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Mantle deformation during rifting: Constraints from quantitative microstructural analysis of olivine from the East African Rift (Marsabit, Kenya)

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ABSTRACT

Lherzolitic and harzburgitic peridotite xenoliths from the Marsabit volcanic field of the East-African Rift, Kenya, display a range of porphyroclastic to ultramylonitic textures that record intense deformation and strain localisation during decompression, cooling and exhumation of subcontinental mantle lithosphere during the early stages of continental rifting. Quantitative microstructural analysis by electron backscatter diffraction of both bulk fabrics and intragrain low-angle boundaries have been applied to these xenoliths to establish how deformation has evolved during this exhumation history. Bulk rock fabric analysis indicates the operation of (001)[100] (E-type) as the dominant slip system in the constituent olivines, with only one porphyroclastic xenolith recording the development of the classical (010)[100] (A-type) fabric. A weak E-type fabric is also present within the fine-grained matrix of the mylonitic and ultramylonitic xenoliths. Low-angle boundaries, preserved within individual olivine grains within the different xenoliths indicate the evolution of intra-grain slip systems from (010)[100] (A-slip) and (001)[100] (E-slip) in porphyroclastic peridotites, to dominant (001)[100] (E-slip) in the protomylonite and mylonite and dominant (100)[001] (C-slip) in the ultramylonite. Bulk fabric and intragrain low-angle boundary analyses are therefore concordant and indicate a systematic evolution of olivine slip systems from A-type to E-type to C-type during strain localisation associated with cooling during mantle exhumation. Both approaches confirm the dominant activity of the (001)[100] E-type slip system during rifting. However, the ultramylonites also provide the first evidence of [001] slip in such an environment. The activation of these two slip systems in olivine might be a useful indicator of an extensional rift margin setting in other peridotites.

1. Introduction

Mantle rocks brought to the Earth surface as xenoliths within volcanic rocks provide unique opportunities to investigate the petrological and microstructural evolution of the upper mantle from different tectonic environments (e.g. Boullier and Nicolas, 1975; Coltorti et al., 1999; Grégoire et al., 2000; Mercier and Nicolas, 1975; Skemer et al., 2010). Mantle xenoliths from continental rift systems have been widely studied in the past several decades, predominantly for geochemical purposes (e.g. Harvey et al., 2012; Ionov et al., 2002; Lenoir et al., 2000; Witt-Eickschen et al., 2003) and more rarely for understanding mantle deformation (e.g. Palasse et al., 2012; Vauchez et al., 2005). Despite these studies, the mechanical processes associated with thinning of the continental lithosphere and exhumation of subcontinental mantle lithosphere are still poorly understood.

One aspect of xenolith research that is starting to receive attention is the relationship between bulk fabrics and the intragrain microstructure (Gray, 2013; Gray et al., in press; Palasse et al., 2012). Such studies attempt to understand the complexities of mantle deformation that are not easily obtained from bulk fabrics alone. One driver for this type of research is that experimental deformation studies of olivine indicate that different slip systems may preferentially operate under different temperature–pressure–stress–water conditions (e.g. Jung et al., 2006) such that different tectonic environments may be characterised by the operation of distinct combinations of slip systems (Karato et al., 2008). For example, in extensional settings, A-type (010)[100] (A-type) or D-type may be the dominant slip systems observed in the lithosphere, and the asthenosphere is characterised by the combination of E- and C-type slip systems (e.g. Jung and Karato, 2001a, 2001b; Katayama et al., 2004; and references

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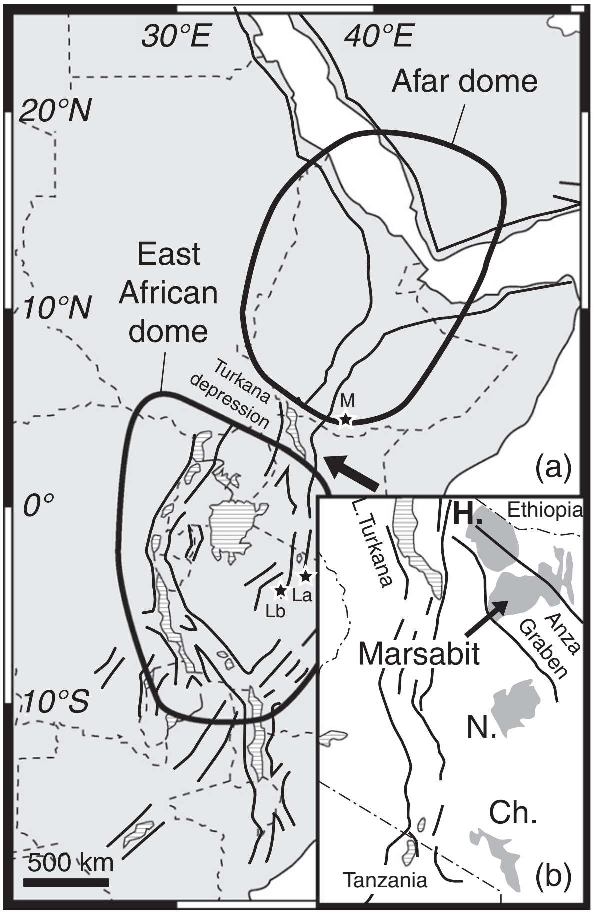

Fig. 1. Geological setting. (a) The East African Rift System, indicating the East African and the Afar domes, separated by the Turkana depression. Small stars indicate the position of some other xenolith-bearing volcanic localities (M: Mega; Lb: Labait; La: Lashaine). (b) Inset shows the main structural features of the Tertiary Kenya rift (N–S) and the Jurassic–Cretaceous Anza Graben (NW–SE). Quaternary volcanic fields are shown in light grey (H: Huri Hills; N: Nyambeni; Ch; Chyulu Hills) modified from Henjes-Kunst and Altherr (1992) (after Kaeser et al., 2006).

herein). Whereas the fore-arc regions of the supra-subduction zone mantle wedge may be characterised by the operation of B-type slip (e.g. Kneller et al., 2005).

The East African Rift System (EARS) is a classic example of a continental rift, exhibiting characteristic patterns of rifting, volcanism and plateau uplift. The EARS is a volcanically active tectonic environment associated with extension of the African continental lithosphere and as a consequence, mantle-derived xenoliths from Kenya (Marsabit province) provide the opportunity to investigate the nature and deformation recorded by the mantle underlying the active EARS. Moreover, the deformation microstructures recorded by xenoliths within kimberlitic magmas may yield information about deformation processes at the base of the continental lithosphere.

The aim of this study is to investigate the deformation processes and active deformation mechanisms in subcontinental upper mantle during the early stages of rifting. Our results from bulk rock fabrics and microstructures preserved in olivine porphyroclasts indicate a complex microstructural evolution and the activation of unusual slip systems, at a range of scales, associated with the progressive exhumation of the subcontinental mantle lithosphere during rifting. Our results provide a potential approach for the recognition of rift-related deformation in other areas of the world.

2. Geological setting

2.1. Geological framework

Marsabit belongs to a series of volcanic fields situated east of Lake Turkana, including Demo Dera (NE Marsabit), Huri Hills (N of Marsabit) and several smaller eruptive centres to the south (Kaisut, Laisamis, Merille) (Fig. 1). Marsabit lies within a topographic depression, in the Anza graben representing the eastward continuation of the so-called Turkana depression located between the Afar dome and the East African dome (Fig. 1). This zone of relatively low elevation (600 m average altitude) separates the East African plateau from the northern Afar plateau and is interpreted to represent the topographic expression of an older Mesozoic–Paleogene rift (Bosworth, 1992; Morley, 1999; Morley et al., 2006a, 2006b; Schull, 1988). The Anza Graben is believed to represent a failed branch of an upper Jurassic–lower Cretaceous rift associated with the separation of Madagascar and the African continent (Ebinger and Ibrahim, 1993; Greene et al., 1991; Morley, 1999; Reeves et al., 1987).

The timing of the initial rifting in the Anza Graben remains uncertain. Volcanic activity in Marsabit is temporally related to the development of the Kenya rift at 1.5–0.8 Myr (Brotzu et al., 1984; Key et al., 1989). However, the Marsabit field is not within the rift but forms an eastern branch of the EARS (Fig. 1). K–Ar dating of the Marsabit shield

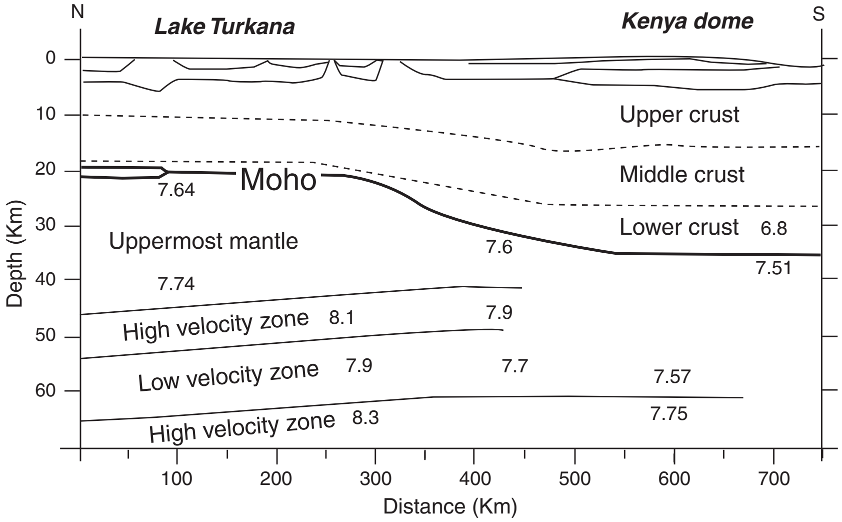

Fig. 2. Velocity model of the axial profile derived from ray-trace and synthetic seismogram modelling between Lake Turkana and Kenya Dome. P-wave velocities are indicated in km/s (after Keller et al., 1994).