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Lower crustal earthquakes near the Ethiopian rift induced by magmatic processes

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[1] Lower crustal earthquakes are commonly observed in continental rifts at depths where temperatures should be too high for brittle failure to occur. Here we present accurately located earthquakes in central Ethiopia, covering an incipient oceanic plate boundary in the Main Ethiopian Rift. Seismicity is evaluated using the combination of exceptionally well resolved seismic structure of the crust and upper mantle, electromagnetic properties of the crust, rock geochemistry, and geological data. The combined data sets provide evidence that lower crustal earthquakes are focused in mafic lower crust containing pockets of the largest fraction of partial melt. The pattern of seismicity and distribution of crustal melt also correlates closely with presence of partial melt in the upper mantle, suggesting lower crustal earthquakes are induced by ongoing crustal modification through magma emplacement that is driven by partial melting of the mantle. Our results show that magmatic processes control not only the distribution of shallow seismicity and volcanic activity along the axis of the rift valley but also anomalous earthquakes in the lower crust away from these zones of localized strain.

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1. Introduction

[2] The occurrence of earthquakes in the lower crust is a common feature of major continental rifts [e.g., *Zhao et al.*, 1997; *Déverchère et al.*, 2001]. However, the origin of such seismicity remains unclear since the lower crust is generally thought to be too hot for brittle failure to occur in unaltered continental crust [e.g., *Brace and Kohlstedt*, 1980; *Chen and Molnar*, 1983]. Plausible models of lower crustal seismicity appeal to the presence of a strong, mafic lower crust that can facilitate brittle failure at higher temperatures, especially in the presence of localized hydrous fluids [e.g., *Seno and Saito*, 1994; *Reyners et al.*, 2007]. While coupled observations of accurately located earthquakes and well resolved lithospheric structure that are required to evaluate theoretical predictions are available from some convergent plate boundaries [e.g., *Jackson*, 2002; *Priestley et al.*, 2008], such tests have not been performed on continental rifts such as the East African Rift system. Despite localization of faulting and volcanism toward the center of the Main Ethiopian Rift (MER), earthquakes are also observed away from the rift axis and beneath the adjacent Northwestern (NW) Ethiopian Plateau to distances of ~150 km from the rift valley [*Ayele and Kulhánek*, 1997; *Keir et al.*, 2006a, 2006b] (Figures 1, S1, and S2).[1] Here, we evaluate the distribution of accurately located seismicity using exceptionally well resolved seismic structure of the crust and upper mantle and electromagnetic properties of the crust, as well as geochemical and geological data. Our results show that the distribution of earthquakes is not only intimately linked to variations in crustal composition, but also to the distribution of partial melt in the lithosphere.

2. Tectonic Setting

[3] The Miocene-Recent MER constitutes the northern part of the East African rift system and is the youngest arm of the Afar rift-rift-rift triple junction [*Wolfenden et al.*, 2004] (Figure 1). The MER is bound by NE striking, Miocene age border faults that separate the NW and Southeastern (SE) Ethiopian Plateaus, on the Nubian and Somalian plates, respectively. These broad, uplifted plateaus are parts of the Ethiopia-Yemen Paleogene flood basalt province and have experienced varying degrees of both hot spot and rift related magmatism for the last ~30 Ma [e.g., *Hofmann et al.*, 1997; *Furman et al.*, 2006]. Since the Quaternary, strain has localized to <20-km-wide right-stepping en echelon rift segments encapsulating NNE striking fissures and volcanic cones aligned along the rift axis perpendicular to the ~N100°E extension direction [e.g., *Bilham et al.*, 1999; *Ebinger and Casey*, 2001; *Bonini et al.*, 2005; *Bendick et al.*, 2006; *Corti*, 2008]. Within these rift segments, strain is accommodated primarily by intrusion of mafic dikes that likely control localization of the seismically active axial normal faults [*Keranen et al.*, 2004; *Keir et al.*, 2006a]. Active volcanism is not completely restricted to the rift axis, with the Quaternary-Recent Debre-Zeit Volcanotectonic Lineament (DZVL) and Miocene-Recent Yerer-Tullu Wellel Volcanotectonic Lineament (YTVL) among the most prominent of similarly aged volcanic centers located on the western rift margin [e.g., *Abebe et al.*, 1998; *Chernet et al.*, 1998; *Keranen and Klemperer*, 2008]. Paleogene to Quaternary volcanics are also observed on the NW Plateau as far north as Lake Tana [e.g., *Kieffer et al.*, 2004].

[4] Despite the majority of strain being currently localized within the MER, the distribution of earthquakes in 1960–2009 recorded on regional stations shows a significant amount of seismicity scattered beneath the NW Plateau [*Ayele and Kulhánek*, 1997] (Figure 1). Few regionally recorded earthquakes have accurate depths estimated using body wave modeling, and are all located within the rift at depths of <15 km [e.g., *Foster and Jackson*, 1998; *Hofstetter and Beyth*, 2003]. However, a dense

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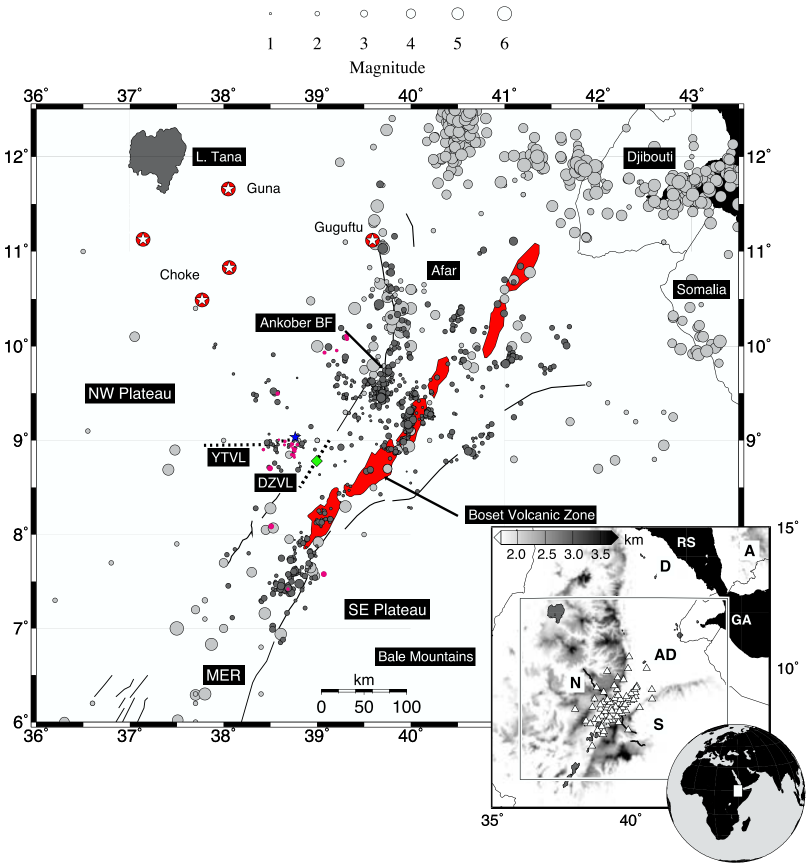

Figure 1. Distribution of earthquakes in Ethiopia. Light gray circles are earthquakes during 1960–2008 located from regional and global stations [*Ayele and Kulhánek*, 1997] (NEIC). Dark gray circles are earthquakes during October 2001 to January 2003 located using a dense local network of seismic stations. Earthquakes recorded by the EAGLE network deeper than 22 km are colored magenta. All earthquakes are scaled to magnitude. Solid black lines show Miocene border faults, and the dashed lines show the Debre-Zeit (DZVL) and Yerer-Tullu-Wellel (YTVL) Volcanotectonic Lineaments. The blue star shows Addis Ababa, and the green diamond shows Debre Zeit. Red filled segments show the volcanically active rift axis of the MER. White stars are major Paleogene-Quaternary volcanic centers on the NW Plateau. Inset shows topography of the region. White triangles are temporary seismic stations during October 2001 to January 2003. Tectonic plates are labeled as follows: A, Arabian; D, Danakil; N, Nubian; S, Somalian. Major rift zones are labeled as follows: RS, Red Sea; GA, Gulf of Aden; AD, Afar Depression.

network of seismic stations deployed during 2001–2003 and well-constrained crustal structure provides ~1900 microearthquakes with mean hypocentral errors of ~1 km in the horizontal plane and ~2 km in depth [*Keir et al.*, 2006a; *Daly et al.*, 2008]. Here, we evaluate seismicity beneath the MER and adjacent NW Plateau in light of new geophysical and geochemical constraints on lithospheric structure and rheology, as well as the distribution and composition of fluid phases.

3. Seismicity and Lithospheric Structure

[5] A clear first-order pattern of the locally and regionally recorded earthquakes is the broad asymmetry in distribution of seismicity either side of the MER (Figure 1). Earthquakes occur near the YTVL and DVZL on the broad western margin of the MER and beneath the NW plateau, with almost no earthquakes recorded beneath the SE Plateau (Figures 1 and S2). Whereas earthquakes within the MER are mostly less than ~15-km-deep, earthquakes beneath the NW Plateau west of the Ankober border fault occur to a depth of ~28 km, and those near the YTVL and DVZL are observed to depths of ~35 km.

[6] The marked asymmetry in distribution of seismicity beneath the two plateaus is mirrored by variations of seismic velocity structure deeper in the lithosphere. Throughout the upper mantle, a broad (~500-km-wide) low P and S wave velocity anomaly underlies the MER and adjacent NW Plateau [*Benoit et al.*, 2006a; *Bastow et al.*, 2008] (Figure 2). Absolute delay times at Addis

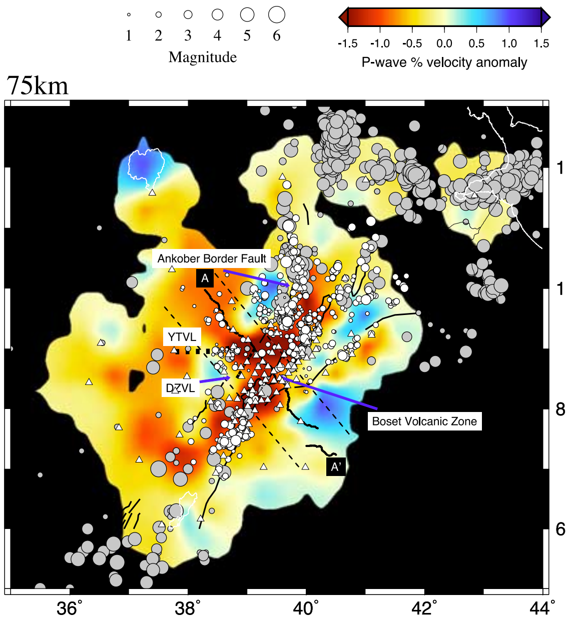

Figure 2. Depth slice at 75 km depth through the *Bastow et al.* [2008] P wave velocity model with earthquake epicenters as in Figure 1 superposed. A–A′ shows the position of the crustal P wave velocity and magnetotelluric profile in Figure 3. Earthquakes constrained in depth using the dense local seismic network are white, and those within the thin dashed lines are projected onto the across-rift profiles in Figure 3. White triangles are EAGLE seismic stations. Modified after *Bastow et al.* [2008].

Ababa indicate that the mantle beneath the NW plateau is among the slowest worldwide [*Bastow et al.*, 2008]. This observation, plus the ratio of teleseismic P and S wave delay times suggests these low-velocity anomalies cannot be explained by variations in composition and temperature alone and require the presence of a small fraction fluid phase, which is likely to be partial melt considering that the MER is unaffected by subduction processes that could hydrate the mantle [*Bastow et al.*, 2005, 2008]. In contrast, the SE Plateau is underlain by relatively fast upper mantle (Figure 2).

[7] The combination of seismic and electromagnetic properties provides clues to spatial variation in crustal modification and the current distribution of partial melt in the lower crust (Figure 3). Crust beneath the NW Plateau is generally ~40–50 km thick. Across the broad western rift margin in the vicinity of the YTVL and DZVL the crust includes a ~10-km-thick, high-density and high P wave velocity (Vp) (7.4–7.7 km s^{-1}) lowermost crust interpreted as gabbroic addition to the crust [*Mackenzie et al.*, 2005; *Cornwell et al.*, 2006; *Maguire et al.*, 2006; *Keranen and Klemperer*, 2008]. There is no evidence of significant magmatic modification beneath the ~38–40 km thick SE Plateau. Vp in normal lower crust (~25–40 km depth) increases with depth from 6.64 to 6.82 km/s on both sides of the rift [*Mackenzie et al.*, 2005], and is broadly consistent with a predominantly mafic granulite composition expected at this depth [e.g., *Christensen and Mooney*, 1995]. In addition, Vs models estimated from inversion of Rayleigh wave group velocities shows Vs in the lower crust generally varies ~3.6–3.7 km/s to the NW of the rift, consistently lower than Vs of ~3.7–3.8 km/s beneath the SE Plateau [*Dugda et al.*, 2007; *Keranen et al.*, 2009]. These estimates of Vp and Vs imply widespread Vp/Vs of ~1.84 in lower crust beneath the NW plateau, above the value of ~1.80–1.82 expected for a predominantly mafic granulite rock composition [*Christensen*, 1996; *Stuart et al.*, 2006; *Keranen et al.*, 2009].

[8] Magnetotelluric (MT) data shows a strong asymmetry between the two sides of the rift valley (Figure 3). Below 25 km, crust beneath the NW Plateau has relatively low resistivity (generally 10–30 Ωm), most likely explained by the presence of a minor connected conductive phase such as hydrous fluid or small fraction of partial melt [*Roberts and Tyburczy*, 1999; *Whaler and Hautot*, 2006]. The importance of at least widespread partial melt in causing high conductivities in lithosphere near the MER is consistent with SKS splitting and surface wave propagation that shows large magnitude (>12%) seismic anisotropy interpreted to be generated by elongate inclusions (<0.01 aspect ratio) of ~0.1% melt fraction aligned perpendicular to the minimum compressive stress direction in both upper mantle and lower crust beneath the MER and NW Plateau [*Nakajima et al.*, 2001; *Takei*, 2002; *Ayele et al.*, 2004; *Kendall et al.*, 2005, 2006]. In contrast, crust beneath the SE Plateau has relatively high resistivity (>100 Ωm) throughout the crust and therefore shows no evidence for significant volumes of fluid phases. We thus observe a broad correlation beneath the plateaus between the spatial extent of seismic deformation, distribution of off-rift volcanic centers, mafic lower crust, and presence of a small fraction partial melt in both lower crust and underlying upper mantle.

[9] Close inspection of our combined data sets shows a striking coincidence between the most prominent cluster of middle to lower crustal earthquakes and an especially low resistivity (1.5–3 Ωm)

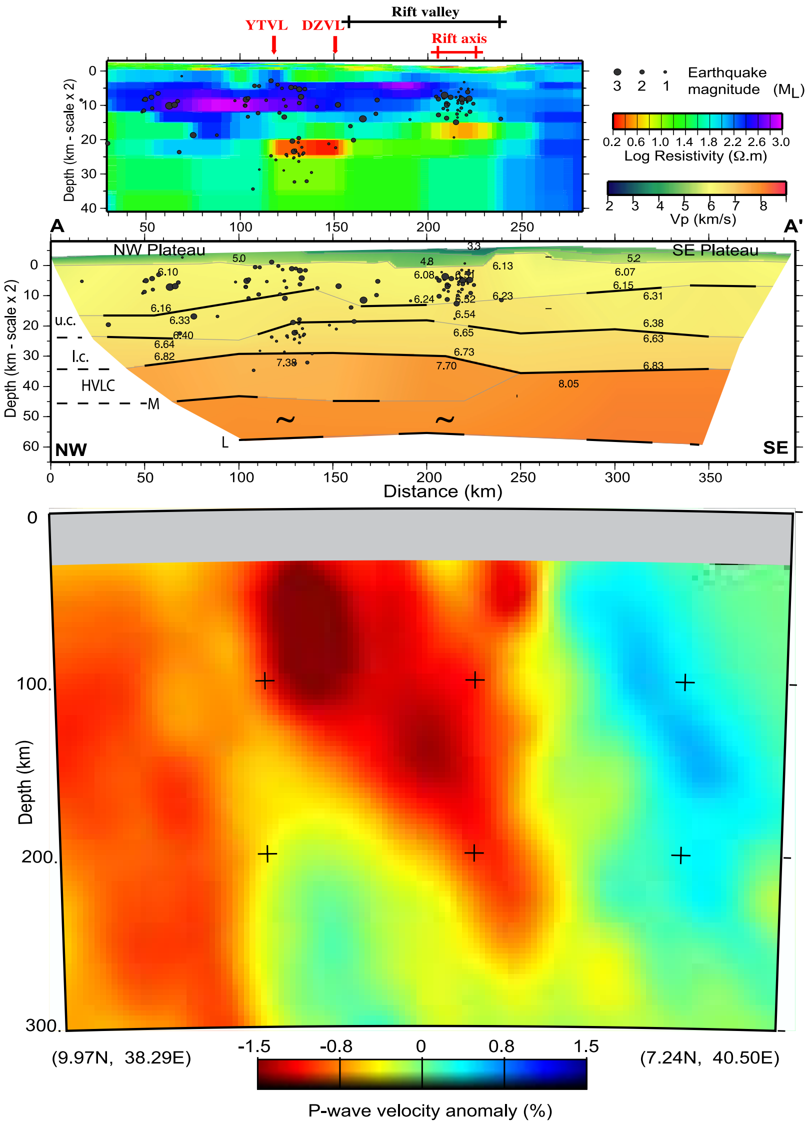

Figure 3. Profiles showing some geophysical properties of the crust across the MER. The position of A–A′ is labeled on Figure 2. Profile A–A′: (bottom) a cross section of the relative P wave velocity model of the upper mantle [*Bastow et al.*, 2008]. (middle) The P wave velocity model of the crust determined using controlled source reflection/refraction [*Mackenzie et al.*, 2005] with earthquake hypocenters (dark gray circles) recorded during October 2001 to January 2003 and located within 50 km either side (dashed lines) of the profile projected onto the section. Labels are as follows: u.c., upper crust; l.c., lower crust; HVLC, high-velocity lower crust; M, Moho. (top) The 2-D resistivity structure of the crust along a portion of A–A′ determined using MT [*Whaler and Hautot*, 2006].

anomaly at ~20–30 km depth (Figure 3). The anomaly extends ~50 km laterally beneath the broad western rift margin and lies near the DZVL and YTVL (auxiliary material). Globally, conductive anomalies of a similar magnitude are rare, and in tectonically active regions are typically associated with concentrations of a connected conductive fluid phase near active shear zones, faults, or in active magmatic systems [*Ogawa et al.*, 2001; *Wannamaker et al.*, 2002]. The anomaly is also coincident with especially high and localized bulk crustal Vp/Vs of >1.9, above that expected for even gabbroic rocks [*Christensen*, 1996; *Stuart et al.*, 2006; *Keranen and Klemperer*, 2008]. In continental settings, Vp/Vs of above 1.87 are often associated with the presence of relatively concentrated hydrous fluids, partial melt, or serpentinite, but serpentinite is unlikely in this tectonic setting [*Stuart et al.*, 2006]. Rather, the observations are indicative of the presence of a pocket of higher than average percent fluid or melt inclusions with small aspect ratios of <0.01, though given the strong evidence that the anomaly is associated with active magmatism a large gabbroic component to

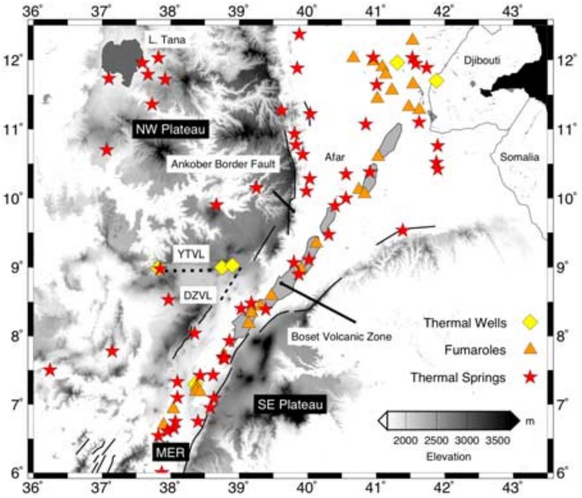

Figure 4. Distribution of known thermal springs (red stars), thermal wells (yellow diamonds), and fumaroles (orange triangles) plotted on the topography of Ethiopia. Geothermal features are prevalent along the axis of the MER and on the NW plateau but are completely absent on the SE plateau. Data provided by G. Demissie of GeoMET Plc.

the bulk composition is likely an additional contributing factor to the especially high Vp/Vs. We also note the slowest portions of the low-velocity mantle anomaly are beneath the rift valley and the rift margin near YTVL and DZVL [e.g., *Bastow et al.*, 2008] (Figure 2).

[10] Geochemistry of erupted products from the DZVL provides further constraints on the composition of fluid phases and the depth at which magmas are generated. Basalts are produced during moderate-degree partial melting of peridotite at $\sim$50–90 km depth and undergo fractional crystallization in complex, poorly developed plumbing systems spanning depths throughout the crust [*Rooney et al.*, 2005, 2007]. Entrained Al-augite xenoliths derived from various crustal depths indicate diking affects the lithosphere to at least a depth of 30 km and pervasive disequilibium textures in the xenoliths indicate dikes were not fully solidified at the time of entrainment [*Rooney et al.*, 2005]. Geochemical and geophysical data are thus consistent with relatively focused accumulation of partial melt throughout both lower crust and upper mantle beneath the DZVL and YTVL.

4. Discussion

[11] The combined geophysical and geochemical observations indicate that lower crustal earthquakes near the Ethiopian rift occur in mafic crust and are especially concentrated near zones with the largest fraction of partial melt, likely sourced from the mantle. Although magmatism outside the MER rift axis may currently be particularly concentrated near volcanic centers, geophysical data suggest a small fraction of aligned partial melt is widespread in the lower crust beneath the NW plateau and may be important in accommodating minor amounts of extensional strain outside the MER [*Keranen et al.*, 2009]. Such a wide zone of magmatism in the lower crust is spatially coincident with similarly distributed brittle failure in the middle to upper crust shown by scattered earthquakes across the NW Plateau, well-developed fracture systems in the uppermost crust inferred from presence of numerous hydrothermal springs (Figure 4), and the diffuse fault pattern observed at the surface [*Abebe et al.*, 1998]. Whereas data supports lower crustal seismicity being directly triggered by active processes in nearby focused magmatic systems, the scattered distribution of upper crustal earthquakes beneath the NW Plateau likely reflects minor and distributed brittle failure above a broad zone of melt accumulation in the lower crust and upper mantle [e.g., *Benoit et al.*, 2006a, 2006b; *Bastow et al.*, 2008] (Figures 3, S1, and S2).

[12] Traditionally, lower crustal earthquakes beneath rifts, including East Africa, were explained by slip on major rift border faults penetrating into relatively cold lower crust [e.g., *Doser and Yarwood*, 1994; *Zhao et al.*, 1997]. However, if this were the case then underlying mantle should also be cold enough for earthquakes to occur [*Chen and Molnar*, 1983], which is not observed in the MER or in other continental rifts [*McKenzie et al.*, 2005]. A physically plausible explanation for deep seismic activity in a rift environment is that the lower crust has a mafic composition, significantly increasing its strength [*Maggi et al.*, 2000; *Déverchère et al.*, 2001]. Our observations of seismicity and crustal structure from the MER are consistent with a generic model of lower crustal earthquakes in regions of relatively high heat flow being confined to strong crust of mafic composition. However, the close association between the most prominent clusters of lower crustal earthquakes and pockets containing the largest percent partial melt suggest that the ongoing process of crustal modification by magma emplacement induces lower crustal seismicity near the MER.

[13] Our unique collection of multidisciplinary geoscientific data sets provides evidence for the close association between magmatism and anoma-

lous lower crustal seismicity near the MER, and is a model that is likely applicable to other continental rifts dominated by magmatic processes. Recent seismicity and geodetic observations from Lake Tahoe in the Great Basin−Sierra Nevada transition show that both the occurrence of a lower crustal (29−33 km) earthquake swarm and increase in upper crustal seismicity is coincident with surface deformation modeled by intrusion of magma into the lower crust [*Smith et al.*, 2004]. Lower crustal earthquakes are interpreted as being triggered by high strain rates and localized stresses at the injection front [*Smith et al.*, 2004]. Such emplacement of magma is proposed to be a fundamental mechanism to sustain crustal thickness and strength in zones of lithospheric extension [*Smith et al.*, 2004; *Thybo and Nielsen*, 2009].

[14] The presence of hydrous fluids, which increase pore pressure and reduce frictional resistance to fault slip, has also been invoked to explain concentrated seismicity within mafic-lower crust near rift zones [*Seno and Saito*, 1994; *Reyners et al.*, 2007]. Such a mechanism is likely to be closely associated with magmatism since the crystallization of melt, combined with dehydration of heated rock provide mechanisms that can locally release high-temperature H_2O-CO_2 brines near zones of magma injection into the lower crust [e.g., *Seno and Saito*, 1994; *Wannamaker et al.*, 2008]. A network of such saline fluids along grain boundaries is highly conductive and provides a mechanism complementary to the presence of partial melt to explain MT observations from the MER. Geochemistry of erupted lavas from the DZVL suggest the parent melts derived from the upper mantle are water-poor [*Rooney et al.*, 2005], but presence of a preexisting lower crust relatively rich in hydrous minerals cannot be ruled out because of sparse direct sampling of lower crust beneath Ethiopia. Irrespective of whether high conductivities near the MER are caused solely by partial melts, or by a combination of crystallizing melt and associated exsolved saline fluids, processes directly related to the ongoing emplacement of melt supplied directly from the upper mantle into mafic lower crust most likely controls the distribution of lower crustal earthquakes.

[15] Lower crustal earthquakes are induced by magmatic processes near pockets of particularly concentrated partial melt residing in deep, mafic crust. Recent observations, numerical modeling, and lab experiments of shallow volcanic systems show that ductile magmas at ~900°C can deform in a brittle fashion if magmatic processes induce localized and exceptionally high strain rates [e.g., *Tuffen et al.*, 2008], and introduces the hypothesis that rheology of the lower crust is not particularly important in facilitating lower crustal earthquakes in the presence of focused magmatism. In Ethiopia, effective elastic plate thickness (Te) increases sharply from ~10 km in the MER to ~40 km at the YTVL [*Ebinger and Hayward*, 1996; *Tessema and Antoine*, 2003]. The resulting large gradient in Te across the rift margin is spatially coincident with progressive deepening of seismicity from ~15 km in the MER to ~35 km beneath the YTVL, which suggests the lower crust requires long-term strength and associated accumulation of stress to allow brittle failure (Figure 3).

[16] Well-constrained seismicity and constraints on geophysical properties of the lower crust are not available beneath most of the western rift margin and NW plateau, yet global catalogs, for which depths of earthquakes are not well constrained, illustrate seismicity is widespread [*Ayele and Kulhánek*, 1997] (Figure 1). The similar abundance of widespread Paleogene to Recent volcanic centers shows unambiguously that pockets of particularly focused partial melt have penetrated much of the NW Ethiopian plateau since ~30 Ma [e.g., *Chernet et al.*, 1998; *Kieffer et al.*, 2004; *Ferrando et al.*, 2008]. Insights gained into the intimate link between earthquakes and focused magmatic processes in strong lower crust, and the correlation with presence of volcanism at the surface, suggest lower crustal earthquakes occur elsewhere where relatively focused magmatic processes further modify relatively strong lower crust.

5. Conclusions

[17] By combining accurate earthquake locations, high-resolution images of both crustal and mantle structure, and locations of volcanic features at the surface, we now know that the distribution of seismicity in the MER is not only controlled by emplacement of magma into the highly strained rift axis, but is intimately related to variations in rock compositions, crustal structure, and variable distribution of partial melt elsewhere in the lithosphere. The marked concentration in lower crustal seismicity corresponds to the locations of major chains of active volcanoes outside the highly strained rift axis, and is mirrored in the rift asymmetric distribution of mafic lower crust containing a locally elevated percentage of partial melt. The integrated geophysical and geochemical observations provide

strong evidence that lower crustal earthquakes are induced by magmatic processes in relatively warm, mafic lower crust. Deep magmatic processes captured during the transition between continental rifting and seafloor spreading in Ethiopia provide a unique snapshot of lower crustal magma emplacement that is now thought to characterize volcanic rifted margins [e.g., *White et al.*, 2008].

Acknowledgments

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