SCIENTIFIC REPORT ON LOAN 1071:

Magma Intrusion and Induced Seismicity in the Northern Rift Zone of Iceland

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Abstract

The original objectives of this loan of 10 6TD seismometers, which supplemented 21 of our own (Cambridge) seismometers were:

1. To map patches of deep crustal seismicity (at 12-25 km depth) caused by melt intrusion in the crust in order to constrain models of crustal accretion along volcanic rift zones;

2. To monitor the rate of change of induced seismicity around the 2014 Bárðarbunga-Holuhraun intrusion site to constrain rate-state models of earthquake failure following the intrusion;

3. To map the ongoing seismicity in the Bárðarbunga caldera and along the Holuhraun dyke path in order to constrain models of dyke cooling and caldera evolution (and possibly eruption).

The deployments and data collection were all successful with a high rate of data return and we are using the data to actively address all three questions, as well as further opportunities that have arisen as a result of having a high-quality long-term dataset from this area of active rifting and volcanism in Iceland.

Background

Over the past decade SEIS-UK has generously supported our work in central Iceland. This has been extremely fruitful both in international publications and in training MSci, MPhil and PhD students. Highlights include recording in detail the 2014-15 Bárðarbunga-Holuhraun dyke intrusion; a detailed tomographic velocity model around the active volcano of Askja; mapping for the first time tiny repeating earthquakes in the deep crust on the Askja rift caused by melt migrating up from the mantle; mapping pervasive strike-slip faulting accommodating rifting on the northern rift zone; showing that the static stress change caused by the dyke intrusion induced an increase of seismicity in some areas and a complete shutdown in others at stress drops of only a few 100 kPa; and making an Iceland-wide tomographic model of the top 15 km of crust from ambient noise analysis.

There is huge value in having long-term recording, which has shown its importance in our recent ability to tease out annual seasonal changes in velocities of a fraction of one percent, and the velocity changes caused by the stress changes created by the 2014 dyke intrusion (Donaldson et al., 2019). This loan of 10 SEIS-UK instruments has enabled us to maintain recording at important sites over a period of more than a decade, as well as to reposition parts of our array to monitor the ongoing inflation of Bárðarbunga caldera. SEIS-UK provided the instruments, cabling and solar panels, while Cambridge provided the infrastructure for each site (batteries, solar panel stands, vaults).

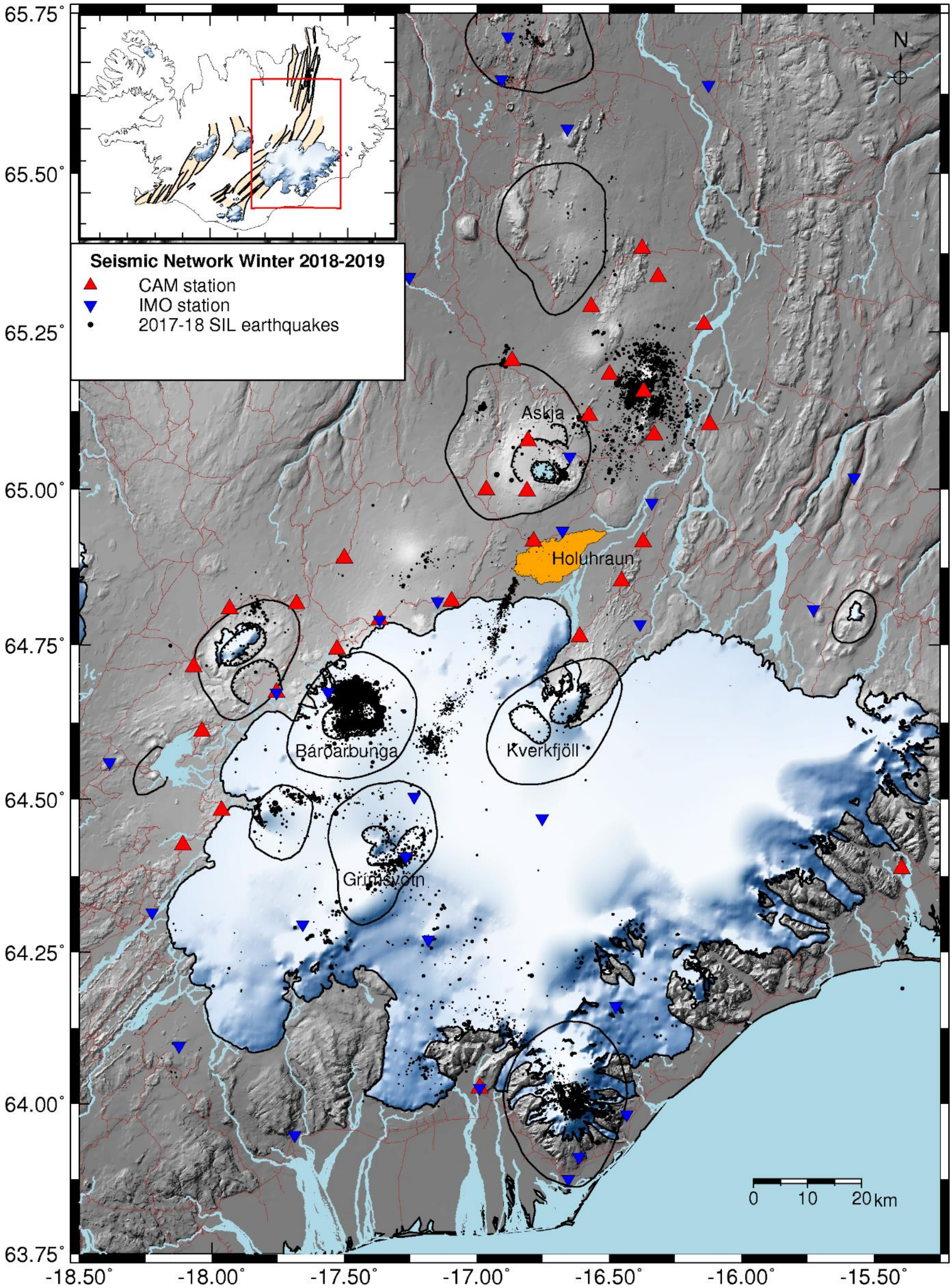

Fig. 1 Map showing locations of seismometers deployed for the period summer 2018 to summer 2019. Inverted blue triangles deployed by Icelandic Meteorological Office (IMO). White shaded areas are icecaps. Small map at top shows setting within the volcanic rift zones (orange) that cross Iceland (Figure by T. Winder).

Survey procedure

The seismic data from 2017-19 was recorded continuously at 50 sps, with GPS always on. This was chosen rather than the more normal 100 sps because 16GB instruments would fill up in c. 10.5 months, and we are only able to service instruments once per year in the summer. It was a fortuitous change because COVID-19 restrictions in 2020 meant that the instruments were recording for over 13 months before we were able to service them in August 2020. No data was lost due to storage restrictions.

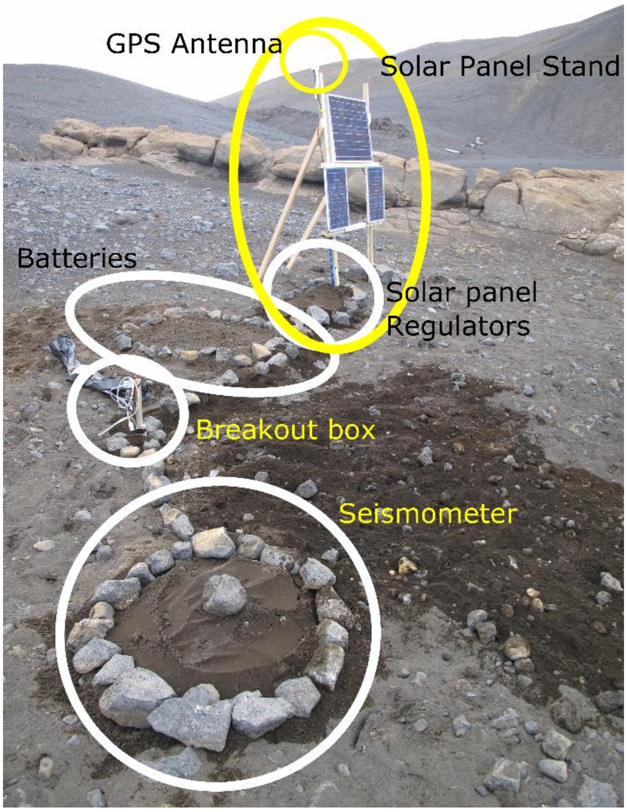

Figure 2. Typical deployment method in Iceland.

Our experience is that almost continuous daylight in summer (this is near the Arctic circle), together with the use of large truck batteries and multiple solar panels on each site, provides sufficient power supply through both the summer and winter months for 6TD seismometers. Typically we use three to four 115 Amp-hr batteries with minimum 60 watts solar panels on each site. Solar panels are mounted sub-vertically to reduce snow adherence in the wetter spring months and to catch the low angle returning sun (Fig. 2). The GPS antenna is attached to the top of the stand so that it projects above the snow cover in winter. We bury the batteries and solar panel regulators, but mount the breakout box on a short stick: this is because when they are buried, they are more prone to becoming flooded as the snow melts. It is also easier to access the sockets for servicing. Our experience of wind turbines is that they do not survive the harsh winter conditions and also produce excess noise, polluting the seismic recordings (Fig. 2).

The prevalence of basaltic rocks means that compasses are unreliable indicators of true north, so we use GPS to orient the seismometers. It is best to use a differential GPS receiver, but when that was not available we found that a normal hand-held GPS unit could be used equally well. We took a fix at the seismometer and then walked quickly 100-200 metres either north or south (depending on the terrain) and erected a pole at that point to provide a visual pointer for aligning the seismometer. At these high latitudes there is excellent satellite coverage, and provided little time was spent in locating the position for the pointer (by simply keeping the longitude on the GPS the same as you walked), the normal time-varying positional errors in the GPS were minimised to less than the practical accuracy of aligning the seismometer.

For a few of our sites we make vaults by burying and concreting fish barrels. We have experimented with packing insulation around the seismometer inside the fish barrel, but have found that it is generally deleterious to the signal because if it gets wet and waterlogged it makes the recordings much worse than if any water ingress is simply allowed to drain away. But we find that simply burying the seismometers, especially where there is hyaloclastite outcrop, produces excellent results. In winter the seismometers freeze into the ground (typical temperatures go down as low as -14C), and couple extremely well. The layer of snow and absence of vegetation or trees reduces wind shear and together with the absence of cultural noise provides a very low noise environment. We recorded events typically down to magnitude -0.5 in the upper crust and -0.2 even at 20 km depth.

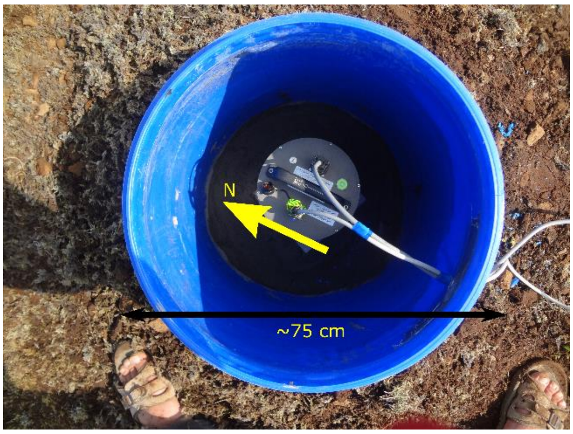

Fig. 3 Installation in a buried fish barrel with sawn off and concreted base. Usually used for ESPs. Note that cable exit is below the top of the seismometer to prevent water running down cables, and a watertight lid is clamped on top. We did not add insulation or other packing round the seismometer.

The most difficult periods are during the spring thaw, when we have sometimes seen seismometers tilting as the ground thaws. On Guralp 6TDs we switch off the auto-centring because once the sensor is up against the end stops it causes frequent spikes across all the channels with repeated failed attempts to auto-centre it. In extremis we would rather lose a horizontal channel and keep the vertical sensor (which is less sensitive to tilt) operating without such noise spikes. We have recently suffered from several failures of regulators, due we think to water ingress to the fuse, which is not encased in protective gel filling.

During the deployment period we also suffered from the GPS WNRO wrap-round problem. SEIS-UK were able to supply us with GPS units that lasted beyond the 2019 crunch point, although we then had to change some of them again in 2020 to avoid further WNRO problems. No data was lost due to WNRO issues.

Processing and modelling

After initial quality control checks the data was converted to miniSEED format. Earthquakes were detected and located using our home-grown Continuous Microseismic Mapping (CMM) algorithm (Drew, White et al. 2013 Coalescence Microseismic Mapping, Geophysical Journal International, 195, 1773–1785, doi: 10.1093/gji/ggt331). This searches in time and space using a signal onset (STA/LTA – short time averaging vs. long time averaging) function for event detection and initial location. At the time of writing this is being replaced by the more versatile QuakeMigrate algorithm, written in Python (Winder, T. et al., in prep. and ESSOAr, 2021), which is available for public use from GitHub https://github.com/QuakeMigrate/QuakeMigrate (see example output in Figure 4 below).

Initial hypocentre locations were refined using NonLinLoc and HypoDD for relative relocations. Locations of events are refined by using waveform coherence to pick relative phase arrival times, with accurate relative locations calculated for clusters of events. Moment-tensor solutions are made using interactive software developed in-house which uses the polarities and amplitudes of both the compressional wave arrivals and the radial and transverse shear arrivals in a full Bayesian inversion (Pugh, White & Christie 2016: A Bayesian method for microseismic source inversion, Geophysical Journal International, doi: 10.1093/gji/ggw186). The way in which stresses generated by the 2014 melt intrusion and the Bárðarbunga caldera collapse trigger brittle failure in the overlying crust is being modelled with programs such as Coulomb-3 following our successful application of these methods to the nearby 2007 Upptyppingar intrusion and the 2014 Holuhraun intrusion.

Data quality (including example data)

The data quality is very good: we are able to use it not just for microseismic mapping, but also for receiver function analysis, particle motion analysis for anisotropy and ambient noise studies. Even in the harsh conditions they experience through the winter, we are achieving typically 95% data recovery. An example of data and the automatic location using QuakeMigrate from a single event at a depth of 4.2 km with a local magnitude of 0.06 is shown in Fig. 4 below.

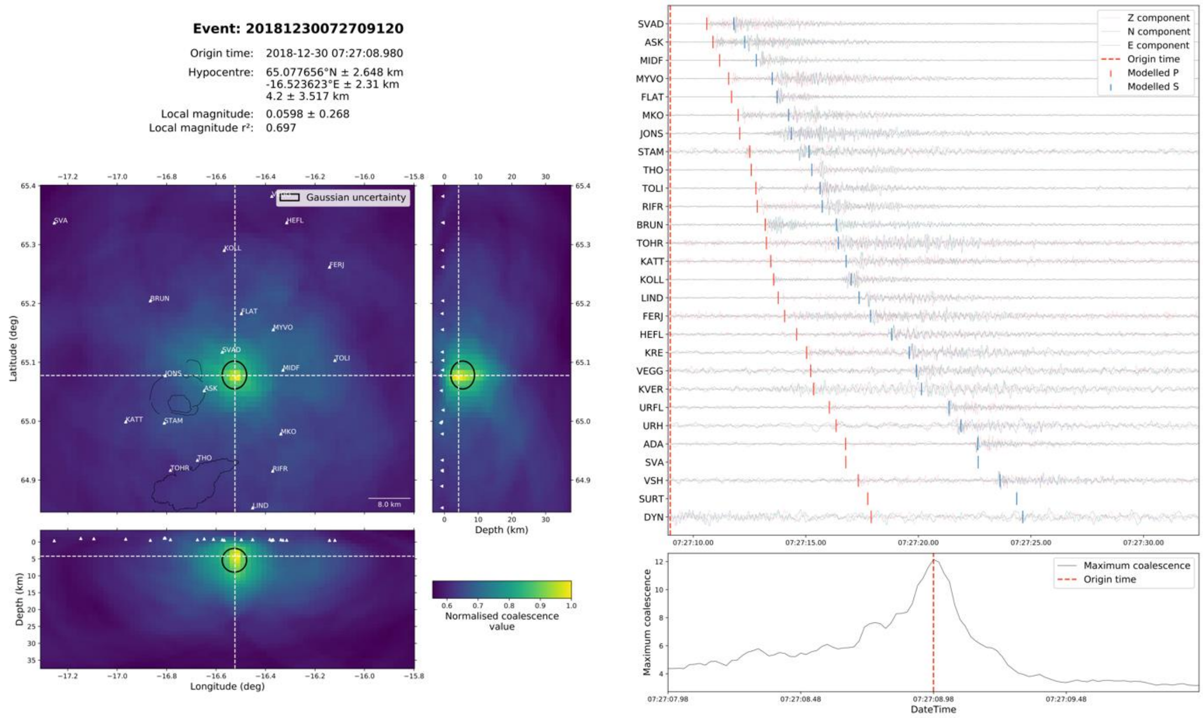

Fig. 4 Right panel shows the three component waveform data filtered between 2-16 Hz from stations across the array (locations shown in first figure and Table, and white triangles in left panel), together with the modelled P and S arrival times from the automatic location shown in left panel. Background shading of the left panel illustrates the location constraint represented as a probability density function. Bottom right shows coalescence function through time, with maximum defining the event origin time (Figure by T. Winder).

Preliminary findings

The original objectives are all being addressed:

1. We have mapped new patches of deep (15–25 km below sea level) seismicity at several places along the rift and it is clear that these are of importance in the way melt is fed into, and forms the crust in a way that has been little recognised in the past (most focus has hitherto been on the high-level magma chambers and mush

zones in the upper part of the crust). The deep activity near Bárðarbunga appears to be increasing since the end of the eruption, signifying an important melt feeder from the mantle to the crust.

2. We continue to monitor the rate of change of induced seismicity around the 2014 Bárðarbunga-Holuhraun intrusion site to constrain rate-state models of earthquake failure following the intrusion. This is a long-term project: sensible estimates of crustal viscosity and relaxation suggest it will take on the order of a decade for shallow stresses to relax, and we are now approaching that time period since the intrusion. Meantime, every year allows us to add better constraints to the modelling.

3. Seismicity is ongoing in the Bárðarbunga caldera with GPS suggesting it is re-inflating. Our moment tensor solutions suggest that normal faults generated during the caldera collapse in 2014 are now reversing their motion in the same locations and are being reactivated as reverse faults.

In addition we are using the data for the following studies:

4. Mapping anisotropy in the crust of this region (in brief, it is fast along strike of the rift and dykes in the shallow crust, and perpendicular to that in the deeper crust where the fast direction aligns with the spreading direction, likely due to shearing and alignment of minerals).

5. We are starting a project to map the attenuation structure of the rift zones and central volcanoes within it, which should help constrain the location of melt or mush zones in the crust.

Conclusions and recommendations

The SEIS-UK instruments have been invaluable for supplementing our own Cambridge seismometers, and have enabled us to maintain long-term monitoring of the seismic activity in this active rift zone. The SEIS-UK staff have provided outstanding support throughout, including Victoria Lane travelling to the field with us when Guralp firmware upgrades were required to correct an error in their former software which could cause the seismometer to lock up and stop recording when the memory was full. These upgrades had to be done in the field with only a 15 sec window to complete a critical stage before the seismometer locked up. SEIS-UK also helped us navigate the unexpected problems caused by WNRO which only became apparent at short notice. The work would have been impossible without the enthusiastic support and help of Bryndís Brandsdóttir and Sveinbjörn Steinthórssen of the Science Institute, University of Iceland. We also thank Heidi Soosalu and many students who have helped with the fieldwork. We are pleased that Prof Nick Rawlinson at Cambridge University has joined the Iceland team and is supervising new Masters and PhD students on the data: the world-class dataset is likely to continue to provide new results and understanding of the tectonics and magmatism of this active area, as well as the seismometer array sitting ready to record the next volcano-tectonic crisis, which is likely to be imminent.

It would certainly be helpful if SEIS-UK were to purchase a GPS North pointer instrument because on magnetic basaltic rocks it is impossible to use a magnetic compass: I note that this would also be useful in deployments elsewhere because one of the most common errors in orientating seismometers is applying the magnetic declination in the wrong direction, which is not immediately obvious, but then makes anisotropy measurements unreliable.

Location of the archived data

The raw and miniseed data are archived at Bullard Laboratories, Cambridge University on two different RAID arrays in different buildings, and also at SEIS-UK. The data (together with data from Cambridge seismometers) will be uploaded to IRIS 3 years after the end of the loan when the current PhD students have finished their analysis of the data, together with all the data from our own seismometer stations (as listed in the Table). In the meantime, we are collaborating and providing this data for research with several researchers in the UK and other countries (Oxford, USA, Germany, Belgium, Estonia, Iceland and France).

The locations of all the microearthquakes we have identified are published in Supplementary Information of our publications, where they are publicly available for download.

Refereed publications

Donaldson, C., Winder, T., Caudron, C. & White, R. S. (2019). Crustal seismic velocity responds to a magmatic intrusion and seasonal loading in Iceland's Northern Volcanic Zone, *Science Advances,* **5**, eaax6642

Volk, O., White, R. S., Pilia S., Green, R. G., Maclennan, J., & Rawlinson, N. Oceanic crustal flow in Iceland observed using seismic anisotropy, *Geophysical Journal International* (in review)

Volk, O., White, R. S., Greenfield, T., Bacon, C., Winder, T., Rawlinson, N. Crack-induced seismic anisotropy dominates shallow crustal velocity structure beneath Askja volcano, Iceland: Implications for body and surface wave models, *Geophysical Research Letters* (in review)

Winder, T., Bacon, C. Smith, J. D., Hudson, T. S., Drew, J. and White, R. S., QuakeMigrate - a Python package for automatic earthquake detection and location using waveform migration and stacking, *Seismological Research Letters,* in prep. and at *Earth and Space Science Open Archive (ESSOAr),* https://doi.org/10.1002/essoar.10505850.1

White, R. S., Edmonds, M., Maclennan, J., Greenfield, T. & Ágústsdóttir, T. (2018). Melt movement through the Icelandic crust, *Proceedings of the Royal Society, Series A,* **377**, 20180010, doi: 10.1098/rsta.2018.0010

White, Robert (2020). Fire and fury in Iceland: tracking volcanic eruptions, *Transactions of the Leicester Literary & Philosophical Society,* **114**, 19–22.

PhD dissertations using data from SEIS-UK instruments

2019 Clare Donaldson: Towards monitoring volcanoes in Iceland and Hawai'i with seismic velocity variations

2020 Omry Volk: Ambient noise constraints on Icelandic crustal structure

(2021) Tom Winder: Tectonics of the northern volcanic zone, Iceland from automatic detection and location of microseismicity

(2021) Conor Bacon: Seismic anisotropy of Icelandic crust

Conference Abstracts

Clare Donaldson, Robert S White, Corentin Caudron (2018), Annual seasonal variations in relative seismic velocity changes in the Northern Volcanic Zone, Iceland, *Geophysical Research Abstracts*, **20**, EGU2018-15393

Conor Bacon et al. (2018) Seismic anisotropy in the Icelandic rift zone, *Geophysical Research Abstracts*, **20**, EGU2018-13641.

Winder, T. et al. (2018) A Surge in Seismicity in a Network of Cross-Cutting Conjugate Strike-Slip Faults Triggered by the 2014 Bárðarbunga-Holuhraun Dike Intrusion, *American Geophysical Union, Fall Meeting, Abstract*

Conor Bacon, Robert S. White, Nicholas Rawlinson (2018) Seismic anisotropy in the Icelandic rift zone, *Postgraduate Research in Progress*

Brandsdóttir, B., White, R. S., Ágústsdóttir, T., Winder, T., Smith, J. D. & Bacon, C. (2019). Caldera Seismicity Associated with the 1998 Inflation of the Shallow Crustal Magma Chamber beneath the Grímsvötn Hotspot Volcano, Iceland, *American Geophysical Union Fall Meeting,* 2019

Conor Bacon, Robert S. White, Nick Rawlinson (2019). Depth Constraints on Seismic Anisotropy in Iceland from Shear Wave Splitting Measurements, *British Seismological Meeting,* 2019

Conor Bacon, Robert S. White, Nick Rawlinson (2019). Depth Constraints on Seismic Anisotropy in Iceland from Shear Wave Splitting Measurements, *American Geophysical Union Fall Meeting,* 2019

Omry Volk, Robert S White, Simone Pilia, Robert G Green, John Maclennan & Nicholas Rawlinson, (2019). Crustal Flow and Formation in Iceland from Radial Anisotropy, *American Geophysical Union Fall Meeting,* 2019

White, R.S., Woods, J., Winder, T., & Brandsdóttir, B., Agustsdottir, T. & Hudson, T. (2019). Tracking subsurface melt movement through the crust in Iceland using seismology, *American Geophysical Union Fall Meeting,* 2019

Tom Winder, Clare Donaldson, Robert S. White (2019). Seasonal Seismicity and Seismic Velocity Variations across the Northern Volcanic Zone, Iceland, are Controlled by Pore-Pressure Variations and Elastic Loading, *American Geophysical Union Fall Meeting,* 2019

Clare Donaldson, Tom Winder, Corentin Caudron, Robert S. White (2019). Crustal Seismic Velocity Responds to a Magmatic Intrusion and Seasonal Loading in Iceland's Northern Volcanic Zone, *American Geophysical Union Fall Meeting,* 2019

Southern, E.O., Winder, T.E.B. & White, R.S. (2020). Bárðarbunga Caldera Collapse and Re-inflation in Iceland During 2014-2019, VMSG Plymouth January 2020.

Winder, Tom & White, Bob (2020). Slowly migrating tectonic microearthquake swarms in the Icelandic Rift Zone: driven by fluid migration or aseismic slip transients? *Geophysical Research Abstracts,* Vol. **22**, EGU2020-19827, *EGU General Assembly 2020.*

Tom Winder, Conor Andrew Bacon, Jonathan Daniel Smith, Thomas Hudson, Tim Greenfield and Robert S White (2020) QuakeMigrate: a Modular, Open-Source Python Package for Automatic Earthquake Detection and Location, *American Geophysical Union Fall Meeting,* 2020

Esme Southern, Tom Winder and Robert S White (2020) Insights from an analogous eruption: Bárðarbunga caldera collapse and re-inflation in Iceland during 2014-2019, *American Geophysical Union Fall Meeting,* 2020, Abstract ID# 741469

Table of instrument deployment details during summer 2018 to summer 2019

Station	Latitude	Longitude	Altitude	Instrument	Sensor
ASK	65.05194	-16.64806	955	3ESP	T36362
BRUN	65.20461	-16.86597	536	6T	T6D73
DYN	64.79086	-17.36648	1146	3T	T3Z76
FERJ	65.26197	-16.1413	521	6T	T6023*
FLAT	65.18279	-16.49796	728	6T	T6041*
HEFL	65.33727	-16.31449	550	6T	T6D80
JONS	65.07747	-16.8057	1174	6T	T6058*
KATT	64.99901	-16.96539	885	6T	T6132*
KOLL	65.29024	-16.56726	593	3ESP	T36800
KVER	64.76347	-16.61068	829	6T	T6026
LIND	64.85278	-16.4523	726	3ESP	T36794
MIDF	65.08676	-16.32961	572	6T	T6010
MYVO	65.1555	-16.36895	639	6T	T6D74
NAIR	64.71465	-18.0681	837	6t	T6150
RIFR	64.91533	-16.37127	657	6T	T6038*
RJUP	64.74295	-17.52738	996	6T	T6J81
SKAF	64.02609	-16.98853	259	6T	T6359
SKEG	64.61016	-18.03726	894	6T	T6112*
STAM	64.99691	-16.80959	1171	6T	T6D77
SURT	64.88963	-17.49961	815	6T	T6D82
SVAD	65.11746	-16.57498	680	6T	T6D81
SVED	64.48185	-17.96292	1092	6T	T6D75
SVIN	64.3866	-15.39449	40	3ESP	T37880
SYLG	64.42524	-18.1097	899	3ESP	T36797
TOHR	64.91658	-16.78473	715	6T	T6108*
TOLI	65.10338	-16.1195	528	6T	T6161*
TUFS	64.81608	-17.68003	862	6T	T6128*
TUNG	64.80818	-17.9328	887	6T	T6208*
URFL	64.8207	-17.09445	990	6T	T6116*
VEGG	65.38205	-16.37467	507	6T	T6D79
VONK	64.67315	-17.75591	1011	3ESP	T36796

Note on Table: asterisks show instruments owned by SEIS-UK. For this loan we borrowed 10 6TD instruments from SEIS-UK, but had 11 deployed because we had arranged for SEIS-UK to borrow two Cambridge seismometers (T6D76 and T6D78) that were already in Leicester after repairs in exchange for keeping two of SEIS-UKs already deployed in Iceland for a further year: this was because SEIS-UK had an urgent loan to New Zealand to fulfil, so we were happy to let them use ours. The twelfth SEIS-UK instrument had failed in 2018, but we did not seek a replacement for 2018-19 due to the low SEIS-UK stocks available at the time.