Eos, Vol. 86, No. 26, 28 June 2005

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 86 NUMBER 26
28 JUNE 2005
PAGES 245–252

Forecasting and Monitoring a Subglacial Eruption in Iceland

PAGES 245, 248

The recognition of geophysical precursors to volcanic activity is a primary challenge in volcano monitoring. That challenge was successfully met by scientists at the Icelandic Meteorological Office (IMO) before the 1 November 2004 eruption of Grímsvötn, a subglacial volcano beneath the Vatnajökull ice cap, Iceland (Figure 1).

Seismic and geodetic precursors were properly recognized, leading to a timely eruption forecast and warning announcements. During the eruption, IMO's monitoring capability was greatly expanded by employing geophysical and meteorological observation tools, which enabled real-time hazard assessment.

Hazards arising from subglacial volcanism are due mainly to the explosive effects of magma-ice interaction, which generates a tephra-laden plume of steam that ascends rapidly into the upper atmosphere. There, it can pose a severe and widespread risk to aviation. The melted ice can also lead to catastrophic outburst floods, known by the Icelandic term "jökulhlaup." They are a severe hazard along affected rivers, with the potential to devastate populated areas.

Grímsvötn is one of the most active volcanoes in Iceland, with a ~62 km^2 caldera covered by 150- to 250-m-thick ice (Figure 1). Its highest peak, Grímsfjall, on the southern caldera rim, reaches an elevation of 1722 m.

Volcanic eruptions there, numbering several per century, are phreatomagmatic because of the ice cover, and they usually persist for days to weeks. Geothermal activity continuously melts the overlying ice, and meltwater accumulates in a subglacial lake within the caldera until the surrounding ice is breached. When that happens, water escapes to cause a jökulhlaup in the river Skeidará, after having traveled ~50 km beneath the Skeidarárjökull outlet glacier (Figure 1b). Jökulhlaups occur there every 1–10 years and last from days to weeks, each time releasing 0.4–4 km^3 of water [*Björnsson*, 2002]. Volcanic eruptions in Grímsvötn often coincide with jökulhlaups.

Monitoring Systems

To monitor seismic and volcanic activity in Iceland, IMO operates a nationwide digital network of 44 seismic stations (network name: SIL) [*Bödvarsson et al.*, 1999], six volumetric borehole strain meters, and 16 continuous GPS stations (network name: ISGPS) (H. Geirsson et al., Current plate movements across the Mid-Atlantic Ridge determined from 5 years of continuous GPS measurements in Iceland, submitted to *Journal of Geophysical*

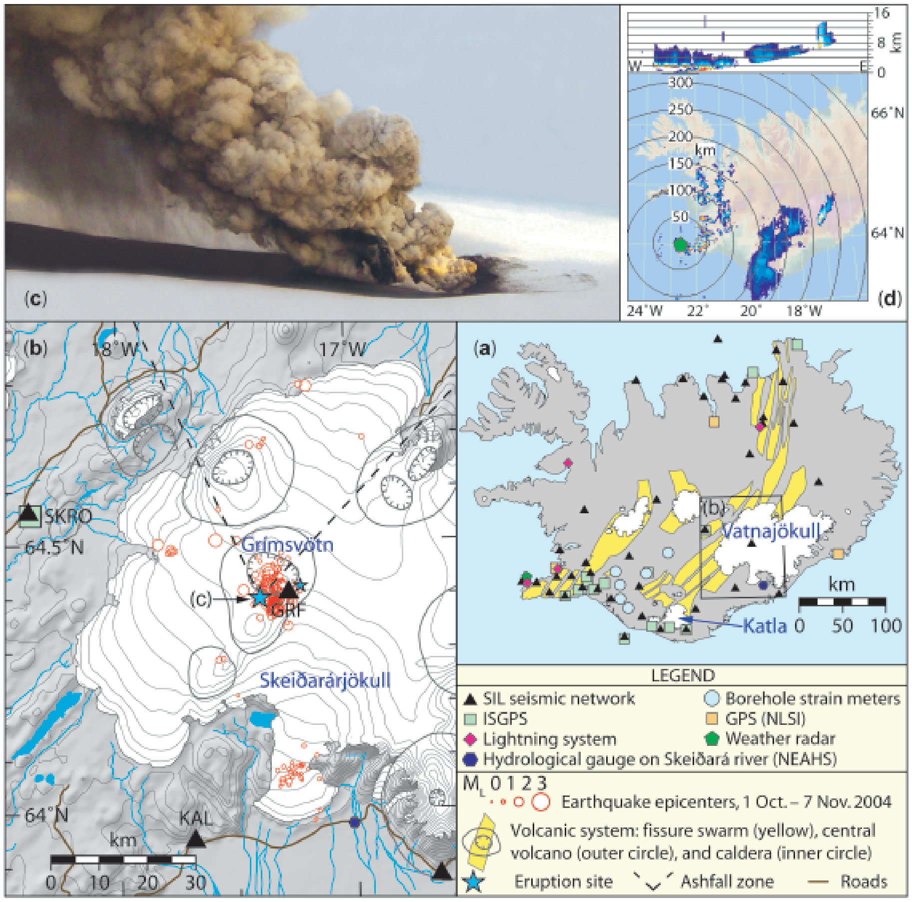

Fig. 1. (a) Map of Iceland illustrating the location of monitoring networks discussed in the text and the geographic extent of Figure 1b. Except where indicated, all networks are operated by IMO, which displays data in real-time at http://www.vedur.is/english/. (b) Map of the Vatnajökull ice cap, showing the 1 November 2004 eruption site and located earthquakes in the month preceding the eruption. Epicenters in Skeidarárjökull outlet glacier represent icequakes induced by the jökulhlaup. Dashed lines encompass the V-shaped zone of tephra deposition. (c) Oblique aerial view from west of the tephra plume at Grímsvötn on 2 November. Note the ashfall from the plume. (Photo by M. J. Roberts.) (d) Weather radar image at 0400 UTC on 2 November. The top portion shows its projection on an EW-vertical plane. The minimum detection height for Grímsvötn is seen at 6 km, and the plume extends up to ~13 km height.

By K. S. Vogfjörd, S. S. Jakobsdóttir, G. B. Gudmundsson, M. J. Roberts, K. Ágústsson, T. Arason, H. Geirsson, S. Karlsdóttir, S. Hjaltadóttir, U. Ólafsdóttir, B. Thorbjarnardóttir, T. Skaftadóttir, E. Sturkell, E. B. Jónasdóttir, G. Hafsteinsson, H. Sveinbjörnsson, R. Stefánsson, and T. V. Jónsson

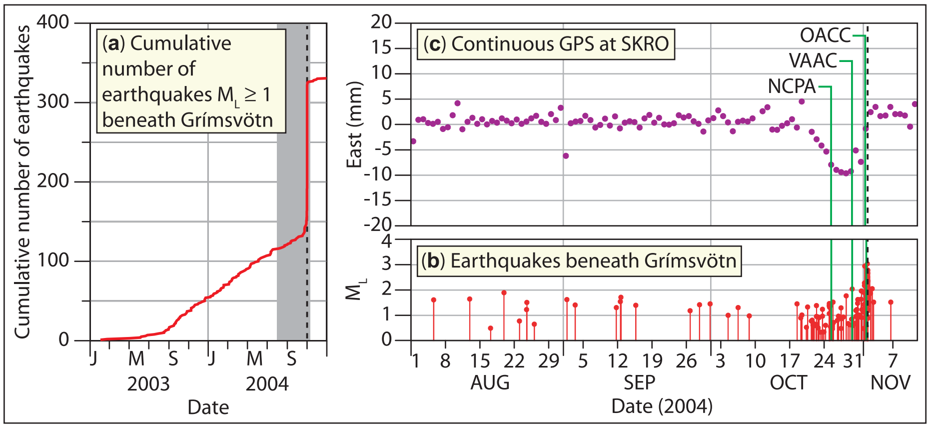

Fig. 2. Precursory signals: (a) Cumulative number of earthquakes located beneath Grímsvötn since 2002, showing the increase in activity in July 2003. (b) Local magnitude (M_L) of Grímsvötn earthquakes in the months preceding the eruption, showing the sudden increase in seismicity on 18 October. (c) East component of continuous GPS measurements from station SKRO (Figure 1b), showing the westward travel coinciding with increased seismic activity. Times of the first NCPA jökulhlaup warning and the first London VAAC and Icelandic OACC eruption warnings are indicated (see text for explanations). Dashed lines indicate onset of the eruption.

Research, 2005), which are complemented by three continuous GPS stations maintained by the National Land Survey of Iceland (NLSI) (Figure 1).

To monitor jökulhlaups, IMO has access to real-time data from water-level gauges and electrical conductivity meters operated by the National Energy Authority Hydrological Service (NEAHS) on rivers throughout the country. Lightning in volcanic plumes is monitored by IMO's four-station lightning location system, in addition to real-time access to locations determined by the United Kingdom's Met Office.

IMO's C-band weather-radar can be used to monitor and track tephra plumes [*Lacasse et al.*, 2004], and over 200 weather stations monitor weather conditions throughout the country. Plume-trajectory predictions are calculated for eruption sites by using current meteorological data.

Geophysical Precursors to the Eruption

In July 2003, seismicity at Grímsvötn increased to two earthquakes per week (Figure 2a). Furthermore, GPS campaign measurements of Grímsvötn's deflation since the last eruption in 1998 and its subsequent inflation showed that in September 2004, Grímsfjall had reached the previous eruption elevation [*Sturkell et al.*, 2005]. Coincidentally, the subglacial lake's surface elevation of 1423 m (F. Pálsson, personal communication, 2004) was the highest attained since the enormous jökulhlaup of November 1996. Under these conditions, drainage of the lake by a jökulhlaup could trigger an eruption.

Inferred signs of increasing geothermal activity in the caldera were recorded at SIL station GRF (Figure 1b) during August–October 2004, initially as occasional ~25-min-long bursts of seismic tremor (1–3 Hz), and later becoming periodic with energy between 2 and 8 Hz. After 18 October, seismicity increased to three events per day (Figure 2b). Synchronous with this increase, the ISGPS station SKRO (Figure 1b) moved 9 mm westward over the following eight days, and returned to its original position on 1 November (Figure 2c), suggesting subsurface magma movement under Vatnajökull. However, neither the strain meter network nor other GPS stations detected the signal (Figure 1a). The upsurge in seismicity prompted IMO to warn the National Civil Protection Agency (NCPA) on 25 October that a jökulhlaup, and possibly a volcanic eruption, were imminent. This initiated NCPA's lowest alert phase, the exploratory phase, which involves conferring with scientists and local authorities.

Signs of the advancing jökulhlaup under Skeidarárjökull came from station KAL (Figure 1b) in several 30- to 40-min-long episodes of harmonic tremor (~4.5 and ~6.5 Hz) on 28 October. When these signs reappeared the following morning, 29 October, IMO contacted NEAHS. Within hours, the electrical conductivity in the Skeidará river revealed an increasing presence of geothermal meltwater and water level started to rise, signifying the beginning of a jökulhlaup. Meanwhile GRF recorded increasing harmonic tremor (2.5–6 Hz), characteristic of a jökulhlaup.

That evening, because of the threat of an eruption following the drainage of Grímsvötn, IMO warned the Volcanic Ash Advisory Centre (VAAC) in London of a possible eruption within the next few days. On 30 October, the propagating jökulhlaup induced 21 icequakes in Skeidarárjökull (Figure 1b), and early on 1 November an earthquake swarm began at Grímsvötn, culminating in a local magnitude (M_L) ~3 event toward morning, followed by constant microseismicity. In response to the escalating activity, that afternoon IMO informed the Icelandic Aviation Oceanic Area Control Center (OACC) that a volcanic eruption seemed inevitable.

Multidisciplinary Monitoring of the Eruption

At 1930 UTC on 1 November, seismicity increased again. By 2000 UTC, earthquakes were continuously occurring and seismic tremor on nearby stations soared (Figure 3), suggesting the beginning of a volcanic eruption.

On this premise, IMO sent a warning at 2010 UTC to the NCPA and OACC that a subglacial eruption at or near Grímsvötn, was about to begin, or was already in progress. Immediately, NCPA upgraded to alert phase and OACC diverted all air traffic to >60 nautical miles (>111 km) distance from Grímsvötn. A volcano-SIGMET warning of a significant meteorological hazard to aviation was broadcast at 2026 UTC, specifying the likely location and probable height of the tephra plume. At 2056 UTC, after assessing the predicted trajectory of a plume from Grímsvötn, the London VAAC issued a warning to air traffic likely to be affected.

At ~2150 UTC, earthquake activity subsided, and a continuous, growing tremor at 0.5–1.5 Hz became distinguishable at GRF (Figure 3b), confirming that an eruption had started. Earthquake locations suggested it was close to Grímsfjall.

At 2250 UTC, the plume was detected by the weather radar at ~8 km height over Vatnajökull, reaching ~12 km four hours later (Figure 1c). Lightning over Grímsvötn, which accompanied the rising plume (Figure 3d), was eventually seen at ~0300 UTC, but darkness and weather conditions prevented visual observation of the eruption site until the following day.

Over the next two days, the strength of the eruption was reflected by the height of the volcanic plume determined by radar, as well as by lightning intensity and tremor amplitude (Figure 3). Ashfall was monitored at manned weather stations. The jökulhlaup peaked in the afternoon of 2 November.

On 3 November, the plume disappeared below the radar, the last lightning was detected, tremor amplitude diminished, and the water level in Skeidará waned. The last sign of a crater explosion was seen at GRF early on 6 November, leaving only a weak tremor signal from the remnants of the jökulhlaup. The jökulhlaup finally ended in early December, after ~0.8 km^3 of water had drained from the Grímsvötn lake (J. Hardardóttir, personal communication, 2005).

Location and Volume Constraints

Earthquake locations at Grímsvötn, improved by a double-difference location method [*Slunga et al.*, 1995], and supported by *P*-wave particle-motion analysis at GRF, reveal a northerly trending event distribution, centered at the southern caldera rim, ~1 km east of the main eruption site (Figure 1b). Focal depths mostly concentrate above 4 km and decrease by ~2 km near the eruption onset.

The detection threshold of the strain meter network for a volume source in the upper crust at Grímsvötn is 0.05–0.1 km^3. The absence of a strain signal, together with the seismicity constraints, suggest that <0.1 km^3 of erupted magma came from below 4 km depth under the southern caldera rim.

Summary and Outlook

IMO's multidisciplinary monitoring approach, employing seismic and geodetic methods, combined with access to hydrological data, enabled the identification of diagnostic precursors to the November 2004 jökulhlaup and

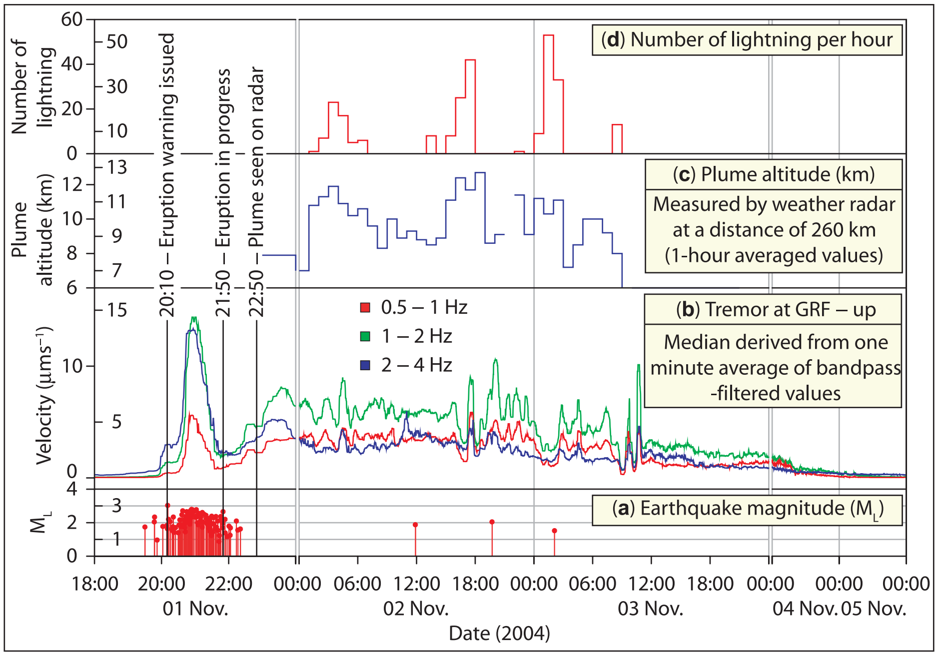

Fig. 3. Combined time series plot of seismic and meteorological observations made during the first five days of the 2004 Grímsvötn eruption. Note the varying timescale. (a) Local earthquake magnitudes. (b) Seismic tremor amplitude in three different frequency bands. (c) Volcanic plume height. (d) Number of lightning. Lightning and tremor amplitude roughly correlate with plume height.

eruption of Grímsvötn volcano. This allowed warnings to be issued up to three days before their onsets, priming NCPA and aviation authorities for immediate action upon receiving the 2010 UTC eruption warning on 1 November.

Lacking visual confirmation, seismic and meteorological observations provided verification of eruption onset and location. During the eruption, these systems monitored eruption energy, plume height and dispersion, and ashfall areas, thus facilitating real-time hazard assessment.

In light of Grímsvötn's remote location and the small erupted volume (<0.1 km^3) and jökulhlaup size (~0.8 km^3), the sensitivity and performance of the systems applied show great potential for monitoring future eruptions and jökulhlaups. Given the likelihood of an oncoming eruption at Katla, a subglacial volcano under the Mýrdalsjökull ice cap (Figure 1a) [*Sturkell et al.,* 2005], these systems may soon be put to the test again. Unlike Grímsvötn, though, Katla's proximity to populated areas poses a severe risk to human life and habitation.

Acknowledgments

This work was funded by the European Union project RETINA (EVG1-CT-2001-00046).

References

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

Bödvarsson, R., S. T. Rögnvaldsson, R. Slunga, and E. Kjartansson (1999), The SIL data acquisition system at present and beyond year 2000, *Phys. Earth Planet Inter., 113,* 89-101.

Lacasse, C., S. Karlsdóttir, G. Larsen, H. Soosalu, W. I. Rose, and G. J. Ernst (2004), Weather radar observations of the Hekla 2000 eruption cloud, Iceland, *Bull. Volcanol., 66,* 457-473.

Sturkell, E., P. Einarsson, F. Sigmundsson, H. Geirsson, H. Ólafsson, R. Pedersen, E. de Zeeuw-van Dalfsen, A. T. Linde, S. Sacks, and R. Stefánsson (2005), Volcano geodesy and magma dynamics in Iceland, *J. Volcanol. Geotherm. Res.,* in press.

Slunga, R., S. T. Rögnvaldsson, and R. Bödvarsson (1995), Absolute and relative locations of similar events with application to microearthquakes in southern Iceland, *Geophys. J. Int., 123,* 409-419.

Author Information

K. S. Vogfjörd, S. S. Jakobsdóttir, G. B. Gudmundsson, M. J. Roberts, K. Ágústsson, T. Arason, H. Geirsson, S. Karlsdóttir, S. Hjaltadóttir, U. Ólafsdóttir, B. Thorbjarnardóttir, T. Skaftadóttir, E. Sturkell, E. B. Jónasdóttir, G. Hafsteinsson, H. Sveinbjörnsson, R. Stefánsson, and T. V. Jónsson, Icelandic Meteorological Office, Reykjavík, Iceland

For additional information, contact K. S. Vogfjörd; E-mail: vogfjord@vedur.is.

MEETINGS

Advances in Large-Scale Crop Modeling

PAGES 245, 247

Intensified human activity and a growing population have changed the climate and the land biosphere. One of the most widely recognized human perturbations is the emission of carbon dioxide (CO_2) by fossil fuel burning and land-use change. As the terrestrial biosphere is an active player in the global carbon cycle, changes in land use feed back to the climate of the Earth through regulation of the content of atmospheric CO_2, the most important greenhouse gas, and changing albedo (e.g., energy partitioning).

Recently, the climate modeling community has started to develop more complex Earth-system models that include marine and terrestrial biogeochemical processes in addition to the representation of atmospheric and oceanic circulation. However, most terrestrial biosphere models simulate only natural, or so-called potential, vegetation and do not account for managed ecosystems such as croplands and pastures, which make up nearly one-third of the Earth's land surface.

On the other hand, over the past 30 years numerous models of crop growth have been developed, and these have proved to be extremely useful tools for scientists and managers of agricultural systems. These detailed models, though, are typically application-orientated and therefore usually are applied specifically to particular crops and locations. These models were not originally designed for large-scale studies and do not include complete nutrient or carbon cycles. Though, the models can provide useful information for large-scale crop modeling, which then has to be adapted for use in terrestrial biosphere models.

A workshop held at the Rothamsted Research Centre, Harpenden, U.K., dealt with the advancing science of including large-scale, generic crop modeling schemes in global terrestrial biosphere models. About 20 scientists from the crop modeling and global biosphere modeling community attended. The workshop was one in a series of workshops sponsored by Quantifying and Understanding the Earth System (QUEST), a program of the U.K. Natural Environment Research Council (NERC). QUEST has several activities, among them the focused strategic activity on Earth system modeling and two research themes: (1) the contemporary carbon cycle and its interactions with climate and atmospheric chemistry, and (2) the implications of global environmental changes for the sustainable use of resources.

Setting the Scene

The modeling of crop productivity and yields on a global scale requires information