Earth and Planetary Science Letters 490 (2018) 216–229

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Long-period seismicity reveals magma pathways above a laterally propagating dyke during the 2014–15 Bárðarbunga rifting event, Iceland

Jennifer Woods[a,*], Clare Donaldson[a,*], Robert S. White[a], Corentin Caudron[a,b,c], Bryndís Brandsdóttir[d], Thomas S. Hudson[a], Thorbjörg Ágústsdóttir[a]

[a] University of Cambridge, Department of Earth Sciences, Bullard Laboratories, Cambridge, UK
[b] Royal Observatory of Belgium, Seismology and Gravimetry Section, Uccle, Belgium
[c] G-Time, Département Géosciences, Environnement et Société, Université Libre de Bruxelles, Belgium
[d] Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

ARTICLE INFO

Article history:
Received 20 December 2017
Received in revised form 9 March 2018
Accepted 12 March 2018
Available online 28 March 2018
Editor: P. Shearer

Keywords:
Bárðarbunga-Holuhraun
dyke intrusion
long-period seismicity
tremor
volcano seismology
Iceland

ABSTRACT

The 2014–15 Bárðarbunga–Holuhraun rifting event comprised the best-monitored dyke intrusion to date and the largest eruption in Iceland in 230 years. A huge variety of seismicity was produced, including over 30,000 volcano-tectonic earthquakes (VTs) associated with the dyke propagation at ∼6 km depth below sea level, and large-magnitude earthquakes accompanying the collapse of Bárðarbunga caldera. We here study the long-period seismicity associated with the rifting event. We systematically detect and locate both long-period events (LPs) and tremor during the dyke propagation phase and the first week of the eruption. We identify clusters of highly similar, repetitive LPs, which have a peak frequency of ∼1 Hz and clear P and S phases followed by a long-duration coda. The source mechanisms are remarkably consistent between clusters and also fundamentally different to those of the VTs. We accurately locate LP clusters near each of three ice cauldrons (depressions formed by basal melting) that were observed on the surface of Dyngjujökull glacier above the path of the dyke. Most events are in the vicinity of the northernmost cauldron, at shallower depth than the VTs associated with lateral dyke propagation. At the two northerly cauldrons, periods of shallow seismic tremor following the clusters of LPs are also observed. Given that the LPs occur at ∼4 km depth and in swarms during times of dyke-stalling, we infer that they result from excitation of magmatic fluid-filled cavities and indicate magma ascent. We suggest that the tremor is the climax of the vertical melt movement, arising from either rapid, repeated excitation of the same LP cavities, *or* sub-glacial eruption processes. This long-period seismicity therefore represents magma pathways between the depth of the dyke-VT earthquakes and the surface. Notably, we do not detect tremor associated with *each* cauldron, despite melt reaching the base of the overlying ice cap, a concern for hazard monitoring.

1. Introduction

Long-period seismicity at volcanoes often involves fluid-related processes associated with magma movement (Chouet and Matoza, 2013). Therefore, it is a crucial tool for elucidating the processes occurring in a volcano plumbing system and for eruption forecasting and monitoring (e.g. Chouet 1996; McNutt 2005). Long-period seismicity includes both short-lived events (long-period events or LPs) and longer-duration seismicity, known as tremor, with peak frequencies in the band 0.5–5.0 Hz (Chouet, 1996).

The 2014–15 Bárðarbunga–Holuhraun dyke intrusion and eruption was a major rifting event in central Iceland (Sigmundsson et al., 2015). A 48 km-long dyke propagated at ∼6 km depth below sea level (b.s.l.) over two weeks from Bárðarbunga, a sub-glacial volcano, to the sub-aerial eruption site in the Holuhraun lava field (Ágústsdóttir et al., 2016). Depressions, known as ice cauldrons, were observed on the surface of Dyngjujökull glacier above the propagating dyke pathway (Sigmundsson et al., 2015). These ice cauldrons have been shown to be caused by relatively small, sub-glacial eruptions and linked to periods of seismic tremor observed by the Icelandic Meteorological Office (Reynolds et al., 2017). There has so far been little convincing seismic evidence showing magma moving from the dyke to the surface, despite knowledge of this

* Corresponding authors.
E-mail addresses: jw845@cam.ac.uk (J. Woods), cgd27@cam.ac.uk (C. Donaldson).

https://doi.org/10.1016/j.epsl.2018.03.020

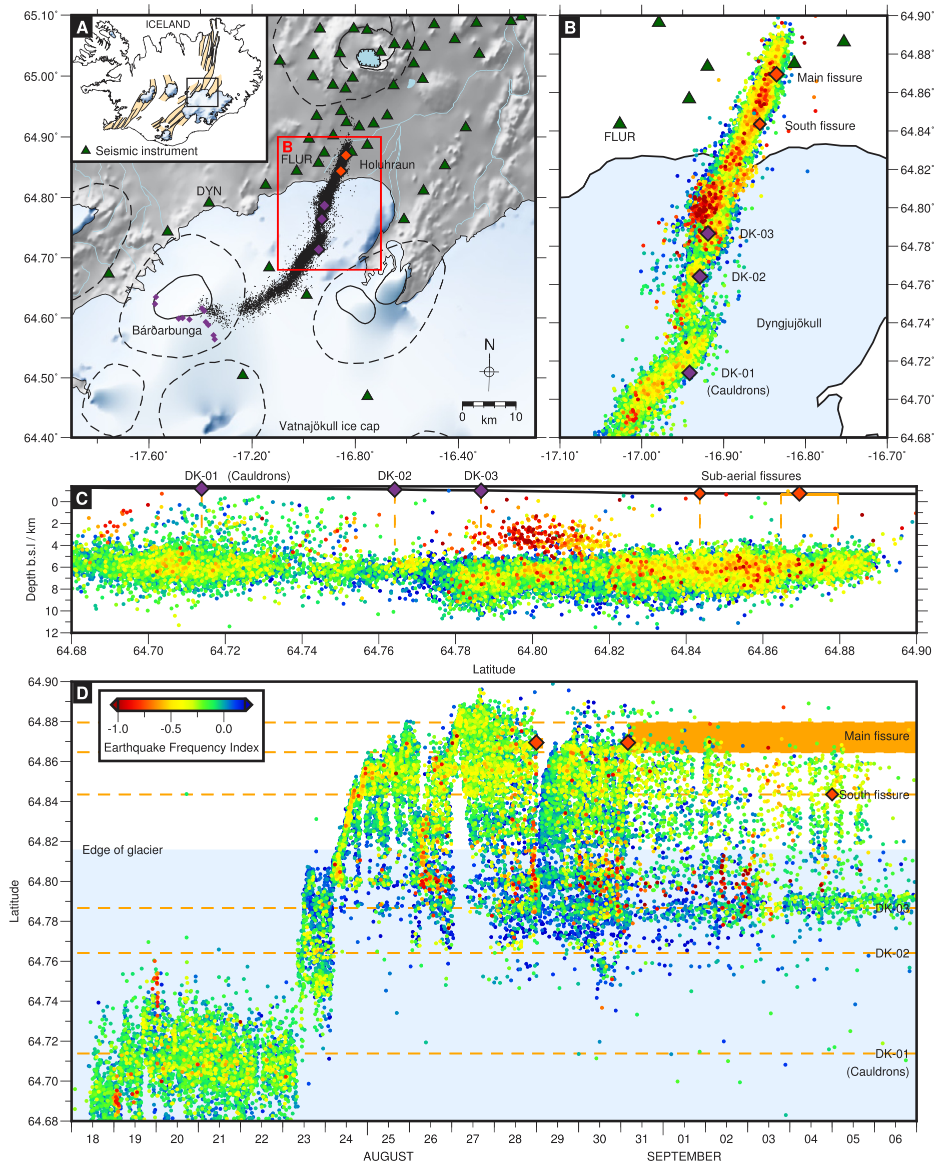

Fig. 1. Frequency Index (FI) of dyke earthquakes for station FLUR. A) and B) map view; C) depth cross section; and D) latitude through time. FI indicated by colour, with red showing lower frequency (lowest FI plotted on top); glacier in light blue; volcanoes and calderas outlined; ice cauldrons indicated by dark purple diamonds (Dyngjujökull cauldron locations from Reynolds et al., 2017, Bárðarbunga cauldron locations from Gudmundsson et al., 2016), eruption fissures shown as orange diamonds; eruption periods shown by orange bands; seismometers indicated by triangles. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

occurring at many places along the dyke path (beneath the ice cauldrons, and at the sub-aerial fissure eruption sites).

We systematically searched for and located both long-period events and tremor during the dyke propagation phase and the first few days of the eruption. We used waveform cross-correlation to detect long-period events, identify similar families of events and to locate tremor. Cross-correlation has an advantage over more traditional onset picking techniques when studying long-period seismicity, which is often emergent in nature (Konstantinou and Schlindwein, 2003). We hope that cross-correlation-based techniques for location of seismic tremor will be incorporated into real-time volcano monitoring.

We investigated how this long-period seismicity is linked to (a) the dyke propagation and associated >30,000 volcano-tectonic (VT) earthquakes (Ágústsdóttir et al., 2016) and (b) sub-glacial eruptions beneath the ice cauldrons formed on Dyngjujökull glacier. To our knowledge, this is the first detailed study of LPs occurring during lateral propagation of a dyke. The excellent seismic network coverage available during this event provided a unique opportunity to investigate in detail whether the LPs and tremor are mechanistically related.

1.1. 2014–15 Bárðarbunga rifting event

Bárðarbunga is a central volcano on the margin of Iceland's Eastern and Northern Volcanic Zones, underneath Vatnajökull ice cap (Fig. 1A). On 16 August 2014, volcano-tectonic earthquakes started occurring under the ice-filled Bárðarbunga caldera. Over the next 13 days, over 30,000 VT earthquakes occurred at approximately 6 km depth b.s.l., tracking a dyke for 48 km as it propagated laterally north-eastwards. On 29 August, a small, 4-hour eruption occurred in the Holuhraun lava field, reoccupying craters from a 19th century eruption (Hartley and Thordarson, 2013). On 31 August a larger, sustained fissure eruption began, which continued until 27 February 2015, erupting an estimated bulk volume of 1.44 km^3 of lava over an area of 84 km^2 (Pedersen et al., 2017). The eruption on 31 August started with a continuous curtain of fire fountaining along the 1.6 km-long fissure. On 1 September the ac-