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Left-lateral transtension along the Ethiopian Rift and constrains on the mantle-reference plate motions

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ABSTRACT

We present the kinematics of the Ethiopian Rift, in the northern part of East African Rift System, derived from compilation of geodetic velocities, focal mechanism inversions, structural data analysis and geological profiles. In the central Ethiopian Rift, the GPS velocity field shows a systematic magnitude increase in ENE direction, and the incremental extensional strain axes recorded by earthquake focal mechanisms and fault slip inversion show ≈N100°E orientation. This deviation between direction of GPS velocity vectors and orientation of incremental extensional strain is developed due to left lateral transtensional deformation along the NE–SW trending segment of the rift. This interpretation is consistent with the en-échelon pattern of tensional and transtensional faults, plus the distribution of the volcanic centers, and the asymmetry of the rift itself. We analyzed the kinematics of the Ethiopian Rift also relative to the mantle comparing the results in the deep and shallow hotspot reference frames. While the oblique orientation of the rift was controlled by the pre-existing lithospheric fabric, the two reference frames predict different kinematics of Africa and Somalia plates along the rift itself, both in magnitude and direction, and with respect to the mantle. However, the observed kinematics and tectonics along the rift are more consistent with a faster WSW-ward motion of Africa than Somalia observed in the shallow hotspot framework. The faster WSW motion of Africa with respect to Somalia plate is inferred to be due to the lower viscosity in the top asthenosphere (LVZ—low-velocity zone) beneath Africa. These findings have significant implication for the evolution of continental rifting in transtensional settings and provide evidence for the kinematics of the Ethiopian Rift in the context of the Africa–Somalia plate interaction in the mantle reference frame.

1. Introduction

The North East Africa is characterized by the presence of several rift zones showing different tectonic settings and variable stages of evolution, from fully oceanic right-lateral transtension in the Gulf of Aden (e.g., Leroy et al., 2004, 2012), passing through an intermediate step of transition from continental to oceanic (Afar and Red Sea), to fully continental (East African Rift System) (e.g., Bohannon, 1986; Bonatti, 1985; Mohr, 1970; Rychert et al., 2012, and references therein). The East African Rift separates the continent into two sub-plates, i.e., Africa and Somalia (Fig. 1). The rift was mainly emplaced along the inherited eastern Africa Neoproterozoic belts (Kusky et al., 2003). In this paper we focus on the geodynamic models of the Ethiopian Rift based on available geological and geophysical data, showing how the regional studies can be better understood when integrated by the larger scale kinematic analysis of the involved plate motion relative to the mantle.

The Ethiopian Rift is located in the northern part of the East African Rift System and it principally represents the divergent margin between Africa and Somalia plates (Fig. 1). Generally, on the basis of geological and geochemical interpretations (e.g. Di Paola, 1970), the Ethiopian Rift can be considered as a system divided in two areas, the Main Ethiopian Rift (MER) in the central part, namely the Africa–Somalia plate boundary, and the Afar depression in the northern part, located at the triple junction of Africa, Arabia and Somalia plates. Here, we will refer to the Ethiopian Rift as the area of the continental rifting separating the Africa and Somalia plates, as also reported by other authors (e.g., Acocella et al., 2003; Bastow et al., 2005; Boccaletti et al., 1998; Keir et al., 2006). The transition from extension-dominated deformation in southern Ethiopian Rift (Acocella et al., 2011) to transtension-dominated deformation (e.g., Casey et al., 2006) coincides with the abrupt change in the orientation of the rift itself, from N–S to NE–SW. The area is surrounded by orthogonal NW–SE trending Mesozoic grabens in Kenya, Sudan and Yemen (e.g., As-Sauri et al., 2010).

The tectonic evolution of the Ethiopian Rift seems to be related to its trend and the geometric constraints of the extensional setting. The NE–SW trending pre-existing Precambrian suture zone beneath the Ethiopian and Somalia plateaus (Abdelsalam and Stern, 1996; Berhe, 1990) has influenced the Cenozoic structural development of the

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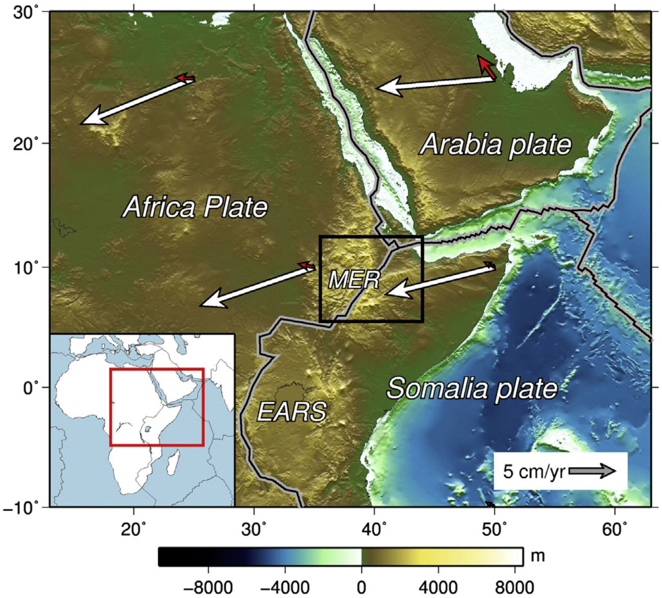

Fig. 1. Regional map of the Africa, Somalia and Arabia plates, including the local study of area (solid black box) along the Main Ethiopian Rift (MER). The white and red arrows show the direction of motion of Africa and Somalia plates relative to shallow (Cuffaro and Doglioni, 2007) and deep (Gripp and Gordon, 2002) hotspot frameworks, respectively. Plate boundary data are from Bird (2003). Note the orientation of the Ethiopia Rift relative to plate motion directions of Africa and Somalia relative to the mantle. EARS—East African Rift System. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

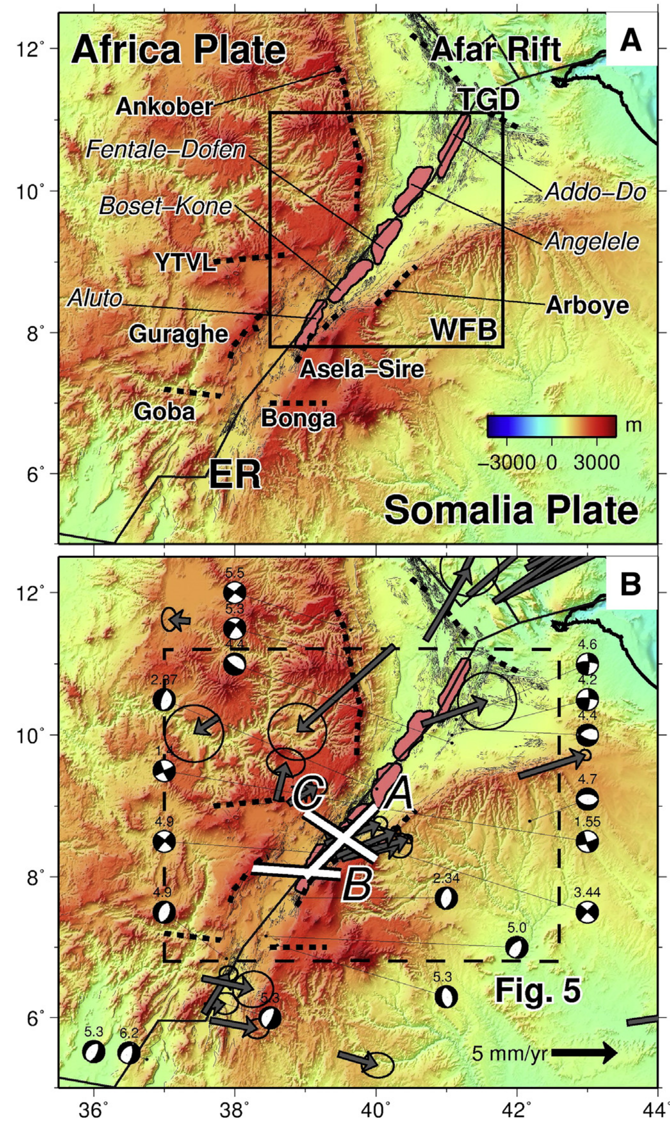

Fig. 2. A) Topographic image of the study area from GEBCO database (http: www.gebco.net) with names of main tectonic features of the Ethiopian Rift. Thick black dashed lines are the major border faults and tectonic lines. The red elongated areas are the tectono-magmatic segments. The rift floor faults in the black open box are the Wonji Fault Belts (WFB). B) GPS velocities in the Africa fixed reference frame (Kogan et al., 2012), and earthquake focal mechanisms from Ayele et al. (2006), Hofstetter and Beyth (2003), and Keir et al. (2006) with the associated numbers referring to the magnitude of events. The white lines (A, B and C) show the geological profiles of Fig. 3. The plate boundary is shown by black line. The black dashed open box is the coordinate range of Fig. 5. TGD Tendaho–Gobbad discontinuity, YTVL Yerrer–Tulu Wellel Volcanic. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

Ethiopian Rift (e.g., Bastow et al., 2005, 2008; Corti, 2008; Keranen and Klemperer, 2008). Numerous studies document the influence of inherited pre-existing weak zones on the location of extension, geometry of faults and continental break up (e.g., Corti et al., 2003; Van Wijk, 2005). In those studies, it is assumed that rifts following fabrics oblique to the regional extension direction tend to display a component of oblique slip.

Several models have been inferred for the tectonic evolution of Ethiopian Rift, depending upon the force that initiates rifting. Active rifting is related to the thermal erosion of a supposed plume beneath the lithosphere (e.g., Ebinger et al., 1989; Merle, 2011). However, Rychert et al. (2012) showed minimal or no deep plume influence on the Afar volcanism and rifting. Passive rifting suggests that lithospheric generated stress aided the rifting, and hence the isostatically mantle rebound can explain the magma generation in the Ethiopian Rift (e.g. Bonini et al., 1997; Bosworth et al., 1992).

Geodetic data indicate that the northern Ethiopian Rift is currently extending in a direction of about N100°E at 7 mm/yr (Calais et al., 2006; Fernandes et al., 2004; Sella et al., 2002). These works point at opening rates that cannot be extrapolated much backwards in time, because this would imply an opening close to the entire width of the rift (Garfunkel and Beyth, 2006). Geological studies, on the other hand, point at much slower opening rates for Ethiopian Rift with a rate of 2.5 mm/yr (Wolfenden et al., 2004). Geodetic measurements of Bilham et al. (1999) show that 80% of the strain in the Ethiopian Rift is localized in the Wonji Fault Belts (WFB) (Mohr, 1987) (Fig. 2A). This evidence has been used to suggest that during early stages of continental break-up deformation is accommodated by magmatic activity in the rift floor, and not by border faulting (Ebinger and Casey, 2001). On the contrary, recent geodetic observations (Kogan et al., 2012) (Fig. 2B) show that geodetic strain is distributed over a narrow area in the southern Ethiopian Rift (<10 km) where there is a standard thickness of continental lithosphere. Moving to the northern Ethiopian Rift, the extensional strain occurs over about 85 km, increasing up to about 175 km in the Afar region where the mantle lithosphere is almost absent. Pizzi et al. (2006) propose a model that considers a possible co-existence of both magmatic deformation at rift floor and brittle faulting at the rift margin.

In this paper, we investigate the active deformation along the Ethiopian Rift, by making use of the integrations of geodetic velocities, focal mechanism inversions, structural data analysis, and new geological profiles. We also analyze the kinematics of the study area in the mantle reference frame, e.g., the hotspots. First, we review and discuss the tectonic settings of the Ethiopian Rift. Three new geological profiles are provided here (A, B and C in Fig. 3, location in Fig. 2B), and also reported with the addition of heat flow, Bouguer gravity anomaly, and Moho depth data trend. Moreover, the crust and mantle structure are integrated with the analysis of the active deformation derived from geodetic and geophysical data, in the frame of global plate motions with

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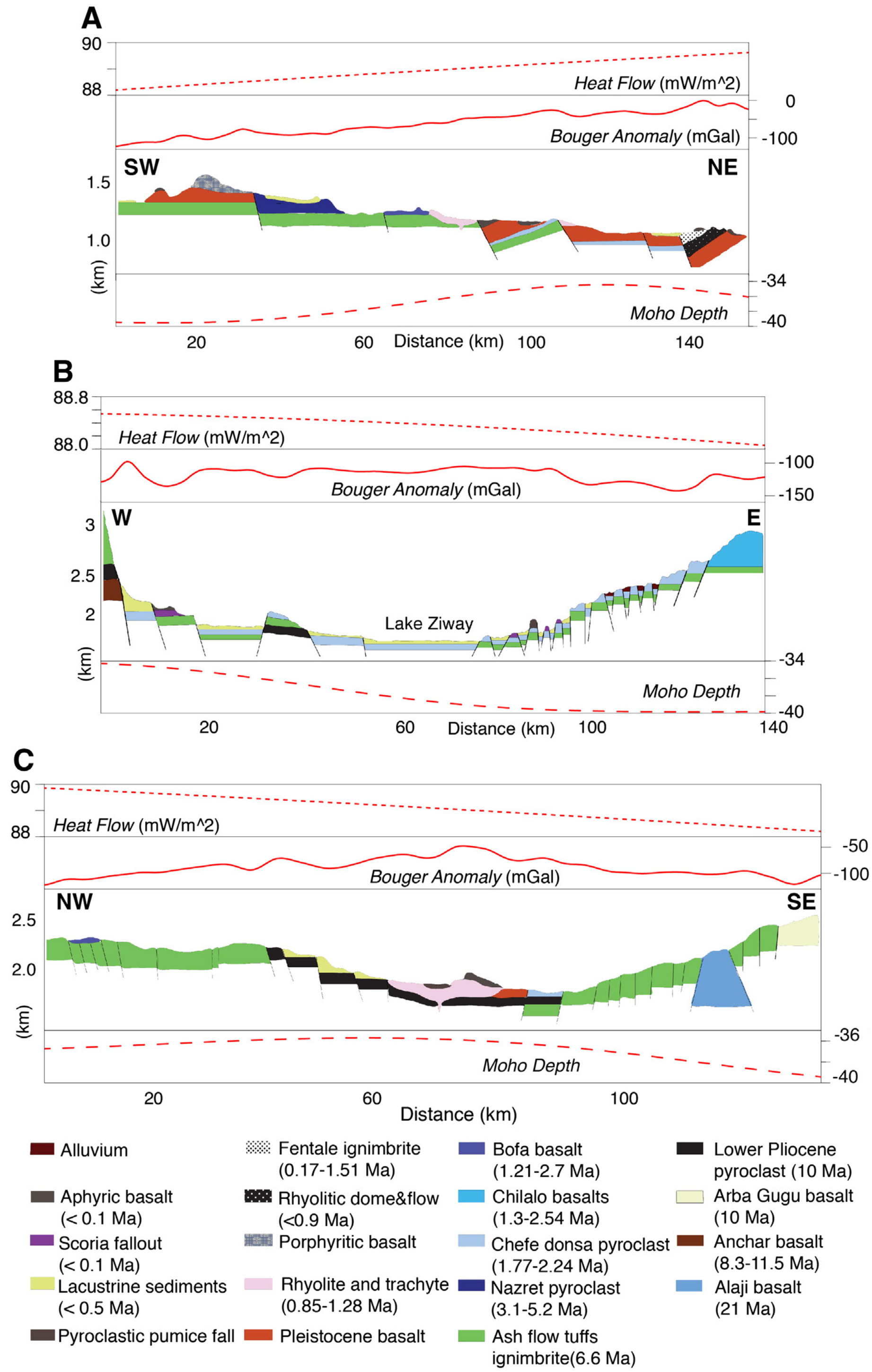

Fig. 3. Geological cross sections along (A) and across (B and C) the Ethiopian Rift (locations in Fig. 2B). Section A is drawn along the strike of the rift and the faults are cut obliquely. This explains the wider spacing among faults. Section B is across the Guraghe–Assela border faults; both sides of the rift are bounded by steep border faults. Section C is across the Boset volcano. There are no clear border faults on the eastern side of the rift, suggesting the western margin to be the master fault (Fig. 3B). The rift (both subsidence and horizontal extension) is accommodated by a number of spaced normal faults having conjugated domino fault systems in the two rift sides. The age data are from Chernet et al. (1998), Abebe et al. (2005), Williams et al. (2004) and Wolfenden et al. (2004). On the profiles, additional geophysical data have been included, to integrate different database trend, such as heat flow, Bouguer gravity anomaly, and Moho depth, derived by Shapiro and Ritzwoller (2004), Balmino et al. (2012), and Keranen et al. (2009) respectively. Thick black dashed lines are the major border faults, tectonic lines or volcanic alignments (see Fig. 2).

respect to the mantle (i.e., the hotspot reference frame). Relative to the mantle, the velocity vectors of Africa and Somalia plates control the kinematics in the Ethiopian Rift. Relative to deep hotspot reference frame (Gripp and Gordon, 2002), the plate motion vectors of Africa and Somalia strike perpendicular to the orientation of the Ethiopian Rift (Fig. 1). Hence, the rift would be characterized by pure extensional deformation opening at a rate of ≈7 mm/yr. In case of shallow hotspot framework (Crespi et al., 2007; Cuffaro and Doglioni, 2007) (Fig. 1), Africa and Somalia plates move almost parallel to the tectonic equator proposed by Crespi et al. (2007), plate motions being oblique to the Ethiopian Rift, and resulting in a more evident left-lateral transtensional deformation, as also suggested by geological and geophysical interpretations. The cross-sections of Fig. 3 cannot be properly balanced due to the left-lateral transtensional component of the Ethiopian Rift. Section A in Fig. 3 is along strike, whereas sections B and C are dip sections accounting for more than 10 km of horizontal extension. In this segment of the rift, the extension appears more concentrated along the western side where the normal or transtensional faults have a larger offset. The dip sections show regular spaced faulting with a conjugated domino arrangement in both sides of the graben.

2. Geodynamic settings

2.1. Tectonics

Structural and stratigraphic relations of volcanic rocks along both rift escarpments of central Ethiopian Rift indicate two stages of rift development (Woldegabriel et al., 1990). Early phase development in late Oligocene–early Miocene was characterized by a series of alternating and opposing half grabens. The half grabens evolved into a symmetrical rift during late Miocene. This sort of alternating rift asymmetry is common to the whole East African Rift System and is interpreted in many ways, including simple shear (Bosworth, 1987), mantle upwelling (Ebinger et al., 1989) and Moho asymmetry (Corti et al., 2006).

Three main fault systems have been collected from literature and distinguished in the Ethiopian Rift: (1) NNE-to-NE-trending border faults (Agostini et al., 2011; Casey et al., 2006), (2) en-échelon rift axis fault systems (Mohr, 1987), and ca. E–W oriented transverse faults (Boccaletti et al., 1998; Korme et al., 2004) (reported at regional scale in Fig. 2). To better characterize the study area, we present in Fig. 3 structural cross sections along and across the rift (Fig. 3A and B, C respectively, profile locations reported in Fig. 2) and the profiles were constructed to analyze the distribution of faults in the rift, with edge data provided by Chernet et al. (1998), Abebe et al. (2005, and references therein), Williams et al. (2004)and Wolfenden et al. (2004). Sections A and B in Fig. 3 are constructed using geological units reported in the 1:250,000 scale geological map of Nazret compiled by Berhe and Kazmin (1978). Cross section C in Fig. 3 is constructed using the geological map of Northern Main Ethiopian Rift (Abebe et al., 2005). Along each section, a topographic profile has been generated with the global 30 arc-second GEBCO grid (http://www.gebco.net). Faults are reported using the database described by Mohr (1987), Casey et al. (2006), and Agostini et al. (2011). Homogeneous legend has been made for all the lithologies. On the profiles, additional geophysical data have been added, to integrate different database trend, such as heat flow, Bouguer gravity anomaly, and Moho depth, derived by Shapiro and Ritzwoller (2004), Balmino et al. (2012), and Keranen et al. (2009) respectively.

The border faults are mainly defined by steep normal faults (Casey et al., 2006) with N30°E to N45°E orientation (Agostini et al., 2011) and with characteristic structural style of eastern and western margins. Border faults are steep, planar and penetrate deep into the crust. This characteristic morphology in the East African Rift is used to suggest that these border faults accommodate strain during the earliest stage of rifting (e.g., Morley, 1989).

The rift axis fault systems are described as a roughly N–S to N20°E trending fault system, namely the Wonji Fault Belt (WFB) (Mohr, 1987), which exhibits a number of sigmoidal, overlapping, right steeping en-échelon fault zones obliquely cutting the rift floor (Fig. 2A). Along the rift floor, Korme et al. (2004) noticed a 15 km wide and NW–SE striking graben filled by Pleistocene diatomites. The Ethiopian Rift shows offset around 7° 30′ N latitude along trend (Boccaletti et al., 1998; Fig. 2A) which, according to Korme et al. (2004), shows that the pre-existing Mesozoic NW–SE structures and related transfer zones may have locally controlled the propagation of the younger NE–SW striking rift margin faults and associated transfer zones.

Prior to 6 Ma, extensional deformation in the Ethiopian Rift was mainly accommodated by border faults. Between 6.6 and 3.5 Ma, a change in style of deformation occurred and shifted to the rift floor. Several models have been proposed to explain this transition of deformation from border faults to the rift floor. According to Bonini et al. (1997, 2005) and Boccaletti et al. (1998), Mio-Pliocene NW–SE to Quaternary E–W extension caused the observed migration of deformation. In this model, the focusing of magmatic activity along the WFB is a passive feature (Corti et al., 2003). On the other hand, Kendall et al. (2005) invoked the magma-assisted rift model for strain localization in the rift floor. This model states that the change in style of deformation is controlled by magma supply that reduces the tectonic stress required to break continental crust (Buck, 2004). Corti (2008) explained the deformation in the Ethiopian Rift as a result of constant ≈N100°E trending extension direction. In this model, all the evolution of the Ethiopian Rift is driven by the reactivation, under an oblique kinematics, of a NE–SW trending pre-existing lithospheric weakness. Fault length and segmentation of WFB faults show comparatively minor values than boundary faults (Kurz et al., 2007), which is in agreement with an oblique rifting-related origin of WFB faults (Clifton and Schlische, 2001).

The orientation of the border faults shows significant along-strike variations (Fig. 2A). In the South, the orientation of border faults is N–S, whereas it changes to NE–SW at around 80°N latitude. This change in orientation occurs in correspondence with the east–west trending Goba–Bonga lineament (Abbate and Sagri, 1980; Corti, 2009) (Fig. 2A). In the northern part of the rift, the eastern margin has a NE–SW orientation while the western margin is oriented N–S when approaching the Afar rift zone. Remarkable along strike variation of structural parameters occurs from Boset to Dofen Angelele magmatic segment (Fig. 2A) and the rift axis is dextrally offset. The density of faulting and the length of faults and fissures increase moving from the southern segment to the northern. Moreover, there are more scoria and spatter cones in the northern Ethiopian Rift compared to the southern part, which, according to Casey et al. (2006), represent the surface manifestation of dike injection at depth.

Along strike, the Ethiopian Rift shows variability, which is potentially caused by local variations in strain accommodation, i.e., transfer zones. Moreover, moving toward the Afar triple junction where the lithosphere is much thinner, the Ethiopian Rift becomes wider.

2.2. Crust and mantle structure

The crust and mantle structure of the Ethiopian Rift were investigated by the Ethiopian Afar Geoscientific Lithospheric Experiment (EAGLE) (Maguire et al., 2003). This study provides robust and detailed information on the nature of crust and mantle along the highly extended continental rift.

Fig. 4 shows Moho depth estimates from receiver functions and joint inversion of receiver functions and surface wave dispersion (Cornwell et al., 2010; Dugda et al., 2005; Keranen et al., 2009; Stuart et al., 2006). Crustal thickness beneath the rift shoulders is generally 40 km, except the SW shoulder which has a thickness of ca. 35 km. Away from the rift, there is a significant E–W oriented crustal thinning in a zone bounded by the Yerrer–Tullu Wellel Volcano Tectonic Lineament (YTVL) and the Goba–Bonga Lineament, separating the northwestern and southwestern shoulder of the rift (Fig. 4). This zone of crustal thinning coincides with an area of mafic intrusions occurring outside the rift, near the intersection of YTVL with the northern Ethiopian Rift (Keranen and Klemperer, 2008). The thin Moho beneath the southern Ethiopian Rift could be the result of two episodes of thinning, one during Mesozoic rifting and the other Cenozoic during the development of the East African Rift System (El Tahir et al., 2013).

Shear wave splitting analysis shows seismic anisotropy with a mean fast NE-trending orientation beneath the Ethiopian Rift (Bastow et al., 2010), becoming more or less parallel to the rift strike (Fig. 7). This anisotropy has been interpreted as due to aligned melt intrusion beneath the rift (Ayele et al., 2004; Bastow et al., 2010; Gao et al., 1997; Kendall et al., 2005) or due to a lattice-preferred orientation (LPO) of

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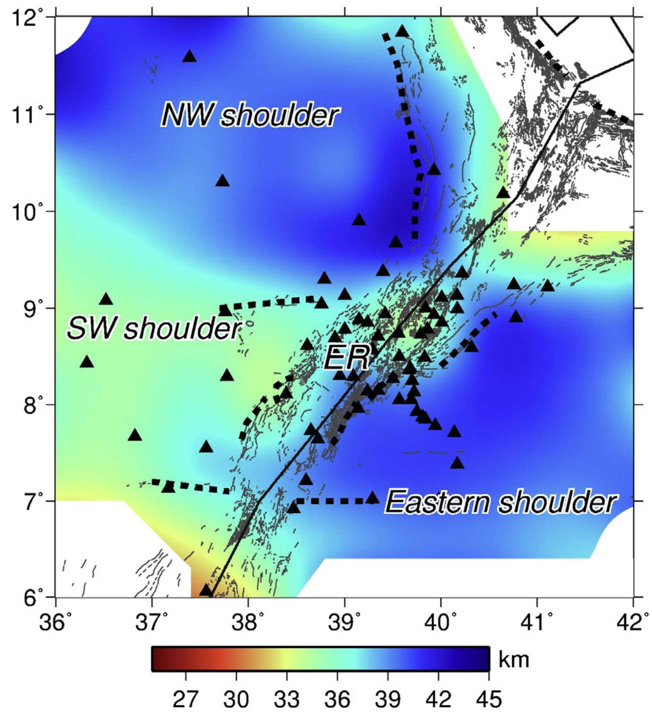

Fig. 4. Moho depth estimate in the Main Ethiopian Rift and surrounding areas. Crustal thickness beneath the rift shoulders is generally 40 km, except SW shoulder which has a thickness of 35 km. Near neighbor interpolation is used to produce the map, after compiling data from literatures (Cornwell et al., 2010; Dugda et al., 2005; Keranen et al., 2009; Stuart et al., 2006), and neglecting the areas where no stations are reported. Triangles are the stations used in the analysis. The thin gray lines are the faults in the rift. Thick black dashed lines are rift border faults. The plate boundary is shown by a black line.

olivine inherited and preserved from Paleozoic orogenic events (Gashawbeza et al., 2004). The observed anisotropy in the Ethiopian Rift and Ethiopian plateau has an optimal depth of 300 km (Gao et al., 2010). This depth range is significantly deeper than the base of the lithosphere in the area, which is less than 100 km (Pasyanos, 2010; Priestley et al., 2008). This argues against the aligned melt intrusion as a source of anisotropy (Gao et al., 2010). According to Gao et al. (2010), the Precambrian lithospheric suture (Gashawbeza et al., 2004) cannot fully explain the observed anisotropy since the splitting delay time is smaller for the thinner Neo-proterozoic lithosphere in the Afar (Ayele et al., 2004; Bastow et al., 2010). Gao et al. (2010) and Gashawbeza et al. (2004) reject the LPO with a fast direction parallel to plate motions relative to the mantle (Gripp and Gordon, 2002) as a cause of seismic anisotropy since the splitting direction is at high angle to the plate motion. However, plate motion relative to the mantle depends on the adopted hotspot reference frame (i.e., deep or shallow, or deeper or intra-asthenospheric decoupling zone, Cuffaro and Doglioni, 2007). The LLAMA, Laminated Lithologies and Aligned Melt Accumulations (Anderson, 2011), or shear boundary layer may explain the seismic anisotropy in the decoupling occurring at the lithosphere base (Panza et al., 2010).

In Tanzania and Kenya, fast polarizations parallel the eastern and western rift system that surrounds the Tanzanian craton (e.g., Gao et al., 1997). Walker et al. (2004) interprets this splitting pattern in terms of number of mechanisms including asthenospheric flow beneath and around the moving Tanzanian craton keel, asthenospheric flow from north of Kenya, fossilized anisotropy in the lithosphere due to past orogenic events and aligned magma filled-lenses beneath the rifts. The lithosphere–asthenosphere boundary beneath the Ethiopian Rift lies at a depth of about 70 km underlined by anomalous low velocity zones (LVZ) in the upper asthenosphere (Bastow et al., 2005, 2008). Global studies show that this zone is characterized by partial melting (Doglioni et al., 2011; Panza et al., 2010). Low-velocity anomaly (LVA) in East Africa is usually explained as a result of anomalously high mantle temperature in the region (e.g., Benoit et al., 2006). Adams et al. (2012) find a plateau-wide low velocity anomaly beneath the East African plateau at a depth of >225 km. This LVA has a width and thickness larger than is typically expected for a single plume head (Adams et al., 2012). Dugda et al. (2007) showed that the mantle lithosphere has been removed beneath the Ethiopian Rift. The absence of lithospheric mantle beneath the rift has long been used to infer the presence of mantle plume. The recent work by Rychert et al. (2012) argues against this idea and showed minimal or no plume influence for the recent activity in the absence or very thin lithospheric mantle in the Afar rift. Moreover, Rooney et al. (2012) show that the mantle temperature in East African rift is toward the lower values of global temperature range associated with large igneous provinces (LIPs). The magma production in the East African Rift system has been inferred as associated with elevated mantle temperature relative to ambient mantle, but lower temperature with respect to the so called large igneous provinces (LIPs, Rooney et al., 2012). According to the same authors, the low-velocity seismic anomaly in the LVZ can be interpreted as a result of compositional heterogeneity in the mantle (e.g., CO_2-rich).

3. Deformation mechanisms from geodetic and geophysical data

Global Positioning System (GPS) geodetic networks have also been used to measure short duration rates and kinematics of deformation in the Ethiopian Rift (Bendick et al., 2006; Bilham et al., 1999; Jestin et al., 1994; Kogan et al., 2012; Pan et al., 2002; Pizzi et al., 2006). Here we discuss the regional strain, mainly characterizing the direction of the extension, in the Ethiopian Rift by considering GPS velocities relative to the Africa fixed reference frame, obtained by Kogan et al. (2012).

They adopted geodetic data from GPS surveys with observations at 29 geodetic monuments traversing the Ethiopian and Afar rifts, providing the most reliable GPS related velocity field currently available for the area. The quantity and distribution of the sites and the length of time series of observations exceed that of previous studies in the region. The GPS velocity fields show a general increase in magnitude in the central Ethiopian Rift from 2.91 to 5.36 mm/yr moving toward the East (Fig. 5). The increase in velocity continues across the Assela–Arboye border fault with the same ENE trend. The general alignment of velocities indicates that the deformation field is dominated by transtension in the central and northern Ethiopian Rift as a result of ENE motion of Somalia in a fixed Africa frame (Fig. 5).

To evaluate the mean direction of the extension derived by geodetic data, we compute geodetic strain rates by making use of the available GPS velocity field obtained by Kogan et al. (2012), and of the public domain software SSPX for the inversion of GPS velocity vectors (Allmendinger et al., 2012; Cardozo and Allmendinger, 2009). The obtained result is reported in the barycenter of the GPS site network used (Fig. 5) and compared with the structural fault slip data of Agostini et al. (2011) (Fig. 5 and Table 1).

Moreover, we invert groups of earthquake focal mechanisms for components of reduced strain rate tensors to characterize seismogenic deformation, using the public software FaultKin 5.5.0, provided by Allmendinger et al. (2012) (Fig. 5 and Table 1).

Hofstetter and Beyth (2003) and Keir et al. (2006) determined the seismic pattern in the Ethiopian Rift. Earthquake clusters usually occur parallel to faults and volcanic centers to depths of less than 14 km (Keir et al., 2006). Although, most focal mechanisms show normal dip-slip movement, some mechanisms around Fentale and Boset magmatic segments have a left-lateral strike slip sense of motion (e.g., Keir et al., 2006). The strike slip focal mechanism data indicate north–south shortening (N–S oriented P axes) while the normal faults accommodate roughly east–west extension (E–W oriented T axes) (Fig. 2), although a dispersion of the orientation can be observed. However, all these focal mechanisms show that strain is partitioned between normal

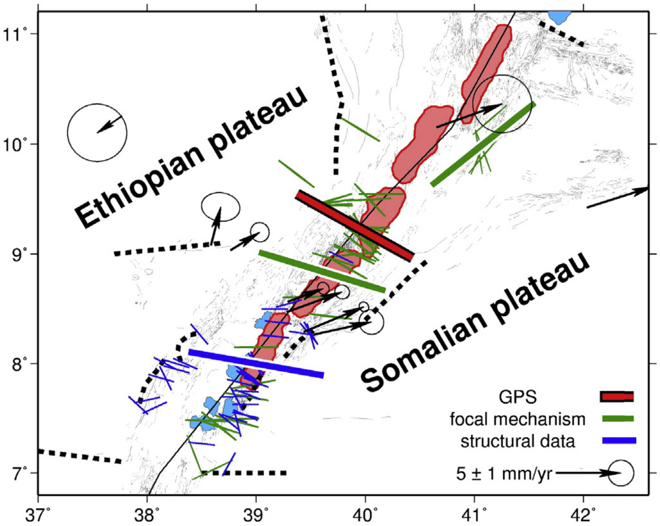

Fig. 5. Regional GPS velocities in the African fixed reference frame (Kogan et al., 2012) (black arrows with 68% error ellipse and site ID). The extension direction within the rift is inferred based on inversion of focal mechanism data (green segments) and GPS data (red segments), using the network of velocity vectors reported in the figure. Extension direction from fault slip or structural data (blue segments) is obtained from Agostini et al. (2011). In the northern Ethiopian Rift, focal mechanism inversion and dyke intrusion show extension direction of N51.5°E (thick green segments). The thick red, green and blue lines are the mean directions of extension with the different techniques. The thick black dashed lines are rift border faults. Solid thin black line is the Africa–Somalia plate boundary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

and sinistral strike slip faults in the Ethiopian Rift (e.g., Acocella et al., 2011).

Relating earthquake focal mechanism and fault slip inversion helps to understand the temporal evolution of deformation through geologic time. The fault slips integrate displacements over multiple earthquake cycles, and are not subject to a single rupture event.

Earthquake focal mechanism solutions (Ayele et al., 2006; Hofstetter and Beyth, 2003; Keir et al., 2006) and fault slip inversions (Agostini et al., 2011) yield incremental strain axes that show a systematic variation along the strike of rift (Fig. 5). For earthquakes, the extensional strain axes are the horizontal projection of extensional strain rate axis determined from focal mechanisms. Fault slip inversions use slickensides and shear sense indicators (e.g., Agostini et al., 2011) on faults in the rift floor and boundary faults and provide extension strain axes.

The similarity of fault slip strain and extensional strain determined from earthquakes argues that the Ethiopian Rift is characterized by steady state deformation at least during the Quaternary (Corti, 2009).

4. Deformation and strain accommodation

In the discussion that follows we describe the deformation type in the central Ethiopian Rift combining the velocity field, fault kinematics and focal mechanism solutions in a study area represented in Fig. 5. Table 1 shows the mean extension directions in Ethiopian Rift from inversion of GPS velocity fields and focal mechanism solutions and structural data. In the central and northern Ethiopian Rift, the extension axis trajectory diverges by about 40° from that of the velocity field (Fig. 5). In this region, the velocity field is not parallel to the extension direction and has a component of boundary normal displacement and significant component of ENE directed shear, showing left-lateral transtensional deformation along the rift axis. Further North, extension axes from focal mechanism solutions (Ayele et al., 2006; Hofstetter and Beyth, 2003) show consistent orientation with the available velocity field, rotating about 55° counterclockwise. This rotation of minimum horizontal stress is manifested by the N122°E striking dyke intrusion in the northern Ethiopian Rift (Keir et al., 2011).

Table 1
Mean azimuth of extensional direction in the Ethiopian Rift derived from different geodetic, geophysical and geological data.

Longitude	Latitude	Azimuth (°)	References
39.900	9.256	119.27	Kogan et al. (2012)
39.060	8.841	107.00	Keir et al. (2006)
39.000	8.000	100.00	Agostini et al. (2011)
41.080	10.000	51.50	Hofstetter and Beth (2003)

GPS velocity field inversion was made using SSPX software (Cardozo and Allmendinger, 2009). FaultKin software (Allmendinger et al., 2012) is used for inversion of focal mechanisms. Structural inversion data are reported from Agostini et al. (2011). In the northern Ethiopian Rift, near Gewane, focal mechanisms show N51.5°E orientation, and this result is here reported separately.

Geological (Wolfenden et al., 2004) and paleomagnetic (Kidane et al., 2006; Kidane et al., 2009, 2010) studies observed differential tilting of blocks in the northern part of Ethiopian Rift. Kidane et al. (2006) have also shown the absence of statistically significant amount of block rotation about vertical axis near Assela border fault, as it would be expected if the region were transtensional (Casey et al., 2006). This shows apparent discrepancy with the GPS velocity field and fault slip inversions. Dupont-Nivet et al. (2008) studied the magnetostratigraphy in the north Ethiopian Rift. Their paleomagnetic directions show a post-depositional counterclockwise vertical axis tectonic rotation (5°–10°) and shallowing of paleomagnetic inclination (5°–10°) related to sedimentation and compaction. However, rotations near faults are inversely proportional to the depth of the decollement plane of the investigated faults, e.g., a shallow decollement (say in the upper 3–4 km of continental crust) requires less energy for rotating with respect to a fault which is rooted tens of km into the entire crust and the lithospheric mantle. Therefore, since the Ethiopian Rift is involving the whole lithosphere, we do not expect to see significant near fault paleomagnetic rotations affecting thick crustal blocks because they are mechanically implausible even along strike-slip or oblique slip faults. Moreover, block rotation may not be the necessary condition to accommodate the regional transtensional deformation in the whole rift. The simplest explanation may be the accommodation of the shear throughout left-lateral strike-slip faulting with associated en-échelon normal faults. Some focal mechanism solutions (Ayele, 2000; Keir et al., 2006) that show left lateral strike-slip offset and faults that cut the rift floor obliquely (Fig. 3A) support this hypothesis.

Independent, analogue modeling (Bonini et al., 1997), geological (Casey et al., 2006), and paleomagnetic studies (Kidane et al., 2009) show that the Ethiopian Rift is characterized by left lateral transtensive deformation. This interpretation is consistent with the right-stepping en-échelon pattern of tensional and transtensional faults in the rift floor (Boccaletti et al., 1998; Gibson, 1969), plus the distribution of volcanic centers and the asymmetry of the rift itself (Corti, 2008).

5. Mantle-reference plate kinematics along the Ethiopian Rift

The hotspot reference frame represents the framework where global plate motions are computed with respect to the mantle (e.g., Wilson, 1973). The hotspot reference frame generates two models depending on the source depth of the Pacific plumes: deep (Gripp and Gordon, 2002) and shallow (Crespi et al., 2007; Cuffaro and Doglioni, 2007) hotspot reference frames. Comparison between these two models shows different kinematics and plate motions. In the case of deep mantle hotspots, few plates still move eastward relative to the mantle, whereas in the case of shallow source, all plates have westward component with a different velocity. Whatever their depth, hotspots indicate relative motion between the lithosphere and the underlying mantle (Doglioni et al., 2005). The decoupling between lithosphere and asthenosphere has a key role for mantle referenced global plate motion (Doglioni et al., 2011).

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Along the Ethiopian Rift, comparison between the deep and shallow hotspot frames shows different plate motions for Africa and Somalia both in magnitude and direction. Table 2 shows a list of Euler poles for Africa and Somalia plates relative to the hotspots, and locations are reported in Fig. 6. In deep hotspot framework, the Africa and Somalia plates' motion vector is almost perpendicular to the NE strike of the rift (Fig. 6A). This should result in extensional deformation with small amount of sinistral component in the Ethiopian Rift.

Here, we find an Euler pole for Somalia plate relative to the shallow hotspots, by combining the mantle-reference motion of Africa (Cuffaro and Doglioni, 2007) and relative motion of Somalia with respect to Africa obtained by Fernandes et al. (2004). In addition, we analyze the kinematics of the Ethiopian Rift relative to the mantle, i.e., the shallow hotspot frame. Cuffaro and Doglioni (2007) determine the Euler velocity vector for Africa in shallow hotspot framework by adding the shallow Pacific Euler vector to NUVEL-1A relative plate motion model (DeMets et al., 1994). They found an Euler pole for Africa located at 61.75°S and 76.73°E with a rate of 1.2134°/My. Somalia plate motion relative to the shallow hotspots occurs at a pole located at 61.5°S, and 79.4°E with a rate of 1.1496°/My, and it was obtained using the relations ${}_{so}\Omega_{HS} = {}_{so}\omega_{af} + {}_{af}\Omega_{HS}$ (Stein and Wysession, 2003), where ${}_{so}\Omega_{HS}$ is the mantle-vector of the Somalia plate, ${}_{so}\omega_{af}$ is the relative vector of Somalia plate with respect to Africa, and ${}_{af}\Omega_{HS}$ is mantle-vector of the Africa plate.

To find a mean direction of motion of the Ethiopian Rift relative to the mantle, we calculated a number of linear velocities (Fig. 6), using the expression $V_r = (V_A + V_S)/2$, where V_r, V_A, and V_S are the linear velocities of the rift and of Africa and Somalia plates relative to the hotspot framework, respectively. Relative to the shallow hotspots, Ethiopian Rift moves at a average velocity of 12.39 ± 0.05 cm/yr in a direction of N108.1° ± 0.6°W (Fig. 6B). In case of deep hotspots, the rift moves at a mean velocity of 1.50 ± 0.25 cm/yr in a direction of N71.9° ± 0.6°W (Fig. 6A). In both reference frames it results an asymmetric development of the Ethiopian Rift due to the westward migration of the center of the rift axis relative to the mantle.

Both Africa and Somalia plates tend to move WSW parallel to the tectonic equator proposed by Crespi et al. (2007). Africa moves faster due to a possibly lower viscosity in the top asthenosphere (LVZ—low velocity zone) (Adams et al., 2012; Bastow et al., 2008; Panza et al., 2007). The NE-trending Ethiopian Rift is slightly oblique to the ENE–WSW flow lines parallel to the tectonic equator (Doglioni, 1990). Therefore a left-lateral transtensive tectonic setting can be envisaged along this segment of the East African Rift.

Northward translation of Africa from paleomagnetic study is usually explained by assuming either that the paleomagnetic pole is moving (True Polar Wander) or plates are wandering (Apparent Polar Wandering). According to Cox and Hart (1986), if a plate undergoes a finite rotation about any Euler pole, then the paleomagnetic pole will undergo the same finite rotation about the same Euler pole. The paleomagnetic poles for Africa from 40 Ma to present are located on the opposite side of the geographic North Pole, and moved toward the present pole since then (Besse and Courrtillot, 2003; Schettino and Scotese, 2005). Any Euler pole that rotates Africa will rotate the paleomagnetic pole as well. Paleomagnetic data do not constrain the paleolongitude.

Table 2
List of Euler poles for Africa and Somalia plates with respect to the hotspot reference frames.

Plate	Deep HSRF			Shallow HSRF		
	°N	°E	ω(°/myr)	°N	°E	ω(°/myr)
Africa	−43.386	21.136	0.1987	**−61.750**	**76.734**	**1.2134**
Somalia	*−53.406*	*4.344*	*0.1192*	−61.500	79.400	1.1496

Underlined — Gripp and Gordon (2002), italics — Cuffaro and Jurdy (2006), bold — Cuffaro and Doglioni (2007), and none — this study.

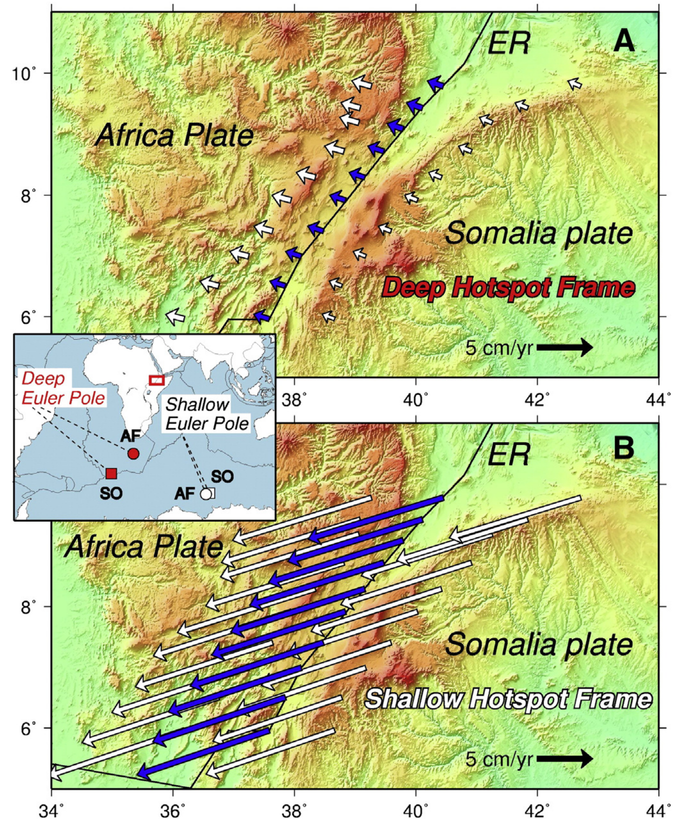

Fig. 6. Velocities of Africa, Somalia and Ethiopian Rift in hot spot reference frames, i.e. (A) deep (Gripp and Gordon, 2002) and (B) shallow (Cuffaro and Doglioni, 2007). In both reference frames, the Ethiopian Rift (blue arrows) is moving westward. Note the oblique orientation of the Ethiopian Rift in both reference frames with respect to the motion of plates, predicting a left-lateral transtension along the tectonic system. However, in the shallow hotspot reference frame (B), the transtensional component is more pronounced, according to the focal mechanisms. Moreover, in the deep hotspot reference frame Africa has a northward component, whereas in the shallow hotspot reference frame Africa has rather a southward component (WSW), in agreement with the paleomagnetic history of Africa, which is moving south during the Cenozoic and Quaternary. Locations of Euler poles are reported in the inset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

Therefore this shows that Africa during the last 40 Ma had a southward motion with respect to the mantle. This is consistent with the reconstruction of Africa with respect to the mantle assuming that hotspots (e.g., Hawaii) are fed by the top of the shear boundary layer (LVZ) as proposed by Doglioni et al. (2005) confirmed by Rychert et al. (2013), by means of receiver function analysis.

Unlike the deep hotspot reference frame, which would predict a northwestward motion of Africa relative to the mantle (Fig. 6A), the shallow hotspot framework rather shows a WSW-ward motion of Africa and Somalia plates (Fig. 6B). This implies a generalized ENE counter-flow of the underlying mantle (i.e. the first order flow of Panza et al., 2010). This ENE directed flow of mantle is inferred to form the anomalously high topography of Africa (Doglioni et al. 2003) and off-axis volcanism in Arabia (Pallister et al., 2010). An alternative popular view is that high topography in Africa is related to a mantle plume, but this model has been questioned for several independent reasons (e.g., Anderson, 2013; Foulger et al., 2005; Trampert et al., 2004). The asthenosphere coming from SW isostatically upraises beneath the rifting area (i.e. second order flow). Therefore it partially melts along the rift axis and forms the tectono-magmatic segments (Ebinger and Casey, 2001) in the already weakened and sheared rift floor. The asthenosphere travels to the NE and shallows in the Afar rift where a mature rifting generates abundant basaltic volcanism. The higher topography in northern Ethiopian plateau is overcompensated by this

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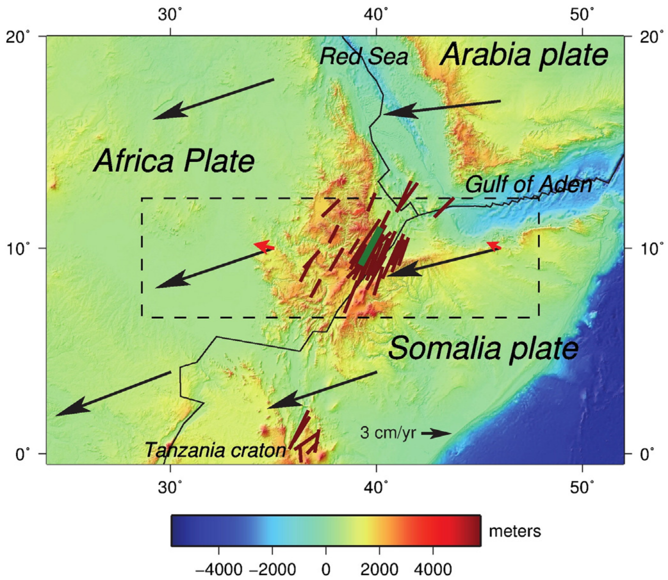

Fig. 7. Africa and Somalia plates' motions relative to the shallow hotspots (black arrows), compared with motions in the deep hotspot reference frame (red arrows), in our area of study (dashed box). Shear wave-splitting direction from Gao et al. (2010) is represented as thin red lines. The thick green bar shows the mean orientation of shear wave splitting direction at the Ethiopian Rift latitude. It has a mean orientation of N28° ± 8°E. In Kenya rift, the shear wave splitting directions are oriented N–S, around the Tanzanian Craton (e.g., Walker et al., 2004). The orientation of the bars represents the fast direction and length is proportional to splitting delay time, and, associated with the directions of the Ethiopian Rift and plate motions could suggest a NE flowing mantle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

mantle material (Adams et al., 2012). Gao et al. (2010) supports the notion of the NE flow of asthenospheric material in their shear wave splitting analysis beneath Ethiopian Rift and adjacent areas (Fig. 7).

6. Discussion and conclusions

The strain recorded by faults, focal mechanisms and GPS is partitioned between left-lateral strike-slip and normal faulting, and it shows a generalized left-lateral transtension along the NE–SW trending segment of the rift. This trend is related to pre-existing Precambrian suture zone beneath the Ethiopia and Somalia plateau which influenced the orientation and development of Ethiopian Rift, accommodating differential motion of Africa and Somalia plates in the northern part of the East African Rift System.

Because of the oblique divergence of Africa and Somalia plates, left-lateral transtension can be used to explain the observed kinematics in the Ethiopian Rift. In this paper, we have presented the kinematics of the Ethiopian Rift, making comparison between styles of tectonic deformation provided by geological, geophysical and geodetic data, and analyzing plate kinematics relative to hotspot reference frames with variable source depths. The similarity in focal mechanism and fault slip inversion shows that the regional stress field may have remained relatively constant throughout the quaternary. Deviation between GPS velocity field and incremental extensional strain axes from earthquakes and fault slip inversion shows that Ethiopian Rift is characterized by left lateral transtensional shearing. The en-échelon pattern of tensional and transtensional faults (WFB) in the rift floor and the asymmetry of the rift itself support this interpretation. Left-lateral oblique-slip faulting and small amount of counter-clockwise vertical axis of relatively shallow block rotations may contribute to the accommodation of the sinistral shearing.

Comparison between deep and shallow hotspot framework shows different Africa and Somalia plate motion and hence kinematics along the Ethiopian Rift. In shallow hotspot frame, the plate motion vectors strike oblique to the orientation of Ethiopian Rift (Fig. 6), resulting in the development of left-lateral transtension. When considering N45°E as the general orientation of the northern Ethiopian Rift (Agostini et al., 2011), and computing the velocity components of the plate boundary motion relative to the shallow hotspots, projected on the extension and strike-slip deformation directions, we obtain 5.63 and 11.04 cm/yr respectively. This shows that, relative to the shallow hotspots, the rift itself has a higher velocity component along the rift strike orientation, and therefore in the area of study, a significant amount of transtensional strain could be accommodated by strike slip deformation. Both Africa and Somalia move WSW ward, parallel to the main directions of plate motion, being Africa faster than Somalia. The difference in velocity could be related to a lower viscosity in the low velocity zone (LVZ) beneath Africa with respect to Somalia (Fig. 8). The computed plate velocities relative to the shallow mantle (Crespi et al., 2007; Cuffaro and Doglioni, 2007) maintain the left-lateral transtension, as for the relative plate motions, and their azimuths are mainly WSW–ENE-trending. Generally, both the Ethiopian Rift relative kinematics and those with respect to mantle entail a left-lateral transtension, having the extensional component oblique to the plate boundary (Fig. 5 and Table 1). Therefore as a consequence, grabens are en-échelon relative to the NE-trending Ethiopian Rift. This results in an angle between velocity vector azimuths and main direction of extension, due to the local deviation of the stress field that also controls focal mechanism stress tensor directions (e.g., WNW–ESE extension) within the rift. Therefore GPS data and focal mechanism directions deviate along transtensional areas.

The WSW-ward motion of the plates implies a generalized relative ENE-directed counter-flow of the mantle. The shear wave splitting technique detects a NE-trending seismic anisotropy beneath the rift and surrounding areas, Therefore the direction of anisotropy is slightly oblique with respect to the shallow mantle-reference plate motion of Africa and Somalia. Although motions of Africa and Somalia relative to the shallow hotspots better explains the observed seismic anisotropy, a component of Precambrian lithospheric anisotropy could exist (e.g., Corti, 2008). In Tanzania and Kenya, the shear wave anisotropy is oriented N–S, which could be interpreted as related to the flowing of the ENE-directed asthenosphere encountering the Tanzanian craton keel (e.g., Obrebski et al., 2011).

Our study shows that the kinematics of the Ethiopian Rift is primarily controlled by its orientation with respect to the Africa and Somalia plate motion direction in the shallow hotspot reference frame, but it has been constrained by the inherited lithospheric weakness and pattern of the Neoproterozoic eastern Africa orogenic-related foliation. We conclude that most long wavelength tectonic and kinematic features in the rift are explicable by the mantle reference motion of Africa and Somalia plates and the pre-existing lithospheric anisotropies. The Somalia and Africa plate motions relative to the Pacific hotspots, with shallow depth of their sources, better explain the left-lateral transtension along the Ethiopian Rift, such as the kinematic consequence of faster SW motion of Africa than Somalia relative to the mantle (Fig. 7). The shallow depth of the source for Pacific hotspots seems to be confirmed by geological, geophysical and geochemical evidence (e.g., Foulger et al., 2005, and references therein), and has been also recently emphasized by Rychert et al. (2013) for the Hawaiian volcanism.

Only the shallow hotspot frame explains most of the geophysical and geological constraints in the area. Inherited Precambrian lithospheric fabrics can sometimes play a dominant role in strain accommodation and observed geophysical features, e.g., shear wave splitting, besides the motion of Africa and Somalia plates relative to the mantle.

Even though, both deep and shallow hotspot frames show westward migration of the rift axis (Fig. 6), the surface tectonics may still be on the early stage to show geologically significant asymmetry in the Ethiopian Rift. Detailed studies on the stress field over the whole Ethiopian Rift, or the inclusion of additional geological dataset (e.g., Philippon et al., 2014) are needed to integrate the results obtained in this paper. It would also

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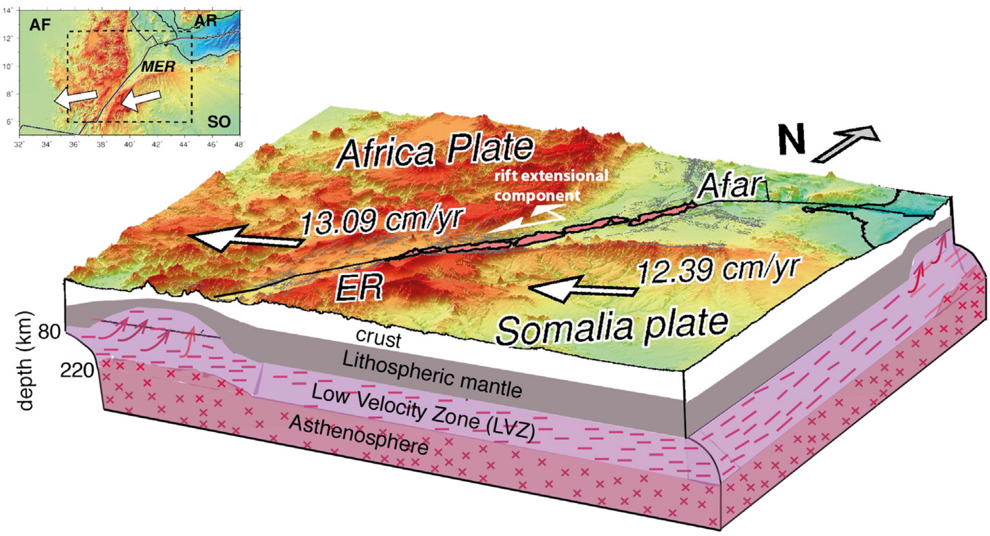

Fig. 8. Cartoon showing the motion of Africa and Somalia relative to the mantle (big arrows with velocities). Lithosphere–asthenosphere boundary is delineated from Bastow et al. (2005, 2008). The thickness of low velocity zone (LVZ) is from a global study (e.g., Panza et al., 2010). The upper asthenosphere is inferred as the main decoupling zone of the lithosphere from the underlying mantle (Doglioni et al., 2011). The left-lateral transtension has the extensional component oblique to the plates' motion resulting in an angle between GPS azimuths outside and inside the rift. The viscosity contrast within the LVZ between Africa and Somalia plates should drive the differential decoupling and consequently the East African Rift. Relative to the lithosphere, the mantle should move ENE-ward and oblique rise of the mantle beneath the rift is expected as a second order flow (see text for details). Refer to Fig. 4 and text for variation of the crustal depth beneath the rift and surrounding areas. The tectono-magmatic segments (red elongated areas) in the rift floor are those of Fig. 2A and are dextrally offset in response to the sinistral shearing between Africa and Somalia plates in the Ethiopian Rift.

be important to have additional GPS sites covering the whole rift to further constrain the motion of crustal blocks and hence the contribution of strike-slip faults in strain accommodation.

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