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Steady rifting in northern Kenya inferred from deformed Holocene lake shorelines of the Suguta and Turkana basins

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ABSTRACT

A comparison of deformation rates in active rifts over different temporal scales may help to decipher variations in their structural evolution, controlling mechanisms, and evolution of sedimentary environments through time. Here we use deformed lake shorelines in the Suguta and Turkana basins in northern Kenya as strain markers to estimate deformation rates at the 10^3–10^4 yr time scale and compare them with rates spanning 10^1–10^7 yr. Both basins are internally drained today, but until 7 to 5 kyr lake levels were 300 and 100 m higher, respectively, maintained by the elevation of overflow sills connecting them with the Nile drainage. Protracted high lake levels resulted in formation of a maximum highstand shoreline — a distinct geomorphic feature virtually continuous for several tens of kilometers. We surveyed the elevation of this geomorphic marker at 45 sites along >100 km of the rift, and use the overflow sills as vertical datum. Thin-shell elastic and thermomechanical models for this region predict up to ~10 m of rapid isostatic rebound associated with lake-level falls lasting until ~2 kyr ago. Holocene cumulative throw rates along four rift-normal profiles are 6.8–8.5 mm/yr, or 7.5–9.6 mm/yr if isostatic rebound is considered. Assuming fault dips of 55–65°, inferred from seismic reflection profiles, we obtained extension rates of 3.2–6 mm/yr (including uncertainties in field measurements, fault dips, and ages), or 3.5–6.7 mm/yr considering rebound. Our estimates are consistent, within uncertainties, with extension rates of 4–5.1 mm/yr predicted by a modern plate-kinematic model and plate reconstructions since 3.2 Myr. The Holocene strain rate of 10^{-15} s^{-1} is similar to estimates on the ~10^6 yr scale, but over an order of magnitude higher than on the ~10^7 yr scale. This is coherent with continuous localization and narrowing of the plate boundary, implying that the lithospheric blocks limiting the Kenya Rift are relatively rigid. Increasing strain rate under steady extension rate suggests that, as the magnitude of extension and crustal thinning increases, the role of regional processes such as weakening by volcanism becomes dominant over far-field plate tectonics controlling the breakup process and the transition from continental rifting to oceanic spreading.

1. Introduction

Deformation rates of the Earth's crust constitute an observational basis for physical models of various processes associated with plate motions, including mountain building, the earthquake cycle, and rifting of continental crust. At divergent plate boundaries, the width of the deforming region may vary as well as the rates at which it stretches (e.g., Molnar, 1988). Continental rifts represent the initiation of divergent plate boundaries, and may evolve into continental break-up, ultimately resulting in new ocean basins (e.g., McKenzie et al., 1970). A crucial aspect to understanding the continental break-up process is the dynamic link between far-field forces exerted by plate tectonics, regional stresses that may arise from mantle plumes, and local mechanical aspects such as fault weakening, inherited rheological discontinuities, and volcanism (e.g., Buck, 2004). This link is likely to dictate the rate and style of rifting.

The role of magmatic versus tectonic processes in continental rifting has been the matter of debate. Recent volcano-tectonic episodes associated with rifting in regions with thin (Abdallah et al., 1979; Wright et al., 2006) as well as thick (Calais et al., 2008) lithosphere suggest that dyke intrusions accounted for most of the strain. Conversely, numerical modeling indicates that continental lithosphere may be broken without volcanism, controlled by shear heating (Regenauer-Lieb et al., 2008). In the East African Rift System (EARS)

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frequent, low-magnitude seismicity has been associated with dyke intrusions (e.g., Tongue et al., 1994), but fault ruptures during large earthquakes have occurred without coupled volcanism (e.g., Ambraseys, 1991; Biggs et al., 2010; Zielke and Strecker, 2009). Thus, despite of its overall magmatic character, strain release in the EARS is not necessarily associated with dyke intrusions and magmatism.

Magma-assisted rifting in the advanced northernmost EARS appears to be efficient (e.g., Wright et al., 2006), but it is not clear how the less advanced sectors farther south behave, and if rates have changed over time. While sea-floor magnetic anomalies reveal that oceanic spreading rates may be sustained over $\sim 10^7$ yr (e.g., Demets et al., 1990), our understanding of deformation rates during continental rifting has remained limited, mainly because of the lack of suitable strain markers at various temporal scales. In an attempt to quantify extension rates and gain insight into strain localization processes at a nascent divergent plate boundary, we studied Holocene deformation within the eastern branch of the EARS in northern Kenya (Fig. 1). Independent estimates of extension in this region have been obtained at the 10^6–10^7 yr scale from balanced cross sections (Hendrie et al., 1994), as well as reconstruction of oceanic magnetic anomalies and transform azimuths (Chu and Gordon, 1999), and at the 10^1 yr scale from geodesy and seismology (Calais et al., 2006). Recently, Stamps et al. (2008) quantified regional deformation rates for East Africa by jointly inverting 3.2-Myr average spreading patterns, GPS velocities, and earthquake slip vectors, finding that extension rates are consistent over 10^1–10^6 yr scales.

In order to bridge the gap between extension on 10^1 yr and 10^6 yr scales in the northern Kenya Rift, we estimated extension rates at the 10^3–10^4 yr scale by taking advantage of easily identifiable lake shorelines and using them as strain markers. These shorelines formed as a result of protracted lake highstands in the Suguta and Turkana basins of northern Kenya during the African Humid Period (e.g., deMenocal et al., 2000), between the early and middle Holocene. Based on these deformed geomorphic markers, we estimated extension rates that agree with regional modern (Stamps et al., 2008) and long-term (Horner-Johnson et al., 2005) models, suggesting that steady extension has been a hallmark on the million-year scale. Furthermore, the tectonic evolution of the Suguta–Turkana region records a progressive localization of extensional deformation, now focused along the ~35-km-wide inner rift trough. Whereas Miocene extension was broadly distributed (e.g., Morley et al., 1992), the consistency of late Pliocene to present-day rates and the combination of localized Quaternary deformation, shallow seismicity, and volcanism suggest that strain has become focused along the rift axis. Sustained constant extension rates and strain localization lend support to previous hypotheses that favored the role of local processes such as plume volcanism and magma-assisted deformation (e.g., Kendall et al., 2005), over far-field plate-tectonic forces, in the evolution from continental rifting to oceanic spreading.

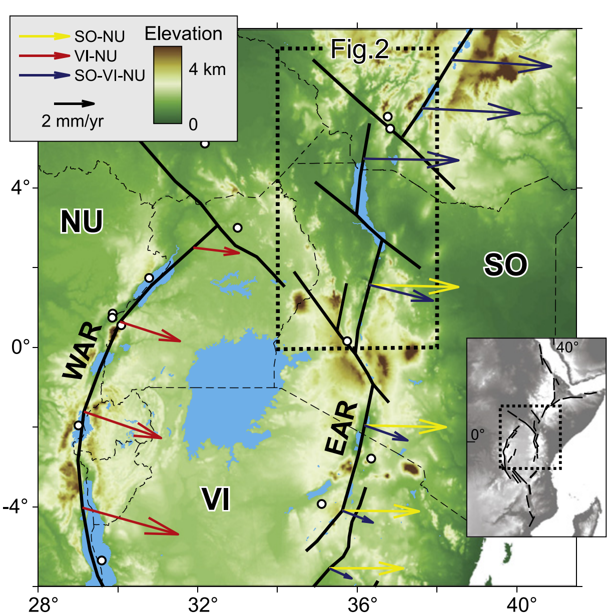

Fig. 1. Plate tectonic setting. Arrows show relative plate motion with respect to a stable Nubian reference frame, calculated with Euler poles from the modern plate-kinematic model of Stamps et al. (2008). Plates: SO, Somalia; VI, Victoria; NU, Nubia. WAR and EAR: western and eastern branches of the African Rift. Vectors in dark blue represent the model that includes the three plates. White dots are M > 5 earthquakes from the Centennial Catalogue (Engdahl and Villaseñor, 2002).

2. Regional tectonic setting

The EARS extends over more than 3000 km and constitutes the boundary between the African or Nubia and Somalia plates (Fig. 1) (e.g., McKenzie et al., 1970). Rifting in the EARS started during the early-middle Paleogene in southern Ethiopia, northern and central Kenya, and propagated northward and southward establishing the eastern branch of the EARS in early Miocene time (e.g., Baker and Wohlenberg, 1971; Ebinger and Sleep, 1998; Ebinger et al., 2000; Tiercelin and Lezzar, 2004; Wichura et al., 2010). During the early stages of rifting in northern Kenya, extension was distributed over a ~150-km-wide region creating several half-graben basins with up to 7 km fill (Dunkelman et al., 1989; Hautot et al., 2000; Hendrie et al., 1994; Morley et al., 1992). Tectonic activity along those basins ceased during the early Pliocene, and subsequently become localized in the present Rift Valley, resulting in the formation of the inner trough (e.g., Morley et al., 1999; Truckle, 1976).

Between ~8°S and ~3.5°N, the EARS is structured into western and eastern branches (Fig. 1), which straddle a central cratonic region, termed the Victoria microplate (Calais et al., 2006). Fig. 1 shows plate-boundary slip vectors calculated using the Euler poles of the two- and three-plate models from Stamps et al. (2008), the latter including the Victoria microplate. Slip vectors from the three-plate model tend to agree better with the regional rift geometry, and predict rates of extension that along the EARS between southern Ethiopia and central Kenya decrease southward from ~7 to 1.4 mm/yr (Fig. 1). This pattern is mimicked by a southward increase in crustal thickness estimated from seismic-refraction profiles (KRISP, 1991), compatible with a decrease in the magnitude of finite extension.

Shallow earthquakes of M > 5 have occurred along the EARS during the past century, with only a few large events associated with surface ruptures (Abdallah et al., 1979; Ambraseys, 1991; Parsons and Thompson, 1991). It is unlikely that seismic slip on crustal faults accounts for all the extension across the rift, unless very large events with long recurrence times are missing from historical catalogs (e.g., Zielke and Strecker, 2009). In fact, both the 2005–2009 Afar (Grandin et al., 2010; Wright et al., 2006) and 2007 Natron (Calais et al., 2008) rifting episodes were associated with dyke intrusions and aseismic fault slip, which accounted for most of the strain, suggesting that part of the extension is coupled with volcano-tectonic processes.

In the Suguta and southern Turkana regions, clusters of shallow microseismicity recorded by a temporary local seismological network have occurred along the rift axis, where volcanic centers are aligned along steep faults (Pointing et al., 1985). This is similar to frequent microseismicity along the axis of the Baringo basin to the south inferred to be related to dyking (Tongue et al., 1994). Tectonic activity in Baringo and within the Central Kenya Rift has also migrated into the present-day rift center, and apparently postdates a change in the regional extension direction from east–west to northeast–southwest (Strecker et al., 1990).