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Dynamics of dyke intrusion in the mid-crust of Iceland

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ABSTRACT

We have captured a remarkable sequence of microearthquakes showing progressive melt intrusion of a dyke moving upward from a sill at 18 km depth in the mid-crust of the northern volcanic rift zone in Iceland. Two-thirds of the earth's crust is created at mid-ocean rifts. Two-thirds of that crust is formed by intrusion and freezing before it erupts of molten rock generated within the underlying mantle. Here we show seismicity accompanying melt intrusion from 17.5 to 13.5 km depth along a dyke dipping at 50° in the mid-crust of the Icelandic rift zone. Although the crust at these depths is normally aseismic, high strain rates as melt intrudes generate microearthquakes up to magnitude 2.2. Moment tensor solutions show dominantly double-couple failure, with fault mechanisms sometimes flipping between normal and reverse faulting within minutes in the same location, but breaking along fault planes with the same orientations. We suggest several possible reasons for the flipping fault mechanisms: the breakage of solidified plugs of basalt within the dyke itself as more melt intrudes; intrusion along sub-parallel fractures or dykelet fingers into the local stress field created near the tip of a propagating dyke; or movement on small jogs or offsets between adjacent *en echelon* dykes. Although the faulting is caused ultimately by melt movement, there is no resolvable volumetric component in the moment tensor solutions. The inferred fault planes from microearthquakes align precisely with the overall plane of the dyke delineated by hypocentres. Melt injection occurs in bursts propagating at 2–3 m/min along channels c. 0.2 m thick, producing swarms of microearthquakes lasting several hours. Intervening quiescent periods last tens to hundreds of hours.

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1. Introduction

Melt generated in the mantle beneath rift systems migrates into the crust where, on average, two-thirds of it freezes as intrusions and one-third is extruded at fissures or volcanic centres (White et al., 1992, 2008). Although there are many observations of shallow magma chambers and of seismicity accompanying dyke propagation in the uppermost 5 km of the crust, earthquakes caused by dyke propagation in the deeper crust are rarely recorded. Limited seismic observations, however, do not necessarily preclude the prolonged presence of melt at depth, as melt may reside aseismically in sills, possibly at multiple levels. Here we report on seismicity exceptionally well recorded by a dense array of seismometers, that accompanies the propagation of a dyke within the mid-crust of the Icelandic volcanic rift system.

Over a period of one year (March 2007–March 2008), the Icelandic national seismic network recorded over 10,000 microearthquakes below Mount Upptyppingar in the Kverkfjöll volcanic system (Fig. 1). The seismicity was produced by melt injection along a southward dipping dyke (Jakobsdóttir et al., 2008). Starting from a depth of c. 18 km below sea level, the deep seismicity migrated in both up- and down-dip directions and also laterally before stopping at c. 13 km depth, where the melt apparently froze without eruption.

The brittle–ductile boundary in the vicinity of Mt. Upptyppingar is marked by the termination of upper crustal seismicity at 6–7 km depth (Fig. 1b; see also depth histogram of seismicity in Fig. 1b of Key et al., 2011). So the earthquakes at 13–18 km depth caused by the Upptyppingar intrusion are well below the brittle zone, in a normally aseismic region. Nevertheless their appearance is of earthquakes generated by brittle failure, with dominant frequencies around 7 Hz. We postulate that high strain rates produced locally by the magma movement generated the seismicity. An unusual feature of the Upptyppingar seismicity is rapid alternation between normal and reverse fault mechanisms, often in the same region and within minutes. These rapid changes are explained best by magma movement.

1.1. Previous reports of seismicity due to melt movement in the deep crust

Much deep seismicity elsewhere attributed to the flow of magma comprises long period (LP) events, with typically a narrow spectrum of energy in the 1–3 Hz range, emergent waveforms and usually only a few tens of events recorded over long periods which may extend to several years (e.g., Pitt et al., 2002). The clearest examples of deep LP

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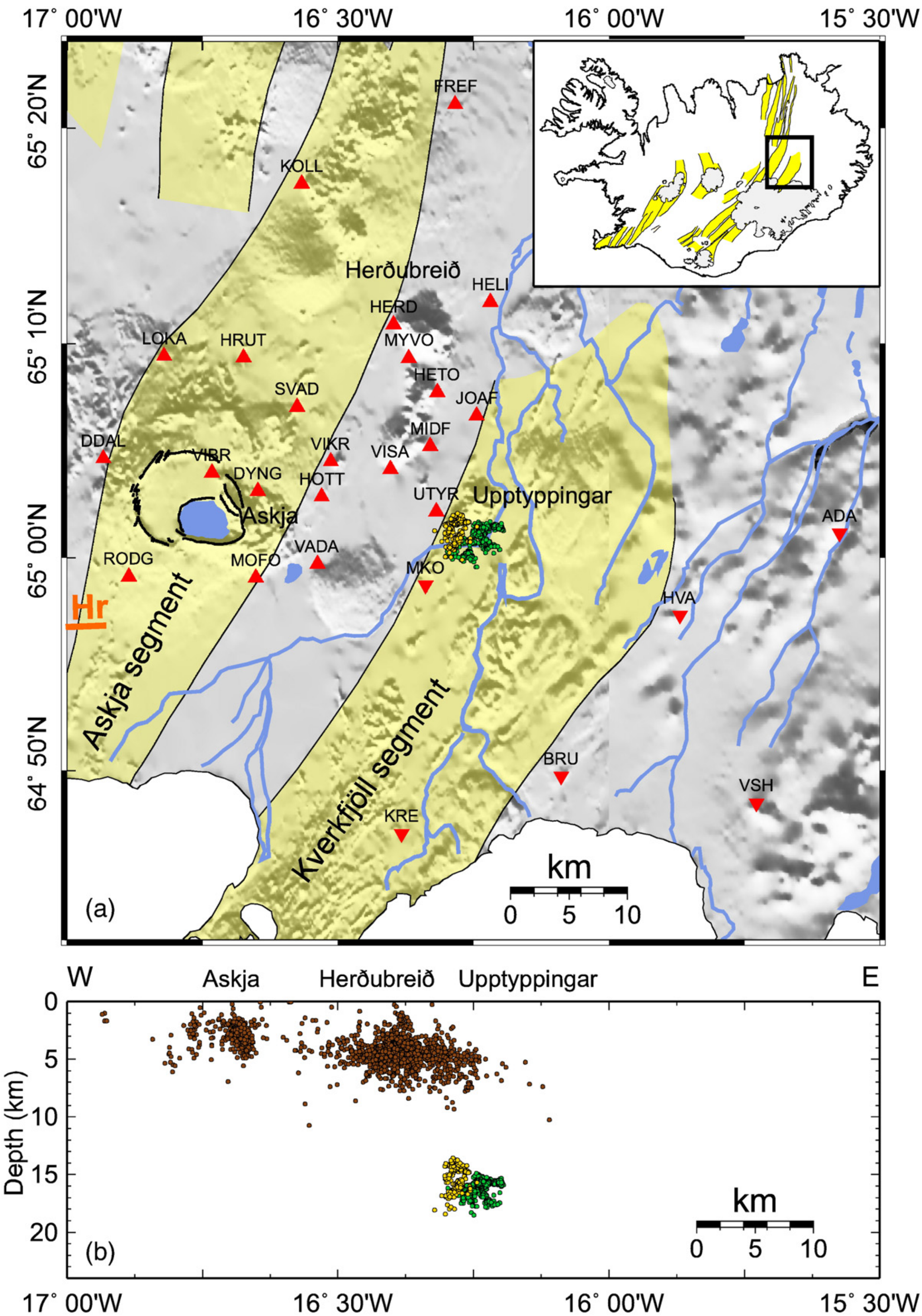

Fig. 1. Location map and Upptyppingar seismicity. (a) Map showing epicentres of seismicity from multi-event double-difference locations (events shown in yellow occurred during the 6–24th July 2007 dyke injection sequence discussed in this paper and those in green show preceding events from the start of dyke growth in March 2007). Red triangles are sites of temporary seismometers during July–August 2007, inverted red triangles are permanent stations of the SIL network. The neovolcanic rift segments of Askja and Kverkfjöll are shaded light yellow, ice caps white, and rivers blue. Orange line labelled Hr shows Hrimalda eruptive fissure with a similar orientation to the strike of the Upptyppingar dyke. Inset shows rift zones coloured yellow cutting across Iceland (from Einarsson and Sæmundsson, 1987). (b) East–west cross-section showing earthquakes in the brittle upper crust during 2006–2009 (in brown) (Soosalu et al., 2010) and deep events caused by melt injection into the crust during March–July 2007 (same colour coding as in part a).

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