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SHORT SCIENTIFIC COMMUNICATION

Dike emplacement at Bardarbunga, Iceland, induces unusual stress changes, caldera deformation, and earthquakes

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Abstract A 45-km-long regional dike was emplaced over a period of 2 weeks in August 2014 at the boundary between the East and North Volcanic Zones in Iceland. This is the first regional dike emplacement in Iceland monitored with modern geophysical networks, the importance of which relates to regional dikes feeding most of the large fissure (e.g., Eldgja 934 and Laki 1783) and lava shield (e.g. early Holocene Skjaldbreidur and Trölladyngja) eruptions. During this time, the dike generated some 17,000 earthquakes, more than produced in Iceland as a whole over a normal year. The dike initiated close to the Bardarbunga Volcano but gradually extended to the northeast until it crossed the boundary between the East Volcanic Zone (EVZ) and the North Volcanic Zone (NVZ). We infer that the strike of the dike changes abruptly at a point, from about N45°E (coinciding with the trend of the EVZ) to N15°E (coinciding with the trend of the NVZ). This change in strike occurs at latitude 64.7°, exactly the same latitude at which about 10 Ma dikes in East Iceland change strike in a similar way. This suggests that the change in the regional stress field from the southern to the northern part of Iceland has been maintained at this latitude for 10 million years. Analytical and numerical models indicate that the dike-induced stress field results in stress concentration around faults and particularly shallow magma chambers and calderas in its vicinity, such as Tungnafellsjökull, Kverkfjöll, and Askja. In particular, the dike has induced high compressive, shear, and tensile stresses at the location of the Bardarbunga shallow chamber and (caldera) ring-fault where numerous earthquakes occurred during the dike emplacement, many of which have exceeded M5 (the largest M5.7). The first segment of the dike induced high tensile stresses in the nearby part of the Bardarbunga magma chamber/ring-fault resulting in radially outward injection of a dike from the chamber at a high angle to the strike of the regional dike. The location of maximum stress at Bardarbunga fluctuates along the chamber/ring-fault boundary in harmony with dike size and/or pressure changes and encourages ring-dike formation and associated magma flow within the chamber. Caldera collapse and/or eruption in some of these volcanoes is possible, most likely in Bardarbunga, but depends largely on the future development of the regional dike.

Keywords Crustal stresses · Dike propagation · Feeder dike · Volcano deformation · Volcano earthquakes · Calderas

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Introduction

For the first time two weeks of seismicity and stress changes induced by a propagating regional-scale dike (strike dimension ~45 km and dip dimension at least ~10 km at the time of writing) have been monitored in great detail with recording and analysis of more than 17,000 earthquakes. The dike initiated close to the Bardarbunga (Icelandic: Bárðarbunga) Central Volcano (a caldera), a part of the 190-km-long and 25-km-wide Bardarbunga Volcanic System (Thordarson and Larsen 2007; Thordarson and Höskuldsson 2008; Larsen et al 2013). From there the dike propagated first to the northeast for about 22 km and then stopped for a while (Fig. 1). At that point, latitude 64.7 °, the propagation direction of the dike changed strike by about 30°, from N45°E to N15°E, when it next propagated. The north-northeast tip of the dike then advanced by about 23 km over several days, heading towards the nearby central volcano Askja (Dyngjufjöll) until the tip became arrested while earthquakes continued. There is evidence of a couple of very small eruptions close to Bardarbunga early in the episode. However, the main eruption so far, still a moderate effusive eruption and continuing at the time of writing, is confined to several fissures fed by the part of the dike north of the glacier (Fig. 1).

From the beginning of the dike's emplacement within the brittle part of the crust dike-induced stress has caused deformation and earthquakes in the area extending many tens of kilometres from the dike (Fig. 1). Stresses have concentrated around the nearby volcanoes such Herdubreidartögl (Icelandic: Herðubreiðartögl), the calderas Tungnafellsjökull, Askja (Dyngjufjöll), and Kverkfjöll and, in particular, the caldera closest to the dike, Bardarbunga (Fig. 1). The concentrated stress has deformed these volcanoes, resulting in numerous earthquakes, many exceeding M5 in Bardarbunga.

This paper focuses on how the interaction between the regional (plate-tectonic) and local (dike-induced) stress fields controlled volcano-tectonic events of the first two weeks of this magmatic event. The dike emplacement is put into the general volcano-tectonic framework of this part of Iceland, with particular emphasis on similarities between the currently active regional dike and regional dikes observed in the eroded dike swarms of East and Southeast Iceland at crustal depths of 1.2-2 km depth. We present new analytical and numerical models of the dike-induced stresses to explain the earthquake activity in the nearby volcanoes, with a focus on the Bardarbunga Volcano, a major collapse caldera.

Volcano-tectonic framework

Dikes in Iceland are of two types (Fig. 2; Gudmundsson 1995): (1) local swarms of inclined sheets (cone sheets) and radial dikes and (2) regional swarms of dikes. These are easily distinguished in the field by their geometric characteristics and, to a lesser degree, composition. The local swarms are very dense, containing thousands of dikes and inclined sheets, the most common thickness being ≤0.5 m. These swarms are confined to the central volcanoes, mostly calderas and stratovolcanoes (Gudmundsson 1995). The dip distribution commonly has two peaks, at 75–90°, primarily for radial dikes, and 20–50°, primarily for inclined sheets. In deeply eroded

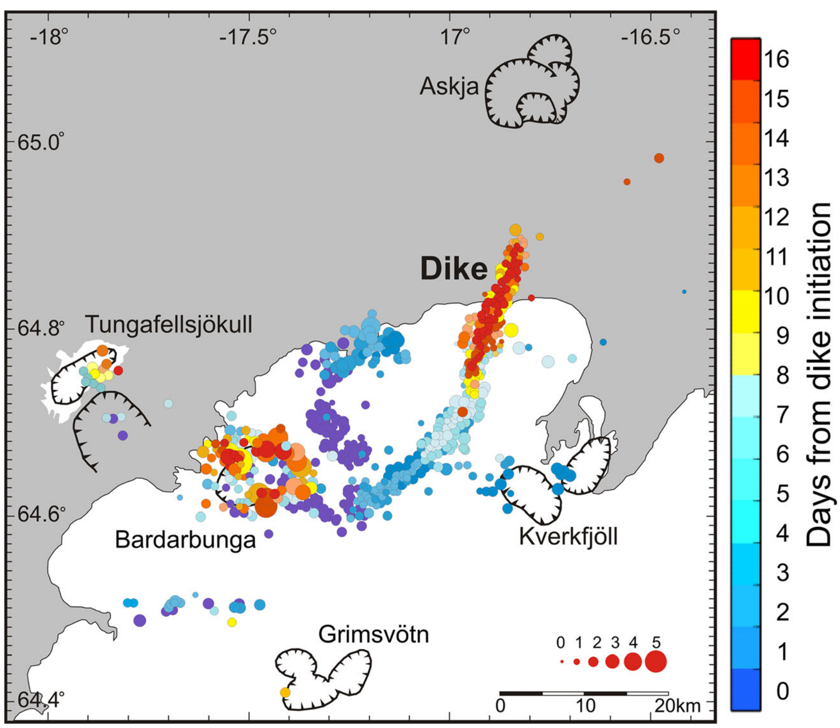

Fig. 1 Earthquake map for the first 16 days of the dike-emplacement episode. The word 'Dike' is located approximately where the fissure eruptions have taken place. The main central volcanoes, all of which are calderas, are indicated, namely Grimsvötn, Tungnafellsjökull, Askja, and Kverkfjöll (Herdubreidartögl, which is not a caldera, is just east of Askja, but not shown here). The white area denotes the main glacier or ice sheet, Vatnajökull. There have been many earthquakes in Askja in the later part of the dike-emplacement episode, but these are not shown here. The regional dike abruptly changed its path (at latitude 64.7°) about 8 days (at a cluster of yellow dots) after its initiation. Earthquake location as a function of time is published with permission by the Iceland Meteorological (2014) (IMO; data available at www.vedur.is). The IMO states that these locations are based on 'preliminary analysed data by the SIL seismic monitoring group of the Icelandic Meteorological Office'

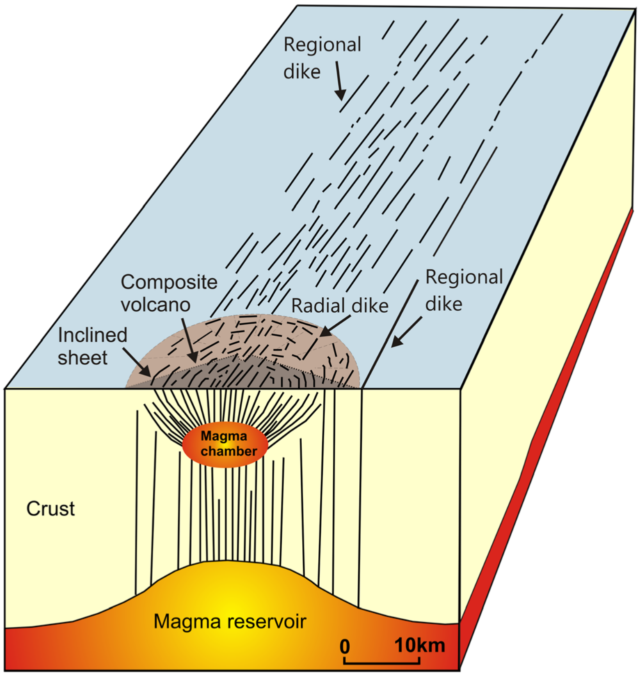

Fig. 2 Schematic illustration of a volcanic system and its local and regional dike swarms. Most volcanic systems in Iceland are supplied with magma from a double magma chamber: a small shallow chamber and a large and much deeper reservoir. Most radial dikes and inclined sheets are injected from the shallow magma chamber and tend to be, on average, much smaller and with more evolved composition than the regional dikes, most of which are injected from the deep-seated magma reservoir, as appears to be the regional dike in Bardarbunga

(~2 km) extinct central volcanoes, the inclined sheets are seen to dip towards the tops of the fossil shallow magma chamber, commonly exposed as felsic and primarily mafic plutons.

The regional dikes occur in elongated swarms, tens of kilometres long and 10–20 km wide, outside the central volcanoes (Fig. 2). The closest well-exposed regional dikes to the present one are in East Iceland, including the dikes of the Alftafjördur (Icelandic: Álftafjörður) Swarm (Fig. 3) having a modal thickness of 3–4 m and a mean thickness of about 4 m (Gudmundsson 1995). Some of the dikes in East Iceland have been mapped along their strike for distances of more than twenty kilometres. The long dikes vary in thickness along their strike, and are commonly 6–10 m thick (Fig. 3). Generally, Tertiary dikes in Iceland, exposed at crustal depths of 0.5–1.2 km, have length/thickness (aspect) ratios of close to 1,000. This aspect ratio tends to increase with depth in response to increasing stiffness (higher Young's modulus) of the host rock, that is, the dikes tend to become longer (increase their strike dimension) and somewhat thinner with depth. Thus, the 5–10 m thick regional dikes at 1–2 km depth (Fig. 3) may be somewhat thinner at greater depths. A conservative estimate of the average thickness of the Bardarbunga regional dike at 5–10 km depth is 4–5 m.

A remarkable feature of the regional dikes of the Alftafjördur Swarm some 120–130 km east of the Bardarbunga regional dike, is that they change orientation at the same latitude as the Bardarbunga dike, 64.7° (Fig. 3). At this latitude the dikes change their strike from around N24°E to about N3°E, that is, by 21°, which is very similar to the 20° change, in the same direction, in the strike of the Bardarbunga regional dike at that latitude. It is well known that dikes form their own fractures, normally striking perpendicular to the minimum principal compressive stress (e.g. Gudmundsson 2011). We thus infer that the change in the regional stress field between the southern and the northern part of Iceland across the whole of of this area has occurred at approximately this latitude since 10 Ma, when the dikes of the Alftafjördur Swarm were emplaced (Martin et al. 2011).

Stress effects of the dike on nearby volcanoes

Central volcanoes in Iceland and elsewhere, particularly calderas, are associated with shallow magma chambers. Many shallow chambers have been detected from geodetic and seismic studies beneath active central volcanoes in Iceland (Sturkell et al 2006; Brandsdottir and Menke 2008; Reverso et al 2014). They are commonly at 2–5 km depth. Also, many tops of fossil shallow magma chambers are exposed as mafic and felsic plutons at 1.5–2 km erosional depth, particularly in Southeast Iceland (Gudmundsson 1995).

The geometries of calderas may be taken as crude indications of the lateral cross-sectional shapes of the associated magma chambers. When modelling magma chambers, the normal procedure is to assume them to be initially in lithostatic equilibrium with the host rock so that the the chamber excess pressure is zero. This means that they can be modelled as cavities, or in two-dimensions as holes, subject to either the external loading, such as tensile stress (or extension) related the spreading vector at divergent plate boundaries and/or internal or external (as here) magmatic pressure (Andrew and Gudmundsson 2008).

Among the central volcanoes in the vicinity of the presently active regional dike, Bardarbunga has been subject to the greatest stress effects (Fig. 4) and has had the greatest earthquake activity, with many earthquakes exceeding M5 (the largest so far being M5.7 based on data from the Icelandic Meteorological Office, www.vedur.is; cf. Fig. 1). We therefore focus on the dike-induced stress changes at that volcano. The Bardarbunga caldera has different sizes and shapes on maps, but is often regarded as 10–11 km in maximum (NE-SW) diameter and 8 km in minimum diameter (Thordarson and Höskuldsson 2008; Larsen et al 2013). It is well known that calderas tend to change their shapes with time (Bosworth et al. 2003; Acocella 2007), partly because of stress concentration and 'breakout' effects (Fig. 4) and may not reflect the exact cross-sectional shape of the underlying shallow magma

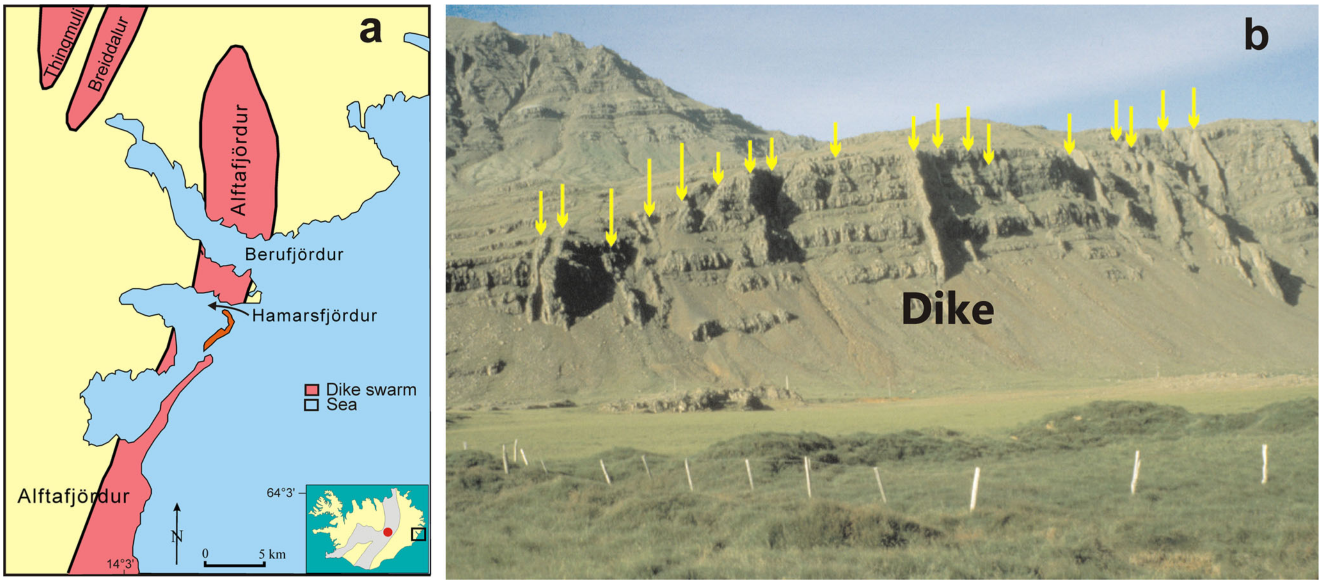

Fig 3 **a** The 10 Ma Alftafjördur Swarm of regional dikes in East Iceland, and the southern parts of the Thingmuli Swarm and the Breiddalur Swarm. The dikes of the Alftafjördur Swarm abruptly become more northerly across the fjord Berufjördur at about latitude 64.7°. Bardarbunga is indicated approximately by a red spot on the inset of Iceland. **b** Dikes of the Alftafjördur Swarm on the north coast of Berufjördur. The dikes indicated by yellow arrows (and one by 'dike') are mostly 5–10 m thick whereas the arithmetic average thickness of dikes in this part of the swarm is 5.5 m. The basaltic lava pile dips 6–8°W; the exposure seen here is at an erosional depth of about 1.2 km

chamber. For simplification, we assume the magma chamber to be circular with approximately the area of the caldera. Minor changes in the shape of the magma chamber would not change the main model results here.

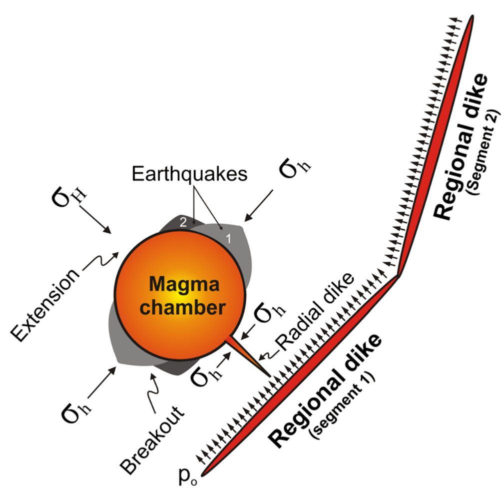

Fig. 4 Overpressure p_0 in the regional dike (shown schematically) induces high horizontal compressive stress σ_H which generates stress concentration around the nearby Bardarbunga shallow magma chamber/ring-fault (σ_h is the minimum horizontal stress). During the formation of dike segment 1, some tensile stresses develop on the opposite side of the chamber (marked by extension) but primarily on the side closest to segment 1, resulting in normal faulting and radial dike injection (which presumably fed a small eruption). Much shear/compressive stress concentrates in the grey area marked by 1 but as dike segment 2 develops, the stress concentration shifts to the area marked by 1. As the size/magmatic pressure of the regional dike change, such as when it erupts, the stress concentrations around the Bardarbunga chamber/ring-fault fluctuate along its boundary, and so does the earthquake activity

The dike magma is inferred to be olivine tholeitite with a density of around 2,750 kg m^{-3}. We propose that the regional dike was injected mostly from a deep-seated reservoir in the lower crust or upper mantle, perhaps at depth of 20–25 km or more (Fig. 1). The overpressure (driving pressure) in the dike at 10 km depth in the crust could then easily be tens of megapascal (Gudmundsson 2011; Becerril et al 2013), but we use the conservative estimate of 10 MPa.

Consider a two-dimensional stress field around a vertical circular hole subject to biaxial compressive stress where the angle θ is the polar coordinate, measured between the direction of the maximum applied horizontal compressive stress σ_H and the radius vector r, that is, the radial distance from the centre of the hole. Then it can be shown (e.g., Savin 1961; Gudmundsson 2011) that the maximum circumferential compressive stress σ_θ^{max} occurs at θ=90° and 270°, and is given by

$$\sigma_\theta^{max} = 3\sigma_H - \sigma_h \quad (1)$$

where σ_h is the minimum horizontal compressive stress. Similarly, the minimum circumferential compressive (maximum tensile) stress σ_θ^{min} occurs at θ=0° and 180° and is given by

$$\sigma_\theta^{min} = 3\sigma_h - \sigma_H \quad (2)$$

Here we apply these results as follows. The applied maximum horizontal compressive stress σ_H is generated by the magmatic overpressure of the dike and the hole is the Bardarbunga magma chamber and associated caldera (Fig. 4). It follows from Eq. (2) that if $\sigma_H > 3\sigma_h$ then there will be tensile stress at points $\theta=0°$ and 180°. The Bardarbunga chamber was presumably close to or in lithostatic equilibrium before the emplacement of the regional dike, so that the effective or applied tectonic stresses at its boundary before the emplacement was close to zero (effective or applied $\sigma_H=\sigma_h=0$). Thus, because the applied σ_H reaches 10 MPa or more, the condition $\sigma_H > 3\sigma_h$ is satisfied and tensile stress is induced. This tensile stress reaches its maximum value at the point closest to the regional dike. At this point, the Bardarbunga magma chamber and the surrounding 'strip of land' ruptured early in the episode, as indicated by distribution of earthquakes generated in the first days of the episode (Fig. 1). The rupture or failure of the rock resulting in normal faulting and almost certainly also in magma injection, possibly as an inclined sheet but, based on the earthquake location (Fig. 1) and the present stress modelling, most likely a radial dike (Fig. 4). This dike appears to have erupted under the glacier early in the episode (probably 23 August), as indicated by seismic measurements and reflected in subsidence at the surface of the glacier (presumably due to magma-related melting at the bottom of the glacier; www.vedur.is). We infer that tensile stress triggered normal faulting and dike/sheet emplacement at the point closest to the regional dike, at $\theta=0°$, but also some extension and possible normal faulting at and around the point on the opposite side. Whether the radial dike soon became arrested or, alternatively propagated into and joined the top part of the regional dike is not known. The chemical signatures of such mixing may be too small to be detected in the lavas erupted at the time of writing.

From Eq. (1) it follows that at points $\theta=90°$ and 270°, by contrast, the compressive stress concentration becomes high so that the shear strength of the rock is reached. The resulting breakouts (Fig. 4) are well known and may change the shape of boreholes (e.g. Gudmundsson 2011) and calderas (Bosworth et al. 2003; Acocella 2007) and, gradually, chambers from circular to elliptical. The concentration of compressive and shear stress results primarily in reverse faulting in these regions, as has indeed been observed during the present episode (based on data from the Icelandic Meteorological Office, www.vedur.is, cf. Fig. 1). So, in terms of the present model (Fig. 4), the reverse faulting in these regions at the boundary of the magma chamber/caldera is primarily due to stress concentration associated with the magma overpressure of the dike and not, as yet, to any large subsidence along the Bardarbunga ring-fault itself. The sites of main compressive/tensile/shear stress concentrations at the magma chamber/ring-fault shift along the boundary, as indicated schematically by the areas marked 1 and 2 in Fig. 4 (for the compressive/shear stress), as the dike dimensions/overpressure change. Testing of this forecast must wait for more detailed earthquake data analysis.

Numerical models (Fig. 5) provide results in excellent agreement with the analytical solutions. These models are all made using the finite-element software Comsol (www.comsol.com). The models here are two-dimensional; extension to three dimensions with depths of structures and processes are taken into account is planned as a part of further development of these models. The results show that the dike-induced tensile stress is raised at the west-northwest boundary of the Bardarbunga magma chamber/ring-fault early in the episode but concentrates primarily at the southeast boundary (Fig. 5a). Further modelling (not shown here) suggests that as the dike propagated northeast, the points of maximum tensile stress become shifted somewhat counter-clockwise around the chamber/ring-fault boundary. The maximum compressive stress, by contrasts, concentrates at the north-northeastern and south-southeastern part of the chamber/ring-fault (Fig. 5b), where the largest earthquakes at Bardarbunga have occurred (Fig. 1). The compressive stress also shifted along the boundary as the dike propagated. The von Mises shear stress also concentrates at the boundary (Fig. 5c) and shifted as the dike propagated to the northeast. Generally, the compressive stress and part of the shear stress coincide with the 'breakouts' indicated in Fig. 4 but they range more widely along the boundary than shown in Fig. 4. This is because Fig. 4 represents primarily the very early stages of the dike emplacement, crudely the emplacement of the first main segment, whereas the numerical models show the stress effects of some of the subsequent northeast-striking segments of the dike (emplaced 18 and 19 August) as well.

The trajectories or orientation of σ_H, the maximum horizontal compressive stress (Fig. 5d), suggest that earthquakes due to reverse faulting occur on north to northeast striking faults while many normal-faulting earthquakes occur on northwest-striking faults. Many of the reverse-fault earthquakes may be reactivated normal faults, in agreement with the analytical results (Fig. 4) and direct observations of dike-induced reverse slip on normal faults (Gudmundsson et al 2008). The orientation of σ_H favours ring-dike emplacement along the south-southeastern and, particularly, the north-northeastern segments (arcs) of the ring-fault (Fig. 5d). This follows also from the 'breakouts', that is, the chamber expansion beneath these segments which tends to lower associated potential energy. Magma flows from higher to lower potential energy (e.g., Gudmundsson 2011), so that chamber expansion and faulting in these parts tend to drag in, or act as sinks for, magma from other parts of the chamber. The resulting magma 'readjustment' in the chamber (assuming little or no inflow), including possible ring-dike formation, could result in some rise of the ring-fault areas, particularly in the 'breakout' parts 1 and 2 (Fig. 4), and a corresponding subsidence of the central part of the caldera.

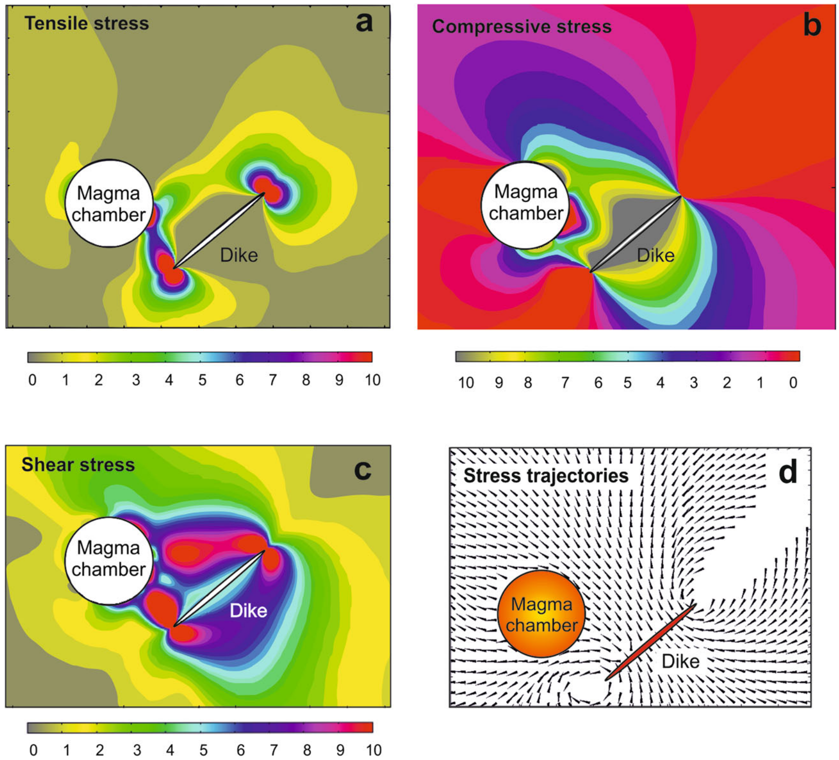

Fig. 5 Numerical (www.comsol.com) models of the dike-induced stresses around the Bardarbunga magma chamber/ring-fault during the early stages (around 19 August) of the dike emplacement (before it changed its path). All the stresses are in mega-pascal. Since tensile and compressive stresses have opposite signs, we here show them as absolute values, but give the increase in tensile (**a**) and shear (**c**) stresses in the opposite direction (to the right) to that of the compressive stress (**b**). North is up on all the figures and the magma chamber is 10 km in diameter. (**a**) Tensile stress concentrates along the west-northwest part of the boundary, but primarily (pink area) along southeast boundary, coinciding roughly with the location of the proposed radial dike (Fig. 4). (**b**) Compressive stress concentrates primarily at the north-northeastern and south-southeastern part of the chamber/caldera, where the largest earthquake at Bardarbunga have occurred (Fig. 1; cf. Fig. 4). (**c**) Von Mises shear stress concentration coincides with the main tensile and compressive stress concentration areas, resulting in normal, strike-slip, and reverse faulting and earthquakes. (**d**). Trajectories (directions) of σ_H (the maximum horizontal compressive stress) suggest that many of the reverse-fault earthquakes occur on north to northeast striking faults (striking perpendicular to σ_H) whereas many normal-faulting earthquakes, and possible ring-dike injections, occur on northwest-striking faults (striking parallel to σ_H). Many of the reverse-fault earthquakes may be along reactivated normal faults

Discussion

The volcano-tectonic episode described here has provided, for the first time, data on the emplacement of a regional dike (Fig. 1) which can be used to test stress-modelling of the interaction between active volcanoes and regional dikes. For example, while field observations and numerical models have long indicated the possibility of a regional dike propagating across volcanic systems and zones (Andrew and Gudmundsson 2008; Hartley and Thordarson 2013), this is the first well-documented case of such an event happening in Iceland. In particular, the Bardarbunga regional dike has already propagated from the EVZ to the NVZ and is close to entering, or has already entered, a different volcanic system (Askja) from the one in which it originated (Bardarbunga).

Volcanoes are known to be dynamic systems, with common changes in local stresses and deformation. This is the first time, however, that the main stress concentrations at a boundary of a shallow chamber/ring-fault have been observed to shift around the boundary in accordance with geometric and overpressure changes in a nearby propagating regional dike. Furthermore, the stress changes at the ring-fault/chamber boundary are in excellent agreement with analytical and numerical models of dike-induced stresses (Figs. 4 and 5).

For this volcano-tectonic episode, which is still on-going at the time of writing, there are several possible developments. The observed fissure eruptions have taken place just north of the edge of the glacier and have, as of 7 September, produced a small fraction of the magma volume in the regional dike (here estimated at 1-2 km^3). Propagation of the fissure to the south beneath the glacier is possible, in which case an explosive eruption may occur. The regional dike may still propagate further to the north-northeast, triggering more earthquakes and possibly eruptions in Askja and/or Herdubreidartögl. Another nearby caldera (a double caldera) is Kverkfjöll (Fig. 1), where an eruption (and caldera collapse) is possible, but less likely than in Bardarbunga.

Bardarbunga, and to a lesser extent Tungnafellsjökull (Fig. 1), are primarily subject to high horizontal compressive and shear stresses induced by the magmatic overpressure in the dike (Figs. 1 and 4) which results in shear-stress concentration at the chamber/ring-fault boundary. There have been earthquakes in Tungnafellsjökull, and further activity there is possible, but a major activity is more likely in Bardarbunga. The analytical and numerical models thus focus on Bardarbunga (Figs. 4 and 5) and explain the common reverse faulting roughly along the north-northeastern and south-southeastern segments of the ring-fault/chamber boundary. The stress trajectories (Fig. 5d) suggest that the strike of many of the active reverse faults is likely to be roughly northeast, and commonly reverse displacement along reactivated normal faults, whereas a ring-dike might form parallel to these caldera segments. Given the high dike-induced stress concentration at Bardarbunga and likely pressure changes in the associated reservoir, it is possible that the volcano will experience a caldera collapse, particularly if a major ring-dike becomes injected. In that case, a Bardarbunga eruption would be likely (but by no means certain) as would be flow of magma along the path of the radial dike towards and into the regional dike (Fig. 4), which would add magma and pressure to, and possibly trigger further propagation of, the regional dike.

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