Scientific Report for Loan 891:

Seismicity of the Krafla Caldera and Geothermal Area, Iceland

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Abstract

This loan comprised fifteen 8 Gb Güralp 6TD seismometers, which were deployed in and around the Krafla caldera in NE Iceland (Fig. 1) during July 2009–September 2010. The work was supported by a NERC research grant and NERC PhD student Jon Tarasewicz. The SEIS-UK 6TD seismometers were supplemented by 9 Cambridge 6TDs, plus ancillary solar panels and batteries from Cambridge. Preliminary results include recording and locating >3,000 microearthquakes that we attribute primarily to geothermal exploitation in the caldera and to the cooling of a shallow magma chamber and hydrothermal activity associated with it.

Background

Krafla volcano lies in the Northern Volcanic Rift Zone of Iceland and was the site of multiple eruptions and intrusion events during 1975–1989 (Brandsdóttir and Einarsson, 1979; Einarsson and Brandsdóttir, 1980; Björnsson, 1985). Microseismicity in the region may be generated by: (i) tectonic rifting processes, (ii) cooling and contraction of a shallow magma chamber and fluid flow around it, (iii) active geothermal exploitation by the power station in the caldera, (iv) magma migration in the subsurface. The national seismic monitoring network operated by the Icelandic Meteorological Office (IMO) is relatively sparse around Krafla; hence, this loan has been used to deploy a dense network within the caldera to monitor and investigate the microseismicity.

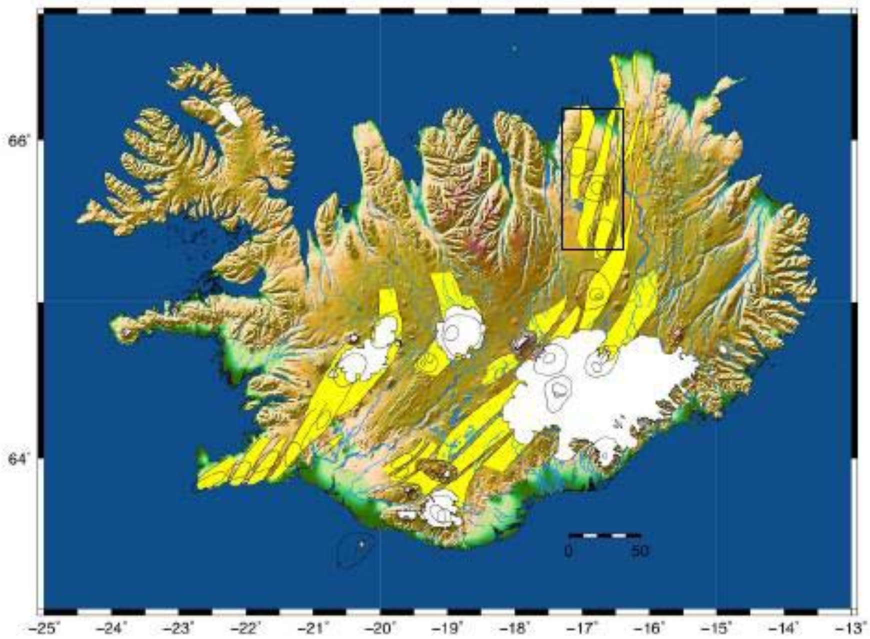

FIGURE 1: *Map of Iceland showing the fissure swarms in yellow with their associated central volcanoes. The study area is shown in the black box.*

Survey procedure

The array was deployed in July 2009, comprising the 15 instruments on this loan supplemented by an additional 9 Cambridge-owned 6TDs. The majority of sensors were buried in soil; one sensor was deployed inside a geothermal well-head hut. Most stations were operated at 100 samples per second (sps). The array was subsequently serviced in December 2009, March 2010 and July 2010 before the final service (of Loan 891) in September 2010. Such frequent servicing was necessary because the Cambridge-owned instruments had only 4 Gb storage capacities. Nonetheless, regular servicing of all instruments also allowed a higher recording rate to be used on the SEIS-UK instruments (100 sps) than if no winter servicing had been carried out. Additional stations were added to the array in July 2010 (as part of Loan 914), and a higher sample rate (200 sps) was used over the summer (July–September 2010) to capture high-frequency signals.

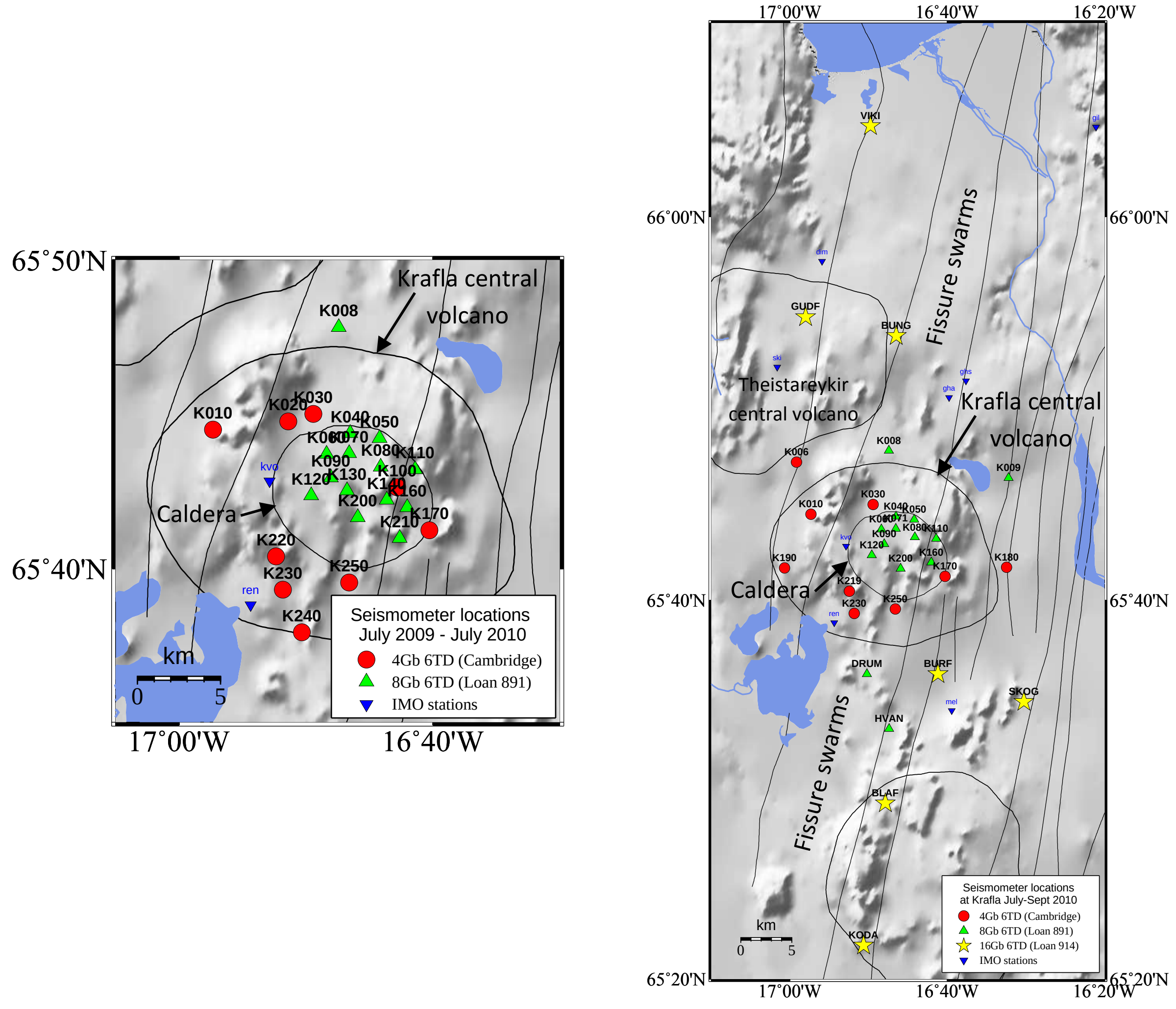

FIGURE 2: *(Left) Krafla caldera network deployment (July 2009). (Right) Network at Krafla from July–Sept 2010 including additional instruments as part of Loan 914 (yellow stars) and after moving some station locations to improve coverage. Fissure swarms and central volcano/caldera outlines after Einarsson and Sæmundsson (1987).*

We suffered a number of instrument failures during Winter 2009–2010, partly due to failure of breakout boxes (which we understand to be have been returned from Sumatra where several had become waterlogged and corroded internally – breakout boxes that failed were working when deployed, but subsequently failed due to corrosion over the winter). Heavy snowfall and drifting also caused power outages in some cases in which stations' solar panels were buried by snow for several weeks. Servicing with frozen ground proved difficult with the standard deployment methods, so we modified our deployment procedure in three main ways: (i) we mounted the breakout box above ground level on a small stick, and protected it with double plastic bags; (ii) we added flying power leads attached to a vertical strut so that batteries could be recharged in the winter without uncovering them; (iii) solar panels were mounted on wooden A-frames much higher above the ground than previously. We now use these modifications as standard in all our deployments.

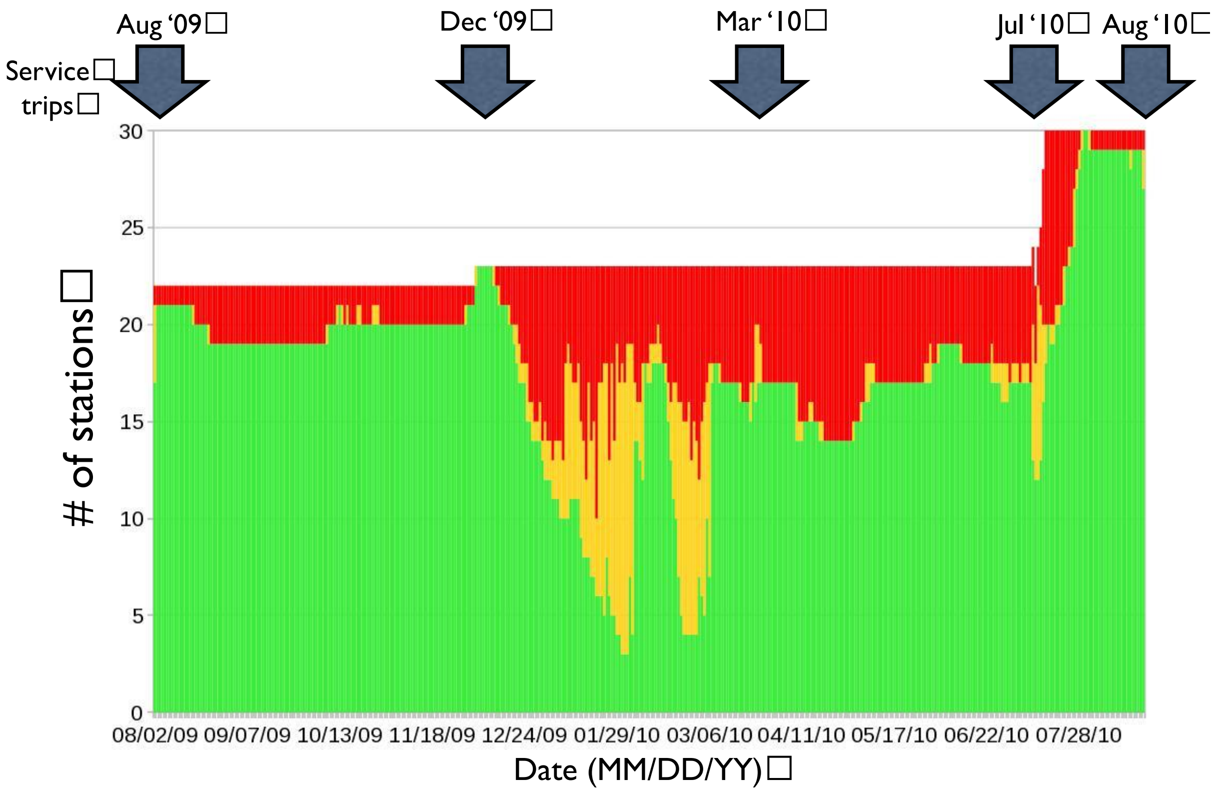

FIGURE 3: *Summary diagram of network performance in the Krafla area showing number of stations operating on each day during the deployment. Green indicates continuous data for the entire day; yellow indicates partial data (most frequently due to power loss overnight in winter); red indicates no useable data that day (due to equipment failure, such as breakout box corrosion or faulty GPS, or to power loss).*

Data quality

Most local events in Krafla are of small magnitude (M_L <1.5) but occur at depths of <4 km. Notwithstanding the initial problems with maintaining instrument power during the Icelandic winter and break-out box failures, data quality is good for local events, with clear P- and S-wave arrivals for many small-magnitude local events (Figure 4).

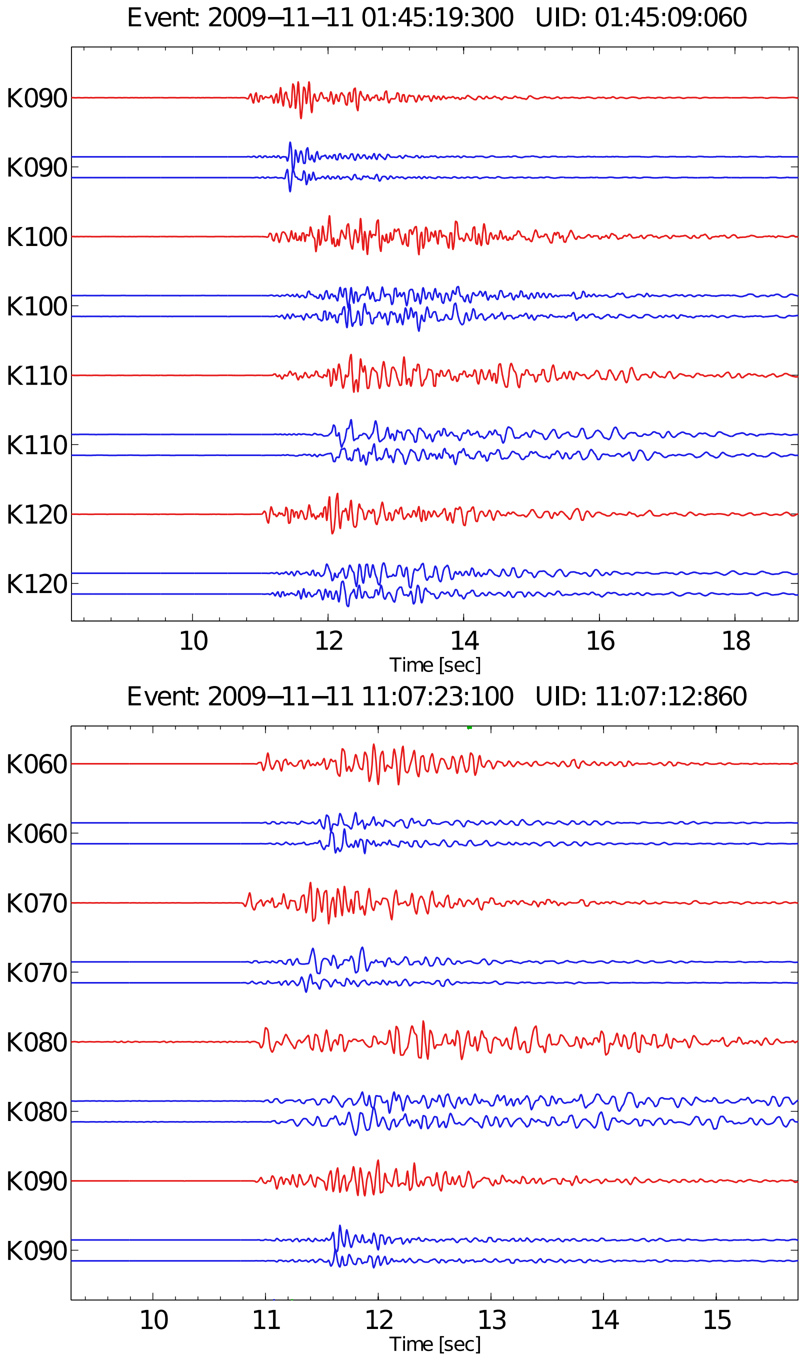

FIGURE 4: *Top and bottom panels show arrivals from two examples of local earthquakes at Krafla. Red traces show vertical component data, blue are horizontal components; all are bandpass filtered between 2–20 Hz. All stations shown here are SEIS-UK 8 Gb instruments except for K100, which is a Cambridge-owned 4 Gb 6TD.*

Processing and modelling

All data were quality controlled and converted to miniseed format using SEIS-UK standard procedures. Subsequently, we have used an automatic Coalescence Microseismic Mapping (CMM) technique to detect and locate microearthquakes in the data. A subset of automatically located events have then been manually refined and relatively relocated. Focal mechanisms solutions have been attempted for some of these events using P-wave first-motion polarities.

Preliminary findings

The dense network we deployed at Krafla detected significantly more events (>3,000 in July 2009–Sept 2010) than were detected by the Icelandic Meteorological Office's permanent network. For example, Figure 5 shows preliminary automatic hypocentre locations during August 2009 to August 2010. Source mechanism inversions have shown that a variety of faulting mechanisms exist, including examples of apparently implosive sources.

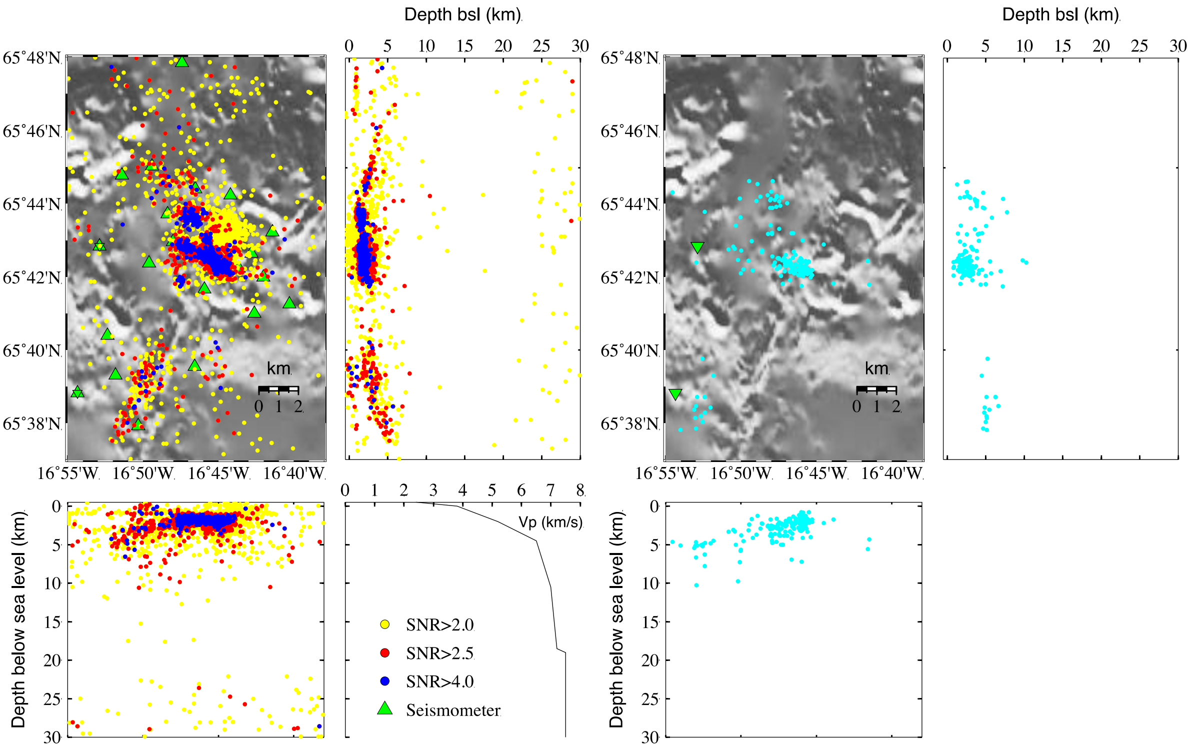

FIGURE 5: *Earthquake hypocentre locations in and around Krafla August 2009 to August 2010. (Left-hand side) Automatic Coalescence Microseismic Mapping (CMM) locations, colour-coded by signal-to-noise ratio of the coalescence signal as indicated (Drew 2010; Tarasewicz et al., 2012). A map and two orthogonal cross-sections are shown, plus the 1-D P-wave velocity model used (S-wave arrivals were also inverted simultaneously using a constant V_P/V_S ratio of 1.78). (Right-hand side) Hypocentres reported in the Icelandic Meteorological Office's (IMO) catalogue for the same time period; note that far fewer were detected by the IMO's permanent network. Green triangles denote available local seismic stations used in each case (more distant stations were also used in IMO locations).*

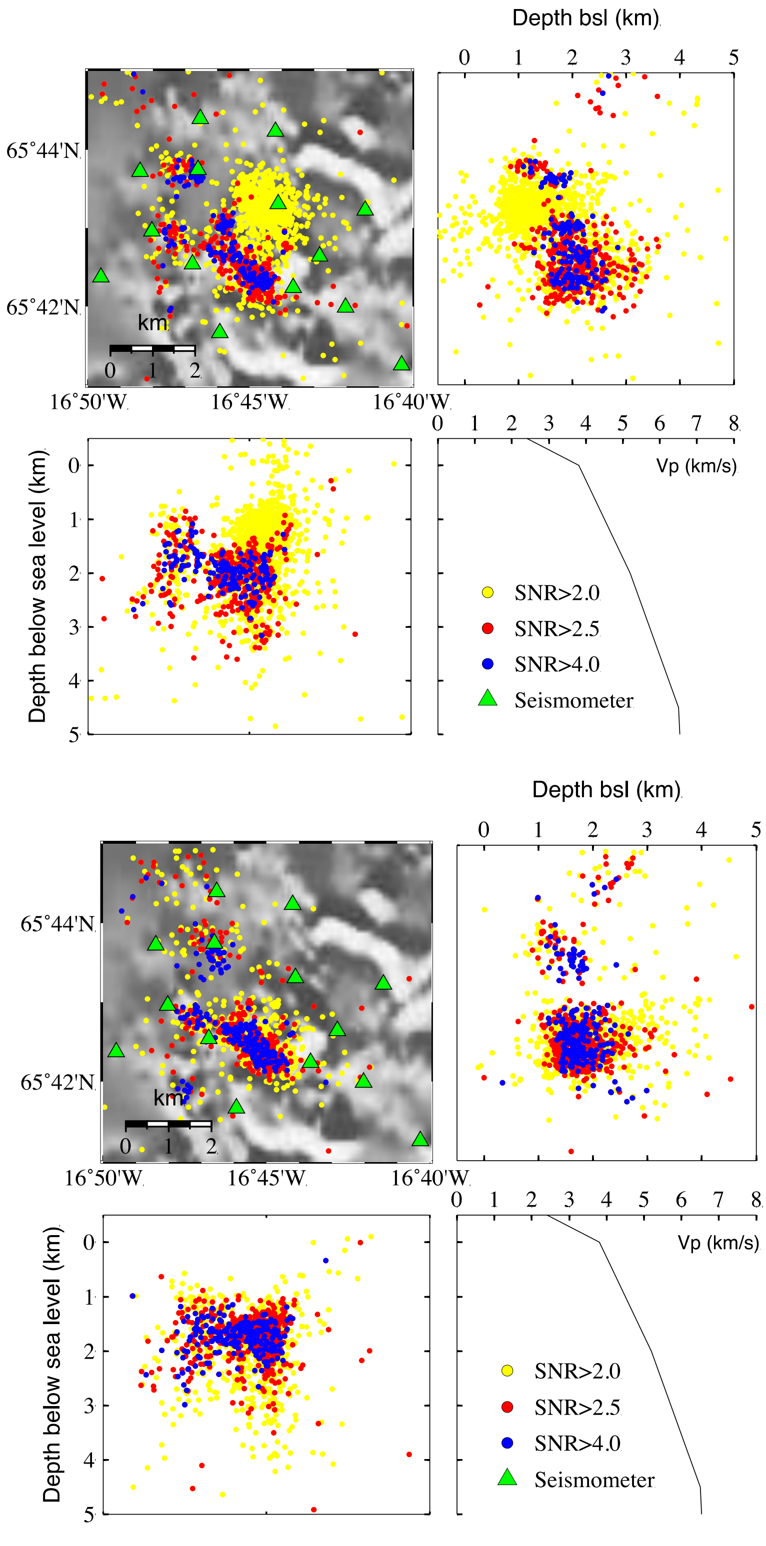

FIGURE 6: *Earthquake hypocentre locations in the Krafla central caldera during Aug–Nov 2009 (top panels) and Mar–Jun 2010 (bottom panels). Events are colour-coded by signal-to-noise ratio (SNR) of the coalescence signal as shown (and as in Figure 4). Note that activity is focused in the same locations in these two example time periods. The prominent cluster of low-SNR (yellow) events in the top panel is related to drilling of a geothermal borehole in that location. Green triangles show seismometer locations.*

Interpretation to date

The majority of earthquakes we have recorded coincide spatially with the location of the main geothermal field exploited by the power company in the Krafla caldera (central large cluster in Figures 5 & 6). These are therefore likely to be associated with geothermal exploitation during the study period. A smaller number of events appear to be related directly to drilling of geothermal boreholes (top panel, Figure 6). Other clusters of events are located beneath the fissure swarm running south from the caldera (Figure 5), which may have a tectonic influence. Finally, there was significant activity under the natural geothermal area of Leirhnjukur and under the lava flow from the most recent eruptions in the 1980s. These events are probably related to fluid flow causing cracking above the shallow, cooling magma chamber. The presence of some implosive source mechanisms is consistent with earthquakes caused by fluid movement. All of these seismogenic sources are currently under further investigation.

Conclusions and recommendations

The dense array deployed in the Krafla caldera has facilitated a significantly lower earthquake detection threshold than the permanent IMO network, significantly reduced location uncertainties and better constraints on source mechanisms. Several identifiable seismogenic processes are present in the data and are the subject of further study.

This deployment under Loan 891 was subsequently augmented by Loan 914 (*Interaction of Tectonics and Magmatism in the Askja and Krafla spreading segments of Iceland*) and work is ongoing to combine data from both loans and data from the IMO's permanent stations in the area to study the seismicity at Krafla and along its transecting fissure swarm.

References

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Tarasewicz, J., B. Brandsdóttir, R. S. White, M. Hensch, and B. Thorbjarnardóttir (2012a), Using microearthquakes to track repeated magma intrusions beneath the Eyjafjallajökull stratovolcano, Iceland, *J. Geophys. Res., 117,* B00C06, doi: 10.1029/2011JB008751.

Publications to date

Greenfield, T. (2011), *Microseismicity of the Krafla Volcanic System, Iceland*, M.Sci. dissertation, University of Cambridge, U.K.

Greenfield, T., R. S. White, J. Tarasewicz, J. Key, H. Martens, and B. Brandsdóttir (2011), *Microseismicity of the Krafla Volcanic System, Iceland*, presented at Volcanic and Magmatic Studies Group Annual Meeting, Cambridge, U.K., 5–7 January.

Tarasewicz, J., R. S. White and B. Brandsdóttir (2010), *Imaging the magma chamber under Krafla, NE Iceland*, presented at meeting "New Advances in Geophysics: Magma Emplacement and Storage in the Earth's Crust", Geological Society, London, U.K., 11–12 February.

Watson, Z. (2013), *Microseismicity within the Krafla Caldera, NE Iceland*, M.Sci. dissertation, University of Cambridge, U.K.

Instrument deployment details

Station code	Latitude	Longitude	Altitude (m)	Install date	Pull-out date	Sensor	Memory (Gb)
JULY 2009 DEPLOYMENT							
K008	65.79724	16.79029	507	31/07/09	-	6125	8
K010	65.74187	16.95551	433	30/07/09	-	6173	4
K020	65.74628	16.85683	514	31/07/09	13/07/10	6150	4
K030	65.75034	16.82364	526	31/07/09	-	6096	4
K040	65.73993	16.77539	560	28/07/09	-	6224	8
K050	65.73723	16.73658	631	28/07/09	-	6109	8
K060	65.72869	16.80646	547	29/07/09	-	6013	8
K070	65.72904	16.77661	559	28/07/09	13/07/10	6029	8
K080	65.72184	16.73532	637	31/07/09	-	6064	8
K090	65.71597	16.80041	542	29/07/09	-	6012	8
K100	65.71067	16.71376	625	30/07/09	10/07/10	6026	4
K110	65.72048	16.69025	613	29/07/09	-	6142	8
K120	65.70619	16.82666	519	01/08/09	-	6110	8
K130*	65.70900	16.77941	544	05/12/09	12/07/10	6137	8
K140	65.70394	16.72746	622	31/07/09	10/07/10	6019	8
K160	65.69981	16.70053	556	29/07/09	-	6120	8
K170	65.68755	16.67146	530	31/07/09	-	6010	4
K200	65.69435	16.76543	474	29/07/09	-	6066	8
K210	65.68327	16.71050	500	29/07/09	10/07/10	6155	8
K220	65.67330	16.87279	461	30/07/09	13/07/10	6024	4
K230	65.65517	16.86379	387	30/07/09	-	6360	4
K240	65.63209	16.83853	356	30/07/09	12/07/10	6359	4
K250	65.65915	16.77652	378	30/07/09	-	6305	4
KNT (test site)	65.71628	16.74637	622	24/07/09	30/07/09	6125	8
* deployed in December 2009, since sensor was found to be faulty on arrival in the field post-shipment in July 2009.							
JULY 2010 NEW DEPLOYMENT SITES							
K006	65.78729	-16.98611	408	14/07/10	-	6150	4
K009	65.77358	-16.53669	356	15/07/10	-	6137	8
K071	65.72937	-16.77582	552	13/07/10	-	6029	8
K180	65.69549	-16.54101	421	15/07/10	-	6026	4
K190	65.69505	-17.01160	393	13/07/10	-	6359	4
K219	65.67458	-16.87433	463	13/07/10	-	6024	4
DRUM	65.60223	-16.83693	384	13/07/10	-	6155	8
HVAN	65.55409	-16.78980	349	13/07/10	-	6019	8

TABLE 1: *Deployment locations and dates for instruments in Loan 891 (8 Gb) and Cambridge-owned (4 Gb) instruments. The network was adjusted in July 2010 to enable different coverage of the Krafla caldera for the purposes of future tomographic work. Pull-out dates marked as '-' indicate that the instrument remained in situ after September 2010 (under Loan 914).*