European volcanological supersite in Iceland: a monitoring system and network for the future

Report

D6.1 - CGPS observations of glacier movements during jökulhlaups and high-precision mapping of icequakes

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Summary

In preparation for an outburst flood from the Vatnajökull ice-cap, Iceland, geodetic and seismic monitoring equipment were deployed for early warning purposes. This was achieved using a continuously recording GPS station, positioned above a subglacial lake that drained in September-October 2015. Continuous seismic measurements were also made on and around Vatnajökull with the goal of characterising seismicity due to subglacial flooding. Here we summarise observations of ice-surface subsidence and glacial seismicity that accompanied the drainage of floodwater. An accurate public warning was issued over 35 hours ahead of the flood reaching the first hydrological gauging station. The innovative methods described here could be applied to other volcanically active regions where the presence of glacial ice could lead to severe flooding.

Introduction

This report outlines the results of task 6.3 within work-package six, which focuses on the monitoring of glacier movement during tremor-generating subglacial floods. In glacial regions, outburst floods (jökulhlaups) can cause widespread damage, especially in connection with subglacial volcanic activity (Tilling, 1989; Björnsson, 2002; Roberts, 2005; Waythomas *et al.*, 2013). Geothermal fields beneath glacial ice are a source of reoccurring jökulhlaups (Björnsson, 2002). Beneath the Vatnajökull ice-cap, Iceland, two neighbouring geothermal fields give rise to two ice-surface depressions known as the Skaftárkatlar ice cauldrons (Björnsson, 2002; Johannesson *et al.*, 2007). These cauldrons are surface expressions of progressive melting and water storage at the glacier base. Concentric crevassing and a visible surface depression are signs of meltwater leakage, whereas a near-flat surface is indicative of water accumulation. By expanding geodetic and seismic monitoring to the north-west region of Vatnajökull, the FUTUREVOLC project has enabled near-real-time monitoring of the Skaftárkatlar region via continuous GPS and seismic observations. This report summarises the results of the monitoring campaign, focussing on geodetic measurements in the eastern Skaftá cauldron and ice seismicity that ensued when the cauldron drained in late September 2015.

Background

Meltwater began to seep from the eastern Skaftá cauldron on 27 September 2015, reaching the edge of Vatnajökull by the early hours of 1 October. By that time, flash-flood conditions had developed at the source of the Skaftá river, intensifying within 24 hours to a discharge of over 3,000 $m^3 s^{-1}$ (Icelandic Meteorological Office, unpublished information). Jökulhlaups from the eastern cauldron occur typically every two to three years, whereas the interval between the previous (June 2010) and the latest flood was over five years. The maximum discharge of the 2015 jökulhlaup was approximately twice the previous maximum for jökulhlaups in Skaftá. Consequently, the flood caused substantial damage to roads and infrastructure in the Skaftárhreppur district (Figure 1). The initial flood-front, which propagated in a subglacial manner from the eastern cauldron, burst through the ice-edge at several locations 1–2 km from the terminus. These outbreaks were marked by dark bands of debris deposited by floodwater flowing across the ice surface. Fragments of ice were scattered over the surface of the glacier, ranging in size from tens of centimetres to several metres. Masses of ice were also detached from the ice terminus as floodwater drained into Skaftá.

Methods

Subsidence of the ~300-m-thick ice-shelf was followed instrumentally via a continuously recording GPS unit, located near the centre of the eastern cauldron (Figures 2 and 3). A single-frequency receiver was installed in July 2013 to trial the monitoring technique.

Having solved various issues regarding power consumption, data storage and telemetry, a dual-frequency *Trimble* NetRS receiver was set-up in the cauldron in July 2014. Data were telemetered to IMO via the Internet, with the initial link made from the cauldron to a repeater station on Vatnajökull via radio modems. The incoming data-stream contained positional measurements at one-second intervals; it was processed in real-time using RTKLIB – an open-source program for GNSS positioning (RTKLIB, 2015), with the results visualised using the procedure described in FUTUREVOLC deliverable 6.4. The open-source R programming language (R Core Team, 2013) was used to provide an on-line plot of ice-surface elevation from the eastern cauldron; this information was made available from August 2015 onwards to civil protection staff and other stakeholders. In addition to the cauldron station, two other GPS platforms were deployed above the inferred subglacial path of floods from the Skaftárkatlar. These stations, positioned 3 and 15 km from the terminus (Figure 2) were set-up with the goal of constraining the travel-time of the jökulhlaup and the effect of floodwater propagation on glacier movement. For details about the design of the two lower GPS stations, see Einarsson *et al*. (2016).

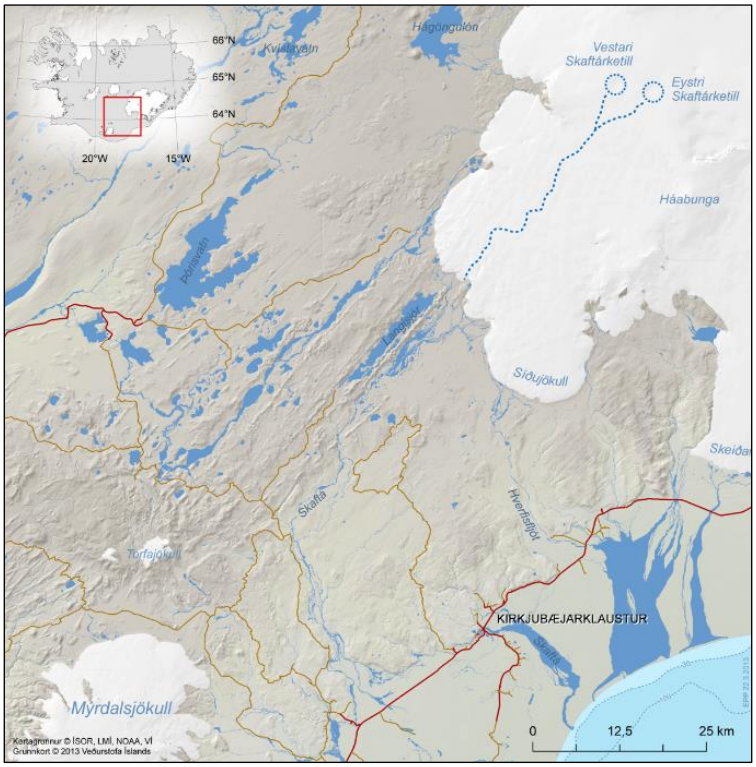

Figure 1: Map of southern Iceland, showing the location of the Skaftárkatlar ice cauldrons in western Vatnajökull. The dashed line denotes the inferred subglacial path of floods from the cauldrons. Note also the routing of the Skaftá river, which originates from western Vatnajökull. The map also depicts the road network in the region.

Seismicity in the Skaftárkatlar region was monitored using data from IMO's national seismic network, known as the SIL network, comprising 70 three-component seismometers. For details about the design and operation of the SIL network, see Böðvarsson *et al.* (1996) and Böðvarsson and Lund (2003). Following a major effort within FUTUREVOLC to expand monitoring capabilities beyond the edge of Vatnajökull, several SIL stations were established within a 30 km range of the eastern Skaftá cauldron; these broadband sites included: Dyngjujökull (djk), Hamarinn (ham) and Húsbóndi (hus), together with a pre-existing SIL station at Grímsfjall (grf). Of the three FUTUREVOLC stations, ham and hus were located on rock outcrops, whereas djk was buried in firn on the Dyngjujökull glacier, as described in deliverable 5.2. Despite the harsh glacial environment, these stations performed well during the summer of 2015; however, at the time of the jökulhlaup, there were technical faults at djk and hus,

rendering the stations off-line. Additionally, data from ham contained many gaps due to a telemetry problem. Another complicating issue was the level of seismicity at the ice-covered Bárðarbunga caldera, north of the Skaftárkatlar. Near-continuous seismicity from Bárðarbunga resulted in elevated background levels at all SIL stations in north-west Vatnajökull; this hindered the detection of ice seismicity associated with the 2015 jökulhlaup, resulting in only seven locatable events in Skaftárkatlar region.

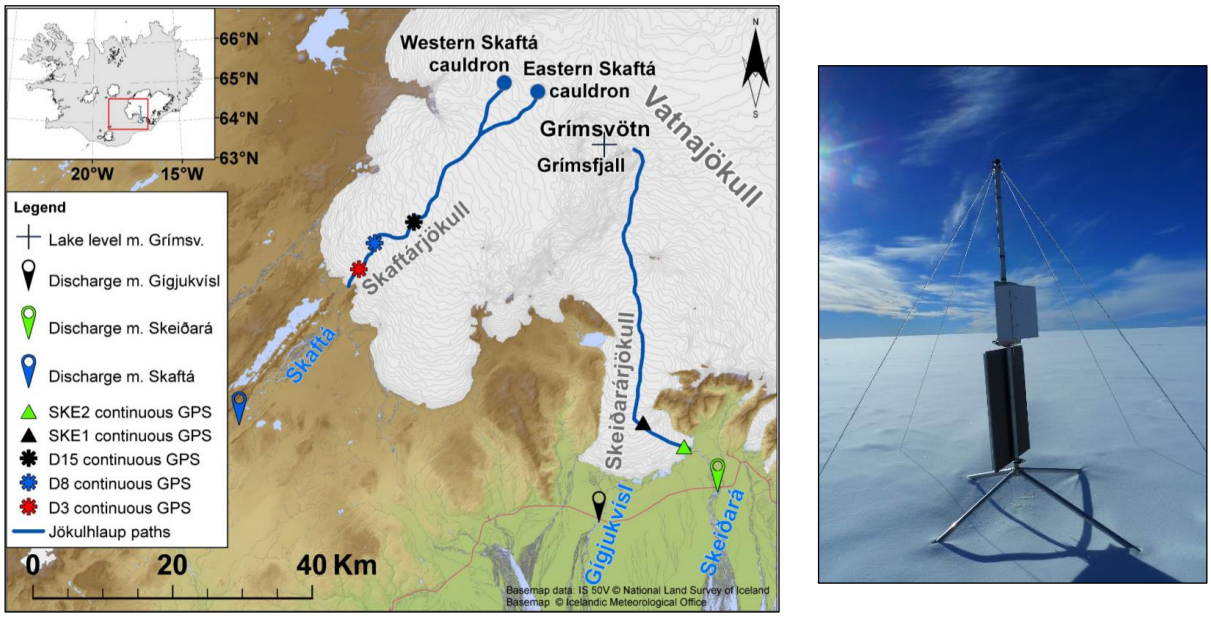

Figure 2: Left: Location of monitoring sites for jökulhlaups from western and southern Vatnajökull (Einarsson et al., 2016). In addition to the CGPS station in the eastern Skaftá cauldron, two CGPS sites were established on Skaftárjökull: stations D3 and D15, located 3 and 15 km from the ice terminus, respectively. Note the location of the Sveinstindur gauging station on Skaftá, approximately 25 km downstream from the ice terminus. Right: the CGPS station in the eastern cauldron. Photographer: Benedikt G. Ófeigsson.

Figure 3: Oblique aerial photograph of the eastern Skaftá cauldron, 26 October 2015. The cross denotes the location of the CGPS station. At the end of the jökulhlaup, over 80 m of subsidence had occurred at the station relative to the surrounding ice-surface. Photographer: Benedikt G. Ófeigsson.

Results and discussion

Figure 4 shows a three-day plot of cauldron elevation measurements, beginning late on 26 September 2015. The plot shows a conspicuous decrease in elevation from 29

September onwards. However, a more detailed assessment using hourly positional solutions, and plotted logarithmically, revealed a clear change from uplift to gradual subsidence as early as 27 September, as hinted in Figure 4. For about 24 hours, water seeped from the cauldron at a rate of just a few cubic metres per second. This could represent a period when outflow is counteracted by the effects of ice pressure. By ~10:00 UTC on 30 September the rate of ice-surface subsidence had increased abruptly, signifying the development of an unstable, rapidly widening breach at the base of the ice cauldron.

Between 18:00 and 19:00 UTC on 30 September signs of floodwater propagation beneath station D15 became apparent (Figure 5), as manifest by sudden uplift of the ice-surface. The pre-flood sliding rate of ice in the region of station D15 was ~0.3 m per day. As the front of the jökulhlaup passed beneath the station, the rate of ice sliding increased tenfold to 3.5 m per day. Ice-surface observations reveal that the front of the subglacial floodwater propagated as a hydraulic bulge, lifting the overlying ice to facilitate downstream movement. Hydraulic flotation of localised regions of ice allowed basal sliding rates to increase markedly, resulting in hydraulic jacking of ice; this explains the lasting uplift signal in Figure 5.

At the onset of the jökulhlaup, the subglacial travel-time between the cauldron and station D15 (Figure 2) gave a propagation velocity of ~0.6 m s^{-1} (2.2 km h^{-1}). Based on this estimate, floodwater is thought to have reached the edge of Skaftárjökull at some point between 01:00 and 02:00 UTC on 31 September. This assumption is reasonable because, by 05:00 UTC, the level of the Skaftá river began to increase rapidly at Sveinstindur (Figures 2 and 6). Just under 24 hours later, between 02:00 and 04:00 UTC the jökulhlaup reached a maximum discharge of over 3,000 m^3 s^{-1} at Sveinstindur (Figure 6).

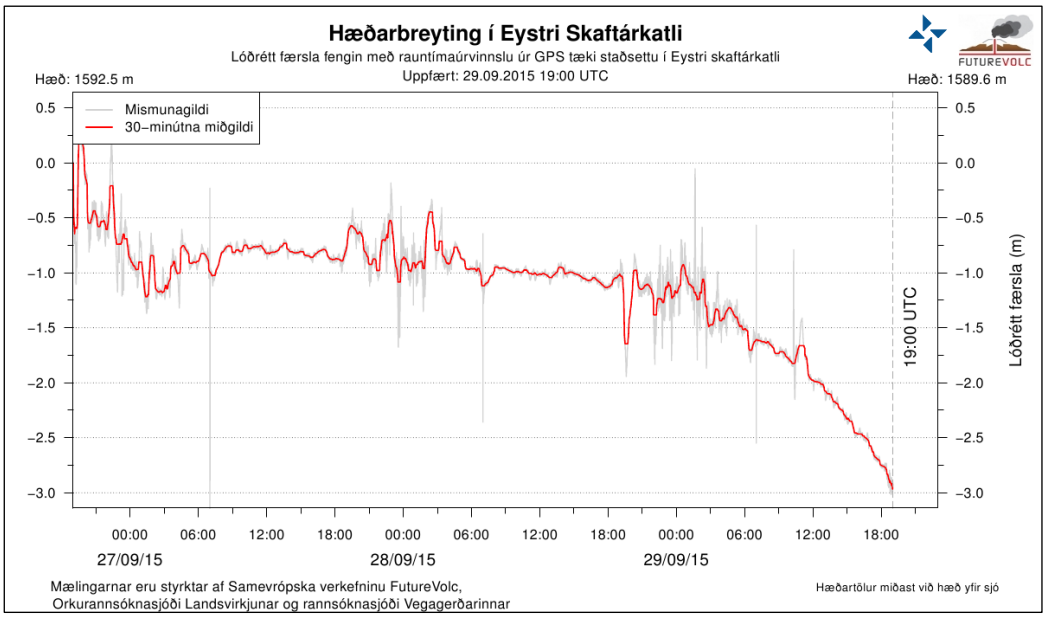

Figure 4: Screen-shot of the online GPS plot, which was made publically available in September 2015. The plot shows the vertical component (in metres) of differenced, 1-s measurements for the period in question. The red line denotes a 30-minute running median, applied to the data to eliminate signal distortions due to atmospheric variations and telemetry issues.

Remarkably, a continuous radio link was maintained with the cauldron station throughout the course of the jökulhlaup (Figure 7). When contact was lost at ~15:00 UTC on 3 October, the cumulative level of subsidence in the centre of the cauldron was 83 m. This value underestimates the actual level of subsidence as the CGPS station was positioned on an ice dome in the centre of the cauldron (Figure 3).

With real-time GPS processing and web-based visualisation in place ahead of the jökulhlaup, Figure 4 was used as the basis for an early warning to the National Commissioner of the Icelandic Police. This was followed by press releases to the public via radio and online news (Figure 8). The availability of real-time GPS results allowed an early warning to be issued 35 hours ahead of the jökulhlaup reaching Sveinstindur. This enabled landowners close to Skaftá to take proactive steps to mitigate the impact of the jökulhlaup.

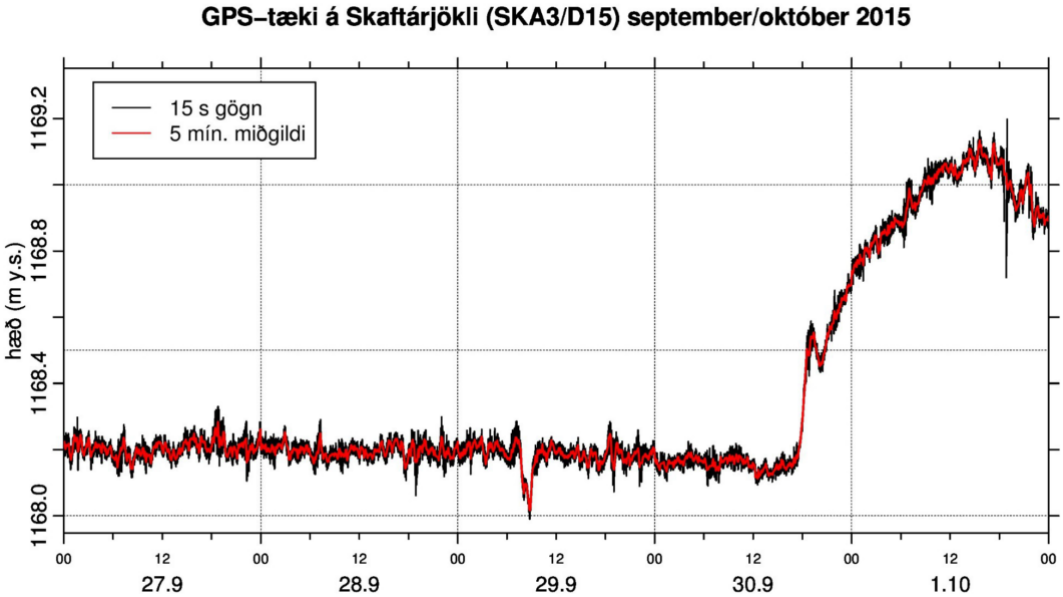

Figure 5: Vertical changes at station D15 on Skaftárjökull (Figure 2) in late September and early October 2015. The results are based on a five-minute median (red line) applied to 15-s data. Note the sudden increase in surface elevation from 18:00 to 20:00 UTC on 30 September; this signifies the subglacial passage of the jökulhlaup beneath the station. The continued increase in elevation is due to progressive accumulation of floodwater beneath the site.

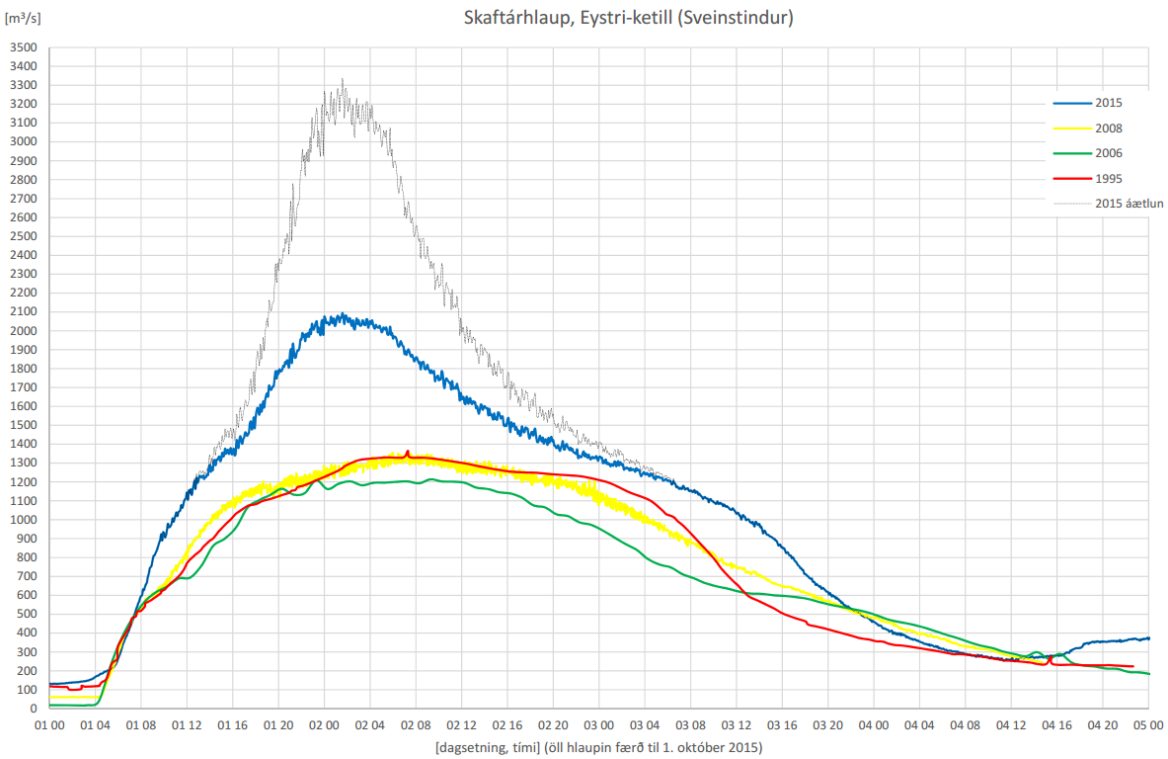

Figure 6: Hydrographs of jökulhlaups from the eastern Skaftá cauldron, as recorded at Sveinstindur (Figure 2) in 1995, 2006, 2008, and 2015 (Icelandic Meteorological Office, unpublished information). Note that 2015 jökulhlaup is depicted twice – the grey line takes into account floodwater flow around the gauging site whereas the blue line does not. Note that the estimated hydrographs are superimposed on the 2015 time-line, beginning at midnight on 01 October 2015. Discharge values are expressed in cubic metres per second.

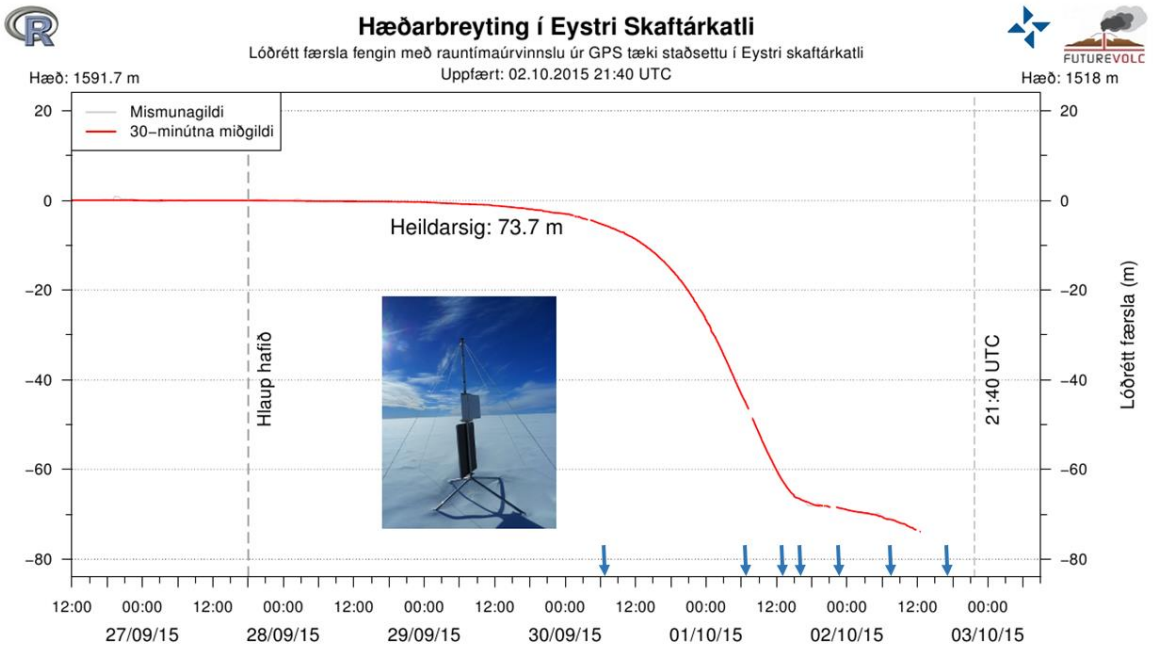

Figure 7: Screen-shot of the online GPS plot at 15:36 UTC on 01 October. After the cauldron had emptied, the eventual level of subsidence was over 80 m. The vertical arrows on the time-scale denote the origin times of suspected icequakes close to the cauldron (see Table 1).

Figure 8: The online availability of GPS measurements from the eastern Skaftá cauldron proved to be hugely popular with the public. Above is an English-language example from Iceland Monitor – a web-site for Icelandic news from www.mbl.is – published on 30 September 2015 before flooding began in Skaftá.

Table 1 summarises the suspected icequakes that were located in the vicinity of the eastern cauldron from 30 September to 02 October. The events listed in Table 1 were too small to be detected automatically by the SIL network. Following manual location, most events were detected at only three stations and the distance to the nearest station was around 10 km, suggesting magnitudes less than M1. Note that most seismicity occurs on 01 October, midway through the drainage of the cauldron (see Figure 7). The processes responsible for the seismicity are unclear, although increased hydrothermal activity in response to a decrease in hydrostatic pressure could be the cause. Equally, the seismicity could result from brittle fracturing of ice during the collapse of the ice shelf.

Origin time (Y-m-d H:M:S)	Latitude (decimal deg.)	Longitude (decimal deg.)
2015-09-30 06:53:43	64.441°	-17.571°
2015-10-01 06:41:52	64.456°	-17.425°
2015-10-01 12:58:46	64.530°	-17.476°
2015-10-01 16:35:55	64.431°	-17.732°
2015-10-01 22:42:59	64.297°	-17.467°
2015-10-02 07:44:15	64.469°	-17.635°
2015-10-02 17:18:14	64.476°	-17.453°

Table 1: Micro-seismicity located within a few kilometres of the eastern cauldron during the 2015 jökulhlaup (see also Figure 7). Focal depths ranged from the ice surface to approximately 1 km. Most events were detected at three SIL stations only, resulting in an epicentral accuracy of around 2 km.

Conclusions

Continuous geodetic monitoring of the eastern Skaftá cauldron yielded unprecedented measurements of ice-surface subsidence, revealing how subglacial floods initiate from hydrothermal zones. Floodwater leaked slowly from the cauldron over a three-day period before a rapid, unstable increase in flow developed. Real-time processing and visualisation of streaming GPS data permitted a public warning about the impending jökulhlaup over a day and a half ahead of the flood beginning in the Skaftá river. Geodetic observations from the lower part of Skaftárjökull show that the subglacial flood-wave was probably 1 m in thickness, mostly likely extending over a front a few kilometres wide. Subglacial water pressure in excess of ice overburden pressure was sustained for approximately one hour while the flood-front passed; this observation helps to shed light on the duration of floodwater outbursts on the glacier surface.

The state-of-the-art methods described here to observe ice-surface deformation could be applied to other flood-prone volcanic regions in Iceland and internationally. Such real-time monitoring systems make it possible to issue accurate warnings during an early phase of unrest, crucially before the onset of flooding hazards.

Acknowledgements

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References

Björnsson H. (2002). Subglacial lakes and jökulhlaups in Iceland. *Global and Planetary Change*, **35**, 255–271.

Böðvarsson R., S.T. Rögnvaldsson, S.S. Jakobsdóttir, R. Slunga & R. Stefánsson (1996). The SIL data acquisition and monitoring system. Seismological Research Letters, 67, 35–46.

Böðvarsson, R. & B. Lund (2003). The SIL seismological data acquisition system – As operated in Iceland and in Sweden. In: Takanami, T. and G. Kitagawa (eds) *Methods and Applications of Signal Processing in Seismic Network Operations*, Springer, Berlin, 131–148.

Einarsson, B., E. Magnússon, M.J. Roberts, F. Pálsson, T. Thorsteinsson & T. Jóhannesson (2016). A spectrum of jökulhlaup dynamics revealed by GPS measurements of glacier surface motion. *Annals of Glaciology*, **57**, in press.

Johannesson, T., T. Thorsteinsson, S. Andri, E.J. Gaidos & B. Einarsson (2007). Circulation and thermodynamics in a subglacial geothermal lake under the Western Skafta cauldron of the Vatnajokull ice cap, Iceland. *Geophysical Research Letters*, **34**, DOI: 10.1029/2007GL030686.

R Core Team (2013). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.

Roberts, M.J. (2005). Jökulhlaups: a reassessment of floodwater flow through glaciers. *Reviews of Geophysics*, **43**, 1–21.

RTKLIB (2015). RTKLIB: An open source program package for GNSS positioning. URL: http://www.rtklib.com/ (accessed: 2016-03-01).

Tilling, R.I. (1989). Volcanic hazards and their mitigation: progress and problems. *Reviews of Geophysics*, **27**, 237–269.

Waythomas, C.F., T.C. Pierson, J.J. Major & W.E. Scott (2013). Voluminous ice-rich and water rich lahars generated during the 2009 eruption of Redoubt Volcano, Alaska. *Journal of Volcanological and Geothermal Research*, **259**, 389–413.