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The role of pre-existing Precambrian structures in rift evolution: The Albertine and Rhino grabens, Uganda

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ABSTRACT

We integrated Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEM), airborne magnetic, radiometric and three-dimensional Full Tensor Gravity Gradiometry (3D-FTG) data to investigate the role of Precambrian structures in the evolution of the largely amagmatic Miocene–Recent aged Albertine and Rhino grabens in Uganda. These grabens represent the northern segment of the Western Branch of the East African Rift System (EARS). The two NE-trending grabens are connected by a right-stepping transfer zone and they extend within the Archean–Paleoproterozoic Northeast Congo block which represents the northeastern extension of the Congo craton. Our results show the following and highlight the importance of pre-existing structures in the evolution of continental rift systems: (1) The NE-extent of the Albertine full-graben is controlled by NE-trending Precambrian fabric and the graben terminates at its northeastern end when it encounters a multiply folded Precambrian basement terrain with poorly-developed NW-trending structural grain. Additionally, the northeastern termination of the Albertine graben coincides with the presence of NW-trending right-stepping high-density bodies within the Precambrian terrain. (2) The transfer zone between the Albertine and Rhino grabens is controlled by NE-trending Precambrian structures which might have facilitated the development of relay ramp faults. (3) Strain localization within the better-developed southeastern border fault of the Rhino half-graben is facilitated by the presence of Precambrian structures better aligned in a NE-direction in the southeastern part of the basin compared to its northwestern part. (4) Further to the northeast, the Rhino graben is segmented and transitions into a narrower ENE-trending half-graben with a better-developed border fault on its northwestern side. This segmentation coincides with the presence of N-trending Precambrian structures. (5) The Rhino graben terminates farther northeast against the NW-trending Precambrian Aswa shear zone; a prominent structure with complex, but generally NW-trending fabric.

1. Introduction

Continental rifts are widespread extensional structures on Earth and have occurred from the Archean to the Present. The study of these extensional structures remains of great interest because: (1) They represent the initial stages of continental breakup transitioning into seafloor spreading and continental passive margins; (2) They are sites of thick sediments accumulation, with the potential to form and trap hydrocarbon resources. Rift systems and passive continental margins have provided the oil and gas industry with ~61% of global hydrocarbon discoveries, while rift systems alone account for ~30% of these discoveries (Fraser et al., 2007); and (3) They are sites of geologic hazards such as earthquakes, volcanism and associated poisonous gas emissions and landslides (Abdelsalam et al., 2004).

Progress has been made in understanding the evolution of continental rifting. However, major process-oriented questions such as how strain is localized and partitioned, what controls rift segmentation and how it affects basins' architecture remain unanswered, especially for largely amagmatic rift systems. Relevant to this study are a number of questions that need to be addressed: (1) What is the role of pre-existing Precambrian structures in strain localization during the early stages of extension in dominantly amagmatic rifts? (2) What are the relative roles of the thickness and rheology of the Precambrian lithosphere and shallow regional fabric representing the inherited anisotropy in shaping rift architecture? (3) How do pre-existing structures influence strain transfer and rift segmentation? and (4) What controls continental rift termination?

Geological and geophysical observations from the East African Rift System (EARS; Fig. 1A) suggest that pre-existing structures can influence the evolution of continental rift systems at different scales. For example, at the regional scale, the Western Branch of the EARS developed within Precambrian entities in the northwestern, western and southwestern margin of the Tanzania craton (Fig. 2). The northern segment of the Western Branch (represented by the Albertine and Rhino grabens (Figs. 1B and 3), the focus of this study) extends in a NE–SW direction within the Northeast Congo block (representing the northeastern edge of the Congo craton) in the north and the Ruwenzori fold belt to

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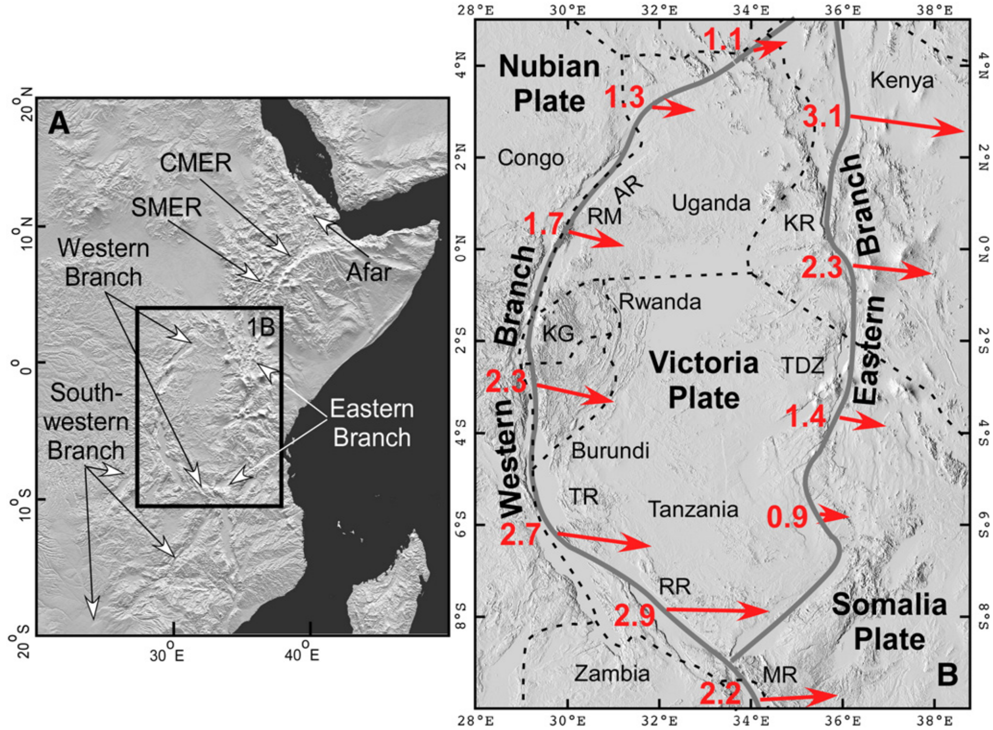

Fig. 1. Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of the East African Rift System (EARS) from www.jpl.nasa.gov (A) and the Eastern and Western Branches of the EARS (B). CMER = Central Main Ethiopian Rift. SMER = Southern Main Ethiopian Rift. KR = Kenya Rift. TDZ = Tanzania Divergent Zone. AR = Albertine and Rhino Grabens. KG = Kivu Graben. TR = Tanganyika Rift. RR = Rukwa Rift. MR = Malawi Rift. Red arrows with numbers represent the angular velocities in mm/year of the Victoria and Somalia plates relative to the Nubian plate as reported by Saria et al. (2014).

the south (Fig. 2; Tack et al., 2010; Fernandez-Alonso et al., 2012; Nyakecho and Hagemann, 2014). Begg et al. (2009) and Westerhof et al. (2014) suggested that the trace of this part of the Western Branch follows a fundamental tectonic boundary separating different bocks of Archean cratons represented by the Ugandan craton or Northern Uganda terrane in the east and the Bomu–Kibalian shield or the West Nile block to the west (Fig. 4). The central part of the Western Branch, approximately from Lake Edward to the northern half of Lake Tanganyika, extends in a N–S direction within the Kibara and Karagwe–Ankole orogenic belt (Fig. 2; Tack et al., 2010; Aanyu and Koehn, 2011; Fernandez-Alonso et al., 2012). From the southern half of Lake Tanganyika to the Rungwe volcanic field at the northern tip of Lake Malawi the Western Branch extends in a NW–SE direction within the Ubende orogenic belt (Daly, 1986; Delvaux et al., 2012; Lenoir et al., 1994).

This work examines the role of pre-existing Precambrian structures in strain localization and transfer, and rift segmentation and termination in largely amagmatic rifts. It focuses on the NE-trending Albertine and Rhino grabens in Uganda which represent the northeastern part of the Western Branch of the EARS (Fig. 1B). The major processes required for the initiation of rifting remain controversial. For example, studies by Hayward and Ebinger (1996) and Buck (2006) have advocated for the important role of magmatism in the initiation of continental rifting suggesting that the forces driving the tectonic plates such as slab pull are insufficient to rupture normal continental lithosphere. Analog models suggest that magma plays an important role in softening the lithosphere, enhancing lithospheric stretching and strain localization (Buck, 2006). Indeed, magma is documented to have played an important role in initiating continental rifting in the Eastern Branch of the EARS especially the Main Ethiopian Rift and the Afar Depression (Fig. 1A; Ebinger and Casey, 2001; Kendall et al., 2005; Wright et al., 2006).

This work benefited from the availability of high-resolution airborne magnetic, radiometric and gravity data for mapping regional Precambrian structures which are barely exposed at the surface. Additionally, Digital Elevation Models (DEMs) extracted from the Shuttle Radar Topography Mission (SRTM) data were used to map the Miocene–Recent structures associated with the Albertine and Rhino grabens. The aim of the work is to examine in detail the complex interplay between the Precambrian and Miocene–Recent structures, not only parallelism, but also the complex interaction between the two structural sets when their trends depart from parallelism.

2. Tectonic setting

2.1. The East African Rift System (EARS)

The Albertine and Rhino grabens occupy an important location within the EARS. They represent part of the extensional structures showing the bifurcation of the rift system from a single discrete rift in central Ethiopia (the Central Main Ethiopia Rift) to two rifts represented by the Eastern and Western Branches (Fig. 1A). Buck (2006) and Corti et al. (2013) suggested that the bifurcation of the EARS around the Tanzania craton (Fig. 2) demonstrates the inability of continental rifts to propagate through thick cratonic lithospheres. In addition, the bifurcation of the EARS is associated with a number of important tectonic elements: (1) It coincides with the trace of the NW-trending Neoproterozoic Aswa shear zone, which represents a fundamental lithospheric-scale boundary between the Northeast Congo block in the southwest and the Saharan Metacraton to the northeast (Fig. 2; Abdelsalam et al., 2002, 2011). Seismic tomography imaging has shown that the lithospheric thickness of the Saharan Metacraton is ~100 km compared to the ~250 km of the lithospheric thickness of the Northeast Congo block (Abdelsalam et al., 2011). (2) It also coincides with a change in the depth of the seismogenic zone (Craig et al., 2011). North of the rift bifurcation, the depth of the seismogenic zone is 20 km or less whereas it is between 20 and 35 km deep to the south.

Northeast of the bifurcation, the EARS is represented by the Southern Main Ethiopian Rift where extensional strain is broadly distributed (Fig. 1A) leading some researchers to refer to this segment of the Main