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Key Points:
- Melt propagated 48 km laterally at 5-7 km bsl prior to erupting, generating more than 30,000 earthquakes
- Seismicity arises from double-couple strike-slip failure orientated subparallel to the dike strike
- Left-lateral fault motion is dominant to accommodate extension across the divergent plate boundary

Supporting Information:
- Figures S1-S4, Tables S1-S3, and Captions for Tables S1-S3, and Movie S1
- Table S2
- Table S3
- Movie S1

Correspondence to:
T. Ágústsdóttir,
ta354@cam.ac.uk

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Strike-slip faulting during the 2014 Bárðarbunga-Holuhraun dike intrusion, central Iceland

Thorbjörg Ágústsdóttir[1], Jennifer Woods[1], Tim Greenfield[1], Robert G. Green[1], Robert S. White[1,2], Tom Winder[1], Bryndís Brandsdóttir[2], Sveinbjörn Steinthórsson[2], and Heidi Soosalu[3]

[1]Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK, [2]Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland, [3]Geological Survey of Estonia, Tallinn, Estonia

Abstract Over a 13 day period magma propagated laterally from the subglacial Bárðarbunga volcano in the northern rift zone, Iceland. It created $>30,000$ earthquakes at 5–7 km depth along a 48 km path before erupting on 29 August 2014. The seismicity, which tracked the dike propagation, advanced in short bursts at 0.3–4.7 km/h separated by pauses of up to 81 h. During each surge forward, seismicity behind the dike tip dropped. Moment tensor solutions from the leading edge show exclusively left-lateral strike-slip faulting subparallel to the advancing dike tip, releasing accumulated strain deficit in the brittle layer of the rift zone. Behind the leading edge, both left- and right-lateral strike-slip earthquakes are observed. The lack of non-double-couple earthquakes implies that the dike opening was aseismic.

1. Introduction

Volcanic eruptions in rift zones are frequently preceded by lateral migration of a magma-filled dike, sometimes for many kilometers [e.g., *Rubin and Pollard*, 1988; *Rubin*, 1992; *Belachew et al.*, 2011]. Some of these dike intrusions freeze at depth while others breach the surface, resulting in a fissure eruption [e.g., *Björnsson and Saemundsson*, 1977; *Abdallah et al.*, 1979; *Hamling et al.*, 2009; *Wright et al.*, 2012]. Seismicity often accompanies propagation of the dike front as the magma forces its way forward [*Einarsson and Brandsdóttir*, 1978; *Brandsdóttir and Einarsson*, 1979; *Battaglia et al.*, 2005; *Morita et al.*, 2006; *Keir et al.*, 2009], commonly fed by a subsiding volcanic center [e.g., *Einarsson and Brandsdóttir*, 1978]. The extent of accompanying seismicity is variable, influenced strongly by the preexisting stresses and material properties of the rift fabric [*Rubin and Gillard*, 1998; *Rivalta et al.*, 2015]. However, when seismicity is present, the migrating earthquake swarm marks the tip of the intrusion [*Brandsdóttir and Einarsson*, 1979; *Grandin et al.*, 2011].

The Bárðarbunga volcanic system is made up of a subglacial central volcano with an ice-filled caldera and a transecting fissure swarm which extends 115 km SW (the Veiðivötn fissure swarm) and 55 km NNE (the Dyngjuháls fissure swarm) [*Jóhannesson and Saemundsson*, 1998; *Larsen et al.*, 2013; *Larsen and Gudmundsson*, 2015]. Episodic rifting within the fissure swarms of Icelandic volcanoes accommodates plate spreading along the divergent plate boundary [*Tryggvason*, 1984; *Wright et al.*, 2012]. Gravity studies suggest that dense intrusions have previously radiated at depth from the Bárðarbunga central volcano [*Gudmundsson and Högnadóttir*, 2007].

In 2014 a dike propagated laterally 48 km from Bárðarbunga central volcano northeast along the Dyngjuháls fissure swarm. After 13 days propagation the dike erupted at Holuhraun, reoccupying old craters formed before the midnineteenth century by magma which also originated within the Bárðarbunga system [*Hartley and Thordarson*, 2013]. This study addresses the origin and extent of migrating seismicity accompanying the 2014 dike intrusion. The spatiotemporal resolution exceeds that of numerous previous observations of dike seismicity [*Passarelli et al.*, 2015; *Rivalta et al.*, 2015, and references therein]. We assess the relationship between the dike trajectory and seismicity and construct precise fault plane solutions to investigate the failure mechanisms along the dike.

1.1. The 2014 Bárðarbunga-Holuhraun Dike Intrusion

On 16 August 2014 an unusual sequence of earthquakes began near the southeastern rim of the ice-covered Bárðarbunga caldera. The earthquakes migrated rapidly 6 km southeastward, delineating a laterally propagating, radial dike, before turning 90° northeastward away from the caldera. Over the next 12 days the dike propagated episodically a farther 42 km beneath the glacier and into the Holuhraun lava field. It advanced

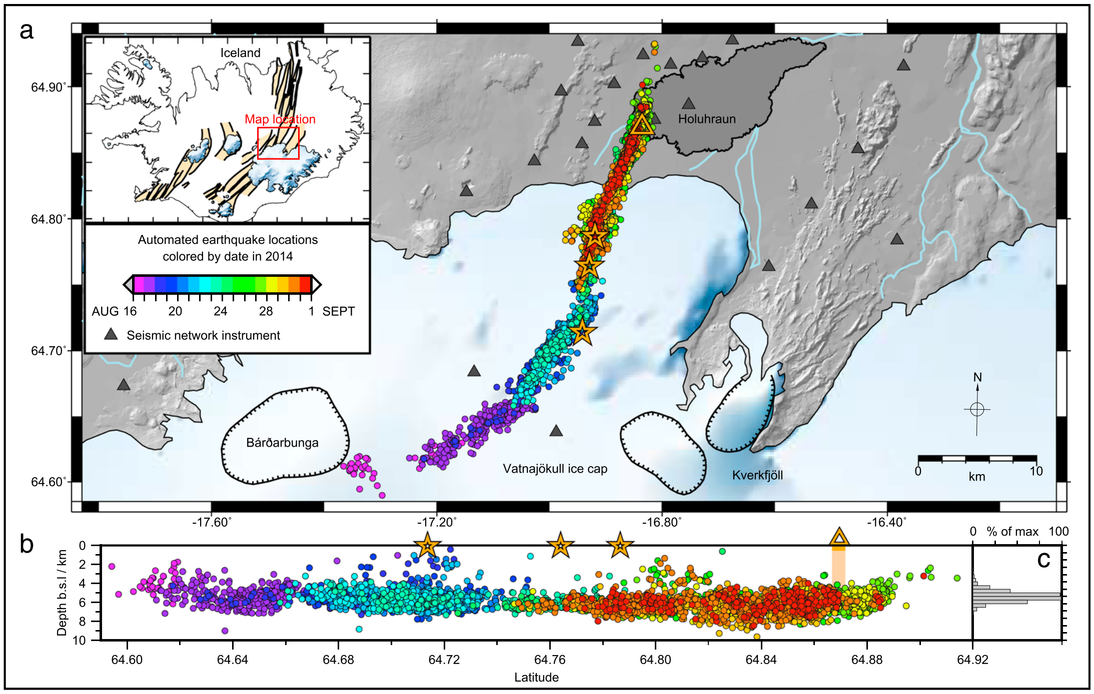

Figure 1. Seismicity produced by the propagating dike 16–31 August 2014, colored by date (see also Movie S1). (a) Earthquake locations in map view. Shaded topography in grey with glaciers in white. Ticked lines delineate central volcano calderas, black triangles seismometers, orange triangles eruption site, orange stars depressions in the ice surface, and dark shading new Holuhraun lava flow (Holuhraun III). Inset shows location on a simplified tectonic map of Iceland with volcanic systems shaded [*Einarsson and Saemundsson*, 1987]. (b) Cross section along dike. (c) Depth distribution of hypocenters.

beyond the eventual eruption site by 2 km, making the total length of the dike 48 km (Figure 1 and Movie S1 in the supporting information). It was not until 29 August that the dike breached the surface, reoccupying the old Holuhraun craters. The initial fissure eruption lasted only 4 h. A further 40 h later, on 31 August, a sustained and larger fissure eruption began. It continued until 27 February 2015, erupting 1.6 km^3 of lava over an area of 84.1 km^2 [*Gíslason et al.*, 2015].

The dike propagation followed a pathway of minimum potential energy [*Heimisson et al.*, 2015; *Sigmundsson et al.*, 2015a]. Five large-scale segments can be identified, each distinguishable by a change in dike strike (Figures 1 and 2 and Movie S1). The strike of the northernmost dike segment in the ice-free region is 025°, consistent with the regional rift fabric orientation of 025° [*Hjartardóttir et al.*, 2015a] but 11° clockwise from the normal to the plate spreading direction of 104°, extending at 18.5 mm/yr [*DeMets et al.*, 2010]. Surface fracturing and graben formation accompanied the intrusion [*Hjartardóttir et al.*, 2015b]. Modeling of geodetic data shows that it was a vertically extensive planar dike [*Green et al.*, 2015; *Sigmundsson et al.*, 2015a]. During the dike propagation Bárðarbunga caldera began to subside and experienced over 50 $M > 3$ earthquakes, suggesting a deflating magma reservoir beneath the caldera.

2. Seismic Data

A seismic network deployed by Cambridge University has been operated in Iceland since 2006 and expanded to surround Vatnajökull ice cap in 2013. In August 2014 the network comprised 72 three-component broadband seismometers (Figures 1 and S1) that recorded the 2014 Bárðarbunga-Holuhraun dike propagation in detail. To complement the network, 14 stations from the national seismic network of the Icelandic Meteorological Office were used, as well as one British Geological Survey station and one University College Dublin station. The network provides good azimuthal coverage, with excellent sampling north of the ice cap. Coverage is less good to the south of the dike due to difficult field conditions on the ice cap. The data used in this study cover the period from 16 to 31 August 2014, encompassing the whole dike intrusion and the onset of the two eruptions. All data were recorded at 100 Hz sample rate with a GPS time stamp.

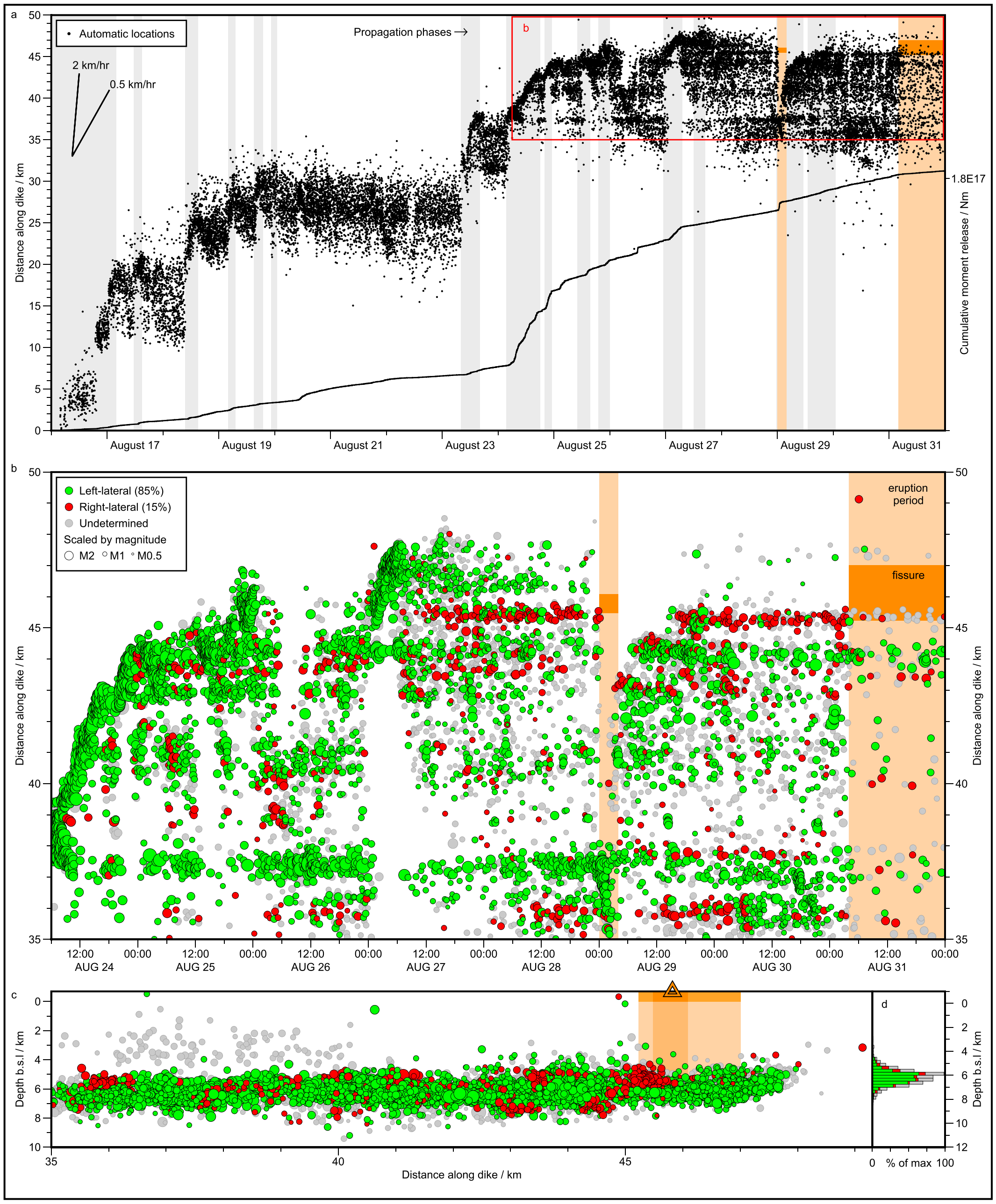

Figure 2. Propagation of seismicity through time with earthquake failure mechanisms. (a) Automated earthquake hypocenters (black dots) delineate segmented propagation of dike, plotted as distance along dike versus time. Propagation phases are shown in grey. Eruption periods are shown in peach and fissure location in orange. Dike cumulative seismic moment release is shown by solid black line. (b) Inset from Figure 2a with left-lateral (green), right-lateral (red), and undetermined (grey) fault mechanism categorizations (see section 3.5). Earthquakes scaled by magnitude. (c) Depth cross section of Figure 2b, with main crater identified by orange triangle. (d) Distribution of depths in Figure 2c.

More than 30,000 earthquakes (M_L 0.5–4) were automatically detected by coalescence microseismic mapping [*Drew et al.*, 2013]. Accurate hypocenter locations were determined using NonLinLoc [*Lomax et al.*, 2000], with average location errors of 0.5 km laterally and 1.0 km in depth. We used a linear gradient velocity model for earthquake locations based on refraction experiments [*Pálmason*, 1971; *Gebrande et al.*, 1980; *Darbyshire et al.*, 1998] with a constant Vp/Vs ratio of 1.78, constrained by the Wadati plots [*Wadati*, 1933] from manually picked phase arrival times along the whole dike (Figure S2 and Table S1).

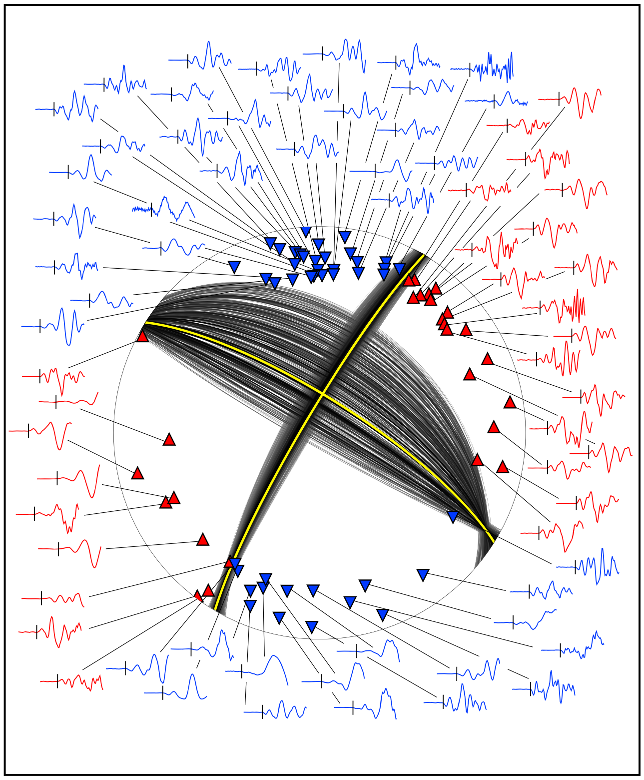

Figure 3. Example of fault plane solution with earthquake arrival waveforms. The fault plane solution is tightly constrained by polarity phase picks at 70 stations, each showing clear first motion polarity on vertical component. Each waveform is cut 0.25 s before first motion, 0.85 s in length, and normalized to the same maximum amplitude. Red triangles represent compressional first motions, and blue inverted triangles represent dilatational first motions. The range of possible fault plane solutions is given by the black lines, with the average fault plane solution highlighted in yellow. Location of this earthquake is shown with a green star in Figure S3.

A manually constructed earthquake catalogue was created by refining earthquake arrival times for more than 500 events, producing 30,000 *P* phase and 28,000 *S* phase picks. Refined earthquakes were located with NonLinLoc to determine earthquake hypocenters with average errors of 0.5 km laterally and 0.9 km in depth (Figures 1 and S2 and Table S3).

3. Bárðarbunga-Holuhraun Dike Seismicity

3.1. Seismicity Migration

During the intrusion new segments of the Bárðarbunga-Holuhraun dike were emplaced in propagation phases at speeds of 0.3–4.7 km/h, with seismicity focused near the dike tip. The advances were separated by periods where the migration stalled for up to 81 h. During periods of most rapid propagation, seismically quiet zones occurred immediately behind the concentrated seismicity of the leading edge. The propagation phases are delineated by tight clusters in space and time of advancing earthquakes, highlighted by grey bands in Figure 2a. They last between 40 min and 13 h, with the longest continuous advance of 5.5 km made in 13 h. Large-scale dike segments were emplaced by episodic intrusion of many smaller segments with similar orientations. Each of the main segments became seismically quiet once a new segment had intruded beyond it, producing the step-like propagation of seismicity apparent in Figure 2a.

3.2. Seismicity Distribution

Throughout the dike emplacement, seismicity remained concentrated at 5–7 km below sea level, near the brittle-ductile boundary where differential stresses in this extensional area are greatest. The brittle-ductile boundary is mapped at about 7 km depth in the Askja volcanic system, located about 20 km along rift from the dike tip [*Key et al*., 2011a, 2011b; *Green et al*., 2014]. Sparse seismicity was observed in the uppermost 4 km of crust at several subglacial locations (orange stars in Figure 1), but none near the eruption fissure, despite the dike breaching the surface. Persistent seismicity was observed at discrete locations along the dike, appearing as horizontal bands of seismicity on a distance along dike versus time plot (Figures 2a and 2b). A cluster at 37.5 km (64.80°N) occurred where the dike stalled for 14 h before surging forward. Another cluster is seen at 46 km (64.87°N), below the southern edge of the eruption fissure (Figures 2a and 2b).

3.3. Seismicity Rates and Moment Release

The majority of the seismic moment release accompanying intrusion of the Bárðarbunga-Holuhraun dike occurred during the rapid propagation phases (grey bands in Figure 2a). The largest increase in the moment release occurred simultaneously with the rapid advance of the dike on 24 August. Between propagation phases seismicity rates generally remained high but smaller magnitude earthquakes were observed. On several occasions the seismicity retreated or appeared to backpropagate, such as following the onset of the initial fissure eruption. In this case the seismicity rate remained high but immediately retreated ~8 km along the dike,

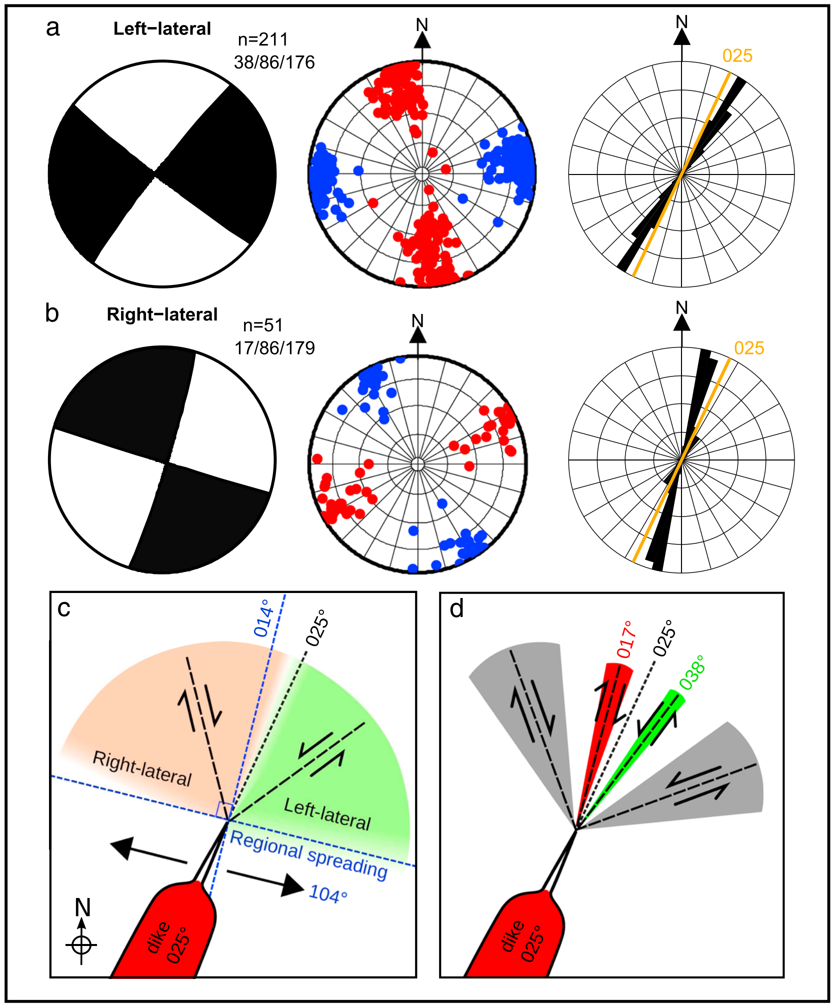

Figure 4. Fault plane solutions from northernmost segment of the dike shown in Figure 2b. (a and b) Mean fault plane solution with strike/dip/rake marked; all *P* (red) and *T* (blue) axes; rose diagram of fault plane strikes, with strike of northernmost dike segment in the ice-free region in orange. Figure 4a shows left-lateral strike-slip faults. Figure 4b shows right-lateral strike-slip faults. (c) Schematic diagram showing fault motion produced by interaction of strike of dike with rift spreading direction. (d) Schematic diagram of dike tip fracture angles. *Rubin and Gillard* [1998] theoretical angles given by grey range, observed angles given by colored range. Left-lateral failure in green and right-lateral failure in red.

before migrating back to the eruption site over the subsequent 8 h. An instantaneous drop in seismicity rate along the entire dike was observed with the onset of the main eruption on 31 August (Figure 2).

3.4. Earthquake Source Mechanisms

In order to investigate the earthquake source mechanisms, we concentrate on the 13 km of the dike nearest the eruption site (red box in Figure 2a, beyond 64.78°N, emplaced from 24 August 2014). This northernmost segment of the dike has a strike of 025° and is where the seismic network provides the best azimuthal and spatial constraints. Lower hemisphere fault plane solutions and inversions of the full moment tensor were constructed using a Bayesian moment tensor solution program MTINV [*Pugh*, 2015]. Each event had a minimum distance to the nearest station of 1–7 km, a maximum azimuthal gap of 30°–50°, and an average of 53 *P* phase polarities (Figure 3). Inversions for the full moment tensor revealed no significant volumetric component, despite the setting of an opening dike. All fault plane solutions are best described by double-couple failure. There is a surprising lack of normal faulting events, given this is an extensional rift setting (Figure S3). Instead, we find that the dominant failure mechanism is strike slip. One nodal plane is consistently subparallel to the strike of the dike so we assume this to be the fault plane (Figures 4a and 4b). There is a significant range in the dike-perpendicular nodal plane orientations (Figure 3), strongly suggesting that they are not fault planes. It is therefore most likely that the fractures generated during the 48 km dike propagation are subparallel to the direction of travel.

The fault plane solutions constrain populations of left- and right-lateral strike-slip mechanisms with consistent fault planes (Figures 4a and 4b). The strike of the average left-lateral fault plane solution is 038° (Figure 4a, green in Figure S3b). This is a rotation of 13° clockwise from the strike of the dike and the regional rift orientation of ~025° [*Hjartardóttir et al*., 2015a]. The right-lateral faulting observed occurs predominantly behind the leading edge, mainly in a cluster at 46 km (64.87°N) near the southern edge of the eruption fissure (red in Figure S3b). The strike of the average fault plane solution for this population is 017° (Figure 4b). The distribution of fault plane strikes is shown in the rose diagrams in Figures 4a and 4b.

3.5. Earthquake Fault Motion Categorization

A categorization method based on the consistency of the nodal planes (described above) was used to analyze the earthquake failure mechanisms in the northernmost dike segment (Figure 2b). Two representative sets of stations from opposite polarity quadrants (dilatational and compressional) were selected with reliable, clear arrivals and stable locations on the focal sphere. Hence, plotting the earthquake arrival waveforms for both sets of seven stations enabled quick differentiation between left- and right-lateral fault motion (Figure S4). Results from manually constructed fault plane solutions are consistent with the categorization (Figures 2b and S3b), allowing for the rapid failure mechanism analysis of ~9500 events.

The fault motion categorization shows that the principal failure mechanism along the dike is left-lateral strike slip (85%, green in Figures 2b and 2c). Right-lateral strike-slip faulting is less common (15%, red in Figures 2b and 2c). The leading edge failure is exclusively left-lateral strike slip. Right-lateral strike-slip failure only occurs after the leading edge of the dike has passed, persistently in a cluster at the southern end of the eruptive fissure, 1 km shallower than the majority of the seismicity (Figure 2c). Uncategorized earthquakes (grey in Figures 2b and 2c) are generally those with signal-to-noise ratios too low to confidently identify first motion polarities.

4. Discussion

As in other intrusions [*Brandsdóttir and Einarsson*, 1979; *Keir et al*., 2009; *Belachew et al*., 2011; *Grandin et al*., 2011], the seismicity was confined to the region close to the front of the propagating dike, suggesting that the flow of magma is aseismic once a pathway has formed and remains open. The quiet zones observed immediately behind the leading edge during rapid propagation phases (grey bands in Figure 2b) may be due to stress shadowing [*Segall et al*., 2013]. During the stalled phases a resupply of magma by lateral flow from Bárðarbunga volcano inflated the region behind the dike tip and allowed the pressure to build up sufficiently to drive the next advance forward [*Sigmundsson et al*., 2015a]. The initial eruption on 29 August may have been short lived because it used up all the magma available in the dike and the pressure dropped. It then took 2 days for a consistent magma supply channel to form between the source and the fissures, before the start of the main, continuous eruption. Locations of persistent seismicity along the dike, behind the leading edge, may be due to an increase in local strength of the surrounding medium which required continual fracturing to maintain magma flow. Equally, they could arise from angular jogs in the dike, such as at the southern end of the eruptive fissure where magma moves upward to the eruption fissure.

During emplacement, dike seismicity remained at 5–7 km depth. However, surface geodetic observations require most of the opening to be above 5 km depth [*Green et al*., 2015; *Sigmundsson et al*., 2015a]. The dike certainly extended shallower than the seismicity at the eruption fissure at Holuhraun. Small magma volumes may also have reached the surface at several other subglacial locations, especially where ice depressions formed at the surface (orange stars in Figure 1) [*Sigmundsson et al*., 2015a]. We infer that the uppermost crust is so weak from the pervasive rift fabric that it fractured in tension and the dike inflated largely aseismically as magma was intruded and eventually froze. A similar lack of shallow seismicity was observed during the 1983 Kilauea dike intrusion [*Rubin et al*., 1998]. Migrating magma in prefractured crust may propagate creating little brittle failure as shown by *Taisne et al*. [2011] where vertical magma propagation at Piton de la Fournaise is associated with fewer and smaller earthquakes than during lateral propagation phases.

Propagation rates vary along the Bárðarbunga-Holuhraun dike from 0.3 to 4.7 km/h. These speeds of lateral dike propagation, guided by preexisting fractures, are comparable to those reported from other studies.

Measured speeds of magma propagation at Piton de la Fournaise range from 0.7 to 2.9 km/h [*Battaglia et al*., 2005; *Peltier et al*., 2005] and from 0.7 to 2.2 km/h for several rifting events during the 1975–1986 Krafla rifting episode, North Iceland, and the 2005–2010 rifting episode in Dabbahu, East African rift [*Wright et al*., 2012]. Highest propagation rates are associated with short periods of rapid advance of the dike front on 16, 18, and 23 August.

The dike seismicity arises predominantly from double-couple strike-slip failure, with a minority of oblique normal faults (Figures 2b and S3b). The lack of non-double-couple earthquakes implies that the opening was aseismic. This is supported by the two orders of magnitude difference between the geodetic moment and seismic moment release of the dike. Seismic moment reflects the brittle energy released by fracturing, whereas geodetic moment records the energy associated with the dike inflation. We calculate the seismic moment to be 1.8×10^{17} Nm and the geodetic moment to be 1.8×10^{19} Nm [*Green et al*., 2015].

Seismicity along the leading edge of the dike arises exclusively from left-lateral strike-slip failure. These earthquakes exhibit greater seismic moment release than those behind the propagating front, where both left-lateral and right-lateral strike-slip failure is observed. Left-lateral strike-slip failure is the dominant mechanism. This can be explained by the obliquity of the fault planes (038°) to the regional spreading axis (104°). Fault plane motion is preferentially left-lateral to accommodate extension across the divergent plate boundary. The strikes of the fault planes agree with theoretical models of dike tip failure which postulate fracturing oblique to the propagation direction. With a standard coefficient of friction of 0.6, fracturing would be expected approximately 30° to the dike strike, but high fluid pressures can cause greatly reduced fracture angles [*Rubin and Gillard*, 1998]. The high magmatic pressures at the dike tip are sufficient to reduce the angle of failure to 13° clockwise to the dike strike as observed (Figure 4d). Notably, no corresponding right-lateral events are observed along the leading edge on faults oriented 13° anticlockwise to the propagating dike tip. Any faults aligned in that direction would be almost exactly orthogonal to the spreading direction of 104° and may therefore fail aseismically in Mode I failure or at magnitudes smaller than our magnitude of completion (M_c 1.1). Nonetheless, small-scale faulting mapped at the surface close to the fissures [*Hjartardóttir et al*., 2015b] shows both left-lateral and right-lateral failure clockwise and anticlockwise to the strike of the dike as predicted by our model.

The path of the dike is governed by the pressure field produced by the overlying topographic load and the local stress field [*Sigmundsson et al*., 2015a]. However, the influence of preexisting weaknesses must also be considered. Fracture movements on preexisting faults occur during rifting episodes, and the fracture density in fissure swarms in the northern rift zone gradually increases with time, indicating that dike intrusions tend to use the same pathways many times. The dike unquestionably reoccupied the old Holuhraun craters, and the northernmost dike segment is parallel with the surrounding rift fabric [*Hjartardóttir et al*., 2015a]. Hence, the dike is likely to have followed preexisting weaknesses within the rift zone.

Throughout the propagation, eruption, and cooling phases, the seismicity remained concentrated at 5–7 km depth. We therefore infer that after the dike emplacement, an open pathway was formed and magma continued to flow along a conduit at approximately 6 km depth. The primary driving force for the magma flow through the 48 km long dike is likely to be the pressure head from the magma reservoir beneath Bárðarbunga. Effects of magma gas release are assumed to be minimal in the case of lateral subhorizontal flow. It seems likely that the overburden pressure may have remained too high at the subglacial locations where ice depressions formed [*Sigmundsson et al*., 2015a] for the pressure head available from the magma reservoir to overcome. Instead, the magma migrated north until it reached a topographic low.

The Bárðarbunga caldera subsided 66 m from the beginning to the end of the eruption, accompanied by 79 $M > 5$ earthquakes [*Sigmundsson et al*., 2015b]. The subsidence provides a measure of the available driving force for the magma flow. The average flow rate during the six month eruption was 100 m^3/s [*Gíslason et al*., 2015], but at the beginning it was as high as 400 m^3/s [*Pedersen et al*., 2015], dropping to zero at the end. A simple model of laminar flow through a tube, with an initial flow rate of 400 m^3/s, a driving force of 1.6 MPa (65 m thickness of magma with a density of 2500 kg/m^3), and a dynamic viscosity of 100 Pa s, requires a tube of 15 m diameter and a flow rate of 2.3 m/s (8.3 km/h). Using the average eruptive rate of 100 m^3/s and an average driving force of half the magma reservoir thickness (0.8 MPa), a similar size tube of 15.6 m diameter is required but with a reduced flow rate of 0.8 m/s (2.9 km/h). This is within the bounds of the observed dike front propagation rates of 0.3–4.7 km/h and suggests that once the flow path has been opened, the lateral magma flow can continue unimpeded. The shape of the conduit need not be circular: equivalent flow rates are derived, for example, in rectangular conduits with a width of 7 m and a height of 100 m. Narrow, tall flow channels would fit the geodetic constraints on the extensional width of a few meters for a vertically extensive dike better than a circular channel.

5. Conclusions

The 2014 Bárðarbunga-Holuhraun dike propagated at 5–7 km below sea level, 48 km to the northeast from Bárðarbunga caldera, before erupting at Holuhraun. The propagation was episodic, advancing at velocities of 0.3–4.7 km/h. Seismicity remains focused around the dike tip and at constrictions or jogs in the dike path. Detailed analysis of the northernmost dike segment reveals that the seismicity arises from double-couple strike-slip failure. Earthquakes along the leading edge are found to be exclusively left-lateral strike-slip failure, which is also the dominant mechanism overall. This preferential fault motion accommodates extension within the rift zone.

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