FIRE AND FURY IN ICELAND: TRACKING VOLCANIC ERUPTIONS

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Volcanic eruptions in Iceland have fascinated writers for centuries. In 1783 Benjamin Franklin correctly identified the cause of the terrible weather that summer in Europe as caused by an eruption in Iceland, which turned out to be the biggest ever historic eruption. In 1864 Jules Verne based his 'Journey to the Centre of the Earth' on a presumed volcanic conduit beneath the Icelandic volcano Hekla. In 2014 we were fortunate to capture the largest eruption in Iceland since 1783, this time with modern instrumentation. We were able to track the molten rock as it travelled underground for 50 km at a depth of about 6 km before erupting in central Iceland, using the 50,000 tiny earthquakes it generated as it cracked its way forwards. This was one of the first times in the world that molten rock has been captured with such detail in the act of propagating underground.

On the morning of 20th July 1783, the inhabitants of the village of Kirkjubæjarklauster and the surrounding farmsteads in south-eastern Iceland were gathered for a Sunday morning service led by their pastor, Rev. Jón Steingrímsson. They had little to be cheerful about; molten rock from the Lakagígar craters had been pouring out of the ground for over a month, and the lava had flowed steadily down the river valleys toward the coastal plain. On some days, the lava had advanced more than l5 km, and still it kept coming. Now it was only a few kilometres from the town and had engulfed another outlying farm.

Jón Steingrímsson preached an impassioned sermon, later to become known as the 'Fire Sermon'; he could hardly have had better visual aids as smoke and fire shot into the air from the volcanic eruption. Yet as the villagers prepared to abandon their homes to the advancing lava, it gradually dawned on them that the lava flow approaching their village had stopped just a kilometre away. That is as close as it ever came. Though the eruptions continued sporadically for another six months, the lava flowed past the town along its own channels, eventually disgorging into the sea.

Despite the relief at escaping burial by the lava, worse was yet to come. Noxious fumes from the eruption had already weakened or killed large numbers of livestock. The winter of 1783-84 was harsh, and next spring little grass grew. And then the real hardship started. An estimated 75% of the horses, 50% of the cattle and 80% of the sheep perished. Even the hauls from fishing declined dramatically. During the following two years one-quarter of the population died of starvation.

Jón Steingrímsson left a fascinating manuscript account of the eruption, and of his life in that harsh environment: it is now available in a 2002 translation. He wrote 'From the 12th of August, 1783, until the 24th of June of the following year my household had absolutely no dairy food. It was thanks only to the supreme power of God that I and mine managed to stay alive. The air was so thickly contaminated that I never ventured to breathe in fully and hardly went outside when there was no sun, all that year and the next.' Then it got worse. 'As Christmas [1783] approached and the winter wore on, people began to die of disease and hunger. That year seventy-six people died in my parish of hunger and other effects of the eruption such as dysentery… For six continuous weeks during the latter three months of winter [*i.e.*, end of January to end of April 1784] I did not take my clothes off and hardly stopped day or night, administering the sacrament to those who were dying and those who lived on but could not get to church… Finally there remained in the parish just ninety-three people.'

The eruption not only was the cause of huge fatalities in Iceland, but the gases spread across north-western Europe, killing many people with respiratory problems in Scotland and reaching Paris, where Benjamin Franklin was US Ambassador. In 1784 Franklin wrote an article in only the second volume of the *Memoirs of the Literary and Philosophical Society of Manchester* where he reported 'During several of the summer months of the year 1783, when the effects of the sun's rays to heat the earth in these northern regions should have been greatest, there existed a constant fog over all Europe'. He correctly identified the origin of the gases causing the unseasonable weather as Iceland, though he was uncertain whether it was due to a volcanic eruption or a meteorite impact.

A similar occurrence happened in May 2010 when the eruption of the sub-glacial volcano Eyjafjallajökull in Iceland sent ash spewing 6,000–9,000 metres into the air. Atmospheric conditions caused it to drift across north-western Europe as far as Italy. Although it was a tiny eruption compared to 1783, the fine-grained ash grounded over 100,000 flights. This time, though, the weather over London and Paris was much better. There was high pressure, the sun shone and the absence of airplane flights actually left the air less polluted. Many people near Heathrow enjoyed barbecues in their gardens with quiet, sunny days.

The large Icelandic eruption in 2014 at Holuhraun in central Iceland that we were fortunate to capture on our seismic instrumentation caused no such problem, despite it being 50 times bigger than the 2010 eruption, and lasting six months. It was the largest since 1783 in this volcanically continually active island. It erupted 1,500 million cubic metres of lava: that would be enough to bury the entire City of Leicester beneath 20 metres (70 feet) of volcanic rock. However, this time there was no giant ash plume, and the eruption location was far from any human dwellings. The difference in the eruption style was that the lava flowed out of fissures in the barren landscape. There was local fire fountaining, with molten rock at about 1100°C ejected typically 100 metres into the air from the craters, but no huge plumes of ash were generated. The difference was because the Eyjafjallajökull eruption occurred beneath a 200 metre thick ice cap. As the molten rock hit the base of the glacier it first melted the ice. Then subsequent lava that was erupted into the molten water chilled rapidly to form fragments of glass, which then fractured violently before being expelled upwards as the water was vaporised and the steam pressure built up.

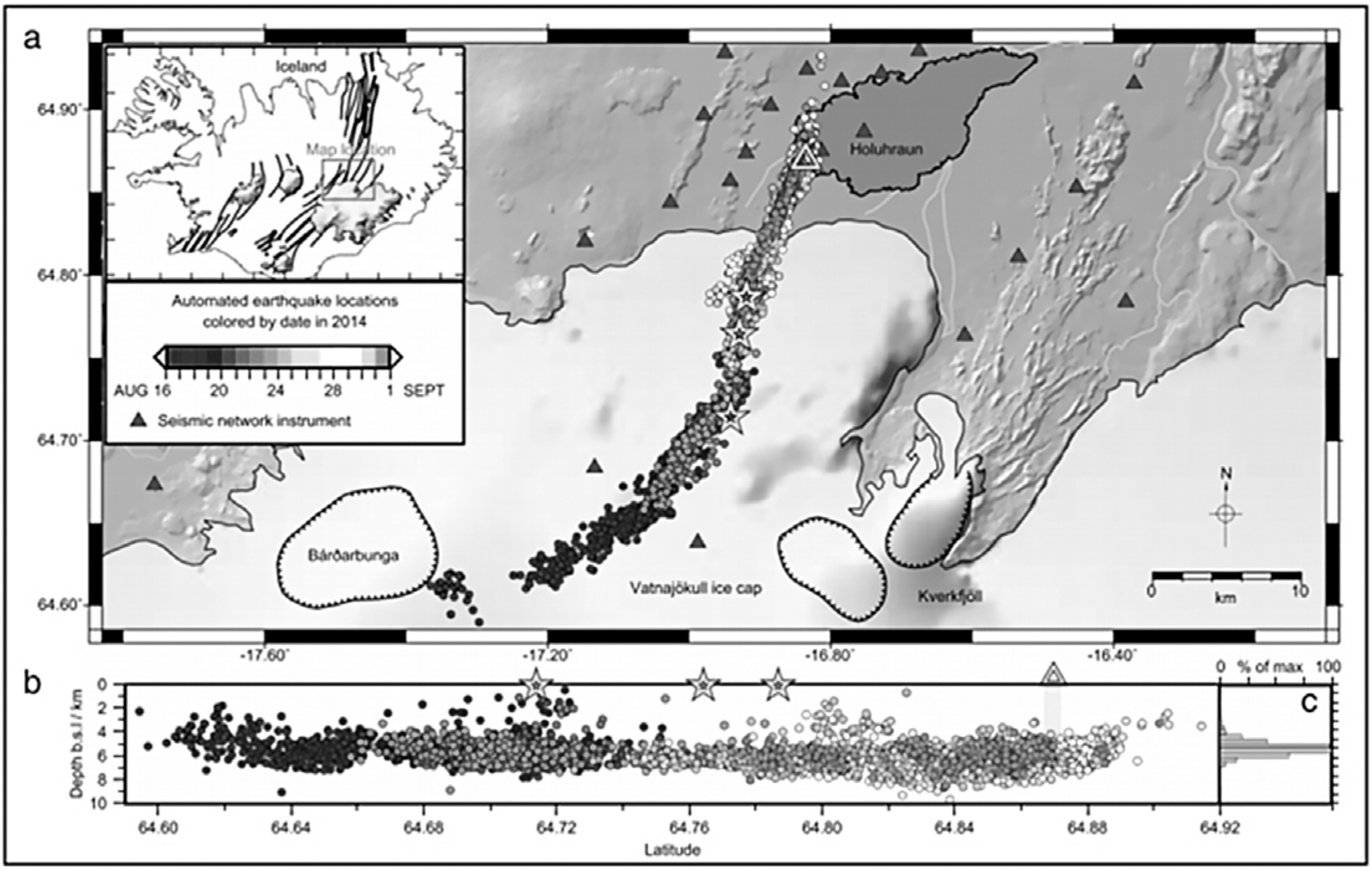
The Holuhraun eruption might have formed a similarly violent ash cloud if the lava had erupted from the parent volcano called Bárdarbunga, which lay under the 800 metre thick Vatnajökull ice cap in central Iceland. But instead, for reasons still not fully understood, the molten rock pushed its way underground some 48 kilometres (30 miles) laterally before erupting benignly just outside the edge of the ice cap at Holuhraun (see map). That would be equivalent to the volcanic source being in the centre of Coventry, with the molten rock forcing its way at a depth of about 6,000 metres (10,000 feet) beneath the surface before erupting in the centre of Leicester. We can calculate the diameter of the underground tube that the molten rock flowed along as about 10 metres (30 feet) from the eruption rate and viscosity of the lava. The energy released by the eruption was enormous: it was equivalent to the energy of a Hiroshima-sized atomic bomb being detonated every two minutes for hour after hour, day after day, month after month.

Although little ash was produced by the 2014 Holuhraun eruption, there was a huge volume of dangerous gases expelled along with the lava. The worst was sulphur dioxide, which at its peak exceeded 35,000 tonnes per day. It was carried away by the wind, and led to daily health warnings in towns around Iceland dependent on the wind direction. Even as far away as Ireland, environmental pollution limits were exceeded several times. Overall, this eruption produced more sulphur dioxide than the whole of the European Union generated from industrial processes, cars, lorries and ships over an entire year.

Fortunately, we already had a network of 60 seismometers recording in the region of the eruption, although they were originally deployed for a different reason, to study an adjacent volcano. A small team of PhD students from Cambridge was already in Iceland working on this other experiment as the eruption started. One of them, who was Icelandic, realised immediately what was happening and was able to hitch a ride on a helicopter and deploy several more seismometers on the otherwise inaccessible Vatnajökull ice cap, right above where the seismic activity was occurring. Another half dozen seismometers were deployed at the edge of the ice cap in the exact location where the eruption eventually happened, some two weeks after the molten rock first left the volcano. The last one was deployed just a few hours before the surface eruption started from a fissure in the ground: in fact the students were the first people to see it, late that night. A short video on YouTube (**https://youtu.be/BL5U28Icl2k**) shows the excitement both of working in this remote and harsh but beautiful environment, and of being able to track the progress of the lava before it erupted, even though it was 6,000 metres underground.

Small volumes of melt penetrated upwards to the base of the ice cap from the lava as it propagated underground. It then melted some of the ice locally, causing depressions on the surface of the glacier (shown as stars in the cross-section below the map). But none of these developed into a full-scale eruption site. That only happened when the molten rock was beneath a low point in the topography, just outside the edge of the ice cap (at location shown as open triangle on the cross-section). In fact, the very first lava erupted through old nineteenth century craters in the same spot. It seems probable that the path the underground lava flow took and its eventual eruption followed the same path as that previous eruption.

The detailed seismic data we recorded enabled us to determine the precise way in which the advancing molten rock cracked open a pathway for itself deep underground. It used pre-existing lines of weakness in the rock, occasionally getting held up for a day or more at places where the rock was stronger, until sufficient pressure had built up to allow it to force its way forward: in other places it diverted sideways a few hundred metres to bypass areas that were resistant to cracking, before finding a weaker path



Open dots show earthquakes produced as the molten rock forced its way forward during two weeks in August 2014. (a) map view: Bárdarbunga is the volcano from which the lava came, Holuhraun the lava flow, white area is Vatnajökull glacier and small triangles show some of the seismometers. (b) cross-section of earthquakes: stars show areas where the depressions formed above small injections of melt under the ice cap; open triangle shows eruption site where melt finally reached the surface.

forwards. Our improved understanding of the way lava can flow such large distances underground will be invaluable in hazard assessments not just of this particular volcano, but of other volcanoes worldwide. After all, if England were a volcanically active country, it would be rather scary to think that a volcano as far away as Coventry could send molten rock underground all the way to Leicester before erupting under the New Walk Museum. In fact this is almost exactly what happened in Hawaii in May 2018 when the volcano Kilauea sent lava underground 40 km to the Leilani Estates subdivision, where it opened fissures in the streets and erupted, destroying 900 houses and forcing 2,000 people to flee. So it is likely to happen again, somewhere.

Further Reading

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