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Torque exerted on the side of crustal blocks controls the kinematics of Ethiopian Rift

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A B S T R A C T

Plate tectonic stress at active plate boundary can arises from 1) a torque applied on the side of lithospheric blocks and 2) a torque at the base of the lithosphere due to the flow of the underlying mantle. In this paper we use a simple force balance analysis to compare side and basal shear stresses and their contribution in driving kinematics and deformation in the Ethiopian Rift (ER), in the northern part of the East African Rift System (EARS). Assuming the constraints of the ER given by the dimension of the lithospheric blocks, the strain rate, the viscosity of the low velocity zone (LVZ) and the depth of the brittle−ductile transition zone, the lateral torque is several orders of magnitude higher than the basal torque. The minor contribution of basal torque might be due to low viscosity in the LVZ. Both Africa and Somalia plates are moving to the ”west” relative to the mantle and there are not slabs that can justify this pull and consequent motion. Therefore, we invoke that westerly oriented tidal torque on Africa and Somalia plates in providing the necessary side torque in the region. This plate motion predicts significant sinistral transtension along the ER and rift parallel strike-slip faulting similar to the estimated angular velocity vector for tectonic blocks and GPS observations. Vertical axis block rotations are observed in areas where the lithospheric mantle is removed and strain is widely distributed.

1. Introduction

Torques acting on the lithosphere determine plate tectonics. Computing models of the origin and magnitude of these forces have proposed, e.g., either bottom up or top down mantle convection (see Doglioni et al., 2007, and references therein for discussion). The torques may originate either from the side of the plates transmitted through the lithosphere or shear traction at the base of plates due to the motion of the plates over the asthenosphere. In the Ethiopian Rift (ER), side torques may be due to the ”westerly” directed tidal drag (Scoppola et al., 2006; Cuffaro and Doglioni, 2007; Riguzzi et al., 2010), Africa and Somalia plates interaction, and gravitational potential energy (GPE) variations. Side torques from plate interactions are due to the Africa and Somalia motion relative to the mantle. Africa and Somalia plates move towards NW in deep (Gripp and Gordon, 2002) and SSW in shallow (Cuffaro and Doglioni, 2007; Muluneh et al., 2014) hotspot reference frames. Coblentz and Sandiford (1994) estimated the magnitude of GPE and intraplate stress in Africa, which indicated the northward motion of the Africa. However, unlike the usual assumption, according to paleomagnetic data (Besse and Courtillot, 2003), Africa has a southward component of motion, supporting the shallow hotspot reference frame (Muluneh et al., 2014). Recently, Stamps et al. (2014) found deviatoric stress resulting from GPE gradient is sufficient to drive Africa and Somalia plate separation and Quaternary to Recent deformation in East African Rift System (EARS).

Others have proposed that the shear at the base of lithosphere due to the northeast ward flow of mantle may drive plate tectonics in the region. For instance, the mantle flow model of Quere and Forte (2006) would infer that the traction beneath the plates drives and sustains rifting. This conclusion is similar to Bird et al. (2008), who argued that the viscous coupling between the lithosphere and underlying mantle drives plate tectonics. Pavoni (1993) also showed that shear traction by convecting mantle at the base of the African lithosphere explains the observed kinematics in the region. GPS study by Calais et al. (2006) proposed that opening of the EARS is driven by the NE mantle flow pushing the cratonic keels

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between the western and eastern branches of the EARS.

Both the side and base torque analyses depend on the viscosity of the asthenosphere which ranges from 10^{19} to 10^{21} Pa s (Cathles, 1975). However, recent estimates of the viscosity in the low velocity zone (LVZ), at the base of the lithosphere, in the upper asthenosphere can be a few order of magnitude lower than previous estimates, especially if computed in a horizontal shearing mantle rather than vertically loaded or unloaded (Doglioni et al., 2011). The lower viscosity in the LVZ is assumed to decouple Africa and Somalia plates from the underlying mantle and controls the kinematics of the Ethiopian Rift (Muluneh et al., 2014).

Moreover, the amount and rate of block rotation are expected to be different depending on whether the kinematics is driven from the sides or the base of blocks (Molnar, 1988). Lamb (1994) introduced the force balance approach to compare the sources of stress that drive tectonics and block kinematics along active plate boundaries.

Motion of crustal blocks in ER (Fig. 1), due to the active separation of Africa and Somalia plates, is evidenced by paleomagnetic data (Kidane et al., 2009), analog modeling (e.g., Corti et al., 2013), GPS observations (Kogan et al., 2012) and tectonic interpretations (Casey et al., 2006). Compilation of the aforementioned kinematic constraints led Muluneh et al. (2014) to attribute lithospheric movements to stress transmitted through the side of plates as a result of WSW-ward motion of Africa and Somalia plates relative to shallow mantle reference frame.

In this paper, we compare the different torques applied to the Ethiopian Rift using the force balance approach (Lamb, 1994). Tectonic and paleomagnetic observations of plate rotations are integrated into our analysis to evaluate the kinematic consequences of the potential torques.

2. Deformation and decoupling at the LVZ

Coupling at the lithosphere–asthenosphere interface has long been assumed to drive plate tectonics. This has been inferred by several geodynamic and seismic anisotropy studies (e.g., Bird et al., 2008). However, recent modeling studies indicate the heterogeneity of mantle in density and viscosity both vertically and horizontally (Panza et al., 2010; Doglioni and Panza, 2015; Doglioni and Anderson, 2015). Meanwhile, the presence of LVZ at the lithosphere–asthenosphere interface hints at possible decoupling and reduction of the drag at the base of the lithosphere and hence allows differential rotation between the lithosphere and the underlying mantle (e.g., Cuffaro and Doglioni, 2007). Conrad and Lithgow-Bertelloni (2006) argued that low-viscosity asthenosphere decreases traction magnitudes by a smaller amount and is important only if it is >100 km in thickness. Doglioni et al. (2011) showed that the decoupling is responsible for westward drift of the lithosphere. Recent work by Naif et al. (2013) identified the presence of thin, partially molten channel of low viscosity layer beneath the oceanic lithosphere that is assumed to detach the underlying mantle from the lid. This layering and the presence of a low-velocity layer has been detected also beneath continental realms such as North America (Rychert et al., 2005; Yuan and Romanowicz, 2010). Moreover, shearing in the LVZ indicates accommodation of differential motion between the lithosphere and deeper mantle (Kennedy et al., 2002). LVZ is incapable of transmitting strong horizontal shear stresses and could provide the decoupling mechanism between plate and deep mantle required to balance the force on the plates (Craig and McKenzie, 1986). The effective viscosity of this layer is 1.5×10^{19} Pa s. Jordan (1974) and Ranalli (2000) claimed that the viscosity contrast necessary to allow full tidally-related decoupling between the mantle and the overlying plate should be 10^{11} Pa s. Traditionally, the classic viscosity value for the mantle is constrained by post-glacial rebound (PGR) analysis. The average viscosity value for asthenosphere using PGR analysis is 4×10^{19} Pa s (e.g., Doglioni et al., 2011, and references therein). However, in PGR analysis a relatively thin low viscosity layer in the asthenosphere remains unsolved or invisible due to the much deeper effect of a 1000 km wide ice cap loading (Scoppola et al., 2006). There is a general agreement among researchers on the existence of lower viscosity sub-lithospheric mantle, however, the viscosity contrast and thickness of the layer are still debated. The effective viscosity that measures the degree of linkage between lithosphere–asthenosphere ranges between 10^{15} and 10^{17} Pa s (Doglioni et al., 2011).

The thickness of LVZ in the East Africa is poorly constrained. Global (Dziewonski and Anderson, 1981) and regional (Panza et al., 2007) studies in the northern Africa show that this zone is found at a depth between 100 and 200 km. Higher than normal upper mantle temperature (e.g., Priestley et al., 2008) beneath Africa can be due to lower than average viscosity in the LVZ. Rooney et al. (2012) argued that the melt production in East Africa is assisted by the presence of volatiles (e.g. CO_2). Experimental studies indicate how the presence of carbonate melt can significantly reduce the viscosity in the LVZ, hence allowing the decoupling between the lithosphere and the underlying mantle. We consider that major decoupling between lithosphere and asthenosphere is taking place at the LVZ and the viscosity value ranging from 10^{15} to 10^{17} pa s is used for force balance calculation.

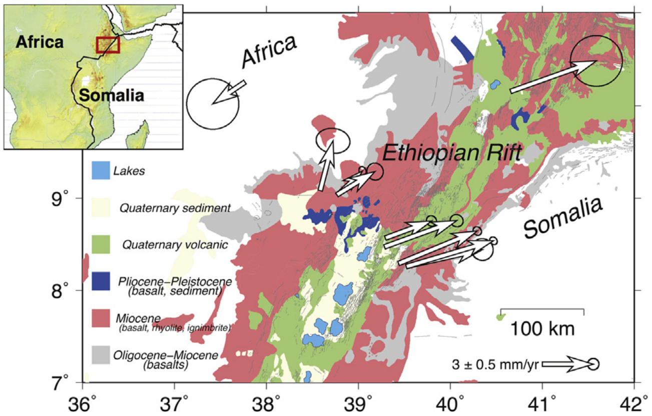

Fig. 1. Tectonic and geological map of the Ethiopian Rift (Mengesha et al., 1996). GPS velocity vectors (Kogan et al., 2012) show a systematic magnitude increase across the central ER. Thin gray lines are faults in the rift. Inset shows map of East Africa and present study area with open red box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Comparison of side and basal torques in the Ethiopian Rift

In ER, side torque can arises from Africa and Somalia plates interaction relative to the mantle. In the case of relative Somalia–Africa plate interactions, the motion vectors are oriented perpendicular to the ER axis and results in rift perpendicular deformation. Similar kinematic consequence is observed from the motion of the two plates relative to the deep hotspot reference frame (HSRF) (Gripp and Gordon, 2002) (Fig. 2a). Alternatively, Africa–Somalia motion relative to shallow HSRF (Muluneh et al., 2014) (Fig. 2b) and regional geodetic survey (Kogan et al., 2012) rather show that ER is characterized by significant rift-parallel left-lateral transtensional deformation. Several geophysical studies indicate the NE oriented regional mantle flow beneath the EARS. The pattern of this flow has been attributed to the South African superplume (Bagley and Nyblade, 2013). This flow of mantle