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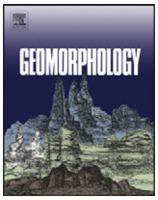

Gravity tectonics of topographic ridges: Halokinesis and gravitational spreading in the western Ogaden, Ethiopia

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ABSTRACT

The Cenozoic history of the western Ogaden region of Ethiopia, between the Ethiopian rift and the South Afar margin, is marked by uplift and incision of the Ogaden plateau down to the Gorrahei Formation, an upper Cretaceous evaporite formation. Debuttressing of this and the overlying sedimentary formations resulted in widespread and spectacular gravitational spreading landforms over a minimum surface area of 15,000 km^2, most of which remains unstudied. After clearing up some misconceptions about the surface geology of the study area, the Kebenawa Ridge in the Audo Range, observations are reported that point to a tectonic style controlled by halokinesis and subsequently, gravitational spreading. The role of diapirism and karstification in the observed halokinesis is discussed, as well as the influence of halokinesis on gravitational spreading. Spreading is in part akin to sackung, in that ridge deformation features include a crestal graben and basal ridge topography extrusion, and deformation was triggered by lateral ridge debuttressing. Ridge spreading also presents analogy with gravitational spreading of the Canyonlands grabens in the Needles District, Canyonlands National Park, Utah. The scale and the mechanisms are found to be basically similar, but two differences are noted. First, incision by the drainage network in response to plateau uplift in Ethiopia has debuttressed the topography along two parallel rivers, instead of a single river (the Colorado River) in Utah. Secondly, incision proceeded to the base of the evaporite layer in the Ogaden, whereas incision has not exceeded the top of the evaporite layer in Utah. These differences may have influenced the details of the spreading mechanisms in ways that remain to be investigated. Overall, in Ethiopia, association of halokinesis and a transitional mode of gravitational spreading at the interface between narrow ridge spreading (sackung) and plateau spreading (Canyonlands-type), illustrates a fascinating and unusual ridge evolution style.

1. Introduction

Topographic spreading occurs at all scales, including high orogens and plateaus such as the Andes and Tibet (e.g., Froidevaux and Ricard, 1987; Mercier, 1987), volcanic edifices (e.g., Borgia et al., 2000; Van Wyk de Vries et al., 2001), low elevation plateaus such as the Canyonlands grabens in the Needles District, Utah (e.g., McGill and Stromquist, 1979; Trudgill and Cartwright, 1994), and topographic ridges, in which case gravitational spreading produces sackung features (e.g., Hippolyte et al., 2006; Jarman, 2006). This paper reports a gravitationally spreading ridge in southeast Ethiopia for which sackung has been influenced by the presence of a ductile layer at depth. Development of sackung features by flow of a basal ductile layer has been popularised by interpretations of three examples in Colorado in a well-known article by Radbrush-Hall et al. (1976), but more recent studies indicate that this mechanism is marginal at a global scale. Most deciphered sackung examples on Earth do not show such causal relationships, and the massively dominant factor for sackung to operate is glacial valley buttressing followed by postglacial debuttressing and/or uplift (Mège and Bourgeois, 2011, who also provide a review of alternative geologic contexts). The example reported here is therefore unusual; it is, however, distinct from the Colorado examples analysed by Radbrush-Hall et al. (1976) in that (1) sackung in Colorado is postglacial, in contrast to the study area; and (2) the ductile level is made of evaporites in southeast Ethiopia, whereas it is made of shale in Colorado. Because of the presence of the evaporite level, halokinesis could take place prior to sackung in southeast Ethiopia; therefore, the finite deformation is more complex than in common sackung cases. The processes involved in ridge spreading in the studied example present similarities to the processes involved in the triggering and evolution of the "gravity syncline" studied by Carena et al. (2000) in the northern Apennines, and also with spreading of the Canyonlands grabens of the

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Needles district, Utah (e.g., Moore and Schultz, 1999), a comparison with which is provided at the end of this article.

2. Kebenawa ridge: geological framework

The Kebenawa ridge is part of the northern Audo Range (Figs. 1 and 2), a series of mesas in western Ogaden separated by the river Shebele and its tributaries that had never been studied before. A stratigraphic framework and a geologic map of the Kebenawa ridge (Figs. 3 and 4) have been established from (1) field data in the Kebenawa ridge collected in 2006, and along a new road between Imi and El Kere in 2005, (2) the known regional and local stratigraphy (Elwerath, 1960, 1965, 1967; Bauduin et al., 1972; Purcell, 1979; Bosellini, 1989), (3) the relevant 1:50,000 topographic map (Ethiopian Mapping Authority, 2001), (4) SRTM (Farr et al., 2007) and ASTER digital elevation models, and (5) satellite imagery including the Geocover 1990 Landsat TM mosaic, ETM+ images made available by the Global Land Cover Facility, ASTER visible and infrared coverage, and ALOS/Palsar radar imagery (band L). Interpretations have been eventually refined, when necessary, using the Spot image coverage made available through Google Earth ©.

2.1. Stratigraphy

Extrapolating from surrounding areas known in greater details, the basement in the study area is made of peneplained Archean to Panafrican rocks. It might have been disrupted by the Karoo rift system which developed from the Late Paleozoic to Jurassic and fragmented the Gondwana during the Jurassic–Cretaceous (Bosellini, 1989). Pre-rift Adigrat fluviatile sandstone deposition was followed by a basin sequence starting with the transgressive formation of Hamanlei, followed by the Uarandab and Gabredarre formations, whose top is assigned to the Tithonian (Purcell, 1979; Bosellini, 1989).

The Gabredarre Formation is followed by the thick evaporitic Gorrahei Formation (Neocomian), the base of which is made of a peculiarly resistant carbonate layer (Fig. 4). The carbonates are being incised by the Shebele river, and form the stratigraphic and topographic base level of the Audo mesas. They crop out in places around the Kebenawa ridge, where it is observed to be horizontal, but it does not crop out within the ridge. The evaporites, mainly gypsum (Fig. 5a), are overlain by the transgressive upper Aptian–Albian Mustahil carbonates (Fig. 5d), and the Paleocene Jessoma sandstones (Fig. 6). The Mustahil Formation is occasionally brecciated with angular carbonate fragments. The Jessoma Formation is observed to be unconformable in most settings in the Ogaden and Somalia (e.g., Bosellini, 1989), but this unconformity could not be demonstrated in the Kebenawa ridge. In the Audo Range, the Mustahil and Jessoma formations constitute a resistant cap that has protected the evaporitic formation from rapid erosion by the Shebele river tributaries. An oligomictic conglomerate (Fig. 5e,f), in which carbonates (grainstone, dolostone, and calcrete), are dominant, gypsum is frequent, sandstone is occasional, and basalt is rare, covers some of the ridge slopes. It has also been observed at the summit of the ridge at the top of the Mustahil and the Jessoma formations (Fig. 5f).

Unrecognized on the earliest geological maps of Ethiopia, where it appears as Jurassic ("Antalo") limestone (Dainelli, 1943; Mohr, 1963), the Jessoma Formation had been correctly identified on the first official edition of the geological map of Ethiopia (Kazmin, 1972) and a hydrogeological survey of the Shebele drainage basin by ORSTOM (Bauduin et al., 1972). Probably because the rocks had been mapped as volcanics of unknown age by Merla et al. (1973), the geological map of Ogaden by BEICIP (1985) reported them as either the Jessoma sandstone or volcanics, and they have been identified as volcanics of

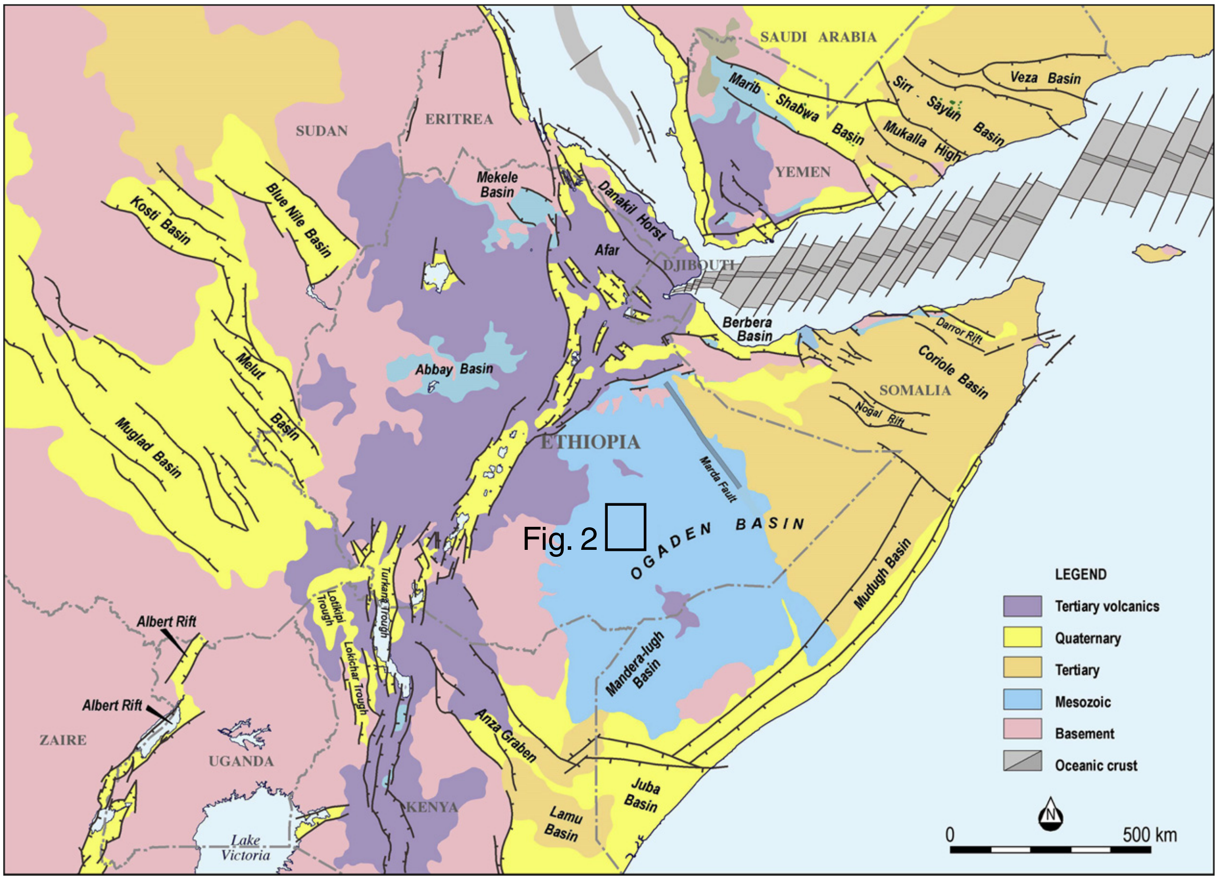

Fig. 1. Geologic map of the African Horn (by courtesy of P.G. Purcell) and location of the study area.