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Strike-slip tectonics during rift linkage

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ABSTRACT

The kinematics of rift segment linkage in magmatic rifts remain debated. Strain patterns from Afar provide tests of current models of how segmented rifts grow in areas of incipient oceanic spreading. Here, we present a combined analysis of seismicity, interferometric synthetic aperture radar (InSAR), and GPS–derived strain rate maps to reveal that the plate-boundary linkage between the Red Sea and Gulf of Aden rifts of Afar is accommodated primarily by distributed extensional faulting. Large rotations about vertical axes predicted by bookshelf faulting models are not detected. Additionally, models of stress changes and seismicity induced by recent dikes provide poor fits to the observed time-space patterns of strike-slip earthquakes. Instead, we explain these features as resulting from rift-perpendicular shearing at the tips of spreading rifts where extension terminates against less stretched lithosphere. Our results demonstrate that distributed extension drives rift-perpendicular shearing, achieving plate-boundary linkage during incipient seafloor spreading.

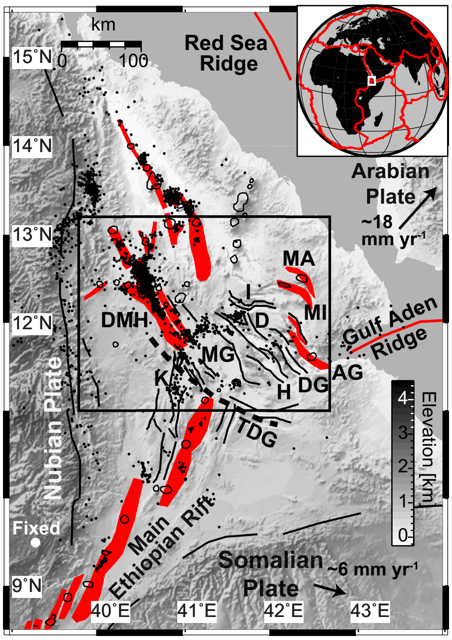

Figure 1. Local seismicity in Afar (A.D. 2005–2009; black dots). Solid red polygons are Holocene magmatic rift segments: DMH—Dabbahu-Manda Hararo; MA—Moussa Alli; MI—Manda Inakir; AG—Asal-Ghoubbet segments. Volcanoes are marked by black outlines. Dashed line marks Tendaho-Goba'ad discontinuity (TDG). Black lines are faults. Tectonic rift segments are: K—Karrayu; MG—Manda Gargori; D—Dobi; I—Immino; H—Hanle; DG—Derele Gaggade. Box marks area shown in Figures 2–4. Inset shows location of Afar.

INTRODUCTION

Continental rifts are three-dimensional structures with complex fault kinematics ranging from extensional to strike-slip (i.e., Kebede et al., 1989; Sigmundsson, 1992). The distribution of strain also evolves from rift initiation to plate rupture. During the initial continental extension, rifts show along-axis segmentation by large-offset faults, but, as plate stretching and heating progress to rupture, magma intrusion may accommodate a large percentage of the plate-boundary deformation, and along-axis segmentation is in part controlled by the distribution of magma chambers (Ebinger and Casey, 2001; Keir et al., 2009). Yet, unlike mid-ocean-ridge segments that are linked by transform faults (>50 km offsets) or smaller non-transform offsets (Macdonald et al., 1988), there are few, if any, strike-slip faults at the surface between en echelon rift segments. Therefore, it remains debated how crustal extension is transferred from one rift segment to another. This gap obfuscates our understanding of the mode and stability of rift linkage in Afar. However, recent seismicity (Ebinger et al., 2008; Keir et al., 2009; Belachew et al., 2011) and high-resolution interferometric synthetic aperture radar (InSAR) and GPS–derived strain maps (Pagli et al., 2014) now allow us to identify the present plate boundary and constrain its kinematics in Afar. Our seismicity and strain rate maps are complemented by independent structural data (Varet, 1975; Hayward and Ebinger, 1996; Manighetti et al., 2001).

The divergence of the Nubian, Arabian, and Somalian plates during the past 30 m.y. created the Afar depression, where extension occurs across the Red Sea, the Gulf of Aden, and the Main Ethiopian rifts (MER; Fig. 1; Barberi and Varet, 1977; Courtillot et al., 1984). Current full spreading velocities are 18 mm/yr for Nubia–Arabia, 16 mm/yr for Somalia–Arabia, and 6 mm/yr for Nubia–Somalia (McClusky et al., 2010; Saria et al., 2014). The Red Sea and Gulf of Aden rifts are extending in a northeast-southwest direction, and they are connected to the much slower, approximately east-west–extending MER by the Tendaho-Goba'ad discontinuity (Hayward and Ebinger, 1996; Manighetti et al., 1998). Extension along the southern Red Sea was initially accommodated on large border faults, but during the past ~4 m.y., strain localized to axial magmatic segments, which mark the active plate boundary from latitude ~15°N to 12°N in the Red Sea rift, and south of 11°N in the MER (Fig. 1; Hayward and Ebinger, 1996; Manighetti et al., 1998). Similar patterns occur in the Gulf of Aden rift (Asal-Ghoubbet rift; Doubre et al., 2007). Between the clear segmentation of the Red Sea and Gulf of Aden rifts, from latitude 12°N to 11°N, the presence of mainly tectonic fault zones without recent

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(Holocene) volcanism suggests that plate opening is accommodated by faulting.

The mode of linkage between the Red Sea and Gulf of Aden rifts in central Afar has been debated. One model of propagating rifts assumes that the Red Sea rift propagates southward as the Gulf of Aden rift propagates northward (Fig. 1; Fig. DR1 in the GSA Data Repository[1]; i.e., Tapponnier et al., 1990; Manighetti et al., 1998; Kidane et al., 2003; Muluneh et al., 2013; Kidane, 2016). According to this model, the two propagating rift tips do not directly join but instead overlap, creating a broad zone of right-lateral shear in central Afar. The shearing is achieved by slip along a series of rift-parallel, left-lateral strike-slip faults: bookshelf faulting. The 1969 Serdo earthquakes, rupturing ~2-km-long, rift-parallel, left-lateral strike-slip faults, together with clockwise block rotations, were originally used as evidence of bookshelf faulting (Courtillot et al., 1984; Tapponnier et al., 1990). However, the 1989 earthquake swarm from the Dobi graben had normal faulting mechanisms (Sigmundsson, 1992). As normal faulting is not explained by the bookshelf model, the author then argued that the model should be modified to include extension together with strike-slip motion. Alternative models have also been proposed; the rift-perpendicular distribution of aftershocks from the Serdo earthquakes was interpreted as a rift-perpendicular transform (Kebede et al., 1989). The paleomagnetic rotations have been explained by models of rigid microplates bounded by narrow zones of strain that may not be stable in time (Acton et al., 1991), but Quaternary fault-slip patterns show more distributed deformation in central Afar (Polun et al., 2017). Importantly, neither model considers strain accommodation by episodic magma intrusion. Here, we present a new model that separates magmatic and tectonic features and leads to distributed extension to link rift segments at plate rupture.

SEPARATING DIKE-INDUCED AND TECTONIC SEISMICITY

We analyzed the seismicity from two local seismic networks that were deployed in Afar between 19 October 2005 and 7 October 2009 (Fig. 1; Table DR1; Ebinger et al., 2008; Keir et al., 2009; Belachew et al., 2011, 2013; Ayele et al., 2015). The catalogues were located using Hypo2000 (https://earthquake.usgs.gov/research/software/#HYPOINVERSE) and a single one-dimensional velocity model. In our study area (black box in Fig. 1), there are a total of 6141 earthquakes with local magnitudes of 0.8–4.7 and a mean horizontal error on the earthquakes epicenters of 1.3 km. In total, 14 intrusions occurred in the Dabbahu-Manda Hararo segment (DMH) between 2005 and 2010 and were identified by geodesy and seismicity (Wright et al., 2012; Belachew et al., 2013), of which 10 are covered by our catalogue. The seismicity patterns in Figure 1 are caused by both tectonic and dike-induced stresses. Dike intrusions cause stress changes in the surrounding crust, inducing earthquakes. Specifically, the stress imposed by a dike intrusion is expected to cause normal faulting above it and strike-slip faulting along two limbs near each of the two dike tips, at ~120° to the strike of the intrusion (Hill, 1977; Toda et al., 2002). We analyzed the seismicity to separate co-intrusive from longer-term tectonic features.

In Figure 2A and Figure DR2, we show the co-intrusive seismicity at DMH. The majority of the co-intrusive events occur within DMH (Fig. 2A), while off-rift earthquakes are observed mainly northeast and southeast of the rift, crudely defining two limbs (Fig. 2A). Nonetheless, earthquakes occur on the sides of DMH irrespective of dike intrusions (Fig. 2B).

We modeled the seismicity around DMH by calculating the stress changes caused by the dikes, using a method that takes into account the dike-induced stress changes caused by the intruded magma on the dike walls and the fact that these stresses act on crustal faults to induce earthquakes (Yun et al., 2006; Segall et al., 2013). We first calculated the dike opening distributions in DMH, and then we related the dike-induced stresses to seismicity based on the seismicity-rate theory of Dieterich (Dieterich, 1994) as described by Segall et al. (2013) (see the Data Repository text and Fig. DR4). We simulated the earthquakes induced by magma intruded in DMH between 2 and 9 km depth (Wright et al., 2012). We assumed a 70-km-long, N150E-striking DMH rift and aligned faults (Varet, 1975; Hayward and Ebinger, 1996; Manighetti et al., 2001). Our modeling predicts increased seismicity due to dike-induced stress changes around DMH, reproducing some of the off-rift earthquakes (Fig. 2C). However, the approximately east-west–trending belt of persistent seismicity southeast of DMH cannot be matched by the model predictions (Fig. 2C). We conclude that the off-rift earthquakes immediately adjacent to the intruded area northeast and southeast of DMH are likely induced by the intrusions, while the rest of the seismicity is caused by tectonic stresses.

To better understand the tectonics of the area, we then analyzed the seismicity catalogue together with the focal mechanisms of the larger events and the strain rate maps derived from InSAR and GPS. We removed from the catalogue all earthquakes spanning the time of an intrusion and subsequent 30 days to make the seismicity comparable to the geodesy, from which the 1 month co-intrusive displacements were removed. Co-intrusive seismicity plots (Fig. DR3) show that dike-induced earthquakes decay more rapidly than 30 days. The resulting seismicity describes the recent tectonic stresses acting in the region devoid of short-term diking processes (Fig. 2B). Although earthquake magnitudes are too small or azimuthal gaps are too large to evaluate isotropic and compensated linear vector dipole (CLVD) components, earthquakes in the central Afar rifts do not occur in swarms characteristic of magma intrusion events, and the focal mechanism analyses are consistent with double-couple mechanisms.

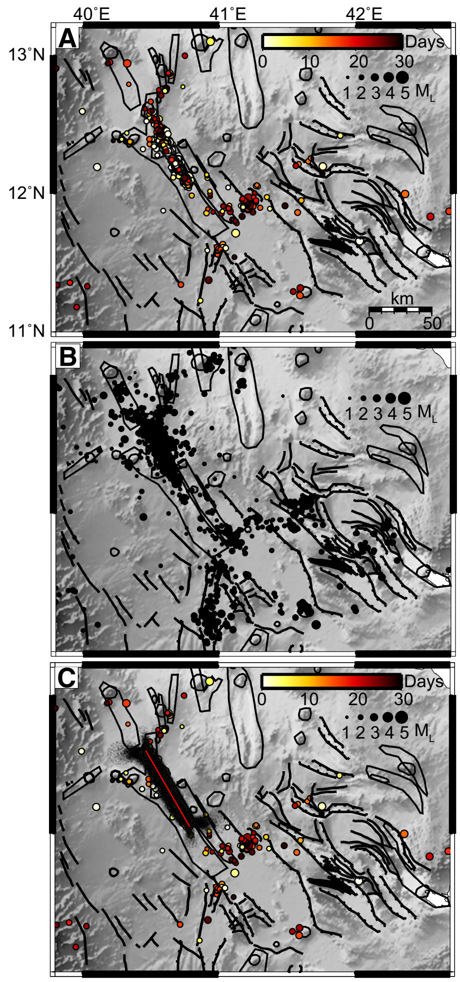

Figure 2. A: Co-intrusive seismicity in Afar. Filled circles are earthquakes, color-coded by day of occurrence since onset of intrusion over a 30 day period (see also Fig. DR1 [see footnote 1]). B: Non-co-intrusive seismicity obtained from plotting complete seismic catalogue minus earthquakes in A. C: Co-intrusive seismicity (as in A) and predicted dike-induced seismicity (black dots). Red line marks intruded area. Black outlines are volcanoes, and black lines are faults.

RIFT-PERPENDICULAR SHEARING AT SEGMENT TIPS

Knowledge of the way in which the crust deforms is fundamental to understanding the ongoing tectonics. Recently, Pagli et al. (2014) combined InSAR data, acquired in different

[1]GSA Data Repository item 2019007, earthquake modeling method, InSAR data analysis, Figures DR1–DR7, and Table DR1, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

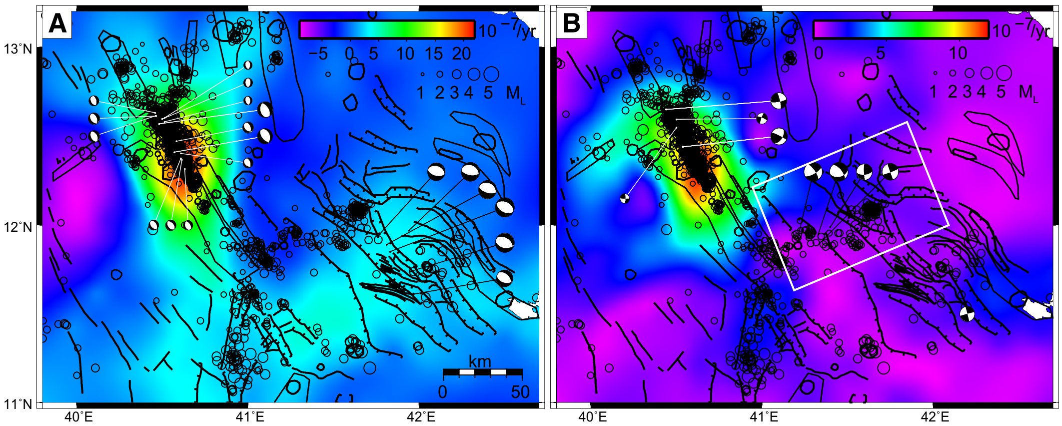

Figure 3. A: First invariant of horizontal strain rate tensor (positive values are extension), normal faulting mechanisms (beach balls) from Craig et al. (2011), and local seismicity (circles), as in Figure 2B. B: Maximum shear strain rate, strike-slip faulting mechanisms (beach balls) from Kebede et al. (1989), Lépine and Hirn (1992), Craig et al. (2011), and Ebinger et al. (2008), and local seismicity (circles) as in Figure 2B. White box marks a band of shear. Rift segment names are same as in Figure 1.

geometries by the European Space Agency *ENVISAT* satellite, with the available GPS data to obtain a continuous high-resolution three-dimensional velocity field of Afar (see the Data Repository text and Figs. DR5–DR7; Wang and Wright, 2012). The velocity field was then used to calculate the horizontal strain rates (e.g., Savage et al., 2001). The InSAR and GPS data span the time period from the start of 2007 to mid-2010, comparable to the observation period of the seismic networks (October 2005–October 2009). All co-intrusive deformation in the DMH segment has been removed from the data, so the resulting strain rates are representative of the tectonic regime. We also augmented our seismicity and strain rate maps with local (Lépine and Hirn, 1992; Ebinger et al., 2008) and teleseismic focal mechanisms (Kebede et al., 1989; Craig et al., 2011).

High strain rates and dense seismicity clusters occur at the DMH axis, where segment-centered extension (Fig. 3A) and shear (Fig. 3B) correlate with normal and strike-slip earthquakes as a result of transient post-rifting deformation (Hamling et al., 2014; Pagli et al., 2014). However, high shear strain rates and seismicity also extend off-rift, in particular, along two west-southwest–trending zones at the northern and southern tips of DMH (Fig. 3B). This is important because it shows for the first time that repeated diking at a rift segment (co-rifting) can generate shear off-rift during post-rifting.

In central Afar, southeast of DMH, extension rates were detected across a 150–200-km-wide region of subparallel basins: Manda-Gargori, Dobi, Immino, Hanle, and Asal-Ghoubbet (Fig. 3A). Normal faulting earthquakes recorded globally also occurred at the same location, showing a tectonic regime dominated by extension rather than distributed shear. Conversely, an ENE-WSW band of seismicity with strike-slip focal mechanisms was recorded at the rift tips, including the Serdo earthquakes (Fig. 3B), showing rift-perpendicular shear with good correlation to the location at which the extension of the central Afar rift terminates (Fig. 3A). We explain these spatial patterns as the result of a rift-perpendicular, right-lateral shear zone at the rift tips, where the extension across a broad region terminates against less stretched lithosphere. The focal mechanism nodal planes and fault patterns are consistent with the shear being accommodated by short left-lateral faults (i.e., 1969 Serdo earthquakes) and relay ramps, although the shear zone may also evolve to a through-going right-lateral transform fault. The shearing is well captured by seismicity but not as clearly by the shear strain rate map, likely because the resolution does not allow us to identify narrow localized shear or because the shear motion is not high enough to be identified by InSAR due to projection along the satellite line-of-sight.

Paleomagnetic rotations have been used as evidence of bookshelf faulting in central Afar (Tapponnier et al., 1990), but recent studies show that rotations are heterogeneous, and that the western rifts (i.e., Manda-Gargori and Dobi) are not rotated (Kidane et al., 2003). The bookshelf model also requires rift propagation in the Manda-Inakir and Moussa-Alli rifts. However, no strain localization or seismicity is recorded there, while extension and normal faulting earthquakes occur in the central Afar rifts. Detailed structural analyses in central Afar show that fault slip is primarily normal, with a minimal oblique component, and bookshelf fault zones have been inactive over the past 5–100 k.y. (Polun et al., 2017). We acknowledge that a zone of bookshelf faulting may have acted in the past, but our analyses of current strain rates and seismicity support a model for Red Sea–Gulf of Aden–MER linkage through a broad zone of overlapping, extensional basins bounded by rift-perpendicular shear zones (Fig. 4).

The Tendaho-Goba'ad discontinuity, which links the MER to the Red Sea and Gulf of Aden zones, consists of conjugate NNW- and NNE-striking faults, owing to the high obliquity between the extension directions (Varet, 1975). In the MER, seismicity occurs mainly in the Karrayu segment, while extension is accommodated over a broader zone (Fig. 3A). This extension may be related to the superposition of the younger MER structures on the ca. 30 Ma Red Sea–Gulf of Aden rift junction (Kidane et al., 2003).

CONCLUSIONS

Our results show that the central Afar rifts are linked by a series of extensional faults bounded by a rift-perpendicular zone of shear, providing a new tectonic model of the Afar plate boundary (Fig. 4). Specifically, plate extension is accommodated within the DMH, while south of it, in the central Afar rifts, strain rates and seismicity are consistent with linkage between the Gulf of Aden ridge and the southern Red Sea through a series of rift segments that connect to the DMH. Owing to the lack of any significant strain rates or seismicity in Manda-Inakir and Moussa-Alli (Fig. 3), these areas are not the locus of the plate boundary at present, arguing against the broad zone of shear deformation required by bookshelf faulting models.

The central Afar rifts are deep, sediment-filled grabens bounded by normal faults that show normal faulting earthquakes. Seismicity, geodetic, and structural data indicate that the central Afar basins are in extension, and they lack the strike-slip faulting and block rotations predicted by bookshelf faulting. We conclude

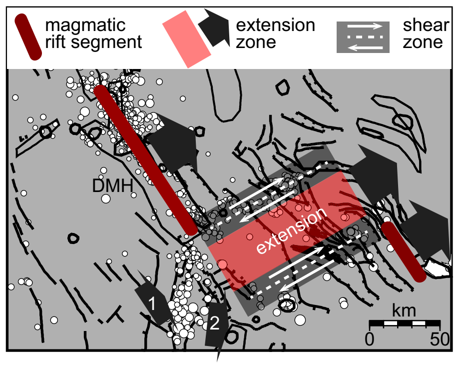

Figure 4. Sketch of plate boundary with respect to stable Nubia. South of Dabbahu-Manda Hararo segment (DMH), fault orientations are consistent with two directions of extension, as shown by arrows 1 and 2. Earthquakes (white circles) are as in Figure 2B.

that the Red Sea, Gulf of Aden, and MER are currently linked by a zone of rift-parallel normal faults bounded by narrow rift-perpendicular shear zones.

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