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Extension and stress during continental breakup: Seismic anisotropy of the crust in Northern Afar

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ABSTRACT

Studies that attempt to simulate continental rifting and subsequent breakup require detailed knowledge of crustal stresses, however observational constraints from continental rifts are lacking. In addition, a knowledge of the stress field around active volcanoes can be used to detect sub-surface changes to the volcanic system. Here we use shear wave splitting to measure the seismic anisotropy of the crust in Northern Afar, a region of active, magma-rich continental breakup. We combine shear wave splitting tomography with modelling of gravitational and magmatic induced stresses to propose a model for crustal stress and strain across the rift. Results show that at the Ethiopian Plateau, seismic anisotropy is consistently oriented N–S. Seismic anisotropy within the rift is generally oriented NNW–SSE, with the exception of regions north and south of the Danakil Depression where seismic anisotropy is rift-perpendicular. These results suggest that the crust at the rift axis is characterized by rift-aligned structures and melt inclusions, consistent with a focusing of tectonic extension at the rift axis. In contrast, we show that at regions within the rift where extension rate is minimal the seismic anisotropy is best explained by the gravitationally induced stress field originating from variations in crustal thickness. Seismic anisotropy away from the rift is controlled by a combination of inherited crustal structures and gravitationally induced extension whereas at the Dabbahu region we show that the stress field changes orientation in response to magmatic intrusions. Our proposed model provides a benchmark of crustal stress in Northern Afar which will aid the monitoring of volcanic hazard. In addition we show that gravitational forces play a key role in measurements of seismic anisotropy, and must be considered in future studies. We demonstrate that during the final stages of continental rifting the stress field at the rift axis is primarily controlled by tectonic extension, but that gravitational forces and magmatic intrusions can play a key role in the orientation of the stress field.

1. Introduction

The transition from continental rifting to seafloor spreading is a fundamental stage of plate tectonics; yet the mechanisms behind it have remained poorly constrained. Many studies which attempt to understand continental rifting have used numerical models (e.g., Brune et al., 2016); analogue models (Corti et al., 2003) or reconstructions of rifted passive margins (e.g., Pindell et al., 2014). Such studies require an understanding of how extension and stress are oriented across a continental rift. In recent years, studies have shown that extension migrates away from rift margins and focuses at rift axes through magmatically accommodated extension (Ebinger et al., 2013). However, the orientation of extension from rift margin to rift axis in the final stages of continental breakup remains poorly constrained. In addition, continental rifts typically host considerable volcanic activity that threatens local populations (e.g., Hutchison et al., 2016). The stress field that acts on a volcano has a profound effect on the orientation of fissure eruptions

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(Wadge et al., 2016) and any changes in the local stress field around the volcano may act as an indicator of an impending eruption (Gerst and Savage, 2004). Therefore an understanding of extension and the associated stress field during continental rifting is crucial for volcanic hazard assessments.

An ideal location to study the stress field during continental breakup is the Danakil Depression of Northern Afar (Fig. 1). In this study we use shear-wave splitting of local earthquakes to measure strain and interpret the stress field at a late stage continental rift. This allows us to gain a deeper understanding of continental rifting, providing observational constraints for future studies of rifting and volcanic hazards.

2. Background

2.1. Tectonic background

The Afar Depression lies at the triple junction between the Main Ethiopian Rift (MER), the Red Sea rift and the Gulf of Aden (Tesfaye et al., 2003) (Fig. 1). Rifting in Afar first involved the separation of Arabia and Africa and has been geochronologically dated as commencing ∼29–31 Ma (Wolfenden et al., 2005), with extension oriented NE–SW and initially accommodated on large (>50 km) border faults. Between 25 and 20 Ma, extension in Northern Afar migrated away from the border faults and focused at rift aligned, axial volcanic segments (Wolfenden et al., 2005). This change in extension mechanism is characterized by a focusing of seismicity and volcanic activity at the rift axis (Wolfenden et al., 2005).

The Danakil Depression is a ∼200 km long 50–150 km wide basin situated in the northernmost Afar Depression (Fig. 1b). It lies predominantly below sea level but is currently sub-aerial. The crust beneath the Danakil Depression thins dramatically from ∼27 km in Central Afar to <15 km at the Danakil Depression (Hammond et al., 2011; Makris and Ginzburg, 1987). This is in stark contrast to the Ethiopian Plateau, in the west, which has a ∼38 km thick crust (Hammond et al., 2011). Due to the low elevation of the Danakil Depression, repeated marine incursions mean the surface geology largely consists of thick layers of evaporites (Barberi and Varet, 1970). The NNW–SSE trending Erta-Ale volcanic range dominates the depression, and is the focus for the majority of Quaternary to Recent basalts in Afar (Bastow and Keir, 2011). Recent volcanic activity includes a fissure eruption at Alu-Dalafilla volcano in 2008, which was oriented sub-parallel to the rift axis (Pagli et al., 2012). The Erta-Ale range acts as the magmatic rift axis within the Danakil Depression; further to the south the rift axis steps en echelon to the southwest to the Dabbahu volcanic segment. The Dabbahu segment underwent a major dike intrusion episode from 2005–2010, which consisted of 14 large volume dikes (Belachew et al., 2011; Ebinger et al., 2010; Wright et al., 2006). To the east of the Danakil Depression, straddling the Ethiopian–Eritrean border, is the NE–SW trending Bidu volcanic complex, which consists of two calderas Nabro and Mallahle (Fig. 1b). In 2011 Nabro underwent a major eruption of VEI 4, which killed 7 people and displaced over 12000 people (Goitom et al., 2015).

2.2. Sources of crustal seismic anisotropy

In this study we use local, crustal earthquakes and thus our measurements of seismic anisotropy are strictly limited to the crust. As extension is focused and aligned in the upper crust of the Danakil Depression, stress induced dilatancy of micro cracks will induce seismic anisotropy (Crampin, 1994); such that the anisotropy direction (ϕ) aligns with the maximum horizontal stress (SH_{max}) (Hudson, 1981). In an extensional regime the minimum

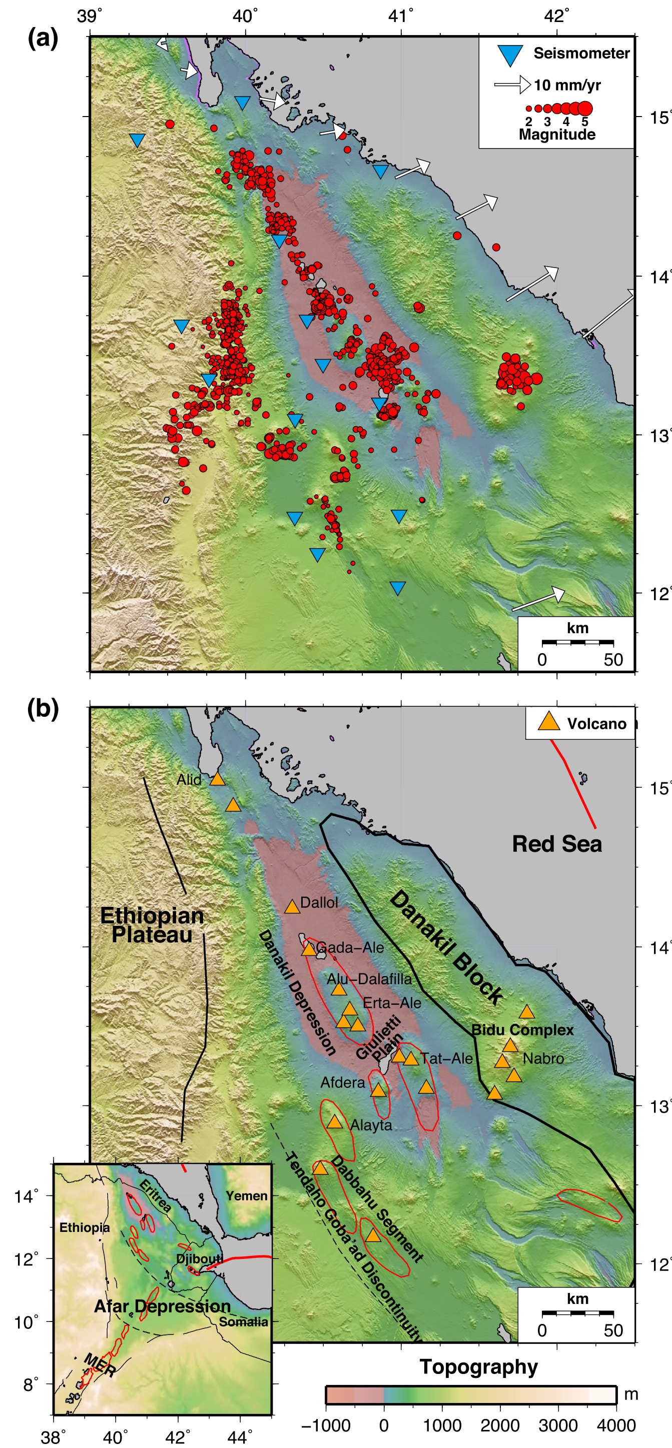

Fig. 1. The Danakil Depression of Northern Afar. **(a)** Red circles are earthquakes recorded between 2011–2013, with horizontal errors <5 km. Blue inverted triangles are seismometers deployed between 2011–2013. GPS velocities taken from McClusky et al. (2010) show the NE–SW regional extension. **(b)** Orange triangles are active volcanoes. Volcanic segments shown in red (Wolfenden et al., 2005). Bottom left inset: The Afar Depression, located at the triple junction between the Main Ethiopian rift (MER), the Red Sea rift and the Gulf of Aden rift. Political boundaries shown with black lines. Topography data taken from NASA's Shuttle Radar Topography Mission. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

horizontal compressive stress (SH_{min}) corresponds to the minimum compressive stress (S_3). In contrast, SH_{max} corresponds to the intermediate compressive stress (S_2). In the absence of a strong regional stress field, anisotropy can also be caused by