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Magmatic cycles pace tectonic and morphological expression of rifting (Afar depression, Ethiopia)

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ABSTRACT

The existence of narrow axial volcanic zones of mid-oceanic ridges testifies of the underlying concentration of both melt distribution and tectonic strain. As a result of repeated diking and faulting, axial volcanic zones therefore represent a spectacular topographic expression of plate divergence. However, the submarine location of oceanic ridges makes it difficult to constrain the interplay between tectonic and magmatic processes in time and space. In this study, we use the Dabbahu–Manda Hararo (DMH) magmatic rift segment (Afar, Ethiopia) to provide quantitative constraints on the response of tectonic processes to variations in magma supply at divergent plate boundaries. The DMH magmatic rift segment is considered an analogue of an oceanic ridge, exhibiting a fault pattern, extension rate and topographic relief comparable to intermediate- to slow-spreading ridges. Here, we focus on the northern and central parts of DMH rift, where we present quantitative slip rates for the past 40 kyr for major and minor normal fault scarps in the vicinity of a recent (September 2005) dike intrusion. The data obtained show that the axial valley topography has been created by enhanced slip rates that occurred during periods of limited volcanism, suggestive of reduced magmatic activity, probably in association with changes in strain distribution in the crust. Our results indicate that the development of the axial valley topography has been regulated by the lifetimes of the magma reservoirs and their spatial distribution along the segment, and thus to the magmatic cycles of replenishment/differentiation (<100 kyr). Our findings are also consistent with magma-induced deformation in magma-rich rift segments. The record of two tectonic events of metric vertical amplitude on the fault that accommodated the most part of surface displacement during the 2005 dike intrusion suggests that the latter type of intrusion occurs roughly every 10 kyr in the northern part of the DMH segment.

1. Introduction

The variability of magma production in the mantle and subsequent transfers of magma to the crust, and potentially the surface, are fundamental, first-order controls on the style and morphology of mid-ocean ridges (MOR) (MacDonald and Atwater, 1978; Carbotte et al., 2001; Macdonald, 2001; Macdonald et al., 2005). Few quantitative constraints exist on how magmatic and tectonic processes are coupled via dyke injection and fault slip in such a way as to maintain crustal accretion and produce typical axial morphologies along a magmatic rift at the scale of a few to tens of thousands of years (White et al., 2006; Standish and Sims, 2010; Grandin et al., 2012). The building of ridge topography results from competition between tectonic activity, which creates the topography via normal faulting, and magmatic activity, which tends to erase the topography by filling the growing depression with volcanic products (Behn et al., 2006). Many stud-

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ies have documented the contributions of diking and faulting to the extension process (most notably in Iceland), on both long-term (Mastin and Pollard, 1988; Forslund and Gudmundsson, 1991) and short-term timescales (Rubin, 1992; Gudmundsson, 2003; Doubre and Peltzer, 2007; Calais et al., 2008; Biggs et al., 2009; Dumont et al., 2016). However, an important yet unaddressed issue is the quantification of this tectonic activity in terms of variations in magmatic activity in the long term. In particular, is the tectonic activity constant through time or, on the contrary, is it related to the magmatic processes?

To address this question, we examine the subaerial Dabbahu/Manda–Hararo (DMH) Afar active magmatic rift segment (Ethiopia, Fig. 1A), which represents a natural laboratory for investigating topographic evolution in response to complex magmatic and tectonic interactions at divergent plate boundaries. Although the DMH rift segment is currently at the ocean–continent transition stage, its morphology and extension rates are comparable to those of intermediate to slow-spreading ridges, suggesting that the same processes are at work in the two settings.

The ∼55 km long DMH rift segment in Central Afar is characterised by a narrow axial graben (∼3 km) flanked by <100 m-high fault scarps. The total relief of the axial valley is <300 m at the DMH rift, typical of intermediate- to slow-spreading MOR morphologies and similar to that observed in Iceland. (Fig. 1, Gudmundsson, 2005.) Four magmatic reservoirs have been identified along the DMH segment (Fig. 1) (Grandin et al., 2009; Wright et al., 2006, 2012; Ebinger et al., 2008; Barisin et al., 2009; Field et al., 2012): two axial magmatic centres at the northern end of the segment; one below Dabbahu volcano; and one midway along the length of the segment, referred to as the mid-segment magma chamber (MSMC). Dabbahu and the MSMC both possess a shallow reservoir that is connected to a deeper reservoir below 15 km depth (Grandin et al., 2010b; Field et al., 2012). The shallow Dabbahu magma storage area may consist of a series of stacked sills at 1 to 5 km depth (Field et al., 2012). In addition, two magmatic reservoirs are located off-axis: Gabho volcano (in the north-east) and the Durrie volcanic centre (in the west) (Fig. 1). In September 2005, a major intrusion ruptured the entire length of the DMH rift, initiating a 5-yr-long rifting episode that involved 13 further smaller dike intrusions and that highlighted complex magmatic interactions between three of the magmatic centres: Dabbahu, Gabho and the MSMC (Wright et al., 2012; Grandin et al., 2010a, 2010a; Hamling et al., 2009). The major dike that initiated the crisis was modelled to be 60 to 70-km-long, ∼1–2 km^3 intrusion and produced 4 m of average regional horizontal opening (Wright et al., 2012, 2006; Grandin et al., 2009). Thirteen subsequent and smaller dikes (∼0.1 km^3 each) were intruded between 2005 and 2010, all emitted from the MSMC and producing a lesser degree of deformation (Buck, 2006; Hamling et al., 2009; Grandin et al., 2010a, 2010b; Belachew et al., 2011; Wright et al., 2012). The transfer of magma to shallow depths activated numerous surface faults and fissures along the length of the dike intrusion (Fig. 2A, Rowland et al., 2007; Wright et al., 2006; Grandin et al., 2009; Dumont et al., 2016). The ground displacement associated with this first dike intrusion was too large in the near-field discriminate the role of individual faults using geodetic approaches (Wright et al., 2006; Grandin et al., 2009). However, the modelling of Grandin et al. (2009) and, more recently, the analysis of surface fault displacements during inter-diking periods between 2005 and 2010 at the DMH rift segment (Dumont et al., 2016) suggest that only faults dipping toward the dike were able to release the dike-induced stresses. In the DMH rift segment, a substantial opening component also prevails, but no evidence for reverse faulting has been identified. Similar phenomena have also been observed in Iceland during the Krafla crisis

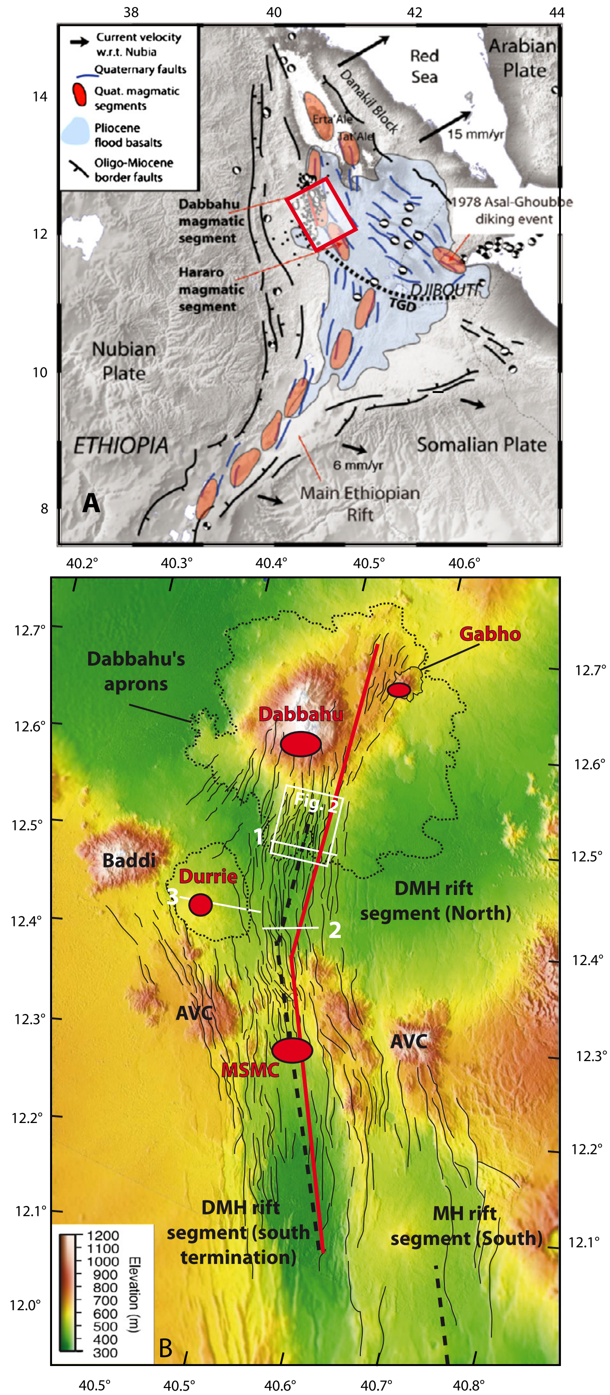

Fig. 1. Regional geological setting. A: Regional setting of the Afar Rift and location of the Dabbahu/Manda Hararo segment – modified after (Ebinger et al., 2008). B: Dabbahu/Manda Hararo rift magmatic complexes and fault pattern. The black dotted line shows the principal rift axis, defined as the lowest point of the depression. White lines labelled 1, 2 & 3 correspond to the topographic sections in Fig. 4. The red line indicates the location of the 2005 dyke intrusion and fault zone reactivation. Note that the September 2005 dike (red line) did not intrude on the alignment of the rift axis, but deviated slightly to the east, below the rift shoulder. Red circles indicate the different magma bodies, located below the Dabbahu and the Gabho volcanoes, and at the mid-axis: the mid-segment magma chamber (MSMC) and the slightly off-axis Durrie volcano. The main study areas are the following: one cross-section located at the contact of the axial depression with the segment-tip volcano of Dabbahu (profile 1), and two cross-sections located at the mid-length of the segment, ranging from the mid-axis to the recent (15 ka; Medynski et al., 2015) slightly off-axis Durrie volcanic centre (profiles 2 and 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)