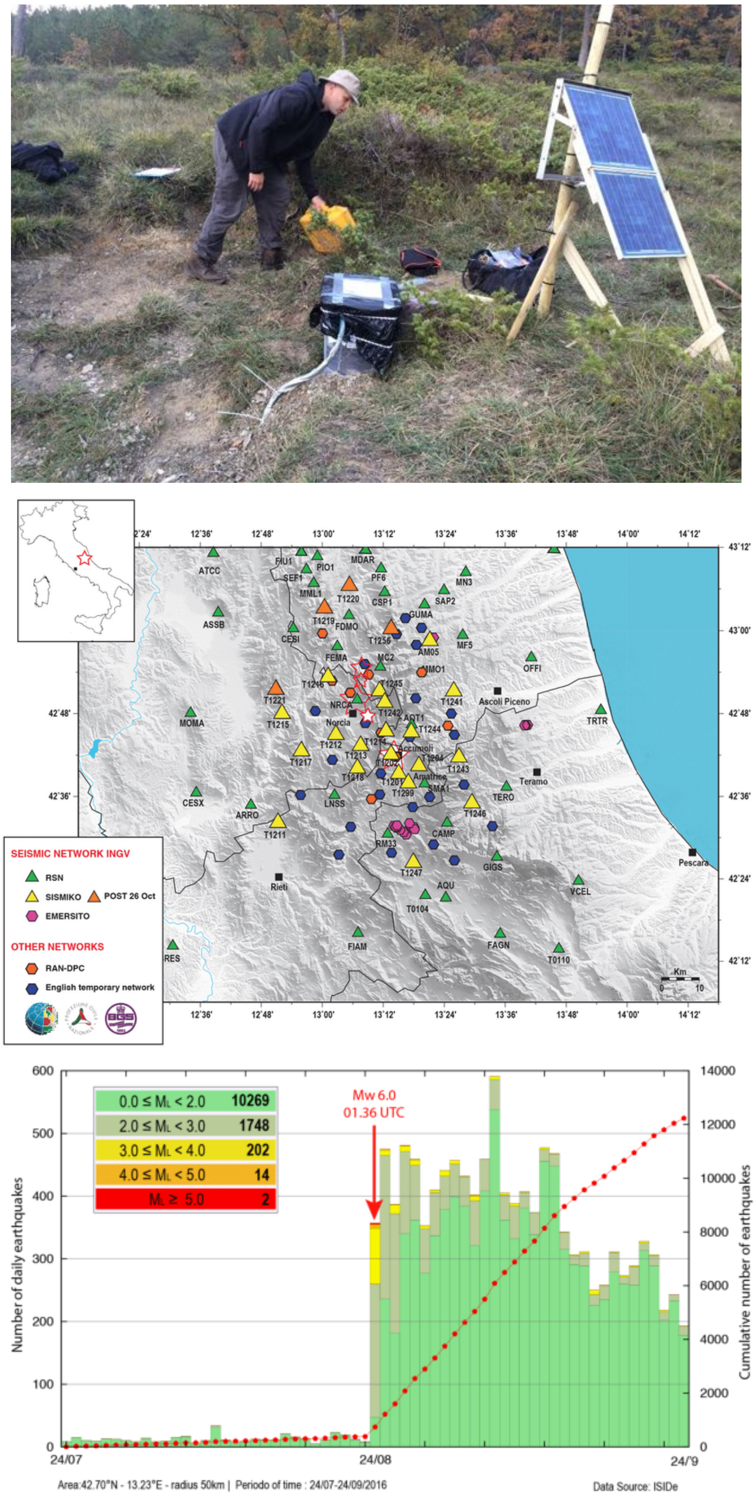


Figure 8: Top: A rapid deployment of a seismometer in Italy following the 24th August Central Italy 6.4 Mw earthquake. (Image from David Hawthorn) Middle: The full seismic network. Bottom: The detailed rates of seismicity captured by the dense network. (Images from Moretti et al., 2016. SISMIKO: Emergency network deployment and data sharing for the 2016 central Italy seismic sequence. Annals of Geophysics, 59, doi:10.4401/AG-7212. License: CC BY 3.0).

Traditional hazard monitoring is based on the ability to identify a period of anomalous activity in relation to normal levels. UK science has a long, successful track record in this field, creating physical models of the subsurface that explain both observations of seismic/magmatic activity during times of activity, and the background state.

However, this approach requires long-term monitoring efforts, with seismic arrays deployed on a decadal scale in volcanic and seismically active regions. These long-term data sets not only allow the development of new and more accurate models of the subsurface at times of quiescence, but will also allow the identification of long-term trends in earthquake and volcanic activity, helping address questions such as how climate change manifests in increasingly extreme weather, how sea level rise and ice melt (the loss of permafrost/increase in seasonal meltwater) affect magmatic and seismic activity. The existence of a seismic array in an area of seismic or magmatic unrest will capture the initiation of the activity, and any precursory changes, which can tell us an enormous amount about the triggers of these hazards. This will provide an understanding of the fundamental processes, such as how magma migrates in the crust or how earthquakes nucleate, and help develop and implement early warning systems.

While long-term monitoring is key, it is imperative that we have instrumentation available to respond quickly and safely to ongoing natural hazards. The UK has a strong track record, using NERC urgency grants and rapid response from the NERC Geophysical Equipment Facility to instrument after earthquakes and volcanic eruptions globally (e.g., after the 24th August Central Italy 6.4 Mw earthquake, Figure 8). Cheap, low power instruments can help facilitate this goal, which would allow us to respond soon after major earthquakes, leading to better mapping of active faults, improved characterisation of aftershocks and more robust forecasting of future damaging earthquakes through static and dynamic triggering. At volcanoes, responding soon after an eruption means we can learn about the mechanism of magma transport, the interaction of different zones of the magmatic plumbing system and the interaction between volcanic and regional stress (e.g., Figure 9). We could also capture the end of an eruption and hence learn about the driving forces behind magma withdrawal, thus answering the question of when an eruption ends. Finally, citizen science may enhance these studies, with new cheap seismometers designed for home use being used in studies to better estimate earthquake locations, magnitudes and dynamics in the UK and internationally.

Tectonic hazards are controlled by processes over a range of spatial scales: from faults and conduits that are kilometres to metres in length, to sub-millimetre cracks and pores that can control fluid migration or rock rheology. New dense networks of seismometers, together with full wavefield imaging techniques can improve the resolution of these images and more accurately locate rupture sources, thus allowing us to better understand these processes.

Finally, tsunami are generated by large thrust earthquakes in subduction zones, which by definition, must lie underwater. Long-term monitoring through ocean bottom seismometers or autonomous vehicles are key for understanding these processes.

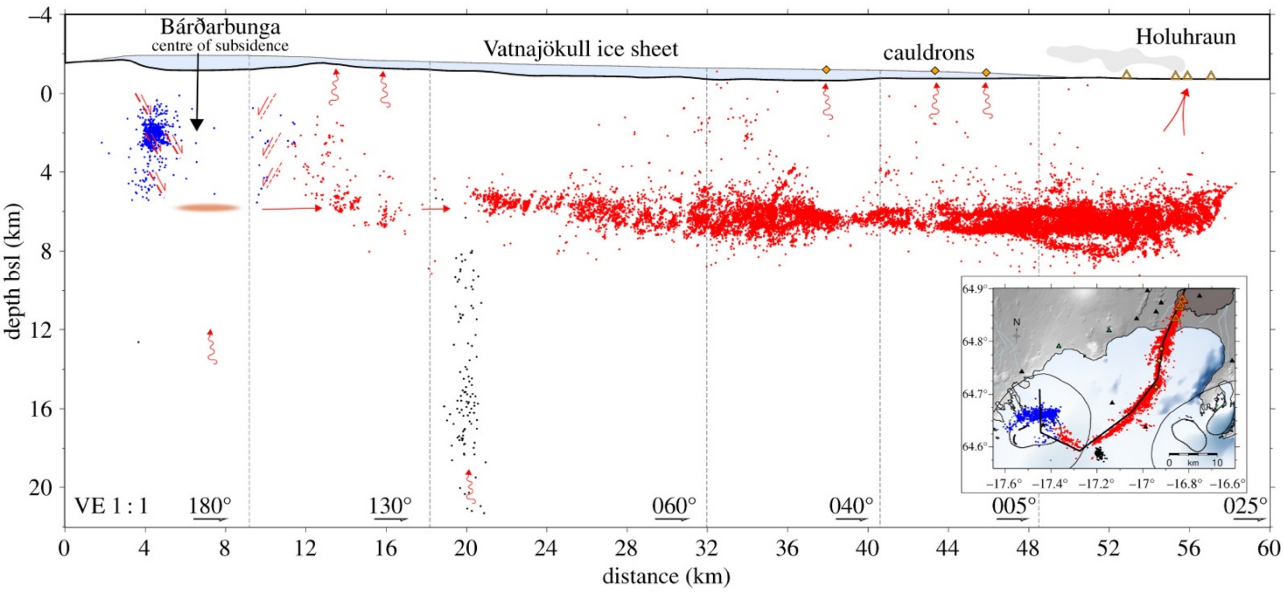


Figure 9: Seismicity associated with the Bardarbunga – Holuhraun eruption from 2012-2017 (Republished with permission of the Royal Society, from White, R.S., Edmonds, M., Maclennan, J., Greenfield, T. and Agustsdottir, T., 2019. Melt movement through the Icelandic crust. Philosophical Transactions of the Royal Society A, 377, doi:10.1098/rsta.2018.0010. Permission conveyed through Copyright Clearance Center, Inc.)

Grand Challenge 5: Planetary Evolution

The Earth provides us with a stable environment within which intelligent life has evolved. However, Earth is a changing planet and has itself evolved over 4.5 billion years since it formed from the solar nebula to its current state. Today, tectonic plates move across the surface and sink into the interior causing great earthquakes, yet we do not understand the convection process that drives this activity, the fate of slabs in the deep Earth or how primordial material is tapped by plumes and brought to the surface. Understanding these phenomena has the potential to allow us to 'rewind' time and better understand the early Earth. This convective process acts to push up or pull down the Earth surface, changing the movement of water and soil and changing the atmosphere and climate. Deeper in the Earth, the metallic core creates a magnetic field to shield life from the solar wind. This is largely controlled by processes at the boundaries of the outer core, thus improved seismic imaging can help us understand how and why the magnetic field is generated and changes with time. Finally, we understand much about how rocky planets form from studying Earth, yet our neighbours, Venus and Mars, look strikingly different. Understanding why and if other planet(esimals) may be habitable requires direct measurement through passive seismology.

Passive seismology is the only technique that allows us to image the interior of the deep Earth and other planets (Figure 10). However,

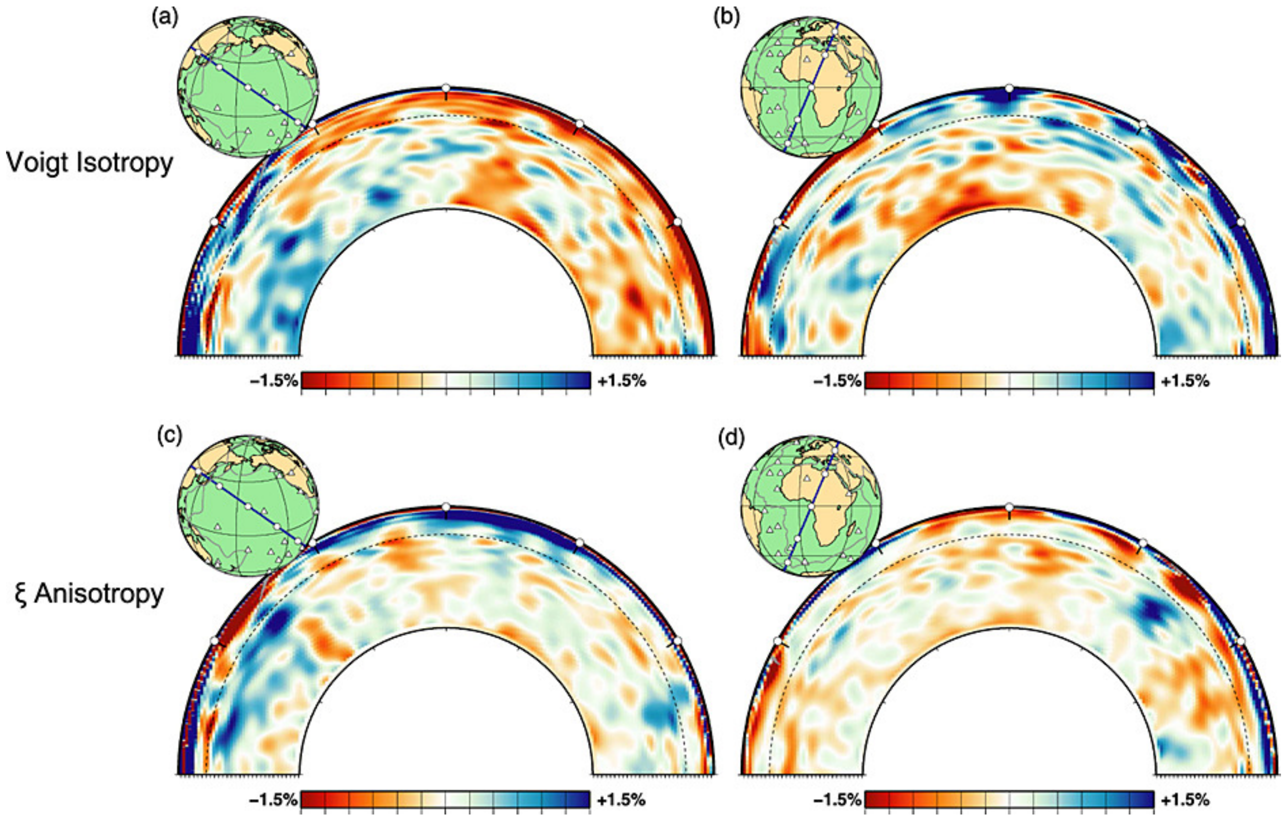


Figure 10: Cross-sections through global radially anisotropic seismic tomography beneath the Pacific (a,c) and Africa (b,d) (Image from Chang, S.J., Ferreira, A.M., Ritsema, J., van Heijst, H.J. and Woodhouse, J.H., 2015. Joint inversion for global isotropic and radially anisotropic mantle structure including crustal thickness perturbations. Journal of Geophysical Research: Solid Earth, 120, doi:10.1002/2014JB011824).

the major limitation in its application has been a non-uniform data coverage, where we are reliant on using large natural earthquakes as sources and single, high-sensitivity seismometers as sensors. Progress requires deployments that fill these gaps in global coverage and the investigation of new types of source and new instruments to measure ground motion. The biggest advance would come from a worldwide deployment of ocean-bottom seismometers (OBSs). Current technology allows for multi-year deployments of hundreds of stations, but long-term solutions to the challenges require permanent OBS networks sending data in real-time (Figure 11) or exploration of game-changing approaches such as using ocean fibre optical cables as distributed seismic sensors (Figure 5). Autonomous vehicles can help, either deploying seismometers at sea or in hostile environments (e.g., Antarctica, active volcanoes) or for direct data collection (Figure 1).

Improvements in the signals we can record will also help. Existing data suffers from noise from human activity, a situation that is likely to get worse in future. Sensors deployed in boreholes 10s to 100s of metres deep would allow more subtle but important seismic signals to be detected. Further, limitations on the frequencies that traditional sensors record mean low-frequency oscillations, such as the normal modes of the Earth where the whole planet rings like a bell, are hard to see. These offer one of the only direct constraints on density structure within a planet. To see these vibrations, very low frequency sensors (sensitive to mHz frequencies) must be deployed more widely, and non-traditional 'geodetic seismology' (such as using GPS measurements to recover ground motion) must be developed.

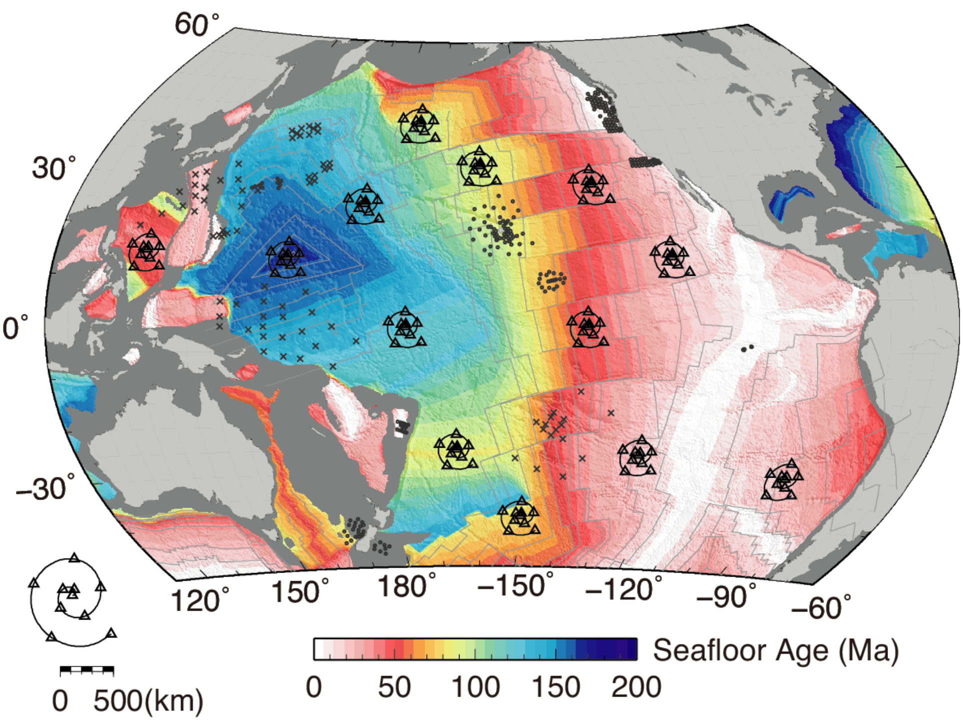


Figure 11: The Pacific Array – A proposed long term Ocean bottom seismometer network to image the Pacific Ocean and improve global seismic tomography images. Triangles show proposed ocean bottom seismometers. Crosses and circles show existing ocean bottom seismometer deployments (Image adapted from Hammond, J.O., England, R., Rawlinson, N., Curtis, A., Sigloch, K., Harmon, N. and Baptie, B., 2019. The future of passive seismic acquisition. Astronomy & Geophysics, 60(2), pp.2-37).

Grand Challenge 6: Environmental Change

The Anthropocene is already presenting major challenges to the global population and Earth's ecosystems. A better understanding of how our environment responds to changes in the Critical Zone (CZ), the interface between rock, soil, water and air, requires tools that can provide us with high-resolution, widespread and continuous data. Passive seismology is a long-established discipline that provides greater understanding of the solid Earth, but more recently, it has proved to be a powerful tool for addressing new scientific questions related to less traditional seismological applications, in novel and efficient ways.

Passive seismology plays a key role in understanding the impacts of a changing climate. It can be used to understand ice dynamics on small and large scales including monitoring the retreat of glaciers and ice sheets through remote recording of ice calving (Figure 12) or glacial outflow events. Through measuring seismic energy from landslide events, river bed transport or wave impacts on coastlines we can better understand processes in the near-surface and shallow crust, such as weathering and alteration processes, many of which have been affected by increases in extreme weather phenomena and a changing climate, e.g., slope destabilisation and coastal erosion. Further, arrays of seismometers can be used to monitor small velocity changes associated with the changing subsurface through changes in water content, or material strength, which can drive Earth surface processes such as landslide events (Figure 13). Migration of energy from these arrays helps track oceanic storms, providing insights in to their potential increase in frequency over time. More recently, seismological principles and instrumentation have been applied in studies of animal behaviour that aim to protect endangered species. In the built environment, the use of seismometers is well established for

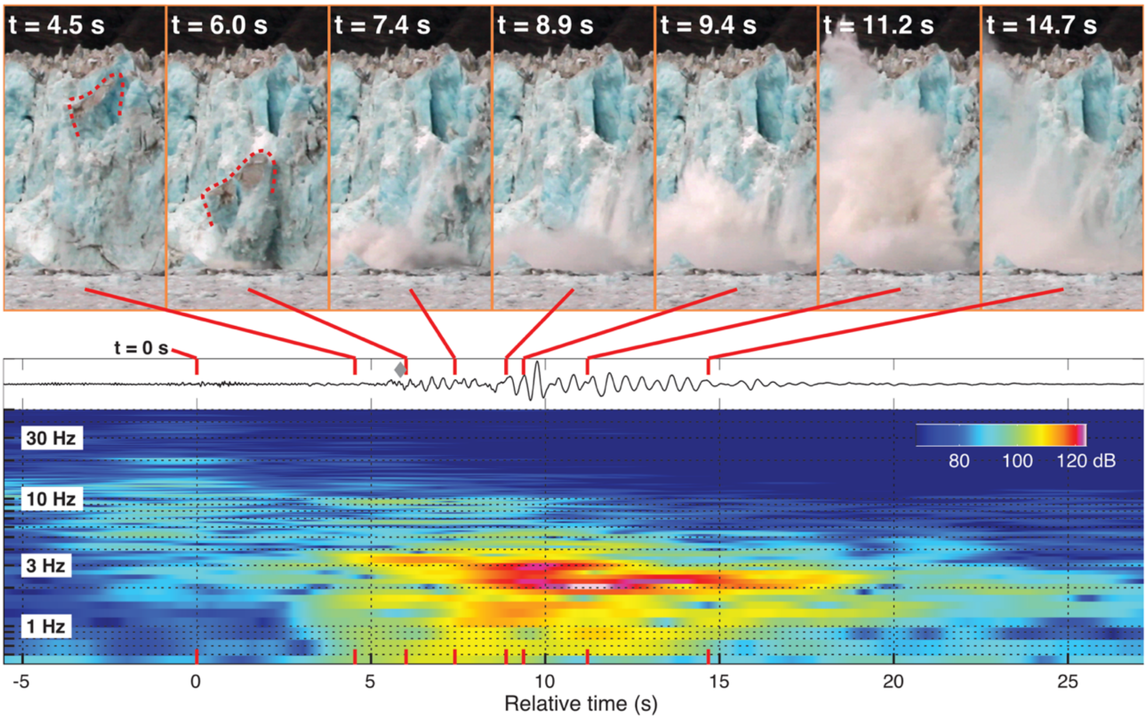


Figure 12: Video stills of an ice calving event (top), associated seismic data (middle) and spectrogram (bottom) (Image from Bartholomaus, T. C., Larsen, C. F., O'Neel, S. and West, M. E., 2012. Calving seismicity from iceberg-sea surface interactions. J. Geophs. Res. Earth Surface, 117, doi:1029/2012JF002513.)

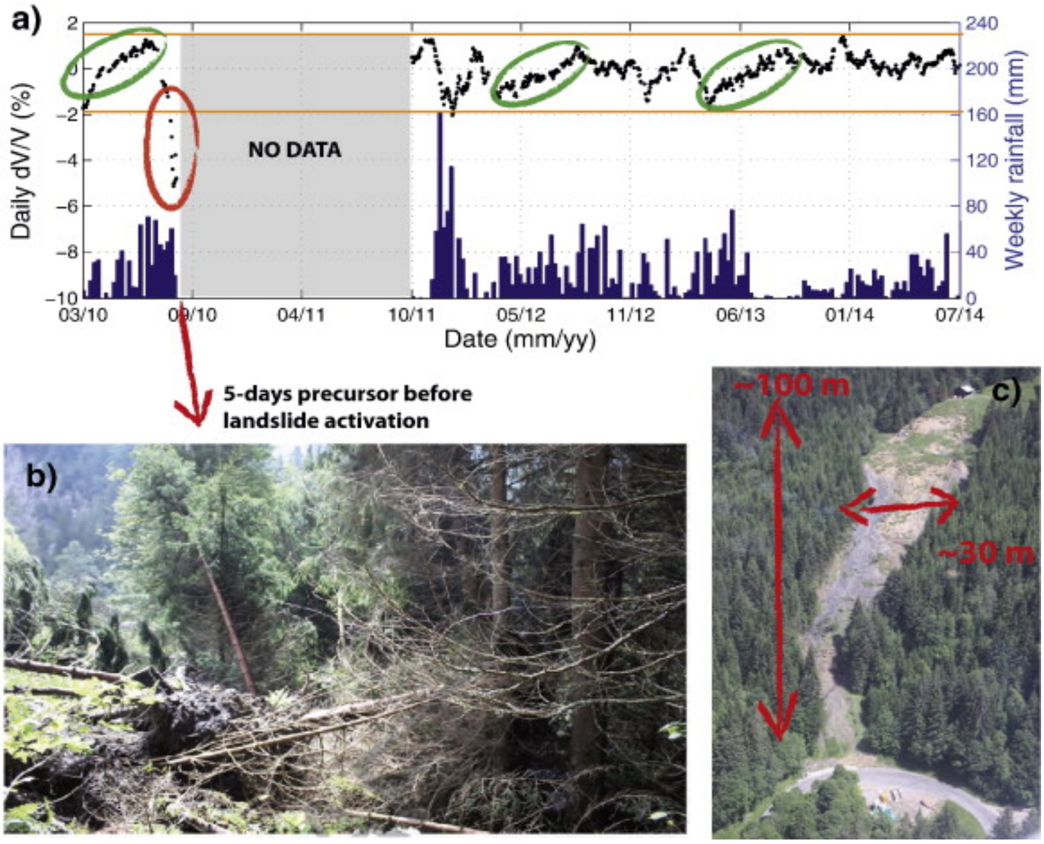


Figure 13: a) Relative velocity changes and daily rainfall across a landslide in the Swiss Alps (b,c) (Figure reprinted from Larose, E., Carrière, S., Voisin, C., Bottelin, P., Baillet, L., Guéguen, P., Walter, F., Jongmans, D., Guillier, B., Garambois, S. and Gimbert, F., 2015. Environmental seismology: What can we learn on earth surface processes with ambient noise?. J. of App. Geophys, 116, doi:1016/j.appgeo.2015.02.001 with permission from Elsevier.

assessing structural health and providing early warning of imminent failure, thus contributing to understanding the dynamic and mechanical behaviour of engineered ground and structures and consequently improving risk mitigation and reducing remediation costs. More recently, it has been shown that fibre optic cables installed in many buildings and cities present opportunities to monitor such behaviour at better temporal and spatial resolution than before.

It is clear that passive seismology can play a role in monitoring environmental change, but more work is needed to maximise this potential. For example: Can passive seismology be used to study changing processes occurring at small-scales (<100 metres) at very high spatiotemporal resolutions in the Earth's CZ? Can changes in the seismic signals caused by small-scale environmental processes and wildlife be successfully isolated from much higher amplitude sources of seismic events and noise? Can variations in these signals act as proxies for changes in the CZ? Answering these questions may allow us to address some of the fundamental questions about these processes, such as how moisture in the subsurface may trigger landslides and potentially provide new monitoring tools.

New equipment, providing dense seismic networks with high sampling rates along with new ways of handling the large amounts of data will be required to facilitate this approach. For example, to isolate environmental seismic signals, recordings are often compared with data from other sources (e.g. cameras, field logs) but without automation, this is a time-consuming process.

Vision for a new facility

To support the research outlined in this report we require a facility larger in scope than the existing passive seismology equipment pool provided by the NERC Geophysical Equipment Facility (GEF). This requires changes to the structure, size and model of operation of the facility. We recommend that a future facility:

- Expand the current network of broadband land sensors to form the backbone of future projects.
- Explore new models of operation with manufacturers and industry to supply, maintain and store thousands of the latest nodal instruments.
- Provide access to arrays of broadband ocean bottom seismometers.
- Provide archival storage for the orders of magnitude increase in raw and meta-data.
- Explore providing data derived products such as seismicity catalogues, Green's functions estimated from cross-correlations or products of other standard seismic techniques to help the community manage new large datasets.
- Become a hub for the identification, development and implementation of new emerging technologies such as autonomous subsea vehicles, floating seismometers, fibre optics and rotational seismology.
- Provide access to skilled technicians with experience in instrumentation, field deployments and data archiving to support use of new, developing technology.