

The Bárðarbunga-Nornahraun eruption, Iceland – an ongoing demonstration of rifting and volcanism

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The basaltic lava emission from a fissure system connected to the the Bárðarbunga central volcano under Vatnajökull is now the largest eruption in Iceland in the past 230 years. Although the central volcano is located in the Eastern Rift Zone, the erupting fissure system protrudes into the fissure swarm of the Askja central volcano in the Northern Rift Zone. The extensive arrays of seismometers and continuously recording GPS-stations have provided real-time seismic and geodetic data, illustrating the subsidence of the central volcano and associated dike injection. Additional observations and measurements on the ground and during frequent overflights with the Icelandic Coast Guard aircraft have yielded unique and complementary insights into these processes.

Notes

The developing lava field is commonly referred to as Holuhraun, which is also the name of a lava flow from 1797. In this article, I adopt the term Nornahraun, as suggested by Þorvaldur Þórðarson: http://earthice.hi.is/names_new_lava_flow_field_north_dyngjokull

The account of the tectonic and volcanic events are mainly based on the continuously updated information on: <http://en.vedur.is/> and <http://en.vedur.is/earthquakes-and-volcanism/articles/nr/2947>

The article is also available at:

<http://forskning.no/blogg/reidar-tronnes/bardarbunga-nornahraun-eruption-ongoing-demonstration-rifting-and-volcanism> and <http://sciencenordic.com/content/b%C3%A1r%C3%B0arbunga-nornahraun-eruption-ongoing-demonstration-rifting-and-volcanism>



Front page

Eruption activity, Sept. 4. Fire fountains and exposed lava streams during early eruptive stages. Photograph: Peter Hartree.

Rift zones and volcanic systems in Iceland

The volcanic rift and flank zones in Iceland have separate volcanic systems, comprising central volcanoes and fissure swarms (Fig. 1). Many of the evolved central volcanoes have calderas and some of these erupt intermediate and silica-rich magmas, including rhyolites with about 70 weight% SiO₂, in addition to basalts. A caldera is a sub-circular depression, normally 2-10 km in diameter, formed by magma chamber pressure loss and collapse resulting from a volcanic eruption or from injection of melt into dikes away from the caldera region. The term dike is used to describe an open fissure (often 1-10 m wide) filled with melt.

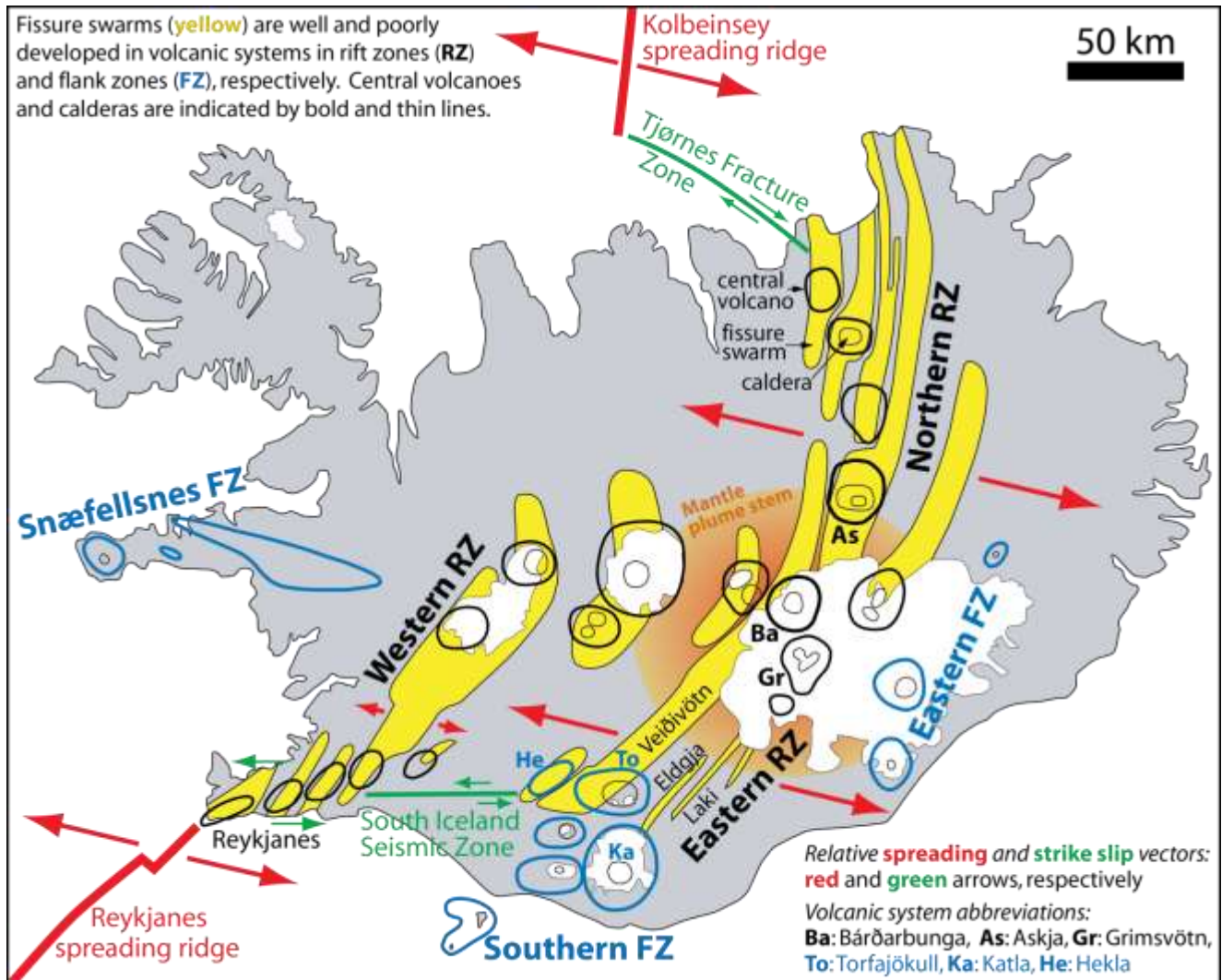


Fig. 1. Volcanic systems, rift zones and relative plate motions in Iceland. Note that the Bárðarbunga central volcano is located close to the vertical axis of the Iceland plume stem. The volcanic system information is based mainly on Jóhannesson and Sæmundsson (1998) and Þórðarson and Höskuldsson (2008).

Long distance sub-surface transport of magma in dikes is a common feature associated with fissure eruptions in the rift zones. The previous three largest eruptions in Bárðarbunga involved basaltic magma transport about 100 km southwestwards from the central volcano along dikes in the Veidivötn fissure swarm (Fig. 1), leading to fissure eruptions on the way. Some of the magma, however, was ultimately injected into silica-rich magma chambers under the Torfajökull central volcano (Fig. 1), causing explosive mixed magma eruptions. Each of these three events, the Veidivötn, Vatnaöldur and Dómadalshraun eruptions in 1477, 871 and about 150 AD, respectively, produced about 1 km³ dense rock equivalent (DRE) of combined basaltic, intermediate and rhyolitic lava and tephra (Larsen, 1984). The 721 (approximately) and 606 year intervals between these eruptions are slightly longer than the 531 year period between the 1477 and 2014 events involving magma from Bárðarbunga.

Several other volcanic systems in the Icelandic rift zones are also characterized by interaction between silica-rich (rhyolitic) magma in shallow chambers under the central volcanoes and deeper basaltic reservoirs and dikes with basaltic melt. The puncturing of rhyolitic magma chambers by dike injection and the mixing of hot basaltic melt (1150-1200 °C) with cooler rhyolite (800 °C) can cause vigorous convection and gas (steam) bubble formation. The relatively viscous rhyolite melt may then be transformed explosively to low-density foam, fragmented and erupted as silicic ash and pumice. This process is analogous to the violent exsolution (release) of CO₂-gas from shaken and depressurized champagne or beer.

Status and volume of the eruption (Nov. 6, 2014)

The vigorous and steady extrusion of basalt from a 2 km long crater row 45 km NE of the Bárðarbunga central volcano now seems to be the largest Icelandic eruption in the last 230 years. Starting in the early morning of Sunday, August 31, it has lasted more than two months. Fig. 2 shows the eruptive activity on Sept. 4, at an early stage before much of the magma was channelized through shallow, but covered, lava tubes.



Fig. 2. Eruption activity, Sept. 4. The pictures show fire fountains and exposed lava streams during early eruptive stages. Later, more of the lava flow activity has occurred in lava tubes, transferring lava over longer distances with less heat loss. Photographs: Peter Hartree.

The area of the current lava field exceeds 65 km². Initially, the lava flowed about 17.5 km towards ENE, parallel to the river Jökulsá á Fjöllum. It then stopped near the foothills of the interglacial Vaðalda shield volcano and spread towards NW and SE after Sept. 12 (Fig. 3-4). A small satellite lava field (0.4 km²) was also produced from a 1 km long eruption fissure about 2 km SSW of the constantly erupting fissure (crater row) during a three-day period, Sept. 5-7.

The volume estimates are uncertain due to the difficult observing conditions in the most remote and climatically hostile area in Iceland. Field work is also hindered by highly variable winds and unpredictable concentrations of toxic volcanic gases. Based on the unwavering observation efforts by scientists at the Icelandic Meteorological Office (Veðurstofa Íslands) and Institute of Earth Sciences, University of Iceland (Jarðvísindastofnun, Háskólans), however, it seems that the eruption has a daily magma output of about 0.02 km³.

The resulting accumulated volume of 1.4 km³ (Nov. 8) has exceeded the total outputs of the Krafla fires, 1975-84 (0.25 km³), the Myvatn fires, 1727-29 (0.25 km³) and the eruptions from Hekla-1970 (0.5 km³), Hekla-1947-48 (0.88 km³), Surtsey-1963-67 (0.73 km³), Katla-1918 (1.0 km³) and Askja-Sveinagjá-1875 (0.5 km³). The largest historic eruptions, including Laki (1783-84, 15.1 km³), Eldgjá (934-940, 19.6 km³) and Hallmundarhraun (about 950, 8.5 km³) are still about an order of magnitude larger. However, if the Nornahraun eruption continues at the current rate, the volume may surpass that of the Hekla-1766 (1.5 km³) and the Örafajökull-1362 (2 km³) eruptions by November 13 and December 9, respectively. By then the Nornahraun eruption would be the fourth largest Icelandic eruption in historic times (after 871 AD). [The volumes above, compiled from Sinton et al. (2005), Þórðarson and Larsen (2008), Þórðarson and Höskuldsson (2008) and references therein, are combined lava and dense rock equivalents of tephra.]

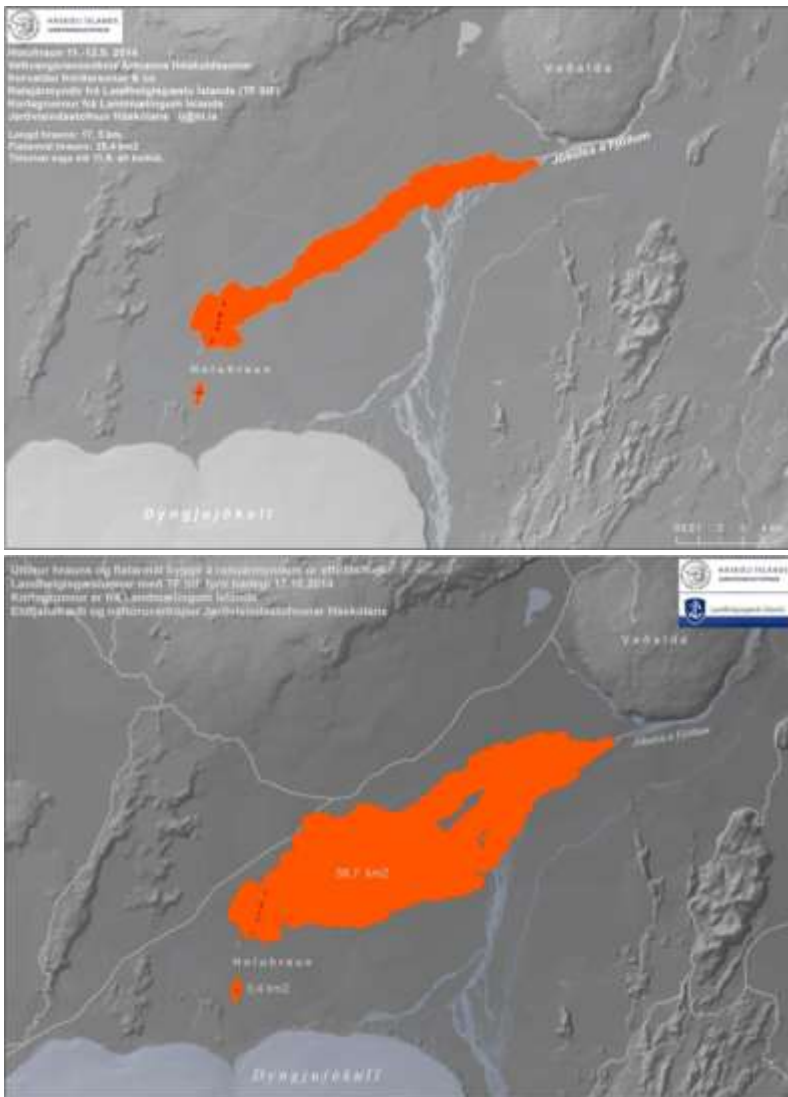


Fig 3. Lava field extent at Sept. 12 (24.5 km²) and Oct. 17 (58.7 km²). Maps produced by Institute of Earth Sciences, University of Iceland (Jarðvísindastofnun, Háskóla Íslands).



Fig 4. Lava field extent at Oct. 22 (63 km²) from thermal imaging, using Landsat 8. Institute of Earth Sciences, University of Iceland (Jarðvísindastofnun, Háskóla Íslands).

Dike injection and rifting

The 2014 volcanic unrest with rifting, dike injection and fissure eruption has been monitored by dense networks of seismometers and continuously recording GPS-stations. The surveillance has given unprecedented insights into the fracturing and melt injection processes and the interaction between a central volcano and fissure swarms in the Icelandic rift zones (Fig. 5).

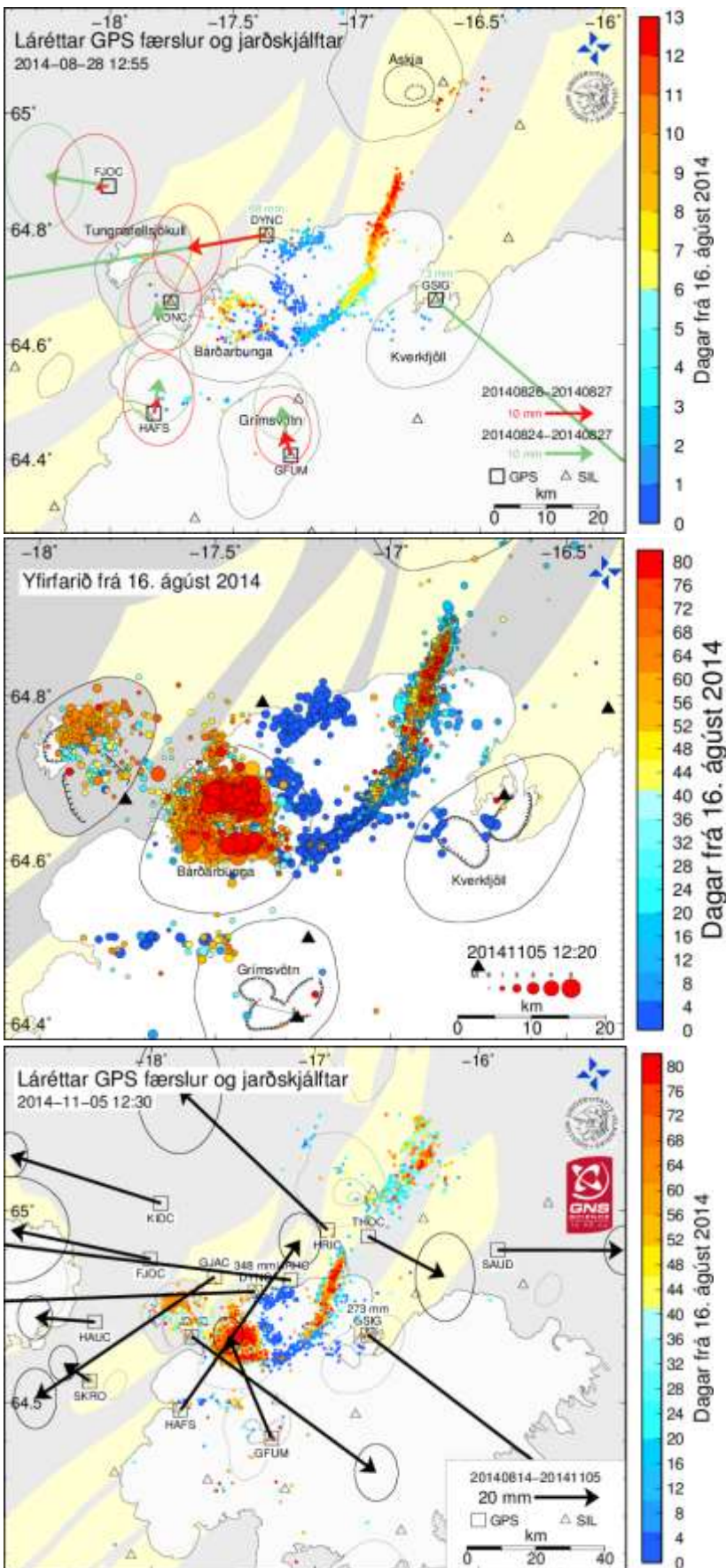


Fig. 5. Seismicity and crustal movements. See also the day-to-day evolution at <http://en.vedur.is/earthquakes-and-volcanism/articles/nr/2949>. The maps were produced by the Icelandic Meteorological Office (Veðurstofa Íslands).

Upper panel: Period Aug. 16 (dark blue) to Aug. 28 (dark red). Earthquake epicenters (coloured dots) and horizontal displacement of continuous GPS stations (red arrows: 24 hr movement Aug. 26-27, green arrows: 72 hr movement, Aug. 24-27).

Middle panel: Manually processed earthquakes in the period Aug. 16 (day 1, dark blue) to Nov. 5 (day 80, dark red).

Lower panel: Earthquakes, Aug. 16 (day 1) to Nov. 5 (day 80) and accumulated horizontal crustal movements (Aug. 14 – Nov. 5). Note that the stations close to the central volcano has converged on the caldera area. The stations east of the NNE-trending dike segment have moved towards ESE-SE, reflecting the dike formation and rifting. HRIC (NW of the dike) has moved in the opposite direction (WNW-NW). Most of the stations SW of HRIC, however, have moved towards W, rather than WNW. This may reflect a southerly vector component towards the contracting central volcano.

The day-to-day evolution of seismicity and horizontal crustal movements is compiled at: <http://en.vedur.is/earthquakes-and-volcanism/articles/nr/2949> (including an animated evolution map at <http://hraun.vedur.is/ja/Bardarb/GPS/Slider/images.html#>). The rifting and volcanic unrest started on August 16, with intense seismic activity within the Bárðarbunga caldera and along an 8 km long SE-trending radial dike from the SE side of the caldera rim (Fig. 5). There was also strong seismic activity along the E and NE margin of the central volcano the same day. During the next few days (Aug. 17-19) the earthquake swarms defined a dike segment propagating 22 km towards NE (N45°E) from the SE tip of the radial dike. In the Aug 23-28 period, the dike propagation changed direction about 20° to a NNE-direction (N15°E). The magma moved another 20 km in the NNE direction before a minor, four hour long, fissure eruption occurred near the dike tip in the early hours of Friday, Aug. 29.

The intrusion of the radial dike towards SE on Aug. 16 was accompanied by displacement southwards for stations HAFS and GFUM, northwards for DYNC and eastwards for the stations west of the caldera (not visible in the 13 day accumulated motion on Fig. 5, upper panel, but on the Aug. 16 map at <http://hraun.vedur.is/ja/Bardarb/GPS/Slider/images.html#>). The further dike propagation towards NE and NNE involved spreading between the continuously measuring GPS-stations DYNC and GSIG of 4-6 cm/day (50-70 cm in the 12 day period, see the daily maps of seismicity and horizontal crustal movements). DYNC and GSIG are about 20 km west and 15 km east of the dike, respectively. The stations FJOC, KIDC and HAUC 30-40 km west of DYNC show only minor westward movement, demonstrating crustal compression between the dike and FJOC. The dike itself, and therefore the local rifting, is likely to be about one order of magnitude larger than the separation measured at distances of 15-20 km.

South of the Bárðarbunga central volcano, the stations HAFS and GFUM were (and are still) moving northwards, in response to the decrease in magma pressure under the caldera and inward movement of the surrounding area (Fig 5, lower panel). Because the Icelandic plate-spreading direction is approximately WNW-ESE, the southerly components affecting DYNC and GSIG (WSW and SE movement, respectively) is a result of the subsidence and contraction of the Bárðarbunga central volcano.

The seismic activity related to dike injection and caldera subsidence has involved 500-800 events/day. The largest events with moment magnitude up to about 5.7 have been confined to the caldera ring fault (caldera rim). In the first month of activity, the number of recorded events exceeded 20000. Even if the number has been lower during the second month of activity, the occurrence of earthquakes exceeding magnitude 5 is still common in the Bárðarbunga caldera. In addition to all the seismic activity, a minor subglacial eruption occurred on the SE flank of the volcano on August 23, probably from the earliest radial dike.

The strong and persistent (until today) seismicity along the ring faults of the caldera is accompanied by extensive subsidence of the caldera floor. On Oct. 6, 18, 25 and Nov. 6 the levels of subsidence were reported as 30, 35, 40 and 44 m, respectively, with concentrated in the NW part of the caldera. With a caldera area of about 60 km² (long and short diameters of about 10.5 and 7 km), an average subsidence of the entire caldera floor of 44 m would represent a volume of 2.6 km³, about twice the erupted lava volume. The observed differential subsidence, however, may correspond to a volume of only 1.2 km³.

The large E-W extension NE of Bárðarbunga resulted in the formation of a 600-800 m wide and 6 km long graben partly under and partly NNE of the northern part of the Vatnajökull ice cap (Dyngjufjökull) just before Sept. 5 (Fig. 6-8). As shown in Fig. 8, the small satellite eruption fissure and the corresponding lava field are within this graben. The projection of the graben trend towards NNE coincides with the continuously erupting crater row.



Fig. 6. Western margin of a 600-800 m wide and 6 km long graben NNE of and under Dyngjufjökull (looking northwards). Dyngjufjöll, with the Askja central volcano, is on the horizon. Upper right: the erupting crater row (gas cloud), 2-3 km further SSW: short-lived satellite lava field (black colour at the right edge). Photo: Morgan Jones, Centre for Earth Evolution and Dynamics, University of Oslo. Note the shadow of Morgan's helicopter slightly west of the main western normal fault (detailed view in Fig. 7).



Fig. 7. Details of the western normal fault, with estimated subsidence of 8 m. The image location is slightly above the geometric centre of Fig. 6. Photo: Jónas Guðnason, Institute of Earth Sciences, University of Iceland (Jarðvísindastofnun, Háskólans).

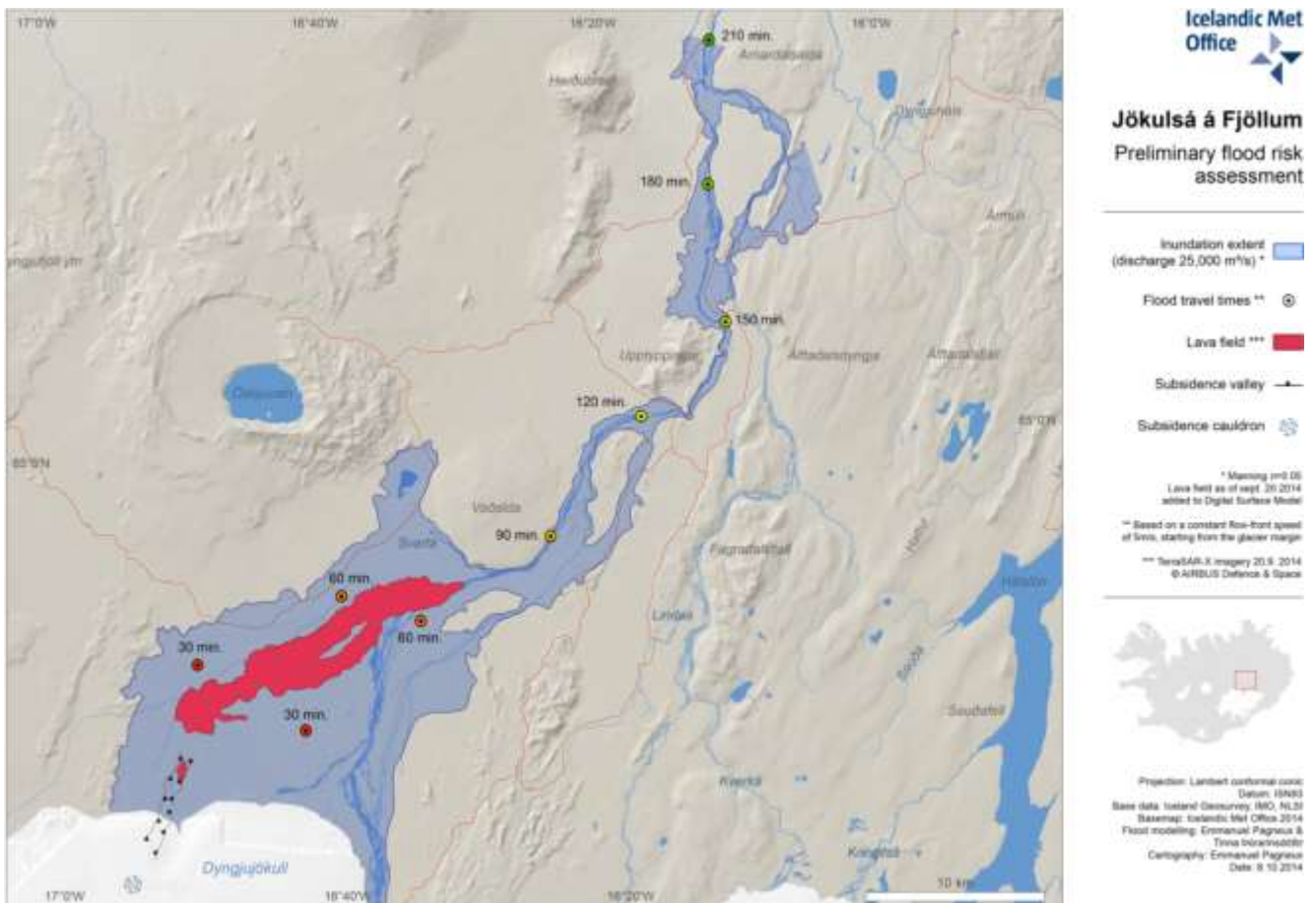


Fig. 8. Expected flooding, caused by melting of ice due to a possible subglacial eruption. Assuming a discharge rate of $25000 \text{ m}^3/\text{s}$, the projected travel time for a corresponding flood wave front is indicated. The map also shows the 6 km long graben structure beneath and NNE of Dyngjujökull. Map produced by the Icelandic Meteorological Office (Veðurstofa Íslands).

The 2014 eruption and rifting – regional perspectives and outlook

The Bárðarbunga volcanic system is one of the most productive systems in post-glacial (Holocene) time. The early Holocene Þjorsáhraun (about about 25 km^3), fed from craters in the Veidivötn fissure swarm, is largest post-glacial lava unit in Iceland, exceeding the historic Eldgjá (19.6 km^3) and Laki (15.1 km^3) lava flows from the Katla and Grimsvötn central volcanoes (Fig. 1, Þórðarson and Höskuldsson, 2008). The Bárðarbunga central volcano is close to the vertical axis of the Iceland mantle plume, which is responsible for the strongly elevated volcanic productivity in the NE Atlantic (Fig. 1, Þórðarson and Höskuldsson, 2008, Jones et al. 2014). Currently, the high rate of mass loss due to the melting of the

Vatnajökull glacier (Björnsson and Pálsson, 2008) also leads to increased decompression melting of the mantle under central Iceland (Sigmundsson et al. 2014).

The large mixed-magma eruptions originating from Bárðarbunga in 1477, 871 and about 150 AD started with dike injection about 100 km southwestwards along the Veiðivötn fissure swarm, causing reactions between the injected basaltic magma and the rhyolite melt under the Torfajökull central volcano. The 2014 eruption differs from this pattern in the sense that the basaltic dike injection is towards NE from Bárðarbunga. The sequential propagation of three dike segments from the caldera (Fig. 5, upper panel) prior to the first fissure eruption near the dike tip on Aug. 29, demonstrates that magma was injected from a NE-trending dike swarm in the Eastern Rift Zone to a NNE-trending dike swarm originally belonging to the Askja volcanic system in the Northern Rift Zone (Guðmundsson et al. 2014). The general change in directions of the fissure swarms at the latitude of central Iceland (64.5 to 65 °N) is present also in the Tertiary lavas plateaus in east Iceland. Therefore, it seems that the stress field and spreading geometry has been approximately stationary during the last 10 Ma (Guðmundsson et al. 2014).

It is difficult to predict how the eruption will evolve and how long it will last. The relatively constant rate of eruption during the first two months is remarkable and could indicate further extension of the eruption period. The magma conduit from the Bárðarbunga central volcano seems well established and the magma supply is closely tied to the deflation of the magma reservoir and subsidence of the caldera floor. The most likely scenario at this mature stage is that the magma supply from the deflating reservoir will decrease and finally end the eruption. Other scenarios, involving opening of new eruptive fissures to the SW or NE, as well as more extensive eruption activity in the Bárðarbunga central volcano, possibly of explosive character, are less likely.

The societal and environmental impacts of this effusive basalt eruption are moderate, because the location is in a very remote area of Iceland. Sulphuric gases, however, have created volcanic haze conditions in E and NE Iceland, as well as in the capital area. People with respiratory problems have been most affected. Satellite measurements have also detected elevated SO₂ trails as far as 1500-2000 km from Iceland.

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