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Evolution of the broadly rifted zone in southern Ethiopia through gravitational collapse and extension of dynamic topography

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ABSTRACT

The Broadly Rifted Zone (BRZ) is a ~315 km wide zone of extension in southern Ethiopia. It is located between the Southern Main Ethiopian Rift and the Eastern Branch of the East African Rift System (EARS) represented by the Kenya-Turkana Rift. The BRZ is characterized by NE-trending ridges and valleys superimposed on regionally uplifted (~2 km average elevation) terrain. Previous studies proposed that the BRZ is an overlap zone resulted from northward propagation of the Kenya-Turkana Rift and southward propagation of the Southern Main Ethiopian Rift. To understand the relationship between the BRZ's extensional style and its crustal and upper mantle structures, this work first estimated the Moho depth using the two-dimensional (2D) radially-averaged power spectral analysis of the World Gravity Map. Verification of these results was accomplished through lithospheric-scale 2D forward gravity models along E-W profiles. This work found that the Moho topography beneath the BRZ depicts a dome-like shape with a minimum depth of ~27 km in the center of the dome. This work proposes that the Moho doming, crustal arching underlying the BRZ and associated topographic uplift are the result of asthenospheric mantle upwelling beneath the BRZ. This upwelling changed to a NE-directed lateral mantle flow at shallower depth. This is supported by seismic tomography imaging which shows slow S-wave velocity anomaly at lithospheric depth of 75 km to 150 km stretching in a NE-SW direction from beneath the BRZ to the Afar Depression. This work proposes that the asthenospheric upwelling created gravitationally unstable dynamic topography that triggered extensional gravitational collapse leading to the formation of the BRZ as a wide rift within the narrow rift segments of the EARS.

1. Introduction

Narrow rifts as exemplified by the majority of the segments of the East African Rift System (EARS) are less than 100 km in width (Fig. 1). They generally develop where the localization of the extensional strain is facilitated by the presence of mechanical and/or thermal weaknesses such as lithospheric-scale heterogeneities and/or intrusion of magmatic bodies (e.g. Ebinger and Casey, 2001; Chorowicz, 2005). These rifts are typically underlain by thinned crust and sub-continental lithospheric mantle (SCLM) where thinning is restricted to a narrow and linear zone that follows the surface expression of the rift basin. For example, from reflection/refraction seismic profile across the Main Ethiopian Rift (Fig. 1) MacKenzie et al. (2005) observed slight crustal thinning beneath the rift. Additionally, MacKenzie et al. (2005) observed faster seismic velocity in the upper crust beneath the rift and attributed this to the presence of mafic intrusions. Also, from passive seismic receiver function study, Stuart et al. (2006) found that the crust beneath the Main Ethiopian Rift becomes progressively thinner towards the north ranging from 38 km in the south to 30 km in the north. Stuart et al. (2006) also found higher Poisson's ratio within the crust beneath the rift and interpreted this to indicate the presence of partial melting. Besides documenting thinning of the crust beneath the Main Ethiopian Rift, Dugda et al. (2007) used joint inversion of seismic Rayleigh wave group velocities and receiver function to show that the SCLM beneath the rift is also thinner reaching only ~50 km thickness compared to the 100–150 thickness of the SCLM in regions that are not affected by rifting.

Additionally, Tiberi et al. (2005) used the inversion of gravity data constrained by previous results from passive seismic receiver function studies to image crustal and upper mantle structure beneath the Main Ethiopian Rift, the Afar Depression and the Ethiopian Plateau (Fig. 1). Tiberi et al. (2005) found that crustal thickness decreases from 33 km along the axis of the Main Ethiopian Rift in the south to 24 km in the southern part of the Afar Depression. Also, Tiberi et al. (2005) found the crust to be thicker beneath the Ethiopian Plateau reaching ~40 km. Further, Tiberi et al. (2005) attributed the presence of denser crust beneath much of the Ethiopian Plateau and portions of the Main Ethiopian Rift to magmatic under-plating.

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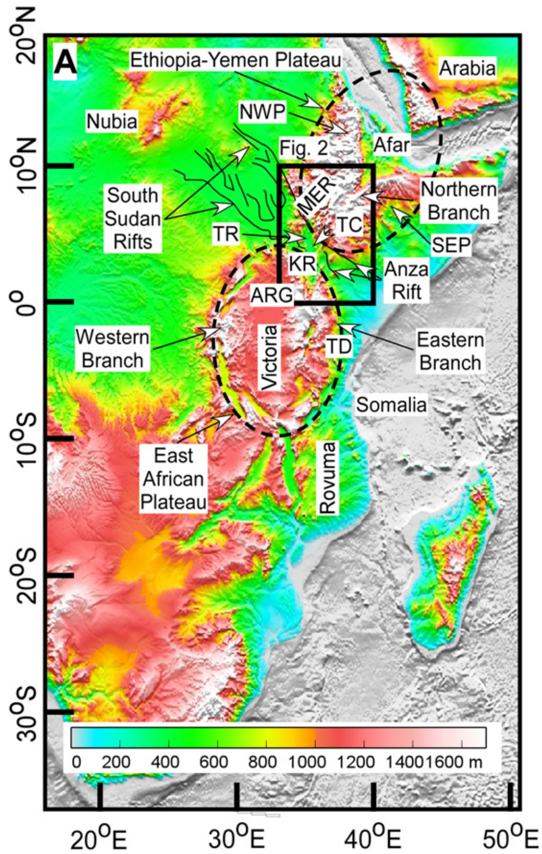

Fig. 1. Global Topographic 30 arc second (GTOPO30) Digital Elevation Model (DEM) showing the East African Rift System (EARS). MER = Main Ethiopian Rift. NWP = Northwestern Ethiopian Plateau. SEP = Southeastern Ethiopian Plateau. TR = Turkana Rift. KR = Kenya Rift. TC = Turkana Topographic Corridor. ARG = Albertine-Rhino Graben. TD = Tanzania Divergence Zone.

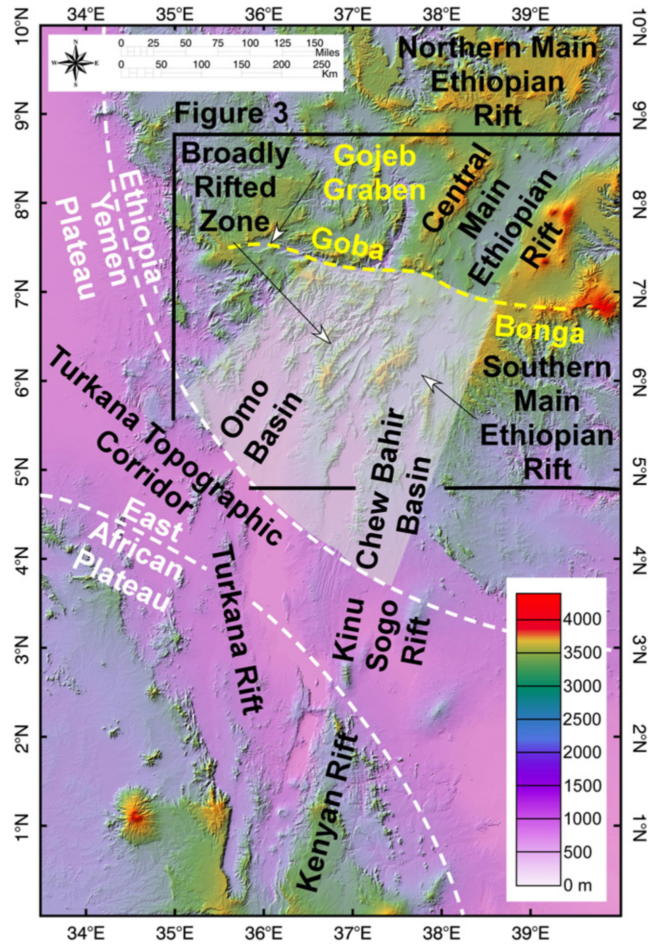

Fig. 2. Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) showing the location of the Broadly Rifted Zone (BRZ) between the Southern Main Ethiopian Rift and the northern continuation of the Kenya-Turkana Rift represented by Omo Basin.

The surface and upper crustal structures of narrow continental rifts are characterized by the presence of curvilinear and high-angle border faults that accommodate extension and control the subsidence in the basins during the early stages of rifting, often through the development of half-grabens with along-strike alternation and change of half-graben polarity (e.g. Ebinger and Casey, 2001).

The EARS (Fig. 1) constitutes rift segments that are 70–100 km wide and form asymmetric rift basins flanked by steep normal faults (Chorowicz, 2005). This rift system can be divided into Northern, Eastern and Western Branches (Fig. 1). The Northern Branch stretches within Ethiopia, Eritrea and Djibouti and it constitutes the Afar Depression in the north and the Main Ethiopian Rift to the south (Fig. 1). The Main Ethiopian Rift in turn is divided into Northern, Central and Southern segments (Fig. 2; Abebe et al., 2007; Corti, 2009). The Southern Main Ethiopian Rift widens further south into a ~315 km zone of diffused extension. This zone is referred to as the Broadly Rifted Zone (BRZ) (Fig. 2; Cerling and Powers, 1977; Moore and Davidson, 1978; WoldeGabriel and Aronson, 1987, 1991; Ebinger et al., 1993, 2000; Bonini et al., 2005; Philippon et al., 2014). The BRZ is also referred to as the Basin and Range of Ethiopia (Moore and Davidson, 1978; Corti, 2009). South of the BRZ, the EARS extends as the Eastern Branch which is represented by the ~70 km wide Turkana Rift in the north, the Kenya Rift in the center, and the Tanzania Divergence Zone to the south (Fig. 1; Ebinger et al., 2000).

The BRZ consists of a number of basins that form a Basin and Range type topography (Figs. 2 and 3; Moore and Davidson, 1978; Ebinger et al., 2000; Corti, 2009). This topography resulted from the presence of tilted blocks of Eocene-Pliocene volcanic rocks bounded by steep normal faults forming asymmetrical grabens or half-grabens. The tilted blocks rest unconformably on Precambrian crystalline basement and the half-grabens are filled with Miocene-Pliocene sedimentary rocks (Figs. 4 and 5). Ebinger et al. (1993, 2000) suggested that the structural characteristics of the BRZ are typical of those found in narrow rift basins. Additionally, although the Precambrian crystalline basement rocks (typically amphibolite metamorphic facies gneisses and migmatites which are indicative of middle crustal level of metamorphism) are exposed in many places on the surface (Fig. 4), no low-angle detachment faults or metamorphic core complexes are observed within the BRZ. These observations suggest that the BRZ developed through processes different from those suggested for wide rifts such as the Basin and Range of the western United States.

Results from remote sensing, structural geology, geomorphological, and geochronological studies were used to suggest that the BRZ is an overlap zone between the Southern Main Ethiopian Rift and the Kenya-Turkana Rift (Fig. 2). In addition, the development of individual basins constituting the BRZ was explained as due to eastward migrating of the Kenya-Turkana Rift during its northward propagation, as well as the southward propagation of the Southern Main Ethiopian Rift (Cerling and Powers, 1977; Moore and Davidson, 1978; WoldeGabriel and Aronson, 1987; Ebinger et al., 2000; Bonini et al., 2005; Philippon et al., 2014). Further, poly-phase oblique rifting and anti-clockwise rotation have been proposed as factors that might have contributed to the widening of the BRZ (Boccaletti et al., 1998; Bonini et al., 2005; Corti, 2009; Philippon et al., 2014).

This study used two-dimensional (2D) radially-averaged power spectral analysis of the World Gravity Map (WGM 2012) to image the depth to Moho beneath the BRZ and its surroundings. Also, this work