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Deformation, hydration, and anisotropy of the lithospheric mantle in an active rift: Constraints from mantle xenoliths from the North Tanzanian Divergence of the East African Rift

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ABSTRACT

We have analyzed the microstructures and crystal preferred orientations (CPO), and calculated the seismic properties of 53 mantle xenoliths from four localities within the North Tanzanian Divergence of the East African rift: two within the rift axis and two in the transverse volcanic belt. Olivine OH concentrations were measured in 15 xenoliths.

Most samples have harzburgitic to dunitic compositions and high olivine Mg#. Microstructures and olivine CPO patterns vary strongly depending on the location. In-axis peridotites display mylonitic to porphyroclastic microstructures, which record recent deformation by dislocation creep. Highly stretched orthopyroxenes in mylonites indicate that the deformation was initiated under high stress and probably low temperature. Orthopyroxene replacement by olivine in mylonitic and porphyroclastic peridotites suggest syn-kinematic melt–rock reactions and further deformation under near-solidus conditions. Exsolutions in orthopyroxene imply significant cooling between melt-assisted deformation and xenolith extraction. Late metasomatism is evidenced by the occurrence of veins crosscutting the microstructure and interstitial clinopyroxene and phlogopite. Axial-[100] olivine CPOs predominate, suggesting activation of the high temperature, low pressure [100] {0kl} slip systems and, probably, transtensional deformation. In the volcanic belt, Lashaine peridotites display very coarse-granular textures, indicating deformation by dislocation creep under low deviatoric stress conditions followed by annealing. Axial-[010] olivine CPOs are consistent with transpressional deformation or simultaneous activation of the [100](010) and [001](010) slip systems. Intermediate microstructures and CPOs in Olmani suggests heterogeneous deformation within the volcanic belt. Olivine OH concentrations range between 2 and 12 ppm wt. H_2O. No systematic variations are observed between in- and off-axis samples. Maximum P wave azimuthal anisotropy (AVp) ranges between 3.3 and 18.4%, and the maximum S wave polarization anisotropy (AVs) between 2.3 and 13.2%. Comparison between seismic properties of in-axis peridotites and SKS splitting data suggests transtensional deformation in the lithospheric mantle beneath the rift.

1. Introduction

Continental rifting is a complex process that results in localized thinning and, in some cases, in disruption of a continental plate. While the surface expression of this deformation is clear and usually well understood, little is known about how the lithospheric mantle deforms to accommodate rifting. The widely differing surface expression of continental rifting has led to contrasting lithospheric extension models. McKenzie (1978) proposed a symmetrical rift model, where the lithosphere deforms by homogeneous thinning and stretching in response to far field extensional forces. To account for the observations in the Basin and Range, Wernicke (1981, 1985) proposed an asymmetrical extension model, in which the deformation is localized on a lithospheric-scale detachment fault. However, such models cannot account for the narrow rift valley and the strong mantle lithosphere thinning observed in East Africa (Dugda et al., 2007, 2009). The latter observations are in better agreement with the Nicolas et al. (1994) model, where rifting occurs via lithospheric rupture and rise of an asthenospheric wedge within the lithospheric mantle. The later model has been further developed by Vauchez et al. (1997) and Tommasi and Vauchez (2001), who, based on the analysis of the influence of inherited structures on the localization of continental breakup, suggested that most major rifts start forming through a transtensional deformation regime produced by the reactivation of the olivine crystallographic fabric frozen in the lithospheric mantle. Numerical models in which the upper mantle has an anisotropic viscosity controlled by the evolution of olivine crystallographic orientations corroborate this

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assumption (Tommasi et al., 2009). Rheological heterogeneities, both in the crust and in the mantle, also have a major effect on the localization of rifting (e.g., Dunbar and Sawyer, 1989; Nyblade and Brazier, 2002; Vauchez et al., 1997).

In addition to being deformed by an extensional regime, the lithosphere within an active rift is often subjected to extensive magma percolation. Dyke intrusions have been proposed to help initiate extension in a thick continental lithosphere (Buck, 2006). The major role of magmas in rifting has been corroborated by seismic anisotropy data in the Afars, which unambiguously point to aligned melt pockets throughout the crust and lithospheric mantle (Bastow et al., 2010; Kendall et al., 2005). At smaller scales, the presence of melt may result in weakening of mantle rocks (Hirth and Kohlstedt, 2003; Zimmerman and Kohlstedt, 2004). It may trigger strain localization if melt is heterogeneously distributed (e.g., Le Roux et al., 2008) or promote homogeneous deformation if it is homogeneously distributed through a large volume (Vauchez et al., 2012). Melt- or fluid-rock reaction may also result in softening through crystallization of weaker phases and/or associated grain size reduction and phase mixing (e.g., Dijkstra et al., 2002; Soustelle et al., 2010).

Mantle xenoliths provide a valuable means by which to study the deformation of mantle lithosphere during rifting. They allow for quantification of the hydration state and characterization of melt–rock reactions and of their timing relative to the deformation. Moreover, the analysis of the microstructures and crystallographic preferred orientations (CPO) bring constraints on the deformation mechanisms and conditions in the lithospheric mantle below active rifts. In the present study, we explore the relations between deformation, melt or fluids percolation, and hydration in a series of mantle xenoliths from four localities in the North Tanzanian Divergence region (East African Rift). This region, still in the early stages of rifting, offers favorable conditions to study the expression of rifting on the lithospheric mantle. In addition, we estimate the seismic anisotropy of these rocks based on their CPO and mineralogical composition and compare these results to seismic anisotropy measurements performed within and around the East African Rift.

2. Geological setting

The East African Rift is one of the few active continental rifts on Earth. It extends over ~4000 km, from the Afar triple junction in the Red Sea to the Gulf of Mozambique (Fig. 1), mostly following the trend of older orogenic belts (Nyblade and Brazier, 2002; Vauchez et al., 1997 and references therein). Rifting and volcanism started 35 Ma ago in Ethiopia and northern Kenya (MacDonald et al., 2001; Morley et al., 1992). It migrated southwards, reaching southern Kenya 8–5 Ma ago (Cerling and Powers, 1977; Crossley and Knight, 1981). The youngest section of the East African Rift splits into two branches around the Tanzania craton. In the Eastern branch, extension is accompanied by intense magmatic activity concentrated within the rift valley. The region experiences relatively intense present-day seismic activity, with earthquakes mainly located within the rift valley or in its immediate surroundings (e.g., Albaric et al., 2010; Nyblade et al., 1996). A major faulting episode at 1.0 ± 0.2 Ma (MacIntyre et al., 1974) gave rise to the present-day rift valley morphology. In addition, off-axis volcanic activity is observed in the North Tanzanian Divergence, south of which rifting occurs in a more diffuse manner, with deformation accommodated in many branches (Fig. 1). Seismic studies show that crustal and lithospheric thicknesses in this young rifting domain vary between 36–44 km and 100–150 km, respectively (Dugda et al., 2009; Julià et al., 2005).

Mantle xenoliths occur in both in- and off-axis volcanoes, providing an exceptional opportunity to study the tectono-thermal evolution of the mantle lithosphere in response to the progression of the East African Rift along the boundary between the Tanzanian craton and the Neoproterozoic Mozambique Belt. The present study focuses on 53 mantle xenoliths from four localities from the North Tanzanian Divergence (Fig. 1): two within the rift valley (Pello Hill and Eledoi) and

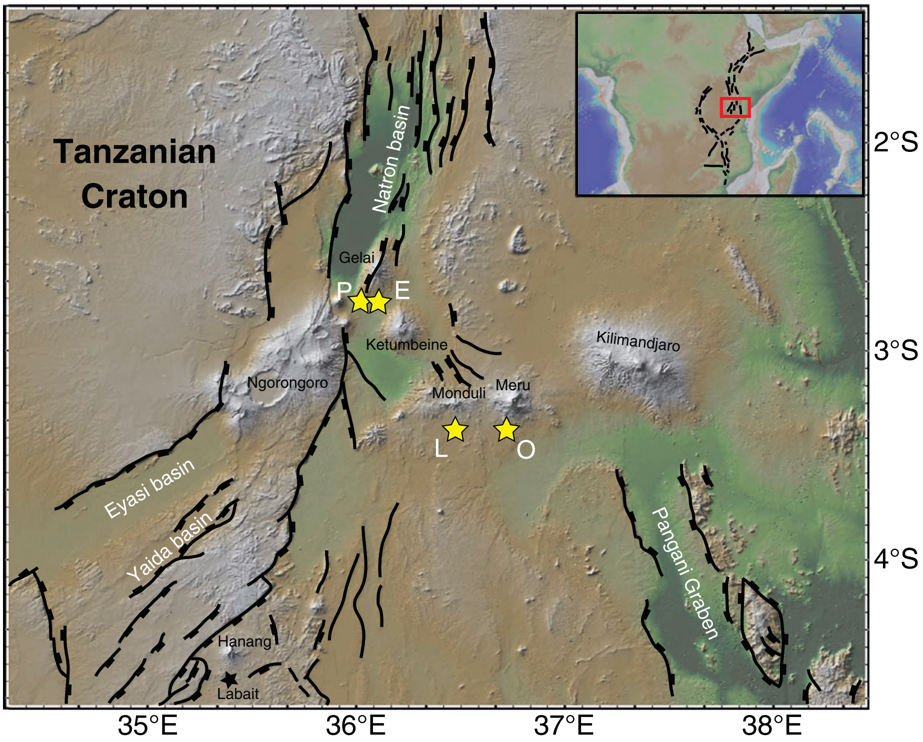

Fig. 1. Digital topographic map (http://www.geomapapp.org, topography data from Ryan et al. (2009) showing the North Tanzania Divergence and the location of the xenolith localities studied here (P: Pello Hill, E: Eledoi, L: Lashaine, and O: Olmani), as well as the Tanzanian craton and main volcanoes. Labait is another locality containing abundant mantle xenoliths, which microstructures and crystal preferred orientations were studied by Vauchez et al. (2005).