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A refinement of the chronology of rift-related faulting in the Broadly Rifted Zone, southern Ethiopia, through apatite fission-track analysis

Maria Laura Balestrieri [a,*], Marco Bonini [a], Giacomo Corti [a], Federico Sani [b], Melody Philippon [c]

[a] Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, UOS Firenze, via G. La Pira 4, 50121 Firenze, Italy
[b] Dipartimento di Scienze della Terra, Università degli Studi di Firenze, via G. La Pira 4, 50121 Firenze, Italy
[c] Universite des Antilles, Geosciences Montpellier, UMR 5243, Campus de Fouillole, 97120 Pointe-à-Pitre, France

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ABSTRACT

To reconstruct the timing of rift inception in the Broadly Rifted Zone in southern Ethiopia, we applied the fission-track method to basement rocks collected along the scarp of the main normal faults bounding (i) the Amaro Horst in the southern Main Ethiopian Rift and (ii) the Beto Basin in the Gofa Province. At the Amaro Horst, a vertical traverse along the major eastern scarp yielded pre-rift ages ranging between 121.4 ± 15.3 Ma and 69.5 ± 7.2 Ma, similarly to two other samples, one from the western scarp and one at the southern termination of the horst (103.4 ± 24.5 Ma and 65.5 ± 4.2 Ma, respectively). More interestingly, a second traverse at the Amaro northeastern terminus released rift-related ages spanning between 12.3 ± 2.7 and 6.8 ± 0.7 Ma. In the Beto Basin, the ages determined along the base of the main (northwestern) fault scarp vary between 22.8 ± 3.3 Ma and 7.0 ± 0.7 Ma. We ascertain through thermal modeling that rift-related exhumation along the northwestern fault scarp of the Beto Basin started at 12 ± 2 Ma while in the eastern margin of the Amaro Horst faulting took place later than 10 Ma, possibly at about 8 Ma. These results suggest a reconsideration of previous models on timing of rift activation in the different sectors of the Ethiopian Rift. Extensional basin formation initiated more or less contemporaneously in the Gofa Province (~12 Ma) and Northern Main Ethiopian Rift (~10–12 Ma) at the time of a major reorganization of the Nubia–Somalia plate boundary (i.e., 11 ± 2 Ma). Afterwards, rift-related faulting involved the Southern MER (Amaro Horst) at ~8 Ma, and only later rifting seemingly affected the Central MER (after ~7 Ma).

1. Introduction

The East African Rift System (EARS) is a region of continental rifting marking the incipient plate boundary between Nubia and Somalia plates (Fig. 1a). Its northernmost sector, the Ethiopian Rift (ER), connects the Afar depression, at the Red Sea–Gulf of Aden junction, with the Turkana depression and Kenya Rift to the South (Fig. 1a). North of Addis Ababa, the ER gradually narrows from the southern Afar depression into the Main Ethiopian Rift (MER), a roughly NE–SW oriented rift separating the Ethiopian and Somalian plateaus. The MER is divided into three main rift segments, Northern, Central, and Southern MER (Agostini et al., 2011). The MER southern boundary may be placed at latitude ~5°N, south of the area, where it splays into two branches, separated by the Amaro Horst, the Chamo basin to the west, and the Galana basin to the east (Fig. 1b). Where the rift zone widens, the deformation becomes more distributed and is accommodated by the ~300 km-wide system of basins and ranges known as Broadly Rifted Zone (BRZ; Baker et al., 1972; Moore and Davidson, 1978; Davidson and Rex, 1980; Ebinger et al., 2000), which characterizes the overlapping area between the Ethiopian and the Kenya Rifts. The BRZ is in a topographic depression between the Ethiopian and the Kenyan plateaus (Fig. 1a). Within the BRZ, West of the Chamo basin, there is a system of narrow north–south and northeast-trending basins collectively referred to as the Gofa Province (GP) (e.g., Davidson, 1983) (Fig. 1b).

Even if the EARS and MER have been the subjects of several studies through the years (for a review, see Corti, 2009, and reference therein), some major questions remain open. One of these concerns the propagation of deformation in the MER, which has been suggested to proceed either northwards (e.g., Wolfenden et al., 2004) or southwards (Buck, 2006; Rogers, 2006). Alternative hypothesis include a heterogeneous time–space evolution, with initial extension in the Southern MER at 20–21 Ma, followed by extension in the Northern MER at 10–11 Ma and finally formation of the Central MER at about 5–6 Ma (Bonini et al., 2005). A complex picture of rift activation and propagation has been also suggested by Rooney et al. (2007): in their view, the MER records a southward propagation of the Red Sea-related deformation from the Afar region and a northward propagation of the EARS, with the two different tectonic domains (Red Sea and East African Rifts) now linking and interacting within the Central MER. Irregular rift propagation due to the presence of preexisting structures has also been proposed by Keranen and Klemperer (2008). More recently, Macgregor (2015) has

* Corresponding author.

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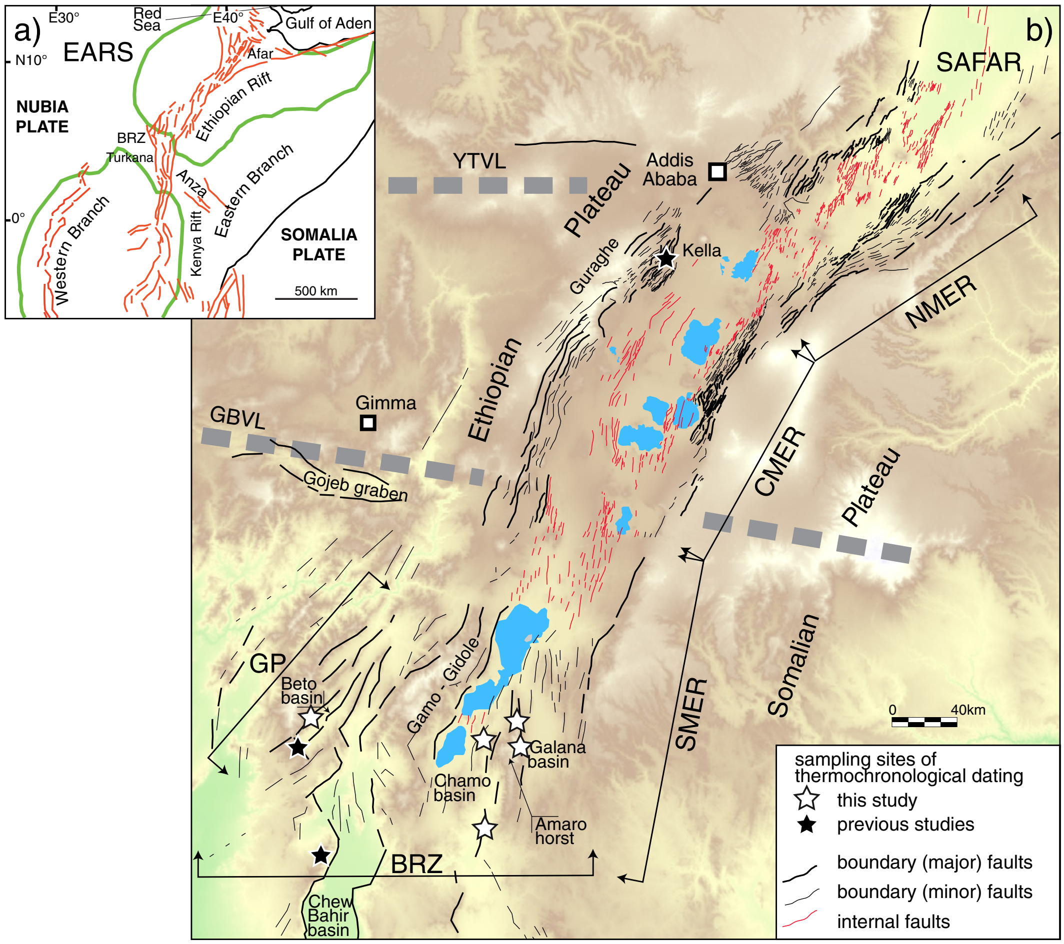

Fig. 1. (a) East African Rift System (EARS). Green bold lines bound plateau elevation higher than 1000 m. (b) Structural map of the Main Ethiopian Rift (MER) and Broadly Rifted Zone (BRZ) (after Ebinger et al., 2000; Agostini et al., 2011) superimposed onto the SRTM (Shuttle Radar Topography Mission) 90 m digital elevation model. Black stars: locations from where thermochronological data were available (Pik et al., 2008; Abebe et al., 2010; Philippon et al., 2014). White stars locations sampled for this study. SAFAR, Southern Afar; GP, Gofa Province; NMER, Northern MER; CMER, Central MER; SMER, Southern MER; YTVL, GBVL, Yerer - Tullu - Wellel and Goba - Bonga tectonovolcanic lineaments.

compiled a series of time maps reconstructing the development of fault trends in the EARS well illustrating the wide variation in the ages of initiation of the EARS basins.

Low-temperature thermochronology – constraining periods of rapid rock cooling possibly induced by rift-related denudation – may represent a key tool to gain some insights into this puzzling scenario. In particular, we can infer the time the rift developed well-defined faulted margins collecting samples along the scarp of the main bounding faults of the rift basins, providing that rift-shoulder exhumation has brought to surface rocks buried deeper than the isotherm corresponding to the closure temperature of the used thermochronometer.

Unfortunately, the majority of the rocks exposed in the MER are Eocene to Pleistocene volcanics, and subordinately Quaternary fluvio-lacustrine sediments that are unsuitable for this kind of analysis. Basement rocks in the MER are exposed only in its extreme southern sector and in northern Afar. Only two apatite fission-track (AFT) data are available in the Central MER from a small basement outcrop (Kella horst, Fig. 1b) at the base of the Guraghe escarpment (Abebe et al., 2010). There, AFT ages of ca. 7 Ma were obtained and interpreted as the time of rock cooling due to rift-related denudation.

At the southern end of the GP, apatite U–Th/He data are available from the fault-scarp bounding the Chew Bahir basin to the west (Pik et al., 2008, Fig. 1b). By data modeling, Pik et al. (2008) excluded significant rift-related denudation before 20 Ma and placed its onset at 20 ± 2 Ma. Northwards, in the Beto Basin of the GP (Fig. 1b), Philippon et al. (2014) analyzed a number of samples, two of which provided young AFT ages (ca. 11 and 7 Ma) directly related to Neogene rift-related denudation.

We have applied AFT analysis on basement rocks from the 3200 m high Amaro Horst of the southern MER (Figs. 1 and 2) and on samples from the base of the northwestern scarp of the Beto Basin in the GP to get further constraints on the timing of rift-related denudation in the BRZ, which represents a key area connecting the Ethiopian and the Kenya rifts (Figs. 1 and 2).

New samples from the Beto Basin are interspaced with the young FT age samples of Philippon et al. (2014) along the main basin-bounding fault scarp with the aim to analyze a horizontal section along the fault-trace (Fig. 2).

2. Geology of southern Ethiopia

The metamorphic basement outcropping in southern Ethiopia consists of highly deformed gneisses, amphibolites, and granulites interlayered with plutonic rocks of Archean to Proterozoic age (e.g., Davidson, 1983; Geological map of Ethiopia, Mengesha et al., 1996) (Fig. 2). The basement is unconformably overlain by sandstones interpreted as the product of the erosion of the basement rocks during Paleocene (Ebinger et al., 1993) and by transitional to tholeiitic flood basalts – with intercalated felsic units – dated between ~48 and ~30 Ma (Ebinger et al., 2000), which may reach a current thickness exceeding 1000 m. No major phases of extension and rift basin subsidence affected