Earth and Planetary Science Letters 319-320 (2012) 83–95

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Elastic thickness control of lateral dyke intrusion at mid-ocean ridges

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ARTICLE INFO

Article history:
Received 19 July 2011
Received in revised form 20 November 2011
Accepted 8 December 2011
Available online 21 January 2012

Editor: Y. Ricard

Keywords:
mid-ocean ridge
dyke intrusion
mechanics of the lithosphere

ABSTRACT

Magmatic accretion at slow-spreading mid-ocean ridges exhibits specific features. Although magma supply is focused at the centre of second-order segments, melts are episodically distributed along the rift toward segment ends by lateral dyke intrusions. It has been previously suggested that an along-axis downward topographic slope away from the magma source is sufficient to explain lateral dyke propagation. However, this cannot account for the poor correlation between dyke opening and surface elevation in the 2005–2010 series of 14 dyke intrusions of Afar (Ethiopia). Using mechanical arguments, constrained by both geodetic and seismological observations, we propose that the large dykes that initiate near the mid-segment magma source are attracted toward segment ends as a result of a thickening of the elastic–brittle lithosphere in the along-rift direction. This attraction arises from the difference of elastic resistance between the segment centre where the lithosphere is thermally weakened by long-term focusing of melts, and comparatively "colder", hence stronger segment ends. The axial topographic gradient in magmatic rifts may be more likely explained as an incidental consequence of these variations of along-axis elastic–brittle thickness, rather than the primary cause of lateral dyke injections.

1. Introduction

Vertical ascent of magma through the lithosphere is a widespread observation in volcanic regions around the world, and is generally explained by the buoyancy of molten rock with respect to solid host-rock (e.g. Weertman, 1971). A more intriguing phenomenon is the horizontal migration of magma during a lateral dyke intrusion. Because lateral dyke intrusions are suspected to be ubiquitous at mid-ocean ridges (MOR) (Dziak et al., 2004; Smith and Cann, 1999), a better understanding of the conditions driving horizontal magma migration is required to assist interpretations of accretion processes in terms of an evolution of melt supply to the ridge (Buck et al., 2005; Rabain et al., 2001).

So far, the most complete set of evidence of lateral dyke intrusions originates from studies of the only two sub-aerial sectors of the MOR system, namely Iceland and Afar. These two hotspot-influenced regions represent two different stages of oceanisation: mature in Iceland, incipient in Afar. The Krafla (Iceland, 1975–1984) and Manda Hararo (Afar, Ethiopia, 2005–2010) rifting episodes consisted in major periods of magmatic unrest, during which 21 and 14 dykes, respectively, were intruded along the rift zones, involving cumulative volumes of magma of the order of 1–3 km^3 (e.g. Björnsson, 1985; Grandin et al., 2010b). Seismic activity coeval with dyke tip propagation has shown that several, if not all, dykes during these rifting episodes have migrated horizontally at velocities of ~1 km/h away from a single mid-segment magma reservoir (Fig. 1) (Belachew et al., 2011; Brandsdóttir and Einarsson, 1979; Grandin et al., 2011; Keir et al., 2009). In both cases, the first dyke of the sequence was the largest in volume and migrated over the longest distance: up to 2 km^3 and 30–35 km at Manda Hararo (Ayele et al., 2009; Grandin et al., 2009) and 0.15 km^3 and 60 km at Krafla (Björnsson, 1985). Subsequent dyke intrusions propagated unidirectionally. They appear to be organised in sub-sequences, with (1) the same direction of propagation and decreasing distance of propagation within a single sub-sequence, and (2) a shift in direction between successive sub-sequences (Buck et al., 2006; Grandin et al., 2010b; Hamling et al., 2009). An increase of eruptive activity and a coeval decrease of the rate of magma intrusion are observed throughout the duration of a rifting episode (Björnsson, 1985; Ferguson et al., 2010; Grandin et al., 2010b).

Several models have attempted to explain lateral dyke intrusions. The common view is that melts first experience a buoyancy-driven vertical ascent through the lithosphere, and then stop ascending at a certain depth level, where their trajectories become horizontal. This change of propagation direction (vertical, followed by horizontal) is believed to occur at a critical level that either represents a level of neutral buoyancy (LNB), defined as the depth above which lithospheric

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doi:10.1016/j.epsl.2011.12.011

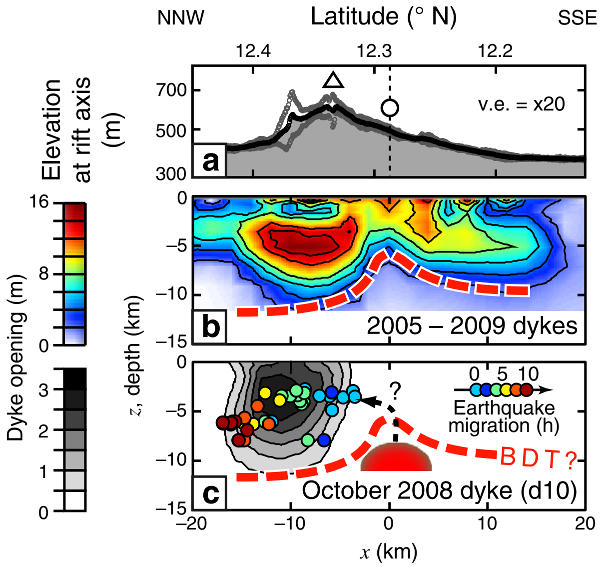

Fig. 1. (a) Surface elevation along the axis of the Manda Hararo–Dabbahu rift (Afar, Ethiopia). The black curve is the elevation averaged in a 5 km wide sliding cross-section centred on the rift axis, and the grey curves show the maximum dispersion of elevations in this sliding region (vertical exaggeration: ×20). The white circle indicates the location of the source reservoir, which is offset by ~7 km to the SSE with respect to the summit of the axial depression, whose location is indicated by the white triangle. (b) Distribution of cumulative opening between September 2005 and June 2009 as a result of intrusion of 13 dykes along the Manda Hararo rift, deduced from inversion of InSAR data. *x* is the horizontal distance along the rift, with origin at the central magma reservoir. Red dashed line shows depth of the brittle–ductile transition (BDT), inferred from depth of maximum dyke opening for the 2005–2009 dykes (vertical exaggeration: ×1). Note the poor correlation between dyke opening and surface elevation (Grandin et al., 2010a,b). (c) Opening distribution for October 2008 dyke (d10). Location of the source reservoir (shown schematically as a red sphere) has been inferred from inflation/deflation cycles imaged by InSAR during the 2005–2010 rifting episode (Grandin et al., 2010a; Hamling et al., 2009, 2010). Circles indicate the migration of earthquake activity coeval to dyke emplacement (Grandin et al., 2011). Earthquakes are colour-coded as a function of origin time. Although earthquake depths are poorly constrained, the lateral migration of seismicity shown here is typical of other intrusion events in the 2005–2010 rifting episode (Belachew et al., 2011; Grandin et al., 2011; Keir et al., 2009).

rocks become less dense than liquid magma (Lister and Kerr, 1991; Ryan, 1993), or the brittle–ductile transition (BDT) where tectonic extension is maximum (Rubin and Pollard, 1987), or a combination. In either scenario, lateral dyke intrusion occurs as a result of magma spreading along an equilibrium interface because the dyke cannot expand in the vertical direction. If the interface is flat, the model predicts that maximum dyke opening should be observed directly above the locus of melt supply (Lister and Kerr, 1991). However, the maximum thickness of most dykes intruded in the Krafla and Manda Hararo rifts was offset from the mid-segment magma source by 10–30 km, with little dyke opening observed in the vicinity of the source (Fig. 1b) (Björnsson, 1985; Grandin et al., 2010b). Explaining this striking observation requires a mechanism capable of efficiently attracting dykes laterally away from the source reservoir.

An extension of the above interpretation states that the commonly observed decrease of along-axis elevation toward segment ends constitutes the primary cause for the lateral propagation of dykes. The proposed reason for horizontal magma migration is the tendency of magma to flow under its own weight along a sloping level located at constant vertical distance below the sloping Earth's surface (Rubin and Pollard, 1987) (blue line in Fig. 2). This model has been put forward to explain lateral dyke propagation from a reservoir located beneath shield volcanoes radially (Pinel and Jaupart, 2004) or along the rift zone direction (Buck et al., 2006; Fialko and Rubin, 1998). However, this "sloping surface model" fails to explain the recent observation of a poor correlation between surface elevation and dyke opening during the Manda Hararo rifting episode (Grandin et al., 2009, 2010b). Indeed, maximum cumulative dyke opening between 2005 and 2010 (~15 m), which has occurred ~10 km north of the central magma reservoir, is located below the site of maximum elevation (400–650 m), whereas lower elevations (300–400 m) correspond to less opening (~8 m) (Grandin et al., 2010b) (Fig. 1a–b). The source reservoir itself, which corresponds to a local minimum of dyke opening and dyke height, is located below a site of intermediate elevation (~500 m).

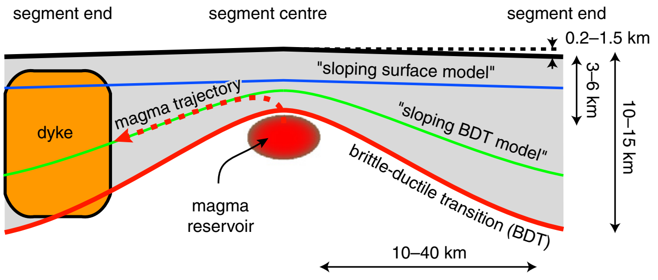

Fig. 2. Along-axis cross-section of an idealised magmatic segment showing deepening of the brittle–ductile transition (BDT, red line) and shallowing of surface elevation (black line) toward segment ends. Magma injected from a mid-segment reservoir (red ellipse) migrates laterally toward one segment end (red dashed arrow), either at a constant vertical distance below surface topography ("sloping surface model", blue line) or following a trajectory parallel to the BDT ("sloping BDT model", green line). Values of depth and distance on the right and bottom are indicative of the typical range found in nature.

In this paper, we alternatively propose that lateral dyke injections are driven by an along-axis increase of the elastic–brittle thickness (or, in other words, a deepening of the BDT) away from the segment centre toward segment ends. Indeed, a greater elastic–brittle thickness toward segment ends means that more elastic potential energy can be stored there, compared to segment centre where magma is injected into a thinner elastic lithosphere. This situation induces a lateral gradient of differential stress that is sufficient to drive dyke injections laterally away from the mid-segment magma source (green line in Fig. 2). The main factor controlling these along-axis variations of elastic–brittle thickness in slow-spreading MORs is likely the thermal structure of the axial lithosphere, which is characterised by a focusing of hot magmatic material at segment centre that thermally weakens the lithosphere and produces comparatively colder, hence stronger segment ends (Chen and Morgan, 1990; Phipps Morgan et al., 1987). Evidence for such variations of strength are established on geophysical observations of the tridimensional structure and segmentation of the MOR lithosphere (e.g. Doubre et al., 2007a; Kong et al., 1992; Kuo and Forsyth, 1988; Lin et al., 1990; MacDonald et al., 1991; Magde et al., 1997), and supported by the thermomechanical models typically employed in attempts to shed light on accretion processes at MORs (e.g. Neumann and Forsyth, 1993; Poliakov and Buck, 1998; Shaw and Lin, 1996; Tapponnier and Francheteau, 1978).

We propose to quantify the effect of variations in the thickness of the elastic–brittle axial lithosphere on dykes propagating laterally, and to compare this effect to that induced by along-axis variations of surface elevation. The paper is organised as follows. First, we review the main factors controlling the phenomenon of dyke intrusion, and highlight the importance of the distribution of stress in controlling the style and depth of dyke intrusions in a vertical section. Then, we compare the efficiency of the two competing models (i.e. sloping topography *versus* thickening of the elastic–brittle lithosphere) in producing lateral changes of stress conditions that promote horizontal magma migration. Finally, we discuss the implications and limitations of our model.