Variations in the Seismogenic Thickness of East Africa

T. J. Craig¹ and J. A. Jackson²

¹School of Earth and Environment, COMET, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK, ²Department of Earth Sciences, COMET, University of Cambridge, Cambridge, UK

Abstract The well-established variation in the depth of earthquakes along both branches of the East African Rift System offers an opportunity to probe the controls on the depth-extent of seismogenesis, and the length-scales over which this may vary. We present an updated compilation of well-determined earthquake depths from teleseismic and regional seismic data for the East African Rift System, combined with a summary of the depth distribution of smaller-magnitude microseismicity from 13 local network deployments. Moderate-to-large magnitude ($M_w > 5$) earthquakes, unrelated to the movement of magmatic fluids, beneath Afar, the Main Ethiopian Rift, and the northernmost sections of the Eastern Branch, are confined to the upper crust. Seismicity along the Western Branch, and the southern-most sections of the Eastern Branch extends deeper, into the lower crust, in places to depths close to the local Moho. Along the Eastern Branch, in northern Tanzania, the transition between these two regimes occurs over a distance of ≤40 km, requiring a change to a higher temperature cutoff for the deeper earthquakes; an effect that must be compositional in origin. This compositional variation in the lower crust is most likely related to the degree of hydration. Earthquakes deep within the lower crust are therefore likely to be a proxy for an anhydrous crustal composition.

Plain Language Summary The maximum depth of earthquakes provides a crucial constraint on how deep the lithosphere can sustain sufficient stresses to produce brittle failure, rather than deforming through slow ductile processes. In East Africa, the maximum depth of earthquakes varies. In the northern sections of the East Africa Rift System, earthquakes are confined to the upper crust shallower than ~15 km, but in the southern and western sections of the rift, we observe earthquakes occurring much deeper, into the lower crust and potentially the uppermost mantle. This variation, and the short distance over which it takes place in Northern Tanzania, indicates that it is controlled by the composition of the lower crust, which is likely to be anhydrous where the deeper earthquakes occur.

1. Introduction

The East African Rift System (EARS; see Figure 1), extending from Afar in the north, to the distributed rifts of Botswana, Malawi and Mozambique in the south, is the largest tectonically active extensional system that displays a significant variation in the depth of earthquakes. With the depth-extent of seismicity providing one of the few direct ways to assess the rheological behavior, and crucially, the strength, of the lithosphere, observations from East Africa therefore provide a critical insight into the controls on lithospheric rheological variation, and the length-scales at which this may occur.

Over the last few decades, improvements in the depth determination of continental earthquakes have led to the recognition that in many places seismicity is confined to the upper crust, down to depths consistent with a seismic/aseismic transition at ~350°C (Chen & Molnar, 1983; Jackson et al., 2008; Maggi et al., 2000). However, in certain places, including East Africa, seismicity instead extends deeper, down through much of the lower crust, and potentially into the uppermost mantle (Craig et al., 2011, 2012; Devlin et al., 2012; Maggi et al., 2000; Schultz-Pelkum et al., 2019; Sloan et al., 2011). Earthquakes at these depths in continental crust must be occurring in material hotter than 350°C (Deichmann et al., 2000; McKenzie et al., 2005), perhaps even as hot as 600°C–650°C, which is similar to the observed cutoff temperature for earthquakes in the oceanic mantle (Craig et al., 2014; McKenzie et al., 2005). The occurrence of earthquakes at temperatures of up to ~600°C at pressures consistent with the lower crust, and at tectonic strain rates, requires that at least the lower crust be composed of an anhydrous (and commonly feldspar-dominated) mineralogical...
composition, rather than a hydrous (and often quartz-dominated) composition as is common for regions where seismicity is limited to the upper crust (Albaric et al., 2009, 2010; Mackwell et al., 1998; Muluneh et al., 2020). In the context of crustal rheology, we use “hydration” to refer not to the presence or absence of free fluids, but rather to the presence or absence of interstitial hydrogen ions (protons) within the mineral lattice, commonly derived from the dissociation of a water molecule (Kohlstedt & Hansen, 2015). The presence of such interstitial defects greatly enhances the rates at which creep processes can occur, resulting in significant rheological weakening, lowering the temperature at which earthquakes cease to occur. By contrast, free fluids are involved in melt migration in regions of active magmatism, leading to localized strain rates that can far exceed tectonic ones, and causing earthquakes to occur at higher temperatures and greater depths than the background seismic activity associated with tectonic, but non-magmatic, processes in the same place (Illsey-Kemp et al., 2018; Lindenfeld & Rümpker, 2011; Reyners et al., 2007).

Figure 1. Map of the East Africa Rift System (EARS). White lines show national borders. Red lines show recently active faults, after Macgregor (2015).
In East Africa, previous studies have demonstrated that seismicity is confined to the upper crust in Afar, the Main Ethiopian Rift, and much of the Eastern Branch through Kenya and into Tanzania, with deeper seismicity present along the Western Branch, the southern sections of the Eastern Branch, and across the distributed branches of the rift system at its southern extent, from Botswana to Madagascar (Craig et al., 2011; Foster & Jackson, 1998; Shudofsky et al., 1987; Yang & Chen, 2010). The variation in the maximum depth of earthquakes is now well-mapped at a large scale. However, with increasing data coverage, and an increasingly long period of observation coupled with the rapid proliferation of local seismic studies over the last decade, we are now able to resolve the small-scale details of the transitions between rheological regimes, which have implications for the causes of these changes, and their tectonic significance. Compositionally-based rheological variations affect the geological evolution of deforming regions, controlling not only the variations in strain rates, and the distribution in seismicity, but also the scaling of tectonic structures, the width of basins, and the scale and geometry of fault systems (e.g., Copley et al., 2014; Scholz & Contreras, 1998), and hence are a first-order control on the evolution of the East Africa Rift System.

2. Determination of Earthquake Depths

To provide the most comprehensive survey of seismicity in East Africa, we apply two different seismological techniques, optimized for earthquakes at different magnitudes, and draw on a wealth of available data from previous studies, including teleseismic observation (e.g., Chen & Molnar, 1983; Craig et al., 2011; Foster & Jackson, 1998; Shudofsky et al., 1987; Yang & Chen, 2010), and local seismic deployments (e.g., Keir et al., 2006; Lavayssière et al., 2019; Weinstein et al., 2017; Young et al., 1991). Our earthquake data set for moderate-large magnitude ($M_w \sim 5.0–6.5$) earthquakes with well-constrained source depths determined by teleseismic and regional waveform inversion, which includes results presented here along with the compilation in Craig et al. (2011), totals 260 earthquakes in the area shown in Figures 1 and 2. We also draw on the results of 13 local seismic networks (see Section 2.3). In the next sections, we summarize the processing approaches and datasets we use.

2.1. Waveform Inversion of Teleseismic Data

For larger events, of $M_w = 5.0$ and greater, we invert long-period body waves observed at teleseismic distances ($30^\circ–90^\circ$) to determine source mechanism, duration and magnitude, and depth. We use the algorithm of Zwick et al. (1994) to invert both vertical and transverse component data, over a window spanning the respective direct arrival ($P$ and $SH$) and principal depth phases ($pP$, $sP$, $sS$). The approach taken here is the same as that described in detail in Craig et al. (2011), to allow for the compatibility between datasets.

Crucially, this approach represents the most reliable and accurate method available for determining the centroid depth of earthquakes where depths are shallow enough, and durations long enough, that the direct and depth phases may overlap. As well as yielding accurate focal mechanism and source duration information, this approach gives centroid depths with a typical accuracy of $\pm 3$ km—sufficient to resolve fine-scale variability in seismogenic thickness. In supplementary material, we show example processing results for a shallow crustal earthquake beneath Zimbabwe (Figure S1) and a deeper lower crustal earthquake near the Tanzania/Uganda border (Figure S2). These two examples illustrate the clear difference in the separation between direct arrivals and subsequent depth phases, which is key in accurately determining the earthquake source depth. For the shallow example, this separation time is shorter than the duration of the earthquake, producing a complex waveform, and leading to significant tradeoffs between the various source parameters, particularly depth, moment, and duration. For the deeper event, clear separation can be seen, reducing the degree to which these parameters trade off, and allowing us to unambiguously identify this earthquake as having occurred at a depth that place it in the lower crust.

Here, we present results from an additional 25 earthquakes occurring between 2013 and 2020 (see Table S1), to add to the compilation contained in Craig et al. (2011).
2.2. Waveform Inversion of Regional Seismic Data

To supplement our results from teleseismic data, we further include the results from regional waveform inversion for lower-magnitude events ($M_W 4.2–5.2$). We use the approach of Heimann et al. (2018) to invert three-component data from stations within 900 km of each earthquake. We typically invert data over a frequency band of 0.03–0.10 Hz, tailored slightly to best suit each earthquake. The sparsity of seismic stations in East Africa limits the data coverage of stations where there is adequate signal-to-noise data for any given earthquake. With this restriction, we are only able to add a further 27 earthquakes whose source parameters could be robustly determined from regional data. As examples, we show processing results from two earthquakes, one shallow event in central Tanzania, and one deeper lower crustal event from beneath Lake Mweru on the border between Zambia and the Democratic Republic of the Congo, are shown in Figures S3–S12.

The enhanced sensitivity of regional waveform inversions to the variability in the local crustal structure, particularly crustal thickness, limits the resolution of such inversions, particularly in terms of the source depth. To compensate for this variability, we use an adaptive velocity model in our inversions, based on the nearest velocity profile from CRUST2 (Bassin et al., 2000) to the catalog location of the earthquake.

The Bayesian approach of Heimann et al. (2018) also allows for the sampling of the full parameter space available in source depth, allowing the potential for multiple minima in the waveform misfit function to be assessed, and, in cases, where depth is ambiguous, earthquakes to be discarded.

However, even well-constrained regional waveform inversions are sensitive to velocity structure variations along each individual source-receiver path, leading to uncertainties that are highly dependent on the network geometry available for a given earthquake, and are difficult to quantify purely by the waveform misfit. In those cases we include here, waveform misfits are tightly constrained ($\pm\ 3$ km), but the additional uncertainty from velocity structure makes this an underestimate of the true uncertainty, which is more likely to be $\sim 5–6$ km.

In addition to the 27 new earthquakes studied here (see Table S2), we also include two further regional mechanisms determined using a similar approach by Ebinger et al. (2019). Earthquakes studied using regional waveform inversion, rather than with teleseismic data, are highlighted on Figure 2a with a white outline, and Figures 2c and 2d with a gray outline.

2.3. Local Seismic Networks

Temporary local networks of seismometers, allowing the detection and location of smaller-magnitude earthquakes, have been operating across East Africa since the early 1990s, although, due to the logistical requirements, they remain sparse. We compile the results from 13 high-quality seismic surveys, covering regions including Afar and the Main Ethiopian Rift (Illsey-Kemp et al., 2018; Keir et al., 2006), the Eastern Branch through Kenya and Tanzania (Ibs-von Seht et al., 2001; Langston et al., 1998; Mulibo & Nyblade, 2016; Weinstein et al., 2017; Young et al., 1991), and the Western Branch from Lake Albert (Lindendfeld et al., 2012a; F. A. Tugume & Nyblade, 2009), through Tanganyika (Lavayssière et al., 2019) and Rukwa (Camelbeeck & Iranga, 1996), to northern Malawi (Ebinger et al., 2019; Gaherty et al., 2019): all shown on Figure 3.

The location accuracy of these different studies varies, depending on the network coverage and geometry used, the location methodology, how well the local velocity structure is known, and the quality control applied to the event selection. A full review of the individual accuracies of each network’s location is beyond this study, but readers are directed to the original studies for their full details. The completeness and...
Figure 3. Microseismic results from East Africa. Histograms are shown for each deployment network and period, with the relevant study shown on the figure. X-axes are normalized with respect to the peak for each network, with the total number written inset. For Ibs-von Seht et al. (2001) and Young et al. (1991), full earthquake locations were unavailable, so the map view shows the location of seismic stations within those networks, instead of earthquake locations (denoted by triangles, rather than circles).
sensitivity of the earthquake catalogs we use similarly vary depending on the details of the network and processing approach taken. However, the majority of these earthquakes are in the range $1 \leq M_w \leq 3$.

In a number of cases, the distribution of small-scale seismicity is complicated by the ability of sensitive local networks to detect microearthquakes associated with the migration of magmatic fluids through the crustal and mantle, a phenomenon capable of producing extremely high strain-rates in the surrounding material, which can cause seismicity in material too hot to generate earthquakes at tectonic strain-rates (Illsey-Kemp et al., 2018; Lindenfeld et al., 2012b; Oliva et al., 2019), including well into the mantle (Lindenfeld & Rümpker, 2011). Such earthquakes usually form discrete clusters (e.g., Lindenfeld & Rümpker, 2011), or identifiable structures related to magmatic fluid movement (e.g., Illsey-Kemp et al., 2018), but can complicate the interpretation of the depth distribution of microseismicity in volcanic areas (e.g., Afar, Figure 3).

### 2.4. Crustal Structure

Earthquake distributions are affected by spatial variations in temperature and composition. Mapping contrasts in internal crustal composition at depth is difficult, but variations in Moho depth can be mapped with a high degree of accuracy, especially beneath seismic stations. We compile estimates of crustal thickness for East Africa based on receiver-function studies beneath local seismic networks (Figure 2b), including data from Ahmed et al. (2013); Borrego et al. (2018); Dugda et al. (2005); Hammond et al. (2011); Hodgson et al. (2017); Nguuri et al. (2001); Plasman et al. (2017); Stuart et al. (2006); F. Tugume et al. (2012), and Wölbern et al. (2010).

The earthquake and Moho depths shown in Figures 2a and 2b are not determined using a consistent velocity structure, but we estimate that variations in the velocity structure used will account for only small (~3 km) differences in relative depths presented here.

### 3. Large-Scale Variations in Seismogenic Thickness

Figure 2 shows the distribution and depth of larger magnitude earthquakes across East Africa, with depths determined using teleseismic or regional waveform inversion. Two regimes of seismogenic behavior dominate. In the first, observed beneath Afar, the Main Ethiopian Rift, and the Eastern Branch north of ~3.5°S, earthquakes are confined to the upper crust, extending to depths of 10–20 km. In the second, observable along the Western Branch, the Eastern Branch south of ~3°S and southwards through offshore Tanzania and Mozambique, and across the distributed rifting at the southern extent of the EARS, earthquakes extend throughout the crust, terminating close to the Moho at depths of ~35–40 km. The variation is clearly shown in the two cross sections on Figure 2.

A similar pattern emerges when considering the depth distribution of microseismicity from the various dense local networks that have operated in East Africa (Figure 3). Networks along the western branch predominantly show seismicity extending to greater depths, in excess of 30 km. The exception to this is that of Gaherty et al. (2019), whose network in northern Malawi records the aftershock sequence following the 2009 Karonga earthquakes (Biggs et al., 2010). That this aftershock sequence is limited to the top 15 km of the crust, in a region where the depths from both teleseismic and regional observations (Figure 2a), and from a co-located local network (Ebinger et al., 2019) show much deeper seismicity down to near the Moho, highlights one of the main issues with using short-term local deployments to infer limits on seismogenic behavior—that they may not capture the long-term seismogenic picture.

Networks in Ethiopia (Illsey-Kemp et al., 2018; Keir et al., 2006) and around Lakes Magadi and Bogoria in the Kenya Rift (northern sections of the Eastern Branch; Ibs-von Seht et al., 2001; Young et al., 1991) show earthquakes limited to the top 20 km of the crust (excepting the aforementioned deeper microseismicity associated with magmatism and magmatic fluid migration beneath Afar; Illsey-Kemp et al., 2018). But further south down the Eastern Branch, networks in northern Tanzania, along the east Tanzanian coast and in northern Mozambique show seismicity extending considerably deeper into the crust, to depths of 30–40 km.

As illustrated by the histograms on Figures 2e–2g and 3, whilst earthquakes in the northern parts of the EAR and the Western branch show a relatively simple depth distributions (where seismicity is concentrated
in a single vertically continuous layer, with only minimal lateral variation), the picture for the Eastern Branch is more complex. Earthquakes deeper than 20 km are concentrated south of $-3.5^\circ$S, and associated with the intersection of the rift system with the margins of the Tanzanian craton (the focus of Section 4), or the continuation of the rift down the passive margins of Tanzania and Mozambique, into the Mozambique Channel. Given this broadly north-south transition in seismogenic behavior, the Eastern Branch therefore offers an opportunity to look at the controls on that transition in finer detail.

We do, however, avoid further discussing data from the coastal and offshore sections of the rift, where it is uncertain if the lithosphere is continental or oceanic, and where there are major variations in crustal thickness. Such regions are south of the vertical gray line on Figure 2c, which indicates the transition from the rifting of continental material to rifting aligned with the passive margin, where the nature of the crust and lithosphere (oceanic, continental, or transitional), is unclear.

4. Small-Scale Variations in Seismogenic Thickness

The transition between seismogenic regions, shown in the Eastern Branch cross section of Figure 2c is shown in greater detail in Figure 4. As the Kenya Rift passes into northern Tanzania past Lake Natron, it splits into three distinct strands: the Eyasi rift, trending NE-SW toward western Tanzania, the Manyara rift, trending N-S, and the Pangani rift, trending SE toward the Tanzanian coast (see Figure 1). The Eyasi branch rapidly terminates as it impinges on the eastern boundary of the Tanzanian craton, whilst distributed deformation associated with the other two branches potentially continues south to the Rungwe triple junction, and east to the Tanzanian passive margin, respectively. All three of these rift strands contain lower crustal earthquakes based on teleseismic and, in the case of Eyasi and Manyara, local data (Albaric et al., 2010; Craig et al., 2011; Foster & Jackson, 1998; Weinstein et al., 2017).

This region, the North Tanzanian Divergence (NTD), shown on Figure 4, is a transitional region in several senses. First, it marks the end of the Eastern Branch as a single localized rift. It also marks the southernmost extent of major contemporary volcanism associated with rifting along the Eastern Branch. Geologically, the region spans both the Neoproterozoic East African Orogen mobile belt in the north and east, and the Paleo-Mesoarchean Tanzanian craton in the west. This region coincides with a change in lithospheric thickness, as determined from both surface-wave tomography (Priestley et al., 2018, black contours, Figure 4a) and from mantle-xenolith thermobarometry (Conticelli et al., 1999; Gibson et al., 2013; Henjes-Kunst & Altherr, 1992; Figures 4a and 4b). To the north, both surface-wave and Kenyan xenolith data indicate lithosphere thinner than 100 km.

The NTD also shows a rapid transition in seismogenic thickness (see Figure 4). Beneath the Natron rift, north of $-3.5^\circ$S, larger-magnitude earthquakes are limited to depths of $\leq 15$ km, and microseismicity to depths of $\leq 20$ km (Weinstein et al., 2017). But south of $-3.5^\circ$S, earthquakes in all three branches of the rift extend much deeper into the crust, to depths of 35–40 km. The slight discrepancy between the depth of larger-magnitude seismicity and microseismicity beneath the Natron section of the rift ($\sim 100$–250 km distance on Figure 4c) has been attributed to microearthquakes in high-strain-rate regions around the edges of magmatic bodies in the mid crust beneath the rift (Oliva et al., 2019; Weinstein et al., 2017).

The transition in seismogenic thickness takes place over a horizontal distance of only 20–40 km. Such a rapid transition is inconsistent with a single cutoff temperature for seismicity, as it would require a lateral temperature gradient similar to the vertical geothermal gradient, a scenario which would be impossible to sustain for any length of time. Instead, this presents another argument that the dominant control on the temperature at which seismicity ceases must be compositional, probably characterized by discontinuities rather than gradients, which allows sharp changes in seismogenic thickness and hence in bulk rheology, to be maintained over geological timescales. Geological or structural observation of such rheological discontinuities is extremely difficult, due to the paucity of lower crustal exposure. However, recent work on the Musgrave Ranges of central Australia also offers evidence for the direct juxtaposition of a brittlely deformed, pseudotachylite-hosting, anhydrous granulite crustal block overlying a significantly more hydrous footwall block, separated by a strongly mylonitized ductile shear zone concentrated in the more hydrous material (Wex et al., 2018), geological evidence for the existence of such short length scale rheological transitions.
As stated in our introduction, in this study we have excluded the consideration of seismicity clearly representing the brittle failure of high-temperature material driven by the high-strain-rate deformation associated with the migration of magmatic fluids (Illsey-Kemp et al., 2018; Keir et al., 2009; Lindenfeld et al., 2012a; Oliva et al., 2019). However, we should not neglect that, despite the link between high-temperature, lower crustal seismicity and anhydrous, dry bulk crustal rheology, crustal fluids do play a role in crustal
seismicity, even at low-strain rates. Pseudotachylites in exposed anhydrous lower crustal sections (e.g., western Norway (Austrheim & Boundy, 1994; Menegon et al., 2017), central Australia (Wex et al., 2018)) show evidence for fluid penetration into the anhydrous crust concurrent with brittle failure, shear-melting, and implied seismogenesis, and may potentially lead to progressive transformation of the mineralogy in close proximity to the rupture plane (Jamtveit et al., 2018). But to continue to host high-temperature brittle failure, rather the deforming through ductile processes, the bulk mineralogy of the surrounding crustal material must remain unaltered, anhydrous, and granulitic. Hence, whilst seismicity in a strong lower crust may indicate the presence of intracrustal free fluids, it must also indicate the continued persistence of a bulk lower crustal rheology dominated by strong anhydrous crustal material.

In the case of northern Tanzania, Albaric et al. (2014) ascribed swarm-like microseismic observations from this area to fluid migration. Given the active magmatism of the area (e.g., Biggs et al., 2009; Wadge et al., 2016), the presence of crustal fluids, and microseismicity related to their migration, is not surprising. But the larger-scale seismicity that forms the focus of this study will not be related to intracrustal melt migration, and must reflect the bulk crustal rheology.

5. Seismicity Into the Mantle?

Earthquakes in the continental mantle are rare. A few isolated events in apparently stable continental interiors are too sparse to draw any generic conclusions on their context or controls on their depths (Craig & Heyburn, 2015; Sloan & Jackson, 2012). Some earthquakes in the northernmost Indian shield where it underthrusts Nepal and southern Tibet occur to a depth of 15–20 below the Moho (Schulte-Pelkum et al., 2019). However, this is likely also to be the depth of the 600°C–650°C isotherm in the Indian lithospheric mantle, which is unusually cold because of the thick lithosphere and relatively thin Precambrian crust of north India (Craig et al., 2020; Priestley et al., 2008). The same explanation is likely for an earthquake at 65 km depth on the northern continental margin of Australia in the Arafura Sea (Sloan & Jackson, 2012). In neither place is there reason to think that the mantle is seismogenic at a temperature above the 600°C–650°C cutoff seen in the oceans.

In the case of East Africa, different studies have argued for both the presence (Yang & Chen, 2010) and absence (Craig et al., 2011) of earthquakes in the uppermost mantle, beneath the seismogenic lower crust. In Figure 5, we plot the difference, for each earthquake, between the centroid depth and nearest estimate of the Moho depth from a receiver function, against the lateral distance separating the earthquake and the seismic station used for that receiver function. All earthquakes shown on Figure 2a are included. Earthquakes with negative values (indicating centroids below the nearest Moho estimate), are highlighted with a red outline. Of the 260 earthquakes considered here, only four are estimated to be deeper than their closest Moho depth constraint (highlighted in red on Figure 5), and only two of these are within 100 km of that estimate. The depths of these two earthquakes exceed the closest Moho estimate by only 3 and 1 km. Allowing for the uncertainties in both earthquakes and Moho, whether these earthquakes are indeed within the uppermost mantle remains unresolvable without a detailed re-examination of both earthquake and crustal data in a consistent velocity structure (e.g., Schulte-Pelkum et al., 2019).

Given that the expected cutoff temperature of earthquakes in anhydrous crustal and mantle material is about the same (~600°C–650°C), the occurrence of some seismicity into the very uppermost mantle is
not unexpected, and has been reported in other regions (e.g., Craig et al., 2012; Monsalve et al., 2006; Schulte-Pelkum et al., 2019). But, between Figures 2c, 2d, and 5, we do not see any significant increase in seismicity associated with proximity to the Moho, nor do we see an identifiable aseismic gap between any potential mantle seismicity and seismicity at shallower depths in the crust. Irrespective of whether seismicity extends slightly into the uppermost mantle, East Africa fits the global pattern of seismicity that is confined to a single continuous layer (except in cases far from thermal steady state, like the underthrusting of India beneath Tibet; see Craig et al., 2012, 2020), even when considering lateral variations that occur on the scale seen in Northern Tanzania (Figure 4).

6. Discussion

The behavior of lower crustal materials (Austrheim & Boundy, 1994; Mackwell et al., 1998; Menegon et al., 2017; Moecher & Steltenpohl, 2011) with dry granulite compositions indicates they are likely to be seismogenic to temperatures of about 650°C ± 50°C, similar to the observed cutoff temperature of earthquakes in the oceanic mantle (Craig et al., 2014; McKenzie et al., 2005). Thus, in places with anhydrous lower crust where the Moho is close to 600°C, the cutoff depth of seismicity is likely to follow moderate variations in the temperature structure, rather than in crustal thickness.

The transition in seismogenic thickness in northern Tanzania, as with those observed at larger scale across the rest of East Africa, and globally (Craig et al., 2011; Jackson et al., 2021; Sloan et al., 2011), is coincident with an increase in lithospheric thickness (see Figure 4) imaged using both geophysical and petrological data, and therefore coincides with a change in the thermal structure on the same scale. We therefore assess whether the change in temperature structure is itself sufficient to account for the observed change in seismogenic thickness.

In Figure 4b, we show a set of theoretical geotherms calculated with variable lithospheric thicknesses between 75 and 200 km, using the approach outlined in Craig et al. (2012, 2020). The crustal structure (both thickness and the distribution of radiogenic elements) in each case is kept the same, changing only the depth to the base of the lithosphere. The two horizontal bars show the resulting variation in the depth of 350°C (light gray) and 600°C (dark gray) isotherms. We note that these calculations ignore the effect of a convective thermal boundary layer at the base of the lithosphere, which would smooth the transition from a conductive lithospheric geotherm to the adiabatic convective mantle. This simplification has minimal effect on the thermal structure in the upper half of the lithosphere, and makes no difference to our interpretation.

Changing only the lithosphere thickness changes the depth of the 350°C isotherm by less than 7 km: insufficient to explain the variation in the seismogenic cutoff depth in East Africa if it is controlled solely by that temperature. Forcing temperatures colder than 350°C to depths greater than 20 km requires both extremely thick lithosphere and very low crustal radioactivity, and would result in extremely low surface heat flow. Additionally, as pointed out by McKenzie et al. (2005), the extension of seismicity into the lower crust, were it to be related only to a colder thermal structure, and a greater depth of the 350°C isotherm, should be accompanied by widespread seismicity in the colder uppermost mantle, for which we find no evidence in East Africa, reinforcing the point that seismicity in the lower crust must be occurring in material substantially hotter than the usual ~350°C upper-crustal cutoff temperature. Significantly more variability is seen in the depth of the 600°C isotherm in Figure 4b, with lithospheric thickness variations alone able to produce variations of up to ~20 km. But similarly, forcing the 600°C isotherm to depths of 10–15 km, consistent with the upper crustal earthquake cutoff in the northern sections of the rift, would require an extremely thin lithosphere, and an extremely radiogenic crust. Finally, if the depth limit of earthquakes was defined by the same temperature across all of the Northern Tanzania, the short lengthscale over which we observe the variations shown in Figure 4c, and the sharpness of the transition between regimes, would require a lateral temperature gradient within the crust that would be extremely difficult to sustain over tectonic timescales.

Therefore, the temperature structure associated with the variation in lithosphere thickness alone, given the relatively small changes in the accompanying measurements of crustal thickness, cannot be responsible for the observed change in seismogenic thickness in East Africa. The deeper earthquakes in the lower crust must occur in material that is hotter than the normal cutoff temperature of ~350° which in turn requires a different (anhydrous) composition. That change in composition, through changing the seismogenic and
elastic thickness (Maggi et al., 2000), will change the bulk crustal rheology and also the details of the thermal structure, through alterations in its conductive properties, and its internal heat production. These variations in thermal structure resulting from conductivity and heat-production contrasts are hard to quantify, but their effects on rheology and mechanical strength are likely to be minor compared to the effect of water content. They are unlikely to produce significant variations in the depth of the 350°C isotherm, and would certainly be insufficient to perturb that isotherm enough for it to account for all the observed variation in seismogenic thickness.

We therefore conclude that, whilst the change in maximum earthquake depth observed in northern Tanzania is roughly coincident with an increase in lithosphere thickness, that increase alone cannot be directly responsible for the observed change in seismogenic thickness. On its own it is incapable of producing the magnitude of the variation seen, and would lead to smoother lateral variations in seismogenic thickness than are seen in Northern Tanzania. The short lateral distance over which the change in seismogenic thickness occurs indicates its compositional origin, and the thermal influence of a thick lithospheric root plays a secondary control. The correspondence between increased seismogenic and lithospheric thickness is likely to lie in the common mechanism behind the creation of both an anhydrous lower crust, and of a stable thickened (and most likely depleted) lithosphere during previous orogenic cycles (e.g., McKenzie & Priestley, 2016; Priestley, 2008), and therefore is correlative, rather than directly causative.

The sharpness of a compositional boundary is probably accompanied by a significant rheological contrast that will have an effect on the tectonic evolution of the region. With the requirement at plate scale for a spatially continuous distribution of strain, any sharp boundaries in rheology are likely to lead to complex localized deformation, as seen in both the North Tanzanian Divergence, with the sudden fragmentation of the rift system, and in Uganda at the northern end of the Western Branch, with the sharp junction of normal-faulting and strike-slip faulting, as seen in the 1990/1991 Sudan earthquakes (Gaulon et al., 1992), where the Western Branch is truncated against the relict Aswa shear zone.

It is also important to note that the change in seismogenic thickness in northern Tanzania, although still poorly mapped out due to the limited seismicity available, trends roughly WNW-ESE, whereas the mapped edge of the surface outcrop of the Tanzanian craton in this location runs roughly NNW-SSE (Figure 4a). The two are broadly coincident, with all regions within the Tanzanian craton itself indicating lower crustal seismicity, but the finer details of the compositional transition at depth may not precisely match the surface outcrop of the craton. However, the established correspondence between lower-crustal seismicity and crustal composition offers the opportunity, as the resolution and coverage of seismicity catalogs inevitably increase, to map the composition of the unexposed lower crust using seismicity.

Data from East Africa fit the global pattern of seismicity confined to a single vertically contiguous layer, rather than a laminated multi-layer system. However, we note the potential for a particular niche rheological case to exist, where the lower crust is hydrous and aseismic, but where the crust is sufficiently thin, and the lithosphere sufficiently thick, to leave the upper mantle cold enough to be seismogenic below an aseismic lower crust. This would produce a vertically layered system, with two potentially seismogenic layers separated by an aseismic lower crust. However, such a situation has yet to be observed in any continental region close to thermal steady-state.

### 7. Conclusions

Seismogenic thickness along the EARS varies. Larger-magnitude earthquakes are limited to the upper crust in Afar, the Main Ethiopian Rift, and the northern sections of the Eastern Branch, south to the North Tanzanian Divergence. Along the entire Western Branch from Sudan to Mozambique, and along the southern sections of the Eastern Branch (from the North Tanzanian Divergence southwards), seismicity extends into the lower crust, close to the Moho, and potentially into the very uppermost mantle. In Northern Tanzania, the transition between these two regimes takes place over ≤40 km. Whilst regions with increased seismogenic thickness broadly correspond (in East Africa and globally) with regions of thicker continental lithosphere, the lengthscales over which substantial changes in seismogenic thickness can take place demonstrate that the change must be caused by a change in lower crustal composition, with changes in temperature structure...
imposed by varying lithospheric thickness acting as a secondary modifier. A consequence of this is that lower crustal earthquakes are likely to be proxy indicators of anhydrous lower-crustal compositions.

**Data Availability Statement**

Seismic data used in this study were retrieved from the Incorporated Research Institutions for Seismology (IRIS) Data Management Centre, principally utilizing the networks II (doi.org/10.7914/SN/II), IU (doi.org/10.7914/SN/IU), GE (doi.org/10.14470/TRS60404), CN (doi.org/10.7914/SN/CN), XI (doi.org/10.7914/SN/XI-2013), IC (doi.org/10.7914/SN/IC-2011), YY (doi.org/10.7914/SN/YY-2013). We are also indebted to the numerous people who have helped in the deployment, collection, and processing of data from local seismic networks in East Africa, as referenced in the text.

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