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Spatial and temporal variation of tectonic uplift in the southeastern Ethiopian Plateau from morphotectonic analysis

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ABSTRACT

We use morphotectonic analysis to study the tectonic uplift history of the southeastern Ethiopian Plateau (SEEP). Based on studies conducted on the Northwestern Ethiopian Plateau, steady-state and pulsed tectonic uplift models were proposed to explain the growth of the plateau since ~30 Ma. We test these two models for the largely unknown SEEP. We present the first quantitative morphotectonic study of the SEEP. First, in order to infer the spatial distribution of the tectonic uplift rates, we extract geomorphic proxies including normalized steepness index k_{sn}, hypsometric integral *HI*, and chi integral χ from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM). Second, we compare these rates with the thickness of flood basalt that we estimated from geological maps. Third, to constrain the timing of regional tectonic uplift, we develop a knickpoint celerity model. Fourth, we compare our results to those from the Northwestern Ethiopian Plateau to suggest a possible mechanism to explain regional tectonic uplift of the entire Ethiopian Plateau. We find an increase in tectonic uplift rates from the southeastern escarpments of the Afar Depression in the northeast to that of the Main Ethiopian Rift to the southwest. We identify three regional tectonic uplift events at ~11.7, ~6.5, and ~4.5 Ma recorded by the development of regionally distributed knickpoints. This is in good agreement with ages of tectonic uplift events reported from the Northwestern Ethiopian Plateau.

1. Introduction

The development of geomorphic features in response to tectonic uplift provides important information regarding nature and spatial and temporal distributions of tectonic forces in contractional and extensional tectonic regimes. The distribution of tectonic activities in regions experiencing tectonic uplift can be mapped through geomorphic proxies, including normalized steepness index k_{sn} (Whipple, 2004; Kirby and Whipple, 2012), hypsometric integral *HI* (Strahler, 1952; Gao et al., 2016), and chi integral χ (Perron and Royden, 2013; Willett et al., 2014). In addition, celerity modeling of knickpoints allows for establishing end-member time constraint for the changes of tectonic uplift rates (Berlin and Anderson, 2007; Miller et al., 2012). Here, we use these approaches (in addition to information about precipitation and lithology) to establish the spatial and temporal distribution of the tectonic uplift in the tectonically active southeastern Ethiopian Plateau (SEEP).

The Ethiopian Plateau is divided by the Main Ethiopia Rift (MER) and the Afar Depression into the Northwestern Ethiopian Plateau and the SEEP (Fig. 1A). The landscape of this region has been shaped by tectonic uplift, volcanism, and extensional deformation associated with the development of the East African Rift System (EARS) (Fig. 1A; Wolfenden et al., 2004; Simmons et al., 2007; Prave et al., 2016). The development and preservation of such an anomalously high plateau (average elevation of ~2.5 km) within a continental rift setting are caused by the dynamics of the Afar mantle plume (Ebinger and Casey, 2001; Sengor, 2001; Faccenna et al., 2013). Morphotectonic studies to constrain the tectonic uplift history of the Ethiopian Plateau have remained considerably sparse. Hence, several fundamental questions regarding the tectonic uplift history of the plateau remain unanswered. These include:

- Was the growth of the Ethiopian Plateau steady or episodic? Results from (U-Th)/He thermochronology studies by Pik et al. (2003) suggest steady-state plateau growth for the Northwestern Ethiopian Plateau since ~29 Ma resulting in ~1 km uplift since then. Conversely, morphotectonic analysis by Gani et al. (2007) and Ismail and Abdelsalam (2012) reported multistage and accelerated growth of the Northwestern Ethiopian Plateau at 30–10 Ma, 10–6 Ma, and 6 Ma–present. This excludes the portion of the plateau away from the escarpment of the MER and the Afar Depression (toward the lowlands of Sudan) where the steady-state model is applicable.

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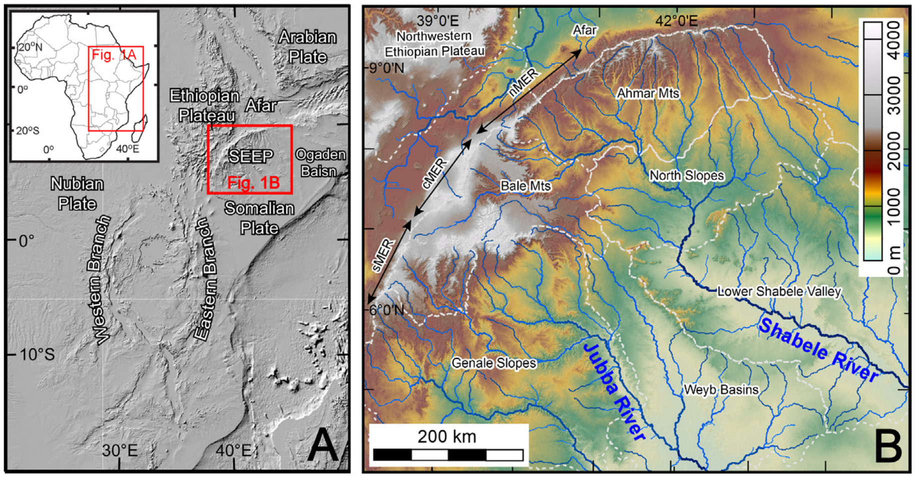

Fig. 1. (A) Digital elevation model (DEM), extracted from the Earth Topography 1 arc sec (ETOPO 1) data (1 km spatial resolution), showing the locations of the Arabian Plate, Nubian Plate, Somalian Plate, western and eastern branches, Afar Depression, and Ethiopian Plateau. (B) Digital elevation model (DEM) extracted from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data (30-m spatial resolution) showing major geomorphological features of the southeastern Ethiopian Plateau (SEEP). The white dot lines show the physiographic segments of the SEEP, and the black lines with arrows show the southern (sMER), central (cMER), and northern (nMER) segments of the Main Ethiopian Rift (MER).

- What is the distribution pattern of the tectonic uplift in relation to the MER and the Afar Depression? The $^{40}Ar/^{39}Ar$ ages and seismic data suggest northeastward propagation of the MER into the Afar Depression. This implies a more active extension into the northern MER than in the southern MER (Wolfenden et al., 2004; Mackenzie et al., 2005). Nevertheless, structural analysis, numerical models, and ^{14}C radiometric dating suggest that extension in the northern MER and the Afar Depression is more advanced than the central and southern MER. This is evidenced from the presence of more pronounced within-rift faults in the former. This proposes a southwestward rift propagation from the northern MER to the southern MER (Hayward and Ebinger, 1996; Keranen and Klemperer, 2008; Agostini et al., 2011; Philippon et al., 2014).

We aim to answer these questions using morphotectonic analysis through the application of various geomorphic proxies (k_{sn}, HI, and χ) and knickpoint celerity modeling. For this, we (i) map the spatial and temporal distribution pattern of the tectonic uplift rates in the SEEP; (ii) establish the timing of tectonic uplift in the plateau since ~12 Ma; (iii) examine the relationship between the tectonic uplift and volcanism; and (iv) compare the tectonic uplift history of the SEEP to that of the Northwestern Ethiopian Plateau.

2. Geologic settings

The topography of the SEEP results from geological events that include the development of a Precambrian orogenic belt (the Arabian-Nubian Shield), Paleozoic-Mesozoic rifting and sedimentation (the Karoo rifting event), and Cenozoic rifting and magmatism (the EARS). Notably, the topography of SEEP is highly influenced by the Cenozoic tectono-magmatic events of the EARS. The plateau is bordered in the northwest by the MER and the Afar Depression, which represent the tectonic boundary between the Nubian and Somalian plates. The two plates are currently moving away from each other at a rate of 4 to 6 mm/y (Kogan et al., 2012). The MER and the Afar Depression asymmetrically divide the ~1000-km-wide Ethiopian Plateau into the SEEP and the Northwestern Ethiopian Plateau (Fig. 1A). Based on its general orientation, the MER is divided into northern, central, and southern segments that developed at different times during the Miocene (Fig. 1B; Boccaletti et al., 1998).

2.1. Geomorphological setting of the southeastern Ethiopian Plateau (SEEP)

The SEEP is bounded by the southeastern escarpment of the MER and the Afar Depression in the northwest and by the Ogaden Basin to the southeast (Fig. 1A). It is deeply incised by the drainage systems of the Jubba and Shabele rivers, which originate respectively from the Bale and Ahmar mountains. Within the SEEP, these rivers span over an area of ~373,000 km^2 (Fig. 1B). Drainage incision reaches up to 900 m in the Bale and Ahmar mountains, reflecting rapid tectonic uplift along the southeastern escarpment of the MER and the Afar Depression (Mège et al., 2015).

The SEEP and the Northwestern Ethiopian Plateau form a broad dome, hypothesized to be the result of the impinging of the Afar mantle plume beneath the lithosphere of the Arabian-Nubian Shield (Sembroni et al., 2016a). The highest regions in the plateau are the Bale and Ahmar mountains, reaching over 4.0 km in elevation. The elevation decreases toward the southeast, and it is only about 300 m at the Ethiopia–Somalia border (Mège et al., 2015). For the purpose of the description of the variation in geomorphic proxies, we divide the SEEP into six physiographic provinces. These are the Bale and Ahmar mountains, the Genale and North slopes, and the Weyb basins and the lower Shabele valley (Fig. 1B).

2.2. Lithology

The SEEP is dominated by (i) Precambrian basement rocks, (ii) Paleozoic – Mesozoic sedimentary rocks, and (iii) Cenozoic volcanic rocks. The Precambrian basement rocks are exposed mostly in the Genale slopes and the Ahmar mountains from uplift and exhumation along the southeastern escarpment of the MER and the Afar Depression (Fig. 2). These rocks include variably metamorphosed volcano-sedimentary and plutonic rocks that were formed during the 900–500 Ma East African orogeny (Stern, 1994). The Precambrian basement rocks are overlain by Paleozoic–Mesozoic sedimentary rocks deposited in two sedimentary episodes. These include the late Carboniferous – Jurassic Karoo rifting episode and the Late Jurassic Gondwana fragmentation episode (e.g., Worku and Astin, 1992). The Karoo sedimentary rocks are strictly continental in nature and were deposited in narrow grabens between horst structures dominated by the Precambrian basement rocks. No Karoo sedimentary rocks are exposed to the surface in the SEEP, but they are found in the subsurface as reported from drilling and seismic data (Worku and Astin, 1992).