The Future of Broadband Passive Seismic Acquisition

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Opening sentence: *James Hammond and co-authors report on a recent meeting on 'The Future of Passive Seismic Acquisition' and suggest new advances in instrumentation are opening up opportunities for dense, large scale deployments of seismometers on land and in the oceans.*

It is an exciting time to be a seismologist. In November 2018, the InSight lander touched down on Mars and the first seismometer was deployed on another planet. This incredible feat means planetary seismologists are currently searching for marsquakes and will hopefully soon be providing images of its interior and helping us 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 the field of terrestrial seismology has reached a turning point with significant developments in instrumentation and the manner of their deployment in recent years. However, 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 meeting in Edinburgh in late 2018 to discuss 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. 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 soon realised 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, whose purpose would be to systematically observe the propagation of movements generated at earthquake centers, along the Earth's surface and through its interior.*"

Pioneering seismologists undertook the task of realising 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 data increased, more and more features became apparent with the identification of 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 an explosion in recorded data, and to the advent of modern day seismology. A 'conference of experts' in 1958 was held in Geneva with a focus on how to identify nuclear tests. It was recognised 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) (Figure 1) (see Peterson & Hutt, 2014 for a review). Importantly, this network relied on technological advances through development of high precision, accurate seismometers that could be deployed anywhere. 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 digitised and the WWSSN became the Global Digital Seismic Network (GDSN) and finally replaced in the 2000s with the Global Seismic Network which now has over 150 permanent stations transmitting real time data that are provided openly through the IRIS-DMC (Figure 1) (Buttler et al., 2004). These networks allowed not only nuclear tests to be monitored, but through their pioneering open data model meant that seismologists could develop detailed seismic tomography models of the 3D structure of the Earth (e.g., Dziewonski & Anderson, 1981) providing evidence for whole mantle convection (e.g., van der Hilst et al., 1997, Grand et al., 1997), large low shear-wave velocity provinces (LLSVPs) at the core-mantle boundary (Trampert et al., 2004, Ishii & Tromp, 2004) and continue to help us understand the deep Earth as resolution improves.

As technology continued to develop, in particular led by the private sector through production of low power sensors and improvements in data storage, it became feasible for seismologists to purchase and deploy their own instruments in targeted dense networks in areas of scientific interest. One of the first examples of this was the NARS (Network of Autonomously Recording Seismographs), the first digital mobile broadband seismic network (Nolet & Vlaar, 1982), deploying 14 seismometers in 1983 across Europe and further afield in targeted arrays. Another, the SKIPPY project, deployed up to 12 seismometers starting in 1994 in Australia for 5 months before moving to a new location (Figure 1). Eventually, through this method, the Australian continent was covered with a station spacing of ~400 km over a 5 year period (Van der Hilst et al., 1994). This model is now being repeated on a much larger scale, with a moveable array in the USA (USArray) at ~40 km station spacing (IRIS Transportable Array, 2003), China at ~35 km station spacing (ChinArray, 2006) and parts of Europe such as the AlpArray at ~50 km station spacing (Hetényi et al., 2018).

To accommodate the enthusiasm of the seismological community to deploy networks of seismometers, many countries established pools of seismometers for use by their national communities. Some of the first included PASSCAL[1] (Program for Array Seismic Studies of the Continental Lithosphere) in the USA, GIPP[2] (Geophysical Instrument Pool Potsdam) in Germany, ANSIR[3] (Research Facilities for Earth Sounding) in Australia and New Zealand and SEIS-UK[4] in the UK (see box for a review of SEIS-UK). These pools provided seismologists access to state-of-the-art equipment, often free at the point of use and the key engineering

[1] https://www.passcal.nmt.edu
[2] https://www.gfz-potsdam.de/en/section/geophysical-deep-sounding/infrastructure/geophysical-instrument-pool-potsdam-gipp/
[3] http://ansir.org.au
[4] https://seis-uk.le.ac.uk

and logistical support to deploy seismic networks in any location around the world. They almost all follow the early approach of the global seismic networks by promoting the open access of seismic data. This means that archives such as the IRIS-DMC now hosts datasets from thousands of seismometers covering a large part of the global land mass (Figure 1).

However, a large part of the Earth is not covered by instrumentation: the oceans. While a submarine global seismic network has not yet materialised, 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, access to power and communication presented significant challenges. Seismologist 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 focussed on relatively short deployments (a few weeks) to support active source experiments imaging the crust, or small deployments to identify and locate earthquakes. However, as power requirements reduce, and data storage improves 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 allowed detailed studies of mid-ocean ridge processes (Forsyth & Scheirer, 1998), extended dense onshore seismic networks offshore to study continental margins or subduction zones (e.g., Hicks & Rietbrock, 2015) (Figure 2), and seismometers have been deployed around ocean islands to understand mantle plumes (e.g., Lasket et al., 2009, Barruol & Sigloch, 2013) and are helping us understand the oceanic plates in more detail (Bogiatzis et al., 2017, Takeo et al., 2018). However, we must look to the private sector for the most ambitious seafloor 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 seafloor providing episodic monitoring of the uppermost crust through both active and passive sources

We have come far in a relatively short period of time, but with new advances in low power instrumentation, autonomous vehicles, super computers and other disruptive technologies of the 21st century, seismologists have an opportunity to take a major step forward in using seismology for Earth observation. With this in mind the British Geophysical Association sponsored a 'New Advances of Geophysics' (NAG) meeting in November 2018 in Edinburgh on the 'Future of Passive Seismic Acquisition'[5]. This was attended by over 100 seismologists from the UK, Europe, US and Japan with attendees from academia and industry. What now provide a summary of the meeting and a vision for the passive seismic facilities required to support the next 20 years of seismological research.

Current advances in broadband passive seismic acquisition: Oceans

Day 1 of the NAG meeting focussed 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 Institute of Oceanography*) showed that, with effective shielding, where the seismometer is protected from ocean currents, broadband seismometers on ocean floors have similar

[5] See https://nagedinburgh.wordpress.com for more details

performance to those on land. Yann Hello (*CNRS-Geoazur*) and John Collins (*Woods-Hole Oceanographic Institute*) developed this point further, showing that with effort in decoupling the seismometer from the casing by direct burial using a remotely operated vehicle (ROV) (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 OBS pool, showing how it is important to understand deployment methods as well as the instrumentation. These examples showed that instrumentation is now capable of capturing very subtle signals that can help us understand the Earth, from the Earth's hum (the 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 a number of 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 Kawakat*su (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). Catherine 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 now capable of performance similar to that available on land, meaning these ambitious imaging projects are achievable. However, a point that recurred at the NAG meeting was that, despite many countries investing in pools of broadband ocean bottom seismometers (e.g., US, China, Australia, Japan, Poland, Germany, Ireland, Canada) and despite the UK playing a leading role in many large projects using OBS, we currently 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 given by the private contractors), this could offer a solution to the missing data in the oceans. We also heard from a number of manufacturers of ocean bottom seismometers who emphasised 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 and not just rely 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 the various manufacturers.

Current advances in broadband passive seismic acquisition: Land

Day 2 of the NAG meeting focussed on passive seismological applications and technology for use on land. Talks in this session could be divided into two themes; a long-term vision involving new technologies that have the potential to revolutionise how we collect seismic data and shorter-term opportunities that, while no less revolutionary in the kind of science we can achieve, can be delivered today.

Two areas of long-term vision were presented. Heiner Igel (*Ludwig-Maximilians-Universitat München*) outlined the current status of rotational seismology, a technique that not only measures velocity/displacement on 3 components, but also their rotational motions (see Schmelzbach et al., 2018 for a review). This allows for more accurate tilt measurements, important for OBS, volcano deformation and free oscillations and for more accurate wavefield constructions, key for seismic tomography and seismic source inversions or maximising data in sparse networks (e.g., deployments on other planets, Brokesova et al., 2012). Excitingly, while noise performance is not yet at the level of more traditional seismometers, a portable rotational seismometer has been developed (blueSeis, Bernauer et al., 2018). Again, the instrumentation has been developed through academic/industry partnerships showing how this model can help to drive innovation in seismology.

Other speakers, following on from Giuseppe Marra's talk on day 1 discussed the use of fibre optic cables to measure seismic signals. This method uses the fact that deformation in the fibre optic cable, which occurs when a seismic wave passes through, will change the scattering properties of the cable. As a result, a pulse of light fired through the fibre optic cable will return with a phase shift, from which can be extracted a seismogram. Excitingly, this provides a distributed signal along the whole fibre optic cable meaning the full wavefield can be reproduced across a wide range of frequencies (so-called 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, thus 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 revolutionise 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 monitor train speed (Chen et al., 2018). This demonstrates a point mentioned by all speakers in this session; this technology has vast unexplored potential to monitoring Earth vibrations, with applications in transport, security and monitoring large infrastructure to name a few. Another example of this use of seismology beyond traditional approaches was presented by Celine Hadziioannou (*University of Hamburg*) showing 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).

Other speakers focussed on the current and near future of passive seismology on land. Hanneke Paulssen (*Utrecht*) reviewed the history of the NARS network and highlighted the revolution these mobile networks had on 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), that focussed more on active source seismology up to today and the vision of a future network EON-ROSE, building a multi-instrument network across the continent involving 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 characterisation of small earthquakes in a mining setting; of key importance now that local detection of earthquakes of a given magnitude triggers suspension of industrial operations until an investigation into whether the 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 to collect a truly unique dataset to investigate changes in anisotropy in response to the recent eruptions on Hawaii (e.g., Johnson & Poland, 2013). Diana Roman (*Carnegie Institute for Science*) described the Quick Deployment Box (QDP), a new novel deployment method ideal for use in these rapid, urgent deployments, which are common when responding to volcanic/earthquake events (Wagner et al., 2017). This shows how experience from academia can drive innovation in ways that may not be apparent to manufacturers themselves.

Finally, a number of speakers discussed an exciting development in land seismology that has borrowed from pioneering work in industry; the deployment of large, dense deployments of seismometers in targeted arrays, so called large-N arrays. Sjoerd de Ridder (*Total E & P*) showed how industry are 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 emphasised that the information recorded by these dense networks is much greater compared to individual instruments or low density arrays, thus allowing for the use of the full wavefield for inversion (de Ridder & Biondi, 2015). This was a message repeated 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 by using natural earthquake sources (Quiros et al., 2017). Brandon Schmandt (*University of New Mexico*) highlighted the varied use of these networks, looking at temporal changes in river and groundwater transport (Schmandt et al., 2017), seismic imaging (Ranasinghe et al., 2018),monitoring volcanoes (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 (Davenport et al., 2015). Importantly, all these studies use relatively high frequency instruments, so called seismic nodes, that are small, low power and often include battery, geophone and digitizer in a single package (see Karplus & Schamndt (2018) and references within for a review). This removes the need for 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 through the application of stacking (e.g., Chapman, 2009). This was summed up by John Hole with the provocative message that for many applications, it may be best to move away from the high data quality given by sparse very broadband instrument networks towards data quantity through 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 broadband seismometers to the degree that they were reliable, with low power consumption and cheap enough that many could be purchased for deployment in networks. Instrument pools, such as SEIS-UK in the UK were developed to facilitate this for the wider community leading to major break throughs in tectonics, volcanology and earthquake dynamics among others. It appears we have now reached this point for broadband ocean-bottom seismometers where reliable, excellent performance sensors can be purchased off the shelf.

However, this does not mean that academia has no role in future instrument development. Excellent examples came from the ocean-bottom seismology community, where groups from SCRIPPS, CNRS-Lyon and Woods-Hole are developing the next generation of 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 via autonomous vehicles (e.g., Sukhovich et al., 2015, Berger et al., 2016a), release of small capsules carrying data to the surface (e.g., Hello et al., 2015) or using future satellite internet networks. Potentially, these instruments may even 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., 2017). With advances in technology we should aim to extend this to the subsurface too through a transportable, ocean bottom seismic network in the oceans as proposed at the NAG meeting by Hitoshi Kawakatsu (e.g., Pacific Array) (Kawakatsu, 2012) (Figure 2). 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 since power for the interrogation system can then be provided by laser interrogators installed 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 should comprise 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 comes at a timely point as the UK passive seismic facilities are under review, providing a chance to implement a strong community vision. The UK and international community reached a consensus at the NAG 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 providing big improvements in earthquake location and seismic imaging, and will open up new areas of Earth observation in future. However, challenges exist with this model. The vast quantities of data these new arrays produce will require not just new facilities to provide instrumentation, but computational resources and long-term data storage to support them. Scientifically, new methodologies are needed to process the large amounts of data that are generated. These are clearly being developed, with novel methods for locating earthquakes presented by Brandon Schmandt and John Hole and new methodologies for imaging presented by Larry Brown, Sjoerd de Ridder and Corinna Roy at the NAG meeting.

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 common in seismic deployments. As a result, is it wise for the UK community through SEIS-UK to purchase thousands of these instruments, or alternatively 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 want from a facility, suggesting they could move beyond manufacturing to a larger service, deploying and even processing data for the academic community. This model is supported by past developments in the hydrocarbon industry in which the emergence of service companies who do exactly analogous tasks created competition which 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, but it shows that manufacturers of seismometers are keen to have a discussion and identify a mutually beneficial model for the future provision of passive seismic equipment.

While the idea of handing responsibility of seismic instrument design from universities, who have a strong track record in this area and have a deep understanding of what we want as a community, 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 their profits is invested in to research and development and other manufacturers have similar models. In today's environment of super-competitive research funding, the possibility to influence that research may be too good an opportunity to ignore. This would also free up time for academics to work on developing new techniques to maximise the use of these big datasets or concentrate on long-term instrumentation design such as fibre optics or rotational seismology. This is not a new model. An example of where this was done successfully 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 (e.g., Klemperer & Hobbs, 1993). The group, starting in the late 1970s and working for 20 years, collaborated with the hydrocarbon industry providing ground-breaking insights into tectonics, while providing 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 individually.

The NAG meeting shows 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 pushing the discipline beyond Earth structure and 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 of 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 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 revolutionised our discipline in many regions. We have an opportunity to develop this in the UK and lead this area of geoscience in the future.

SEISUK box:

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, crustal, mantle and deep earth structure, science-based 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 in all five continents of the Earth from the tropics to the Polar Regions and SEIS-UK provided instruments for benchmark testing the seismometers now on Mars. It has supported loans varying in size between 1 and 150 instruments and of duration of a few weeks up to 2 years. The facility has enabled UK researchers to lead in major international seismic experiments during the last 20 years and has supported over 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 (e.g., the mating behaviour of seals was studied using SEISUK seismometers). Its instruments have even been used to detect the vibrations generated by premier league footballers scoring 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 is initially used by the project's researchers and PhD students but then publicly released through IRIS (Incorporated Research Institutions for Seismology, based in the United States of America). This enables the data to be used by researchers worldwide with on average 850 Gb of data downloaded from SEISUK experiments per month. This is the equivalent of over 550 seismometers running continuously at 100 samples per second each month.

Anyone interested in applying to use the equipment should go to SEIS-UK's website *https://seis-uk.le.ac.uk/ where there is further information about the facility. For information about current loans and activities follow the twitter feed @SEIS-UK or contact seis-uk@le.ac.uk.*

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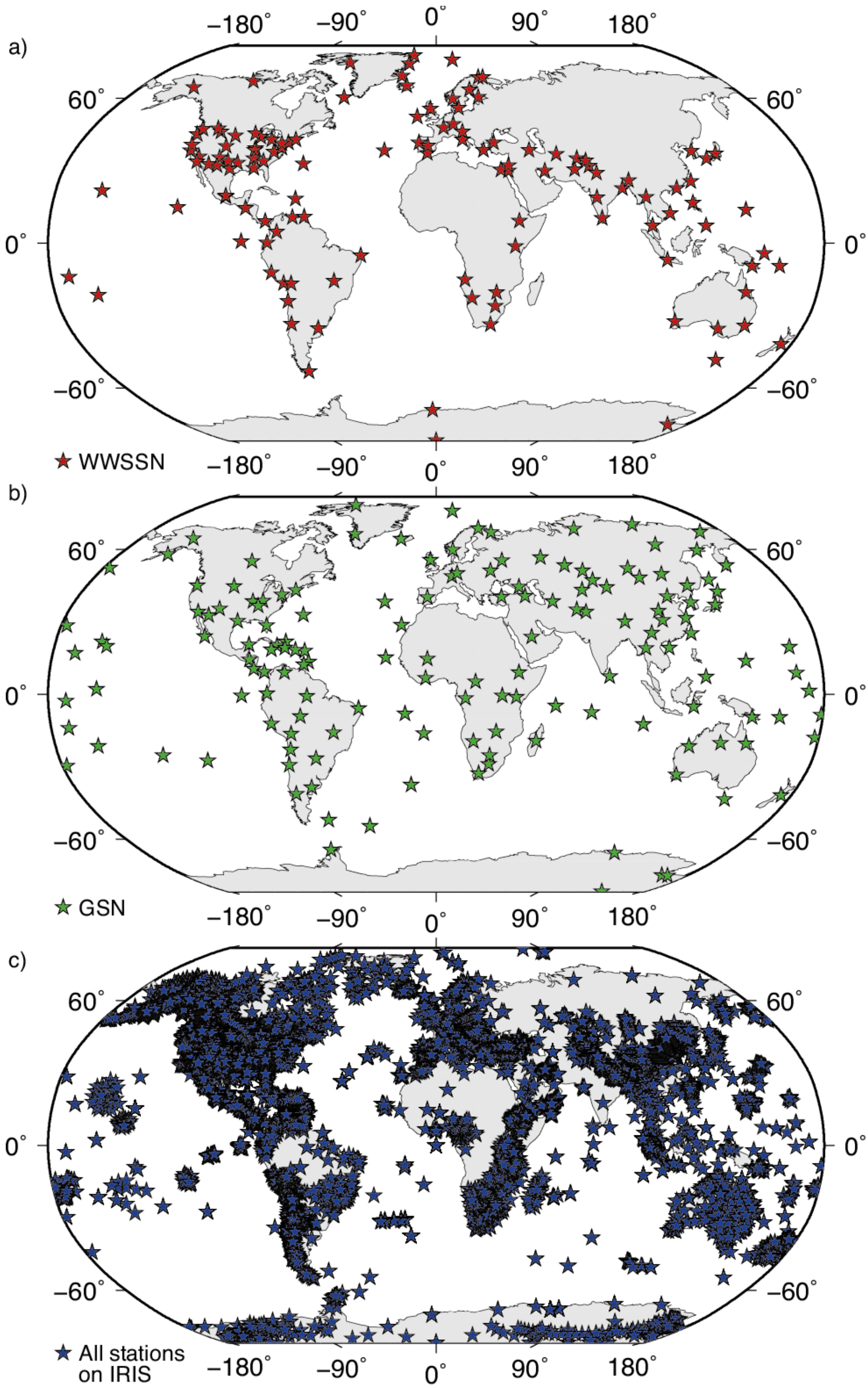

Figure 1: a) The Worldwide Standardised Seismic Network (WWSSN) (after Peterson & Hutt, 2014), b) The current Global Seismic Network, c) All seismic stations archived on the IRIS-DMC from 1980-2019.

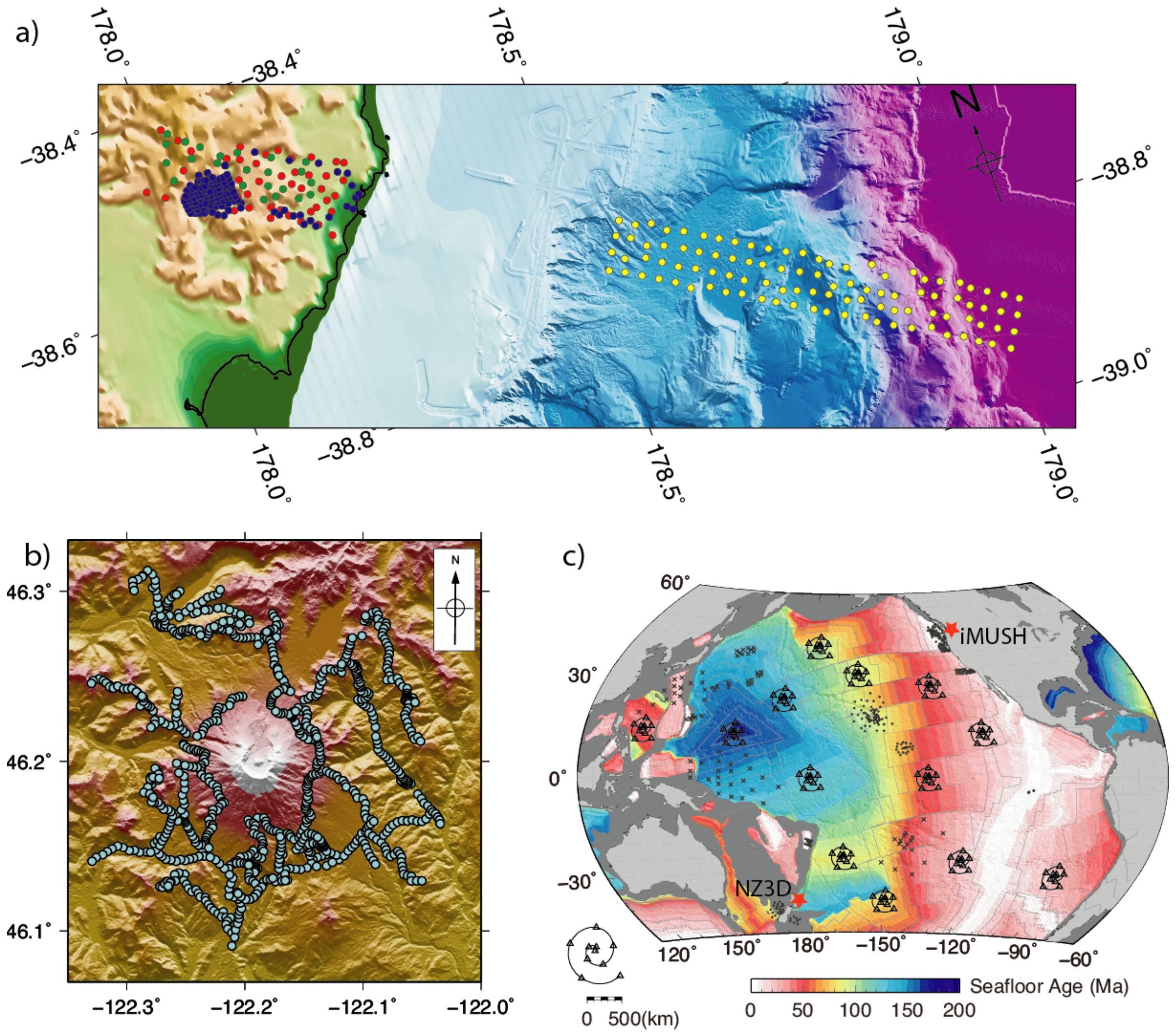

Figure 2: a) The NZ3D FWI (New Zealand 3D Full Waveform Inversion) experiment. Yellow circles show Japan Agency for Marine-Earth Science and Technology (JAMSTEC) owned broadband OBS stations deployed form December 2017 – April 2018, red circles show SEISUK owned broadband Guralp 6TD seismometers, green 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 of the project). (b) The Mount St Helens nodal deployment as part of the iMUSH experiment (Hansen & Schmandt, 2015). 904 nodes were deployed for a period of 2 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.