The future of passive seismic acquisition

James Hammond and **co-authors** report from a BGA meeting on how advances in instrumentation are opening up opportunities for dense, large-scale deployments of seismometers on land and in the oceans.

1 Small, cheap and remarkably useful: modern high-frequency seismic nodes are increasingly popular for deployments in remote areas and novel seismological situations. (Steve Jacobsen)

It is an exciting time to be a seismologist. In November 2018, the InSight lander touched down on Mars and deployed the first seismometer on the surface of another planet. This feat means planetary seismologists are now searching for marsquakes and hope to provide images of its interior that will help to understand how rocky planets form. However, we have been doing this for a long time in more familiar territory back home on Earth where, in recent years, the field of terrestrial seismology has reached a turning point with significant developments in instrumentation and the manner of their deployment. Despite this, equipment available to the UK community has not kept pace and needs urgent regeneration if the UK is to lead in the field of passive seismology in the future.

To begin the process of redesigning the UK's equipment for the next few decades, the British Geophysical Association sponsored a New Advances in Geophysics (NAG) meeting in November 2018 in Edinburgh on The Future of Passive Seismic Acquisition. What follows is a historical account of how and why we arrived at the present-day UK seismological research and resource base, a summary of the Edinburgh meeting, and a vision for the passive seismic facilities required to support the next 20 years of seismological research.

History of passive seismology

In 1883, John Milne postulated that earthquake energy could be recorded at great distances (Milne 1883). This was proven in 1889 when a recording of a teleseismic earthquake (from Japan) was made by Ernst Von Rebeur-Paschwitz on a seismometer in Potsdam, Germany (Von Rebeur-Paschwitz 1889). Von Rebeur-Paschwitz soon realized that a set of seismometers deployed at stations globally could enhance our understanding of the Earth, stating in 1895: "Primarily we would seek the establishment of an international network of earthquake stations … to systematically observe the propagation of movements generated at earthquake centres, along the Earth's surface and through its interior," (Wiechert 1906).

Pioneering scientists undertook the task of realizing this vision and the discipline of seismology was born. Early successes included identification of different waves travelling through the Earth at increasing speed with depth (Oldham 1900). As the volume of data increased, more features became apparent: the crust–mantle boundary (commonly known as the Moho; Mohorovičić 1910a,b,c), the core (Gutenberg 1914), deep earthquakes in subduction zones (Wadati 1928, Benioff 1949) and the inner core (Lehman 1936).

The need for a robust method to detect underground explosions after the second world war led to a huge increase in recorded data, and to the advent of modern-day seismology. A "conference of experts" was held in Geneva in 1958 with a focus on how to identify nuclear tests. It was recognized that a global network of seismometers would be an effective way to monitor underground explosions (Department of State 1960), an effort in which the UK played a leading role (Keen *et al.* 1965). From this, the first global seismic network was formed, the Worldwide Standardized Seismograph Network (WWSSN), shown in figure 2 (see Peterson & Hutt 2014 for a review). Importantly, this network relied on technological advances, notably the development of high-precision, accurate seismometers that could be used anywhere.

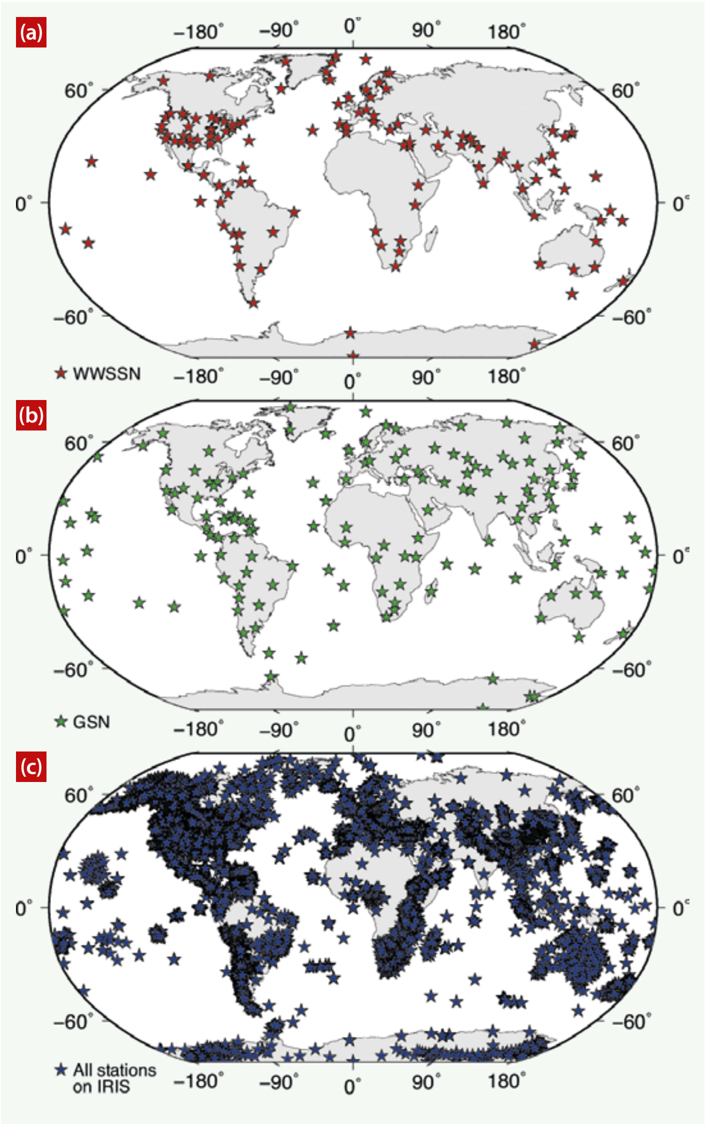
"Terrestrial seismology has reached a turning point in instrumentation and deployment"

The WWSSN was superseded in the 1970s when a consortium of academics took ownership of the network through the Incorporated Research Institute for Seismology (IRIS). Many seismometers were digitized and the WWSSN became the Global Digital Seismic Network (GDSN). It was replaced in the 2000s by the Global Seismic Network, which now has more than 150 permanent stations transmitting real-time data (figure 2), all provided openly through the IRIS Data Management Center (Butler *et al.* 2004). These networks not only allowed nuclear test monitoring, but their pioneering open data model gave seismologists a powerful tool to develop detailed seismic tomography models of the 3D structure of the Earth (e.g. Dziewonski & Anderson 1981) and provided evidence for whole mantle convection (e.g. van der Hilst *et al.* 1997, Grand *et al.* 1997) and large low-shear-velocity provinces (LLSVPs) at the core–mantle boundary (Trampert *et al.* 2004, Ishii & Tromp 2004). The IRIS-DMC continues to help us understand the deep Earth as resolution improves.

As technology developed, in particular led by the private sector through production of low-power sensors and improvements in data storage, it became feasible for seismologists to buy and deploy their own instruments in targeted dense networks in areas of scientific interest. One of the first examples of this was the Network of Autonomously Recording Seismographs (NARS), the first digital mobile broadband seismic network (Nolet & Vlaar 1982), deploying 14 seismometers in 1983 across Europe and further afield in targeted arrays. Another example from Australia, the SKIPPY project, deployed up to 12 seismometers for five months before moving to a new location, starting in 1994. Eventually, through this method, the Australian continent was covered with a station spacing of ~400 km over a five-year period (Van der Hilst *et al.* 1994). This movable array model is now being repeated on a much larger scale, in the USA (USArray) at ~40 km station spacing (IRIS Transportable Array 2003), in China at ~35 km station spacing (ChinArray 2006) and in parts of Europe such as the AlpArray at ~50 km station spacing (Hetényi *et al.* 2018).

To accommodate the enthusiasm for such arrays, many countries established pools of seismometers for use by their national communities. Some of the first included PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere, https://www.passcal.nmt.edu) in the USA, GIPP (Geophysical Instrument Pool Potsdam, https://bit.ly/2UhvB16) in Germany, ANSIR (Research Facilities for Earth Sounding, http://ansir.org.au) in Australia and New Zealand, and SEIS-UK in the UK (see box "Seismic arrays for the UK"). These pools provided seismologists with access to state-of-the-art equipment, often free at the point of use, and key engineering and logistical support to deploy seismic networks anywhere around the world. They almost all follow the early approach of the global seismic networks by promoting open access to seismic data. This means that archives such as the IRIS-DMC now host datasets from thousands of seismometers covering a large part of the global land mass (figure 2).

2 (a) The Worldwide Standardised Seismic Network (WWSSN). (After Peterson & Hutt 2014)
(b) The current Global Seismic Network.
(c) All seismic stations archived on the IRIS-DMC from 1980–2019.



However, the majority of the Earth's surface is not covered by instrumentation: the oceans. While a submarine global seismic network has not yet materialized, great strides have been made in deploying seismometers in the oceans. As early as 1937, seismometers were deployed on the ocean floor (Ewing & Vine 1938), but technological problems linked to the high-pressure environment, power and communication presented significant challenges. Seismologists rose to these challenges by developing self-contained systems that can sit on the sea floor before floating back to the surface on receiving a signal from a ship above (see Suetsugu & Shiobara 2014 for a review). Initially, these focused on relatively short deployments (a few weeks) to support active source experiments imaging the crust, or small deployments to identify and locate earthquakes. But, as power requirements have reduced and data storage improved, broadband seismometers can now be deployed for months or longer on the sea floor to facilitate the kind of imaging experiments more common on land. These have made possible detailed studies of mid-ocean ridge processes (Forsyth & Scheirer 1998) and extended dense onshore seismic networks offshore to study continental margins or subduction zones such as the NZ3D project in New Zealand (figure 3) or South America (e.g. Hicks & Rietbrock 2015). Seismometers have been deployed around ocean islands to understand mantle plumes (e.g. Laske *et al.* 2009, Barruol & Sigloch 2013) and are helping to understand the oceanic plates in more detail (Bogiatzis *et al.* 2017, Takeo *et al.* 2018; figure 3). However, we must currently look to the private sector for the most ambitious sea-floor instrumentation, with ground-breaking arrays deployed over Ekofisk and Valhall oilfields beneath the North Sea. These contain thousands of narrow-band seismometers deployed permanently on the sea floor, providing episodic monitoring of the uppermost crust through both active and passive sources.

"Disruptive technologies of the 21st century are giving seismologists an opportunity"

We have come far in a relatively short period of time, but advances in low-power instrumentation, autonomous vehicles, supercomputers and other disruptive technologies of the 21st century are giving

Seismic arrays for the UK

SEIS-UK, based at the University of Leicester, was established in 2000 with the purpose of supporting onshore seismic research projects involving UK researchers. Since 2003, it has been funded by the UK's Natural Environment Research Council (NERC) and is part of the research council's Geophysical Equipment Facility.

It provides seismic equipment and data management facilities to the UK academic community and their research partners for use in the deployment of temporary seismic arrays on land. This model has led to some high-impact science in areas as wide ranging as active tectonics, crust, mantle and deep Earth structure, archaeology, glaciology, climate change, sedimentology, volcano monitoring and magma chamber imaging, environmental hazards, geothermal resource mapping and global sea-level and ice mass-balance studies. These projects have been conducted worldwide, from the tropics to the poles; SEIS-UK provided instruments for benchmark testing the seismometers now on Mars. It has supported loans of between 1 and 150 instruments for a few weeks up to two years. The facility has enabled UK researchers to lead in major international seismic experiments during the last 20 years and has supported more than 120 individual experiments.

A particular strength of SEIS-UK is the provision of training and support for researchers who may be new to seismology and need help with experiment design or data processing. This has been key to the increased use of seismic methods in physical geography and in zoology, where, for example, the mating behaviour of seals was studied using SEIS-UK seismometers. Its instruments have even been used to detect the vibrations generated by the crowd when Premier League footballers scored goals, helping widen the public awareness and interest in seismology in a country with very few naturally occurring earthquakes.

The data collected during projects supported by SEIS-UK are initially used by the project's researchers and PhD students, but are then publicly released through IRIS. This enables the data to be used by researchers worldwide with on average 850 Gb of data downloaded from SEIS-UK experiments per month. This is the equivalent of more than 550 seismometers running continuously at 100 samples per second each month.

Anyone interested in using the equipment should see https://seis-uk.le.ac.uk. For information about current loans and activities, follow the Twitter feed @SEIS-UK or contact seis-uk@le.ac.uk.

seismologists an opportunity to take a major step forward in seismology for Earth observation. Hence the BGA's New Advances in Geophysics meeting, which was attended by more than 100 seismologists from the UK, Europe, USA and Japan with attendees from academia and industry (https://nagedinburgh.wordpress.com).

Advances in the oceans

Day one of the NAG meeting focused on new technologies, methods and experiments in the oceans. Many talks described new developments in broadband instrumentation that would allow long-term deployments of broadband seismometers in the oceans. **John Orcutt** (Scripps Institution of Oceanography) showed that, with effective shielding, where the seismometer is protected from ocean currents, broadband seismometers on ocean floors have similar performance to those on land. **Yann Hello** (CNRS-Geoazur) and **John Collins** (Woods-Hole Oceanographic Institute) developed this point further, showing that decoupling the seismometer from the casing by direct burial using a remotely operated vehicle (Suetsugu & Shiobara 2014), drilling boreholes (Collins *et al.* 2001, McGuire *et al.* 2018) or through automated deployment methods (Hello *et al.* 2017), even better performance can be obtained. **Gerrit Hein** (University of Hamburg) also presented detailed noise models for the German ocean-bottom seismometer (OBS) pool, showing how it is important to also understand deployment methods. These examples showed that instrumentation is now capable of capturing subtle signals that can help understand the Earth, from the Earth's hum (continuous oscillations of the Earth; Deen *et al.* 2017) and normal modes where the Earth rings like a bell after major events (Bécel *et al.* 2011), to slow-slip events and non-volcanic tremor at subduction zones (McGuire *et al.* 2018).

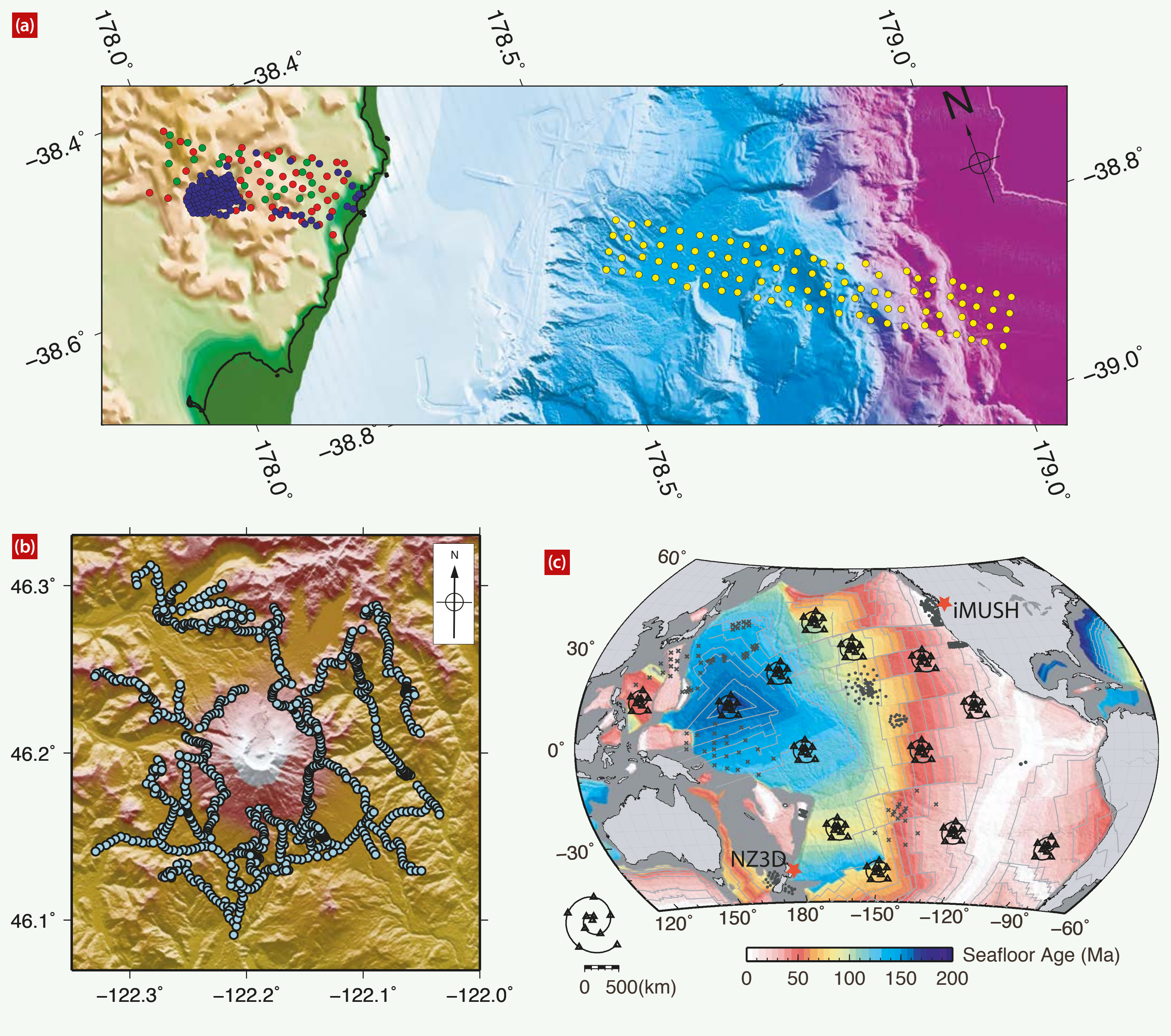
The meeting also heard from several scientists leading large deployments of ocean-bottom seismometers to answer fundamental questions about the Earth. Two talks from **Catherine Rychert** (National Oceanography Centre, Southampton) and **Hitoshi Kawakatsu** (ERI-Tokyo) described how large deployments are allowing for a new understanding of the lithosphere–asthenosphere boundary, helping us to investigate what makes up a tectonic plate and how mantle convection drives tectonics (Harmon *et al.* 2018, Takeo *et al.* 2018). Rychert also discussed new results from the VOILA project, using land and ocean-bottom seismometers to understand subduction processes in the Caribbean (Collier *et al.* 2017). **Karin Sigloch** (University of Oxford) presented new results from the RHUM-Rum experiment, which aims to image a mantle plume beneath Reunion (e.g. Stähler *et al.* 2016). These experiments again demonstrate that OBS systems are capable of performance similar to that available on land, making these ambitious imaging projects achievable. However, a point that recurred at the meeting was that, despite many countries investing in pools of broadband ocean-bottom seismometers (e.g. USA, China, Australia, Japan, Poland, Germany, Ireland, Canada) and despite the UK playing a leading role in large projects using OBS, UK researchers have no access to these instruments from within the UK and must rent instruments from overseas.

Finally, much discussion was given to future developments in ocean-based seismology. One highlight came from **Giuseppe Marra** (National Physical Laboratory), who showed the potential use that ocean-bottom fibre-optic cables have in measuring passing seismic waves (Marra *et al.* 2018). If applicable to existing ocean cables (and access is given by the private contractors that own and operate them), this could offer a solution to the problem of the missing data in the oceans.

We also heard from several manufacturers of ocean-bottom seismometers who emphasized the continuing development of their instrumentation. Many of these developments in OBS technology are conducted through partnerships between academia and industry, highlighted by **Bruce Townsend** (Nanometrics) in his talk describing developments they are making in collaboration with Scripps Institution of Oceanography. However, several of the manufacturers of seismic instrumentation at the meeting requested that academics work far more closely with them when developing proposals for new instrumentation, rather than just relying on them to deliver pre-specified products, otherwise opportunities for new development will be missed. This presents an opportunity for academia to benefit from and even to enhance the innovation that is driven by competition between manufacturers.

Advances on land

Day two of the meeting focused on passive seismological applications and technology for use on land. Talks in this session fell into two themes: a long-term vision involving new technologies that have the



3 (a) The NZ3D FWI (New Zealand 3D Full Waveform Inversion) experiment. Yellow circles show Japan Agency for Marine–Earth Science and Technology (JAMSTEC) owned broadband ocean-bottom seismometer (OBS) stations deployed from December 2017 to April 2018; red circles show SEIS-UK-owned broadband Guralp 6TD seismometers; green circles show Earthquake Research Institute (ERI), University of Tokyo-owned Geospace GSX nodes; and blue circles show GIPP-owned DSS cube nodes (see https://nz3dfwi.weebly.com for more details). (b) The Mount St Helens (Washington, USA) nodal deployment as part of the iMUSH experiment (Hansen & Schmandt 2015): 904 nodes deployed for two weeks in July 2014. (c) The proposed Pacific Array including 13 deployments consisting of 10 broadband OBS deployed in a spiral form for good wavenumber coverage. Crosses and circles show existing OBS deployments by Japanese and US scientists (after Hitoshi Kawakatsu, personal communication). Red stars show the approximate locations of the iMUSH and NZ3D FWI experiments.

potential to revolutionize how we collect seismic data, and shorter-term opportunities that, while no less revolutionary in terms of science, can be delivered today.

Two areas of long-term vision were presented. **Heiner Igel** (Ludwig-Maximilians-Universitat München) outlined the status of rotational seismology, a technique that not only measures velocity/displacement in three components, but also their rotational motions (see Schmelzbach *et al.* 2018 for a review). This allows for more accurate tilt measurements, which are important for OBS, volcano deformation and free oscillations, but also for more accurate wavefield constructions, key for seismic tomography and seismic source inversions or maximizing data in sparse networks (e.g. on other planets, Brokešová *et al.* 2012). Excitingly, while noise performance is not at the level of more traditional seismometers, a portable rotational seismometer has been developed (blueSeis, Bernauer *et al.* 2018). Again, this has come from academic–industry partnerships, showing how this model can help to drive innovation.

Other speakers, following on from Marra's talk on day one, discussed the use of fibre-optic cables to measure seismic signals. This method uses the fact that deformation in the cable when a seismic wave passes through it changes the scattering properties of the cable. As a result, a pulse of light fired through the cable will return with a phase shift, from which can be extracted a seismogram. Excitingly, this provides a distributed signal along the whole cable, meaning the full wavefield can be reproduced across a wide range of frequencies (a technique known as distributed optical fibre acoustic sensor, DAS). **Charlotte Krawczyk** (GFZ Potsdam) showed an application of this in Iceland, where a 15 km long fibre-optic cable clearly recorded anthropogenic and earthquake signals, permitting the imaging of faults and dykes at exceptional resolution (Jousset *et al.* 2018). **Mike Kendall** (University of Bristol) in a review of reservoir microseismicity (e.g. Kendall *et al.* 2011) argued that this technology could revolutionize the hydrocarbon industry, with dense monitoring and easy deployments down boreholes. **Mengmeng Chen** (University of Southampton) presented the DAS system developed at the University of Southampton and used to monitor submarine cables and train speed (Chen *et al.* 2018). These applications emphasize a point mentioned by all speakers in this session: this technology has vast unexplored potential for monitoring Earth vibrations, with applications in transport, security and large infrastructure to name a few. Another example of this use of seismology beyond traditional approaches was presented by **Celine Hadziioannou** (University of Hamburg), who showed how seismic data can help us understand how atmospheres, oceans and solid Earth are coupled and can potentially be used to model long-term variations of climate-related ocean-wave weather (Juretzek & Hadziioannou 2017).

> **"Dense networks get much more data than single instruments or low-density arrays"**

Other speakers focused on the current and near-future of passive seismology on land. **Hanneke Paulssen** (University of Utrecht) reviewed the history of the NARS network and highlighted the revolution these mobile networks produced for broadband passive seismology (Nolet & Vlaar 1982). **Fiona Darbyshire** (Université du Québec à Montréal) described similar efforts in Canada, starting with the pioneering LITHOPROBE experiment (Rondenay *et al.* 2000), which focused more on active-source seismology, and moving on to the vision of a future network, EON-ROSE, a multi-instrument network across the continent using broadband seismometers, GNSS and magnetospheric sensors (Boggs *et al.* 2018). **Corinna Roy** (University of Leeds) presented a novel inversion method to better image crustal velocity structure and to improve characterization of small earthquakes in a mining setting. This task is key now that local detection of earthquakes of a given magnitude triggers suspension of hydraulic fracturing operations until an investigation into whether the industrial operations induced the earthquake has been carried out (Kendall *et al.* 2019).

Jessica Johnson (University of East Anglia) showed results from a new urgency deployment on Hawaii to collect a truly unique dataset to investigate changes in anisotropy in response to the recent eruptions of Kilauea (e.g. Johnson & Poland 2013). **Diana Roman** (Carnegie Institute for Science) described the Quick Deployment Box, a novel method ideal for use in such rapid, urgent deployments, which are common when responding to volcanic and earthquake events (Wagner *et al.* 2017). Her work shows how academia can drive innovation in ways that may not be apparent to equipment manufacturers in isolation.

Finally, several speakers discussed an exciting development in land seismology that has borrowed from pioneering work in industry: large-*N* arrays, i.e. the deployment of large, dense deployments of seismometers in targeted arrays. **Sjoerd de Ridder** (Total E & P) showed how industry is pioneering this method, outlining the Ekofisk life-of-field seismic system of almost 4000 multicomponent seismometers deployed in the North Sea among other examples (e.g. de Ridder & Dellinger 2011). He emphasized that the information recorded by dense networks of seismometers is much greater than that from individual instruments or low-density arrays, thus allowing the use of the full wavefield for inversion (de Ridder & Biondi 2015). This was a message emphasized by many other speakers. **Larry Brown** (Cornell University) showed how dense arrays allow reflection seismic methods, normally relying on expensive explosive seismic sources, to be applied using natural earthquake sources (Quiros *et al.* 2017). **Brandon Schmandt** (University of New Mexico) highlighted the varied uses of these networks, looking at temporal changes in river and groundwater transport (Schmandt *et al.* 2017), seismic imaging (Ranasinghe *et al.* 2018), monitoring volcanoes with excellent examples from the iMUSH project on Mt St Helens shown in figure 3 (Glasgow *et al.* 2018; figure 2) and imaging on crustal and lithospheric scales. **John Hole** (Virginia Tech) showed a drastic improvement in earthquake location, improving accuracy and magnitude completeness in experiments in Virginia (Beskardes *et al.* 2015). Importantly, all these studies use relatively high-frequency instruments, called seismic nodes, that are small, low power and often include battery, geophone and digitizer in a single package (shown in figure 1; see Karplus & Schmandt 2018 and references within for a review). This removes the need for the solar panels, strong vaults cemented to bedrock and extensive cables that typify broadband seismometer deployment. Despite their lack of broadband response, these simple instruments can be used to detect relatively broadband signals by stacking data (e.g. Chapman 2009). This was summed up by Hole with the provocative message that, in many cases, it may be best to move away from high data quality coming from sparse networks of very broadband instruments towards data quantity achieved by the dense deployment of nodes.

What next for broadband passive seismology?

The meeting showed that we are at a turning point for broadband passive seismology. Historically, a big step forward came when manufacturers developed reliable broadband seismometers that had low power consumption and were cheap enough to make it feasible to buy enough for network deployments. Instrument pools such as SEIS-UK were developed to facilitate this for the wider community, leading to major breakthroughs in tectonics, volcanology and earthquake dynamics, for example. It appears we have now reached this point for broadband ocean-bottom seismometers: reliable, excellent-performance sensors can be bought off the shelf.

But this does not mean that academia has no role in future instrument development. Among the ocean-bottom seismology community, groups from Scripps, CNRS-Lyon and Woods-Hole are developing the next generation of broadband instruments in partnership with industry (e.g. Nanometrics, OSEAN). These have the potential to be deployed for years, rather than months, transmitting data from the ocean floor using autonomous vehicles (e.g. Sukhovich *et al.* 2015, Berger *et al.* 2016a), by releasing small capsules carrying data to the surface (e.g. Hello *et al.* 2015) or through future satellite internet networks. Such instruments might even, potentially, be able to deploy and recover themselves (Berger *et al.* 2016b).

There is an ambition to completely map the ocean floor by 2030 (Mayer *et al.* 2018). With advances in technology we should aim to extend this to the subsurface, through a transportable, ocean-bottom seismic network in the oceans as proposed at the meeting by Kawakatsu (e.g. Pacific Array, Kawakatsu 2012; figure 3). The development of methods to interrogate existing fibre-optic cables already installed across long transects of the seabed may also provide a revolutionary way to obtain ocean-bottom data and would solve the power-consumption problem because power for the interrogation system can then be provided by laser interrogators on land. This technology already exists and has been demonstrated, and raises the question of the extent to which innovative future ocean-bottom systems should be nodal (composed of individually deployed instruments) or use fibre-optic cables for transects.

On land, the main question is what sort of instrumentation do we as a community want for the next 20 years? This question is timely. UK passive seismic facilities are currently under review, providing a chance to implement a strong community vision. The UK and international community reached a consensus at the meeting that dense deployments of hundreds to thousands of low-power, easy-to-deploy instruments, combined with fewer broadband instruments, is the future of land passive seismology; it will provide big improvements in earthquake location and seismic imaging and will open up new areas of

Earth observation in future. But challenges exist with this model. The quantities of data these new arrays produce are vast and will require not just new facilities to provide instrumentation, but also computational resources and long-term data storage to support them. Scientifically, new methodologies are needed to process the large amounts of data generated. These are already being developed, with novel methods for locating earthquakes presented by Schmandt and Hole, and new methodologies for imaging presented by Brown, de Ridder and Roy at the meeting.

"Passive seismology has a bright future with more and better data than ever before"

Power issues mean that instruments for large, dense arrays are still developing rapidly and it could be argued that they are not yet ideal for use on multi-year deployments. As a result, is it wise for the UK community through SEIS-UK to purchase thousands of these instruments? Would an alternative approach be to work more closely with the manufacturers in a partnership to guide the innovation of these instruments in future, while providing access to the instruments in the short term? In a provocative challenge, the industrial participants at the meeting asked what the UK scientific community actually wants from a facility. They suggested that the sector could move beyond manufacturing to providing a more comprehensive service, deploying and even processing data for the academic community. This model is supported by past developments in the hydrocarbon industry. There the emergence of service companies, undertaking exactly analogous tasks, created competition that led to diverse and innovative acquisition and processing products and services. A concern with this model is that it might limit innovation and, importantly, training for young UK scientists within universities. However, its presentation here shows that manufacturers of seismometers are keen to identify a mutually beneficial model for the future provision of passive seismic equipment.

While the idea of handing over responsibility of seismic instrument design from universities, who have a strong track record and a deep understanding of community needs, to private industry may be controversial, it does allow us to embrace the innovation and, importantly, investment in research and development that is not easy to obtain from traditional research funders. For example, Guralp stated that 20–30% of its profit is invested in research and development; other manufacturers have similar models. In today's environment of supercompetitive research funding, the opportunity to influence that industry research may be too good to ignore. This would also free up time for academics to work on developing techniques to maximize the use of these big datasets or concentrate on innovative long-term instrument design such as fibre optics or rotational seismology.

This is not a new model. A successful example of this approach in the UK was the BIRPS project, a consortium aiming to image deep crustal and lithospheric structure in the seas around the United Kingdom and further afield using reflection seismology (Klemperer & Hobbs 1992). For 20 years, starting in the late 1970s, the group collaborated with the hydrocarbon industry, providing ground-breaking insights into tectonics and an opportunity for contractors to experiment with new equipment. While this model may not be perfect for passive seismology, it shows that a partnership can create innovation that industry and academia cannot provide separately.

Conclusion

The meeting showed that passive seismology has a bright future, with new instrumentation and techniques providing more and better data than ever before, revealing new and ground-breaking images and theories about the Earth's interior and structure, and pushing the discipline into wider Earth observation. While the exact model of how we achieve this is unclear, there is an enthusiasm for innovation and a new model for how we conduct passive seismic experiments. The challenge for us as a community is to take advantage of this, identifying the science we want to achieve over the next 20 years and planning how we should build future facilities to enable this. We plan future meetings, beginning with a community meeting on 30 April 2019 in Cambridge, to develop this consensus and we encourage the community, in particular early-career scientists, to engage in this process. The international community has shown how major investment in equipment built around big science questions (e.g. USArray, ChinArray, AlpArray) has revolutionized our discipline in many regions. We now have an opportunity to develop this in the UK and lead this area of geoscience in the future. ●

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