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Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Calls, Final Report -

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Host Organisation name	Dublin Institute for Advanced Studies (DIAS)
Project Title	Development of the Hekla volcano real-time seismic monitoring network, HERSK
Contract Number	2017-sc-039

Date: *14th November 2018*

This report covers the period November 1st 2017 to October 31st 2018

2. (a) Project information:

Final project report (*max **2500**words, excluding figures and headings*):

(i) *Progress* of objectives and scientific/engineering targets beyond the state of the art & *methods* used

Eruptions of Icelandic volcanoes have the potential to significantly impact economic activity in Ireland as happened in 2010 when Irish airspace was closed for about two weeks following the eruption of Eyjafjallajokull. Project HERSK (HEkla Real-time Seismic networK) entails the installation of a real-time seismic network on Hekla volcano in Iceland, see Figure 1. Hekla is one of the most active and dangerous volcanoes in Iceland. About one third of volcanic ash deposited during the last 7,000 years in Scandinavia, Germany, Ireland, and the United Kingdom originates from Hekla (Swindles et al., 2011).

The main goals of HERSK is to better the understanding of pre-eruptive processes in rift dominated volcanic systems, to ensure a smooth information flow on the status of Hekla to Irish stakeholders (e.g. the GSI) and to improve early warning capability. The network was successfully installed and micro-seismicity at Hekla is now recorded continuously in unprecedented detail. The network transmits data in real-time to the seismic data centres at IMO (Icelandic Met Office) in Reykjavik and at DIAS (Dublin Institute for Advanced Studies). We accept that the infrastructure might be destroyed when the next Hekla eruption occurs. However, it will give the unique capability to seismically monitor a fissure eruption close up. The understanding of pre-eruption seismicity will be improved. In previous Hekla eruptions shallow seismicity was detected whilst the magma was still at significant depth but rising towards the surface (Soosalu et al., 2005; Sturkell et al., 2013). If similar behaviour occurs before the next eruption it might be detectable earlier and in more detail as station coverage has now been improved significantly. The HERSK dataset is expected to have strong potential for very high-impact publications (e.g. Nature publications) in the medium and long term.

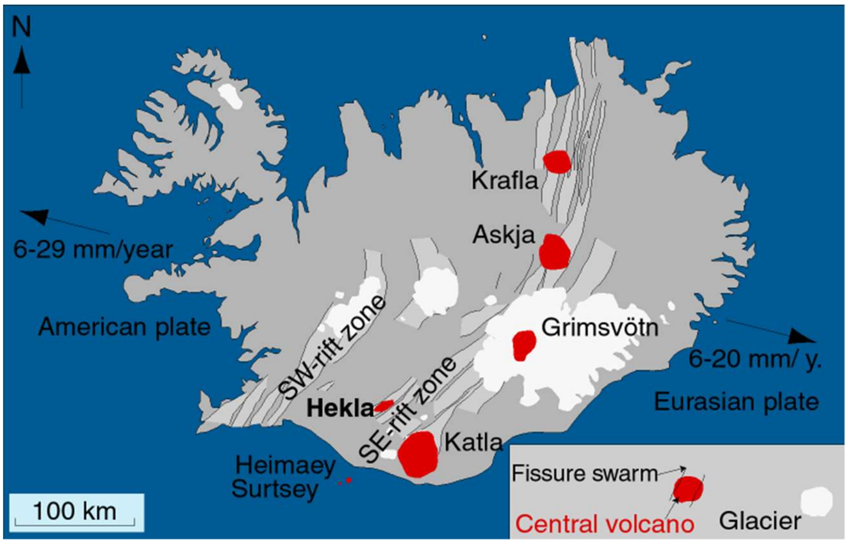


Figure 1 *Locations of central volcanoes, rift zones and major fissure swarms in Iceland (from https://sites.google.com/a/chadwickschool.org/earth-science-news2/volcanoes/v-13).*

The HERSK project was motivated by our previous temporary deployment of 5 broadband seismometers on Hekla in 2012, see Figure 2a. These stations were deployed for about 2 months and did not transmit data in real-time. The installed stations detected completely unexpected background micro-seismicity originating mainly from the northern flank of Hekla, see Figure 2a (Eibl et al., 2014). Figure 2b shows waveforms for a typical event that we recorded about 1 km (HEK03) and 2.5km (HEK02) northeast of the summit. The amplitudes of these micro-earthquakes were too low to be detectable on the other nearest seismic stations, 4 and 6.5 km from the summit. Hence previous to our deployment in 2012 it was not known that there was a continuous low level seismicity on the volcano.

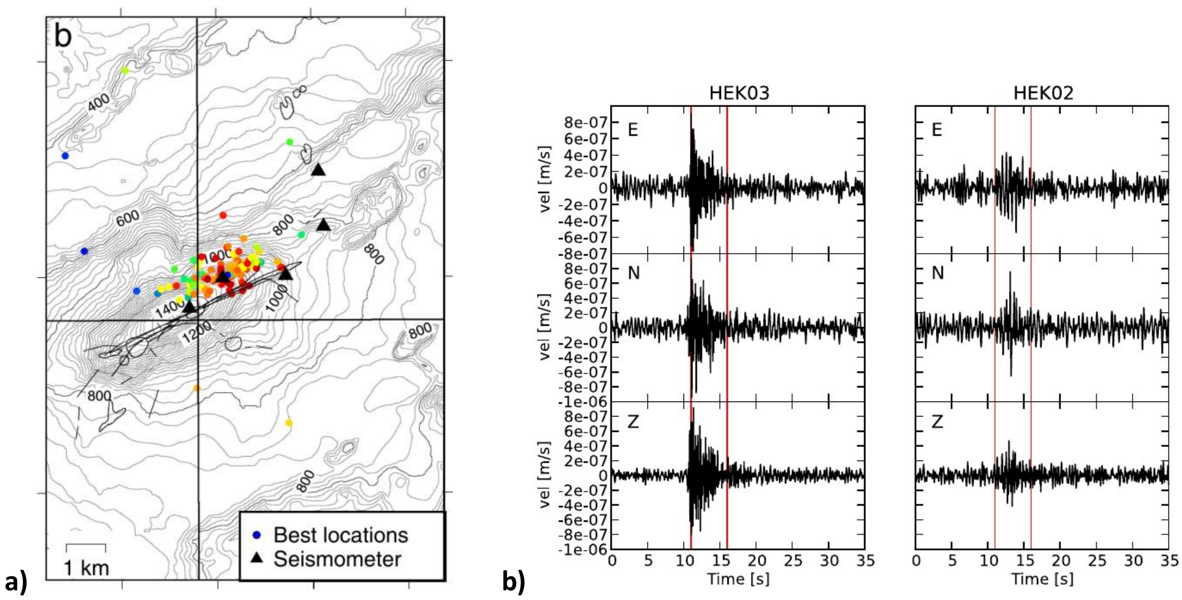


Figure 2 *a) Station locations and detected micro-earthquakes for the 2-month installation in 2012. b) Typical micro-seismic event seismograms recorded about 1km (station HEK03) and 2.5km (station HEK02) from Hekla summit. Note the slightly earlier arrival at station HEK03 and the lack of distinct seismic phases due to the close proximity of the source (both from Fig. 3 in Eibl et al., 2014).*

For HERSK we proposed again a network of 5 broadband seismometers, available from the Irish contribution to the recently concluded European project Futurevolc. However this time the data is transmitted in quasi real-time. Transmitting data in real-time uses a lot of electrical power and providing this on top of Hekla is a logistical challenge that has not been achieved before due to very harsh conditions on Hekla, which is frequently covered in snow and small glaciers even in summer. Our solution to this technical challenge is to install wind-powered communication hubs lower down the volcano in 3 places, collocated with one seismometer each, see maps in Figure 3. Three other seismometers are installed higher up on the volcano. Special cables of 1km length connect these seismometers with the hubs to provide them with electrical power and internet connectivity using 3G mobile network modems. The equipment related to this unique field set-up weighs about 200kg per station and transport logistics involved the usage of ski-doos and quadbikes from IMO, for photos of the fieldwork see section 'Implementation' below.

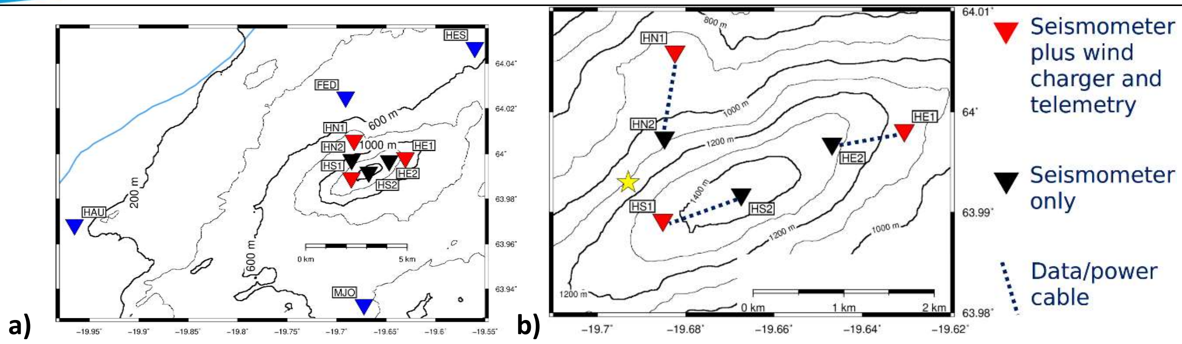


Figure 3 *a) Station geometry of the installed HERSK network (red and black symbols) and pre-existing installations of the national network in Iceland operated by IMO (blue symbols).*
b) Location of multicore cables (dashed lines) connecting the remote stations marked by black symbols with the power and communication hubs which are co-located with the seismometers marked by red triangles. The star marks the epicentre of an earthquake recorded on the 27th September 2018, see main text for details.

Preliminary results show that the HERSK network indeed detects micro-seismicity on Hekla, see as an example the dayplots of stations HN2 and HE2 for the 8th October 2018 in Figure 4. The data are high-pass filtered from 2Hz. High frequency background noise was particularly low during this day and hence very small events become detectable.

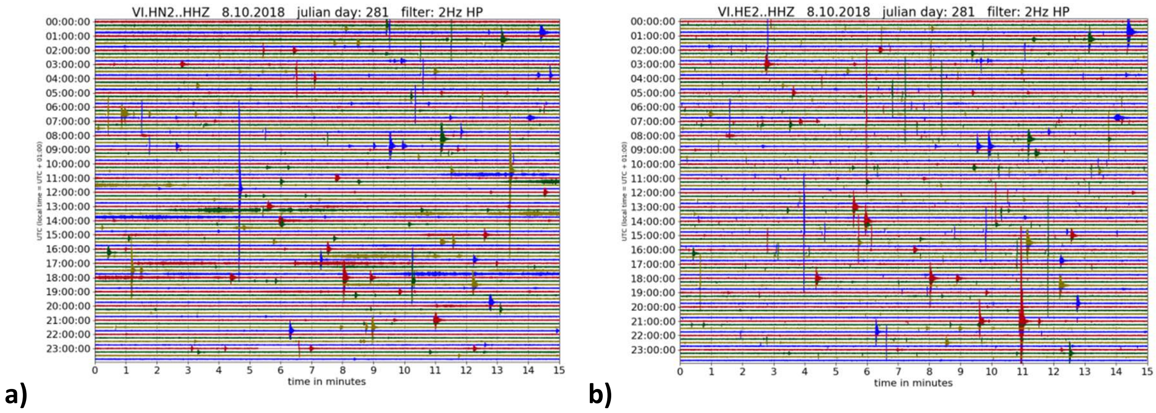
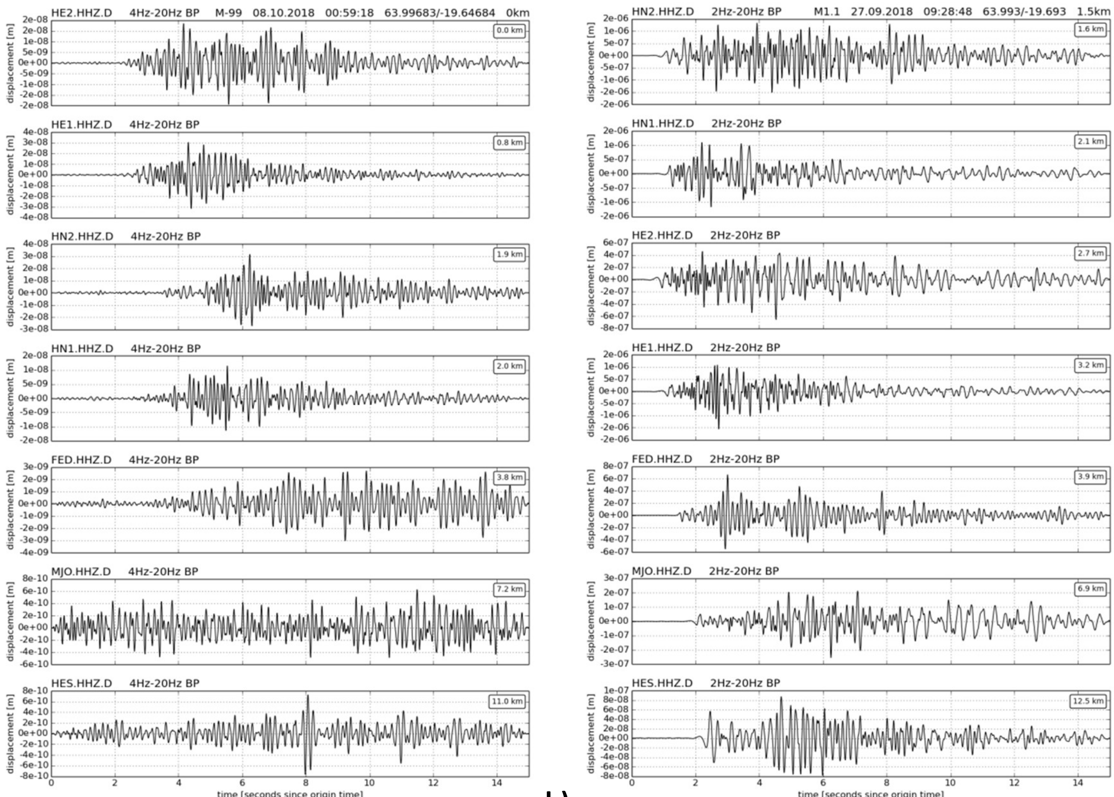


Figure 4 *Dayplots for the vertical components recorded on the 8th October 2018 at stations a) HN2 and b) HE2, both high-pass filtered from 2Hz.*

The seismograms for an earthquake detected on the 8th October 2018 around 00:59:20 UTC are shown in Figure 5a. The precise location and magnitude of this event has not been determined yet. The event is too weak to be detected by stations FED, MJO and HES of the Icelandic national network operated by IMO. The new HERSK stations HE2, HE1, HN2 and HN1 however detect the earthquake with a good signal to noise ratio. This demonstrates that the HERSK dataset will provide us with a very detailed image of the micro-seismicity at Hekla.

The HERSK data will also benefit the location calculations of stronger earthquakes that are detected even without the new installations. This is demonstrated by Figure 5b which shows seismograms for the magnitude 1.1 earthquake of the 27th September 2018, 09:28:48 UTC. This event was detected and reported by the automatic IMO system with a depth of 1.5km and an epicentre location of 19.693^0 West and 63.993^0 North, marked by a yellow star in Figure 3b. The high signal to noise ratios of the HERSK station data provide the potential to improve location accuracy and source characteristics of events detected at Hekla. Only two of the HERSK stations have been added to the automatic IMO earthquake detection system to avoid flooding of the IMO system with micro-earthquakes from Hekla (K. Jonsdottir, *personal communication*, 1st October 2018).



a) **b)**

Figure 5 *a) Seismograms for an earthquake detected on the 8th October 2018 around 00:59:20 UTC, bandpass filtered from 4 to 20 Hz. Station names are given in the top left of each sub-panel and the distance of each station from HE2 is given in the right top of each sub-panel. b) Seismograms of the magnitude 1.1 earthquake of the 27th September 2018, 09:28:48 UTC, bandpass filtered from 2 to 20 Hz. The epicentre location is indicated by the yellow star in Figure 3b and the epicentral distance of each station is given in the right top of each sub-panel.*

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

The first management meeting was held on the 20th December 2017 in DIAS, 5 Merrion Square, Dublin 2. It was decided to change the originally proposed geometry of the real-time seismic network. Instead of using one central power hub and one central communication hub we split the network into three parts with one power/communication hub each. The reason for this change was the realization that it is too difficult to lay cables across the steep northern flank of Hekla. Also cable lengths would be longer than 1km which risks failing RS232/422 data links. An additional advantage of this new layout is an increase in the number of stations from 5 to 6 and also better resilience for real-time data streaming in case a power/communication hub fails.

The second management meeting was held on the 14th February 2018 in the Park Inn Hotel, Reykjanesbær near Keflavik where the Eurovolc kick-off meeting was held. It was pointed out that the newly proposed network layout has no seismic station located directly on Hekla summit. It was suggested to attempt a wind-powered communication hub directly on Hekla summit, using the existing IMO gas-monitoring hut there as icing shelter for the wind generator. In addition the coordinates for the proposed new station locations were forwarded to the IMO engineers so that they can check the locations during the trip for the test installation. It was also agreed that Kristin Vogfjord (IMO) will apply for permission that DIAS can access the real-time data streams of the two permanent seismic IMO network stations nearest to Hekla, station names MJO and FED.

Consumables were ordered and delivered to IMO in Reykjavik in time for the first part of fieldwork which was carried out 14th to 15th May 2018. IMO staff transported all equipment required for the installation of 4 seismometers onto Hekla volcano using skidoos. The equipment comprised 4 seismometers, 2 cable drums of 150kg each, 4 batteries of 30kg each, 2 aluminium boxes for batteries and electronics, 2 masts and wind chargers, 2 solar panels and 4 plastic drums, see Figures 6 to 7. The test installation of a wind generator directly on Hekla summit showed that icing in this location is too severe, even on the relatively sheltered site of the gas monitoring hut. During the next management meeting held on the 22nd May 2018 at DIAS, 5 Merrion Square in Dublin it was decided to attempt a wind generator installation 1km southwest from the summit during the main fieldwork phase.

Figure 6 *IMO staff transporting equipment with skidoos at 900m elevation on the eastern flank of Hekla volcano.*

Figure 7 *left: Cable drum on skidoo trailer at 1,300m elevation, right: unloading equipment at the top of Hekla at 1,488m elevation. The small hut in the background houses a gas monitoring station operated by IMO.*

The PI travelled 11th to 15th June 2018 to Iceland in order to discuss details for the upcoming field season and to test and prepare equipment. A management meeting was held on the 12th June. It was noted that no MEMS accelerometers will be available for deployment along some of the seismometers and also no tiltmeter which was proposed to be possibly installed at Litla Hekla summit. However, this will be partly compensated by the fact that the new network geometry consists of six seismometers while it originally was only five. DC/DC power and RS232/422 converters were tested and installed in field boxes ready to be deployed, see Figure 8 left. An opportunity presented itself to travel during the last day to Litla Hekla and install the first seismometer, station HN1. The site is close to a small existing hut on Litla Hekla summit, see Fig. 8 right. The planned installation of the second seismometer HN2, connected via a 1km long cable to the hut, was not possible because of too much snow cover. Because of frozen ground station HN1 could only be installed temporarily at that stage.

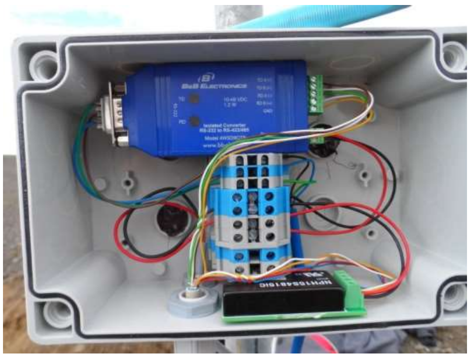


Figure 8 *left: field box containing the black DC/DC power and the blue RS232/422 converter, right: installation site of HN1 on top of Litla Hekla at 953m elevation, in the background the green hut used for housing of batteries and electronics.*

Exceptionally wet and cold weather in May caused high accumulations of snow on Hekla and the planned deployment of the remaining five stations in the second half of July had to be re-scheduled to September. The PI and Heiko Buxel from the BGS travelled 11th to 20th September to Iceland for the main fieldwork phase. A management meeting was held at IMO on the 12th September 2018 and final decisions agreed. The field party consisting of the PI, Heiko Buxel, Bergur Bergsson (IMO) and Vilhjalmur Kjartansson (IMO) departed the same day to the field base at Landgraedsla Riskins, the Icelandic Soil Conservation Service in Gunnarsholt about 30km southwest from Hekla volcano. Favourable weather conditions allowed for a successful and efficient installation of all 3 wind generator / communication hubs, the associated 1km long cable runs and the six seismometers. However, relatively extreme conditions were experienced during several days at the summit stations HS1 and HS2. High humidity, strong winds and sub-zero temperatures made for very difficult conditions during the installations of the seismometers, see Figure 9 left. It was observed that the wind charger at station HS1 was completely frozen in within only two days, see Figure 9 right. Because of these conditions the hub at HS1 is not powered sufficiently to stream data from HS1 and HS2 to the data centres at IMO and DIAS. The other 4 stations however are transmitting data continuously since they were installed.

Figure 9 *left: installing HS2 at Hekla summit, right: frozen over wind charger at HS1 two days after it had been installed.*

In summary it can be noted that nearly all Milestones and Tasks, see lists below, were delivered fully. Exceptions are tasks 6, 7 and 10 and milestone 4. No accelerometers were installed as part of Task 7 as explained above. No webcams were installed because the HERSK sites are located too close to potential vent sites. Instead several webcams that already operate off Hekla provide good coverage of potential eruption sites, see "Deviations from original project plan" below for more details. The real-time event detector (Tasks 6, 10 and Milestone 4) was not configured and tuned as planned, mainly because of time constrains due to the 2-month delay of the main fieldwork phase. However, the HERSK stations were included into the real-time python tool OSAS developed and operated by the PI at DIAS. Dayplots of the stations are accessible at https://osas.dias.ie/drumplots/2018/VI, power spectrum density plots at https://osas.dias.ie/pqlx/VI/HHZ/ALL/, and spectrograms at https://osas.dias.ie/spectrograms/2018/VI. Instead of using simple python tools for event detection a dedicated Seiscomp3 installation has been installed at DIAS. The Seiscomp3 software can be used in real-time and also offline mode to playback existing data for event detection and location. This is a marked improvement on the original plan and the related costs will be covered by DIAS.

Milestone 1 (Month 7): Onsite preparation of power and communication hub and laying of cable runs

Milestone 2 (Month 10): Installation of sensors and telemetry

Milestone 3 (Month 10): Establishment of a real-time data connection from HERSK to the seismic observatories in Reykjavik (IMO) and in Dublin (DIAS)

Milestone 4 (Month 12): Real-time event detector tuned and operational

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Identify suitable site locations for sensors	Month 0 - 2	Month 2
2	Ordering of consumables	Month 4 - 5	Month 6
3	Presentation of project at IGRM 2018	Month 5	Month 4
4	Equipment preparation	Month 6	Month 8
5	Installation of power generator and cable runs	Month 7	Month 11
6	Development of real-time data tool in python	Month 8 - 10	Month 11, using OSAS and Seiscomp3 instead
7	Installation of sensors, webcams and telemetry	Month 10	Month 11, partly
8	Establishment of real-time connectivity to IMO, DIAS	Month 10	Month 11
9	Tuning of real-time event detector in python	Month 11	Month 12, Seiscomp3 installed, not fully tuned yet
10	Presentation of first results at EGU 2019	After project end	After project end

<u>References:</u>

Eibl, E.P.S., C.J. Bean, K. Vogfjörd, A. Braiden (2014), Persistent Shallow Background Microseismicity on Hekla Volcano, Iceland: A Potential Monitoring Tool, Journal of Volcanology and Geothermal Research, doi: 10.1016/j.jvolgeores.2014.11.004

Soosalu, H., P. Einarsson, B.S. þorbjarnardóttir (2005), Seismic activity related to the 2000 eruption of the Hekla volcano, Iceland, Bull. Volcanol., 68 (1), 21-36, doi: 10.1007/s00445-005-0417-7

Sturkell, E., K. Ágústsson, A.T. Linde, S.I. Sacks, P. Einarsson, F. Sigmundsson, H. Geirsson, R. Pedersen, P.C. LaFemina, H. Ólafsson, H. (2013), New insights into volcanic activity from strain and other deformation data for the Hekla 2000 eruption, J. Volcanol. Geotherm. Res., 256, 78-86, doi: 10.1016/j.jvolgeores.2013.02.001

Swindles, G.T., I.T. Lawson, I.P. Savov, C.B. Connor, G. Plunkett (2011), A 7000 yr perspective on volcanic ash clouds affecting northern Europe, Geology, 39 (9): 887-890, doi: 10.1130/G32146.1

(iii) Outputs (please provide a short description *and* complete the table below)

The HERSK project was presented to the wider geoscience research community in Ireland at the IGRM 2018 with the poster entitled "*Seismic real-time monitoring of Hekla volcano, Iceland*".

An oral presentation was delivered by the PI at the 7th September 2018 at the 36th General Assembly of the European Seismological Commission in Malta. The title was "*The logistical challenge of establishing a real-time seismic network on Hekla volcano, Iceland*".

A poster with the title "*HERSK, the first real-time seismic network on Hekla volcano in Iceland*" was presented at the meeting "Geoscience 2018" on the 6th November 2018 in Dublin Castle.

Publications to date:

[Conference Publications]

Möllhoff, M., C.J. Bean, K.S. Vogfjörd, B.H. Bergsson (2018), Seismic real-time monitoring of Hekla volcano, Iceland, 61st Irish Geological Research Meeting (IGRM2018), Cork, doi: 10.13140/RG.2.2.20233.75365/1.

Möllhoff, M., B.H. Bergsson, H. Buxel, V. Kjartansson, B. Bergsson, C.J. Bean, K.S. Vogfjörd (2018), The logistical challenge of establishing a real-time seismic network on Hekla volcano, Iceland, 36th General Assembly of the European Seismological Commission, Malta, ESC-S11-402.

Möllhoff, M., C.J. Bean, K.S. Vogfjörd, B.H. Bergsson, H. Buxel, V. Kjartansson, B. Bergsson (2018), HERSK, the first real-time seismic network on Hekla volcano in Iceland, Geoscience 2018 - Meeting the Challenges, 6th November 2018, Dublin Castle.