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THE EAST AFRICAN RIFT SYSTEM

Uwe RING

Department of Geological Sciences, Stockholm University, SE-106 91 Stockholm, Sweden;
uwe.ring@geo.su.se

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ABSTRACT

The East African Rift System is one of the most outstanding and significant rift systems on Earth and transects the high-elevation Ethiopian and East African plateaux. Rifting putatively developed as a result of mantle plume activity that initiated below East Africa. The rift is traditionally interpreted to be composed of two distinct segments: an older, volcanically active Eastern Branch and a younger, much less volcanic Western Branch. Rift-related volcanism commenced in the Eocene and a major phase of flood basalt volcanism occurred in Ethiopia by 31-30 Ma. Rift development in the Eastern Branch has a distinct northward progression with a juvenile rifting stage in northern Tanzania, well advanced rifting in Kenya and the transition of continental rifting to incipient sea-floor spreading in Ethiopia and Afar. The Western Branch in general has not yet progressed to an advanced rifting stage and rift basin architecture retains a pristine geometry.

The onset of topographic uplift in the East African Rift System is poorly dated but has certainly preceded graben development. It is widely believed that topography has been caused by plume activity. The uplift of the East African Plateau might be connected to African Cenozoic climate change and faunal and human evolution.

Der Ostafrikanische Graben ist eines der außergewöhnlichsten und signifikantesten Riftsysteme der Erde und durchschneidet die angehoben Plateaus in Ostafrika und Äthiopien. Die Grabenbildung wurde vermutlich durch einen Manteldiapir ausgelöst. Der Ostafrikanische Graben wird traditioneller Weise in zwei Segmente unterteilt: einen älteren, vulkanisch sehr aktiven westlichen Ast und einen jüngeren, vulkanisch weniger aktiven östlichen Ast. Der riftgebundene Vulkanismus begann im Eozän und eine wichtige Flutbasaltphase fand in Äthiopien um 31-30 Ma statt. Die Grabenbildung im östlichen Ast zeigt eine deutliche Progression. Ein juveniles Stadium ist im nördlichen Tansania ausgebildet und geht in eine fortgeschrittene Etappe in Zentralkenia über. In Äthiopien und dem Afar-Dreieck findet schließlich ein Übergang von kontinentalem Rifting zu beginnender Ozeanbodenspreizung statt. Der westliche Ast befindet sich noch in einem anfänglichen Entwicklungsstadium und die Architektur der Gräben zeigt eine ursprüngliche Geometrie.

Der Beginn der Entwicklung riftgebunder Hebung in Ostafrika ist nicht bekannt, fand aber sicher vor der eigentlichen tektonischen Ausbildung des Grabensystems statt. Es wird weithin angenommen, dass die topographische Entwicklung durch Manteldiapirismus ausgelöst wurde und vermutlich mit känozoischen Klimaveränderungen und faunistischen und anthropogenen Evolutionen einhergeht.

1. HISTORICAL PERSPECTIVE – EDUARD SUESS AND THE EAST AFRICAN RIFT SYSTEM

The East African Rift System (Fig. 1) serves as the classic example of a continental rift. Although Eduard Suess never visited East Africa, he had the scientific foresight to understand and further develop reports of explorations and discoveries by David Livingstone, Henry Morton Stanley, Gustav Fischer, Joseph Thomson, Samuel Teleki and Ludwig von Höhnel during the 19th century. Eduard Suess was probably the first to realize that the East African Rift System is a result of continental extension and thinning of the crust. He wrote the very first foundation paper on the geology of rift valleys and introduced the concept of the 'East African rift fracture' in 1891 when formulating his synthesis “Die Brüche des östlichen Afrika” (Suess, 1891). He also took precedence in introducing the term 'graben' into the geological literature in the first German edition of his treatise “Das Antlitz der Erde” (Suess, 1883). The work of Eduard Suess on rift valleys was strongly influenced by early work in the Rhine Graben by Élie de Beaumont (1827, 1847).

Eduard Suess' thoughts on the East African rift system encouraged John Gregory to further explore the faulted basins of Kenya in 1893, and subsequently expressing the term 'rift valley'; in 1896 Gregory coined the name 'Great Rift Valley of East Africa' (Gregory, 1896). John Gregory is widely regarded as the founding father of the geology of the East African Rift System.

2. CONTINENTAL RIFTING PROCESSES

Before embarking on the East African Rift System, current concepts on the tectonic evolution of continental rift zones are being summarized. Continental rift zones are sites of lithospheric stretching, which occurs in response to far-field plate forces, such as slab pull and ridge push, as well as tractions at the lithosphere-asthenosphere boundary induced by mantle flow. The extension of the crust is achieved through normal faulting that thins the brittle crust. In some (most?) continental rift zones the lower crust is weak and thins via viscous flow (Buck, 1991; Masek et al., 1994; Lavier and Manatschal, 2006). Dense lithospheric mantle rocks rise upward to replace the thinning crust, enhancing subsidence in the fault-bounded basins (McKenzie, 1978; Weissel and Karner, 1989). For deformation compatibility reasons the lithosphere mantle also extends and thins and is replaced by hotter asthenosphere. This process transfers heat to the lithosphere beneath the extending region, reducing rock density and subsequently causing regional, time-dependent uplift over time scales of tens of millions of years (Şengör and Burke, 1978; Keen, 1985). Mantle upwelling may be enhanced by plumes and/or small-scale mantle convection induced by the steep thickness gradients at the transition between thinned and unthinned lithosphere (Buck, 1986; King and Anderson, 1998). The distribution of plate boundary deformation and (plume-related) magmatism is generally influenced by pre-existing heterogeneities in lithospheric thickness, strength, and composition. Deformation and magmatism preferentially localize along large-scale pre-rift tectonic boundaries (Nyblade and Brazier, 2002; Corti et al., 2007).

Continental rift zones are typically made up by a series of asymmetric graben and are truly three-to-four-dimensional features. From their very inception, rift zones show regular along-axis structural segmentation into basins bounded on one or both sides by large offset border faults (Ebinger et al., 1984; Bosworth, 1985; Rosendahl, 1987). The border faults are flanked by broad uplifts that may rise 3 km above the surrounding regional elevations (Fig. 1), in some extreme cases like the Rwenzori Mountains in the Ugandan sector of the East African Rift more than 4 km (Ring, 2008; Bauer et al., 2010) (Fig. 2a). Initially discrete border-fault segments interact and are mechanically connected through transfer faults and relay ramps oriented oblique to the strikes of border faults (Larsen, 1988; Morley and Nelson, 1990). In general, border fault lengths, rift flank uplift, and basin dimensions increase with increasing strength of the lithosphere (Weissel and Karner, 1989; Ebinger et al., 1999). This is why young rift segments in strong, cratonic lithosphere are characterized by long, narrow graben with deep rift lakes bounded by impressive escarpments (Fig. 2b).

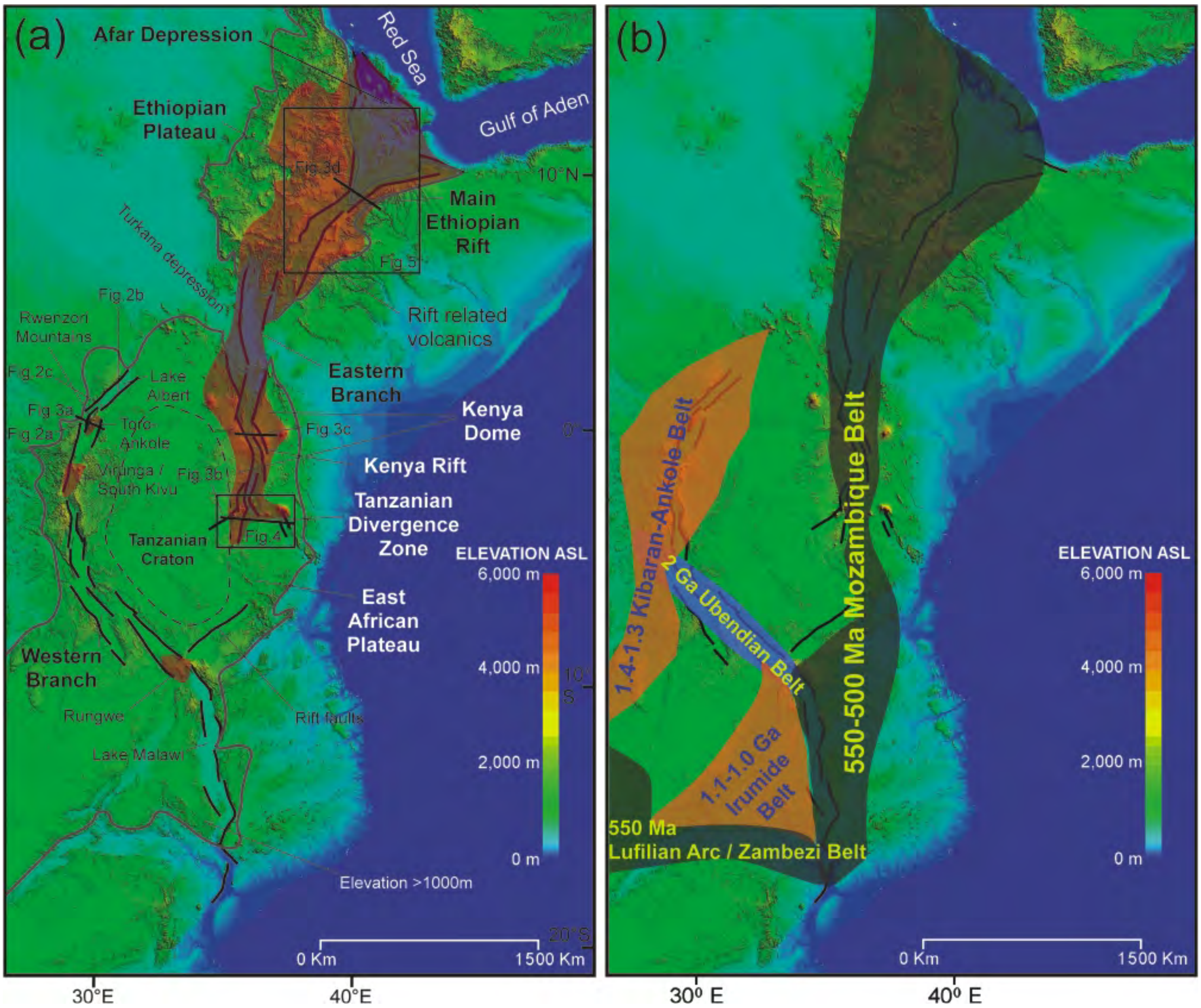

FIGURE 1: (a) The East African Rift System superimposed on the Ethiopian and East African plateaux (image from NASA SRTM, 250m resolution, http://srtm.csi.cgiar.org/). The East African Rift System comprises a series of individual graben (rift valleys) that link-up to form the Western and Eastern Branch. The localities of Figs 2, 3, 4 and 5 are shown. (b) Tectonic overview map of southeast Africa showing schematically various mobile belts on which the East African Rift has been superimposed. The age data refer to the major orogeny in the mobile belts.

Observations from amagmatic and magmatic passive continental margins show differences in the style of continental break-up, i.e. the rift to rupture process. Where magma is absent until the onset of seafloor spreading, rift segments widen to as much as five times their original widths, drastically reducing plate strength (e.g., Hopper et al., 2004; Lizarralde et al., 2007). The presence of magma during rifting decreases the amount of stretching required to achieve plate rupture, as can be seen in the much narrower widths of conjugate magmatic margins worldwide (Coffin and Eldholm, 1994; Menzies et al., 1997; Leroy et al., 2010). As continental rifting progresses to seafloor spreading, strain localizes to aligned chains of eruptive centers and smaller faults within the central basin and the border faults become inactive (Hayward and Ebinger, 1996; Keranen et al., 2004; Beutel et al., 2010). Subsequently, the mid-rift volcanic centers and their underlying magma chambers may reorganize themselves into mid-ocean ridge sytems.

Figure 2: (a) Mountainous topography in the Rwenzori Mountains of west Uganda south of Lake Albert. The Rwenzori Mountains are a promontory of the Albertine Rift shoulder and rise to 5109 m.a.s.l. (photo courtesy Daniel Koehn). (b) Rift shoulder of Lake Albert in the Albertine Rift of west Uganda, Western Branch of East African Rift System. Unlike other rift lakes of the Western Branch, Lake Albert is not deep and has a maximum depth of 51 m, and a surface elevation of 619 m.a.s.l. (photo courtesy Friederike Bauer). (c) Late Miocene to Quaternary lacustrine and fluvial sediments are common in the East African Rift System (photo courtesy Friederike Bauer).

3. East African Rift System

3.1 African Superswell and Plumes

Africa has been a center of continental accretion in the Precambrian and Cambrian (Shackleton, 1986; Dixon and Golombek 1988; Ring et al., 2002; Fritz et al., 2013) (Fig. 1b). Today it is surrounded on three sides by divergent plate boundaries. Global seismic tomography and geodynamic modeling suggests that it sits above a major mantle upwelling, the African Superswell, and is beginning to break apart along the East Africa Rift System (Grand et al., 1997; Nyblade and Langston, 2002; Ritsema et al., 1999; Simmons et al., 2007; Hansen et al., 2012, Hansen and Nyblade, 2013). Seismic anisotropy data in East Africa have been interpreted to be due to the African Superplume rising from the lower mantle underneath Zambia and flowing to the NE beneath East Africa (Bagley and Nyblade, 2013, their fig. 3). The upwelling material along the East Africa Rift System is explained as hot, relatively fertile ‘asthenospheric’ mantle rising from the top of the African Superswell. Geophysical and geochemical data acquired over the past decade provide compelling evidence that the uplifts and volcanic outpourings developed above an anomalously hot asthenosphere (Hart et al., 1989; Hofmann et al., 1997; Keranen et al., 2009). This might be the reason why Africa has the highest mean elevation of all continents.

The East African Rift System comprises several discrete and diachronous rift sectors. Traditionally an Eastern (including the Ethiopian Rift) and a Western Branch are being distinguished (Fig. 1). Field data have shown that the present trace of the Eastern and Western Branches of the East Africa Rift System largely reflect earlier sutures (Ring, 1994; Burke, 1996). Tomographic sections support this view and show that the deep roots of the cratonic blocks play a major role in guiding the upwelling hot mantle emanating from the top of the African Superswell in the upper few hundred kilometers of the mantle (c.f. Ebinger and Sleep, 1998; Sleep et al., 2002). The earliest basaltic volcanism in the East African Rift System commenced between 45-39 Ma in southwest Ethiopia and northernmost Kenya (Morley et al., 1992; Ebinger et al., 1993). During this time period kimberlites were emplaced in Archean cratons surrounding the rift (Harrison et al., 2001; Batumike et al., 2007; Roberts et al., 2012). The relatively widespread distribution of the kimberlites suggests heating and mantle metasomatism along the asthenosphere-lithosphere boundary long before any regional extensional tectonism and surface expression of rifting across the broad East African Plateau (Ebinger et al., 2013).

Rifting has progressed to incipient seafloor spreading in the Afar Depression (Corti, 2009; Ebinger et al., 2013). Further south, the Ethiopian, Eastern and Western rift valleys are superposed on the broad Ethiopia and East African plateaux. The Turkana topographic depression between the two plateaux marks a failed Mesozoic rift system, allowing the possibility that the plateaux are part of one large zone of uplift extending from southern Africa to the Red Sea (cf. Nyblade and Robinson, 1994).

Controversy revolves around how many plumes might underlie the African Superswell, and the depth extent and continuity of the hot asthenospheric material. One end-member class of models invokes just one single plume (Duncan and Richards, 1991). Ebinger and Sleep (1998) elaborated on this view and showed how topography at the base of the lithosphere might channel the plume material into streams and pools. According to the modeling by Ebinger and Sleep (1998), melting occurs where the base of the lithosphere slopes upwards, i.e. where rising material reaches thinner lithosphere and can flow upwards and decompresses. Subsequent rifting may trigger more melting and may also promote the flow of plume material over greater distances (Davies, 1998). ^{3}He/^{4}He geochemical data (Pik et al., 2006) appear to challenge the one-plume hypothesis. These data suggest two types of mantle sources for magmatism: (1) a large, deep-seated mantle plume characterized by a high-^{3}He signature, possibly originating from the core–mantle boundary according to seismic mantle tomography, which triggered flood basalt eruptions some 30 myr ago in the Ethiopian plateau and which subsequently interacted with shallower mantle sources to produce the syn-rift volcanism of the Ethiopia–Afar province. (2) A second-order type of shallow mantle upwelling, presumably originating from depths shallower than 400 km as suggested by seismic wave imaging, distinct from the main Afar Plume and disseminated within the African Plate under the uplifted and rifted swells.

3.2 MAGMATISM OF RIFT SECTORS

Partial melting in rift settings is chiefly controlled by the temperature and volatile content of the underlying asthenosphere, as well as the degree of decompression, which depends on

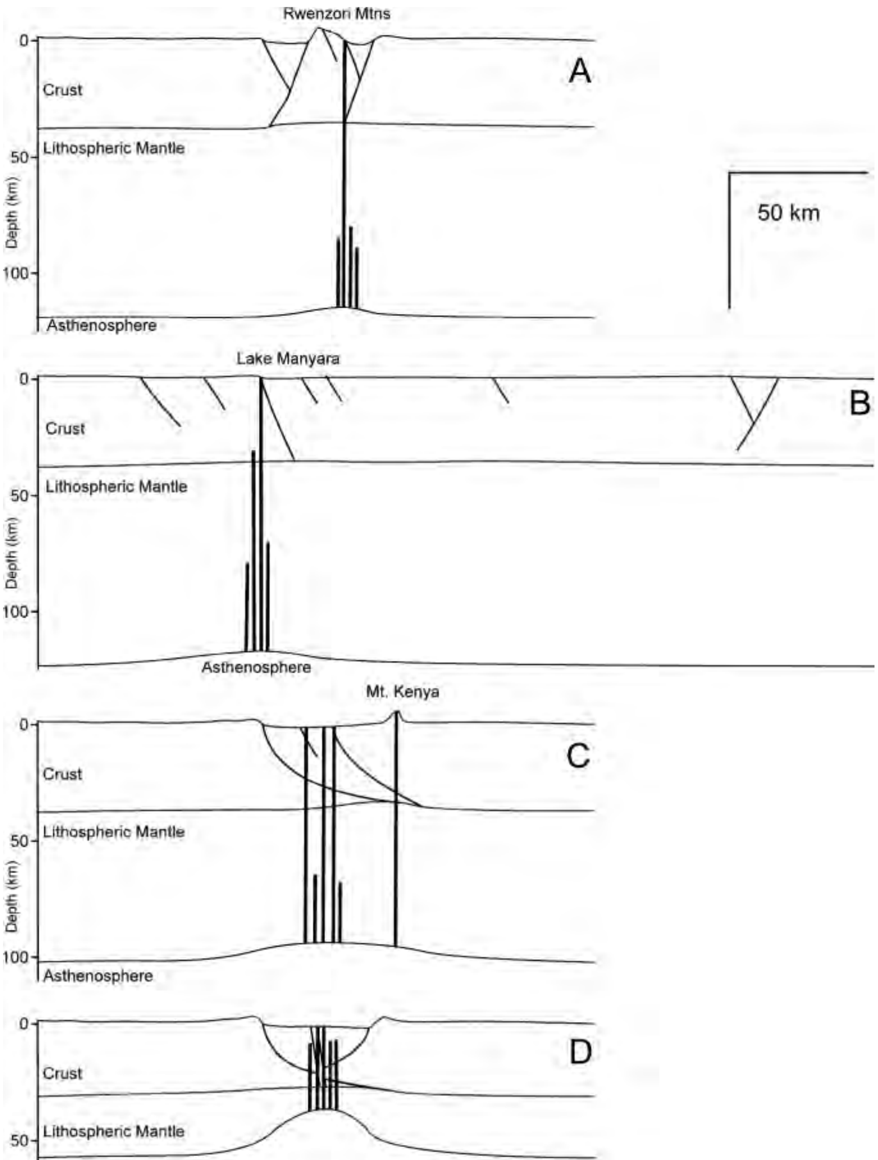

FIGURE 3: Simplified lithospheric cross sections through Western and Eastern Rift Branches showing different styles of rifting, lithospheric attenuation and magmatism. For localities of the cross sections refer to Fig. 1(a). (A) Albertine Rift of west Uganda. The lithosphere is hardly thinned at all and the lower crust is not viscously deforming; the chemistry of the magmatic rocks is primitive and the volume of magmatism is very limited. Pronounced rift-flank uplift created the >5,000 m high Rwenzori Mountains; note that the Rwenzoris are connected to the eastern rift shoulder in the north and split from the rift shoulder in the south along the Lake George Basin. (B) Tanzania Divergence Zone of Eastern Branch. Note the wide area affected by rifting; other than that the lithospheric structure is similar to (A) indicating early stages of rifting. (C) Central Kenya Rift. The lithosphere is notably attenuated and thinned resulting in a viscous lower crust in which high-angle upper crustal normal faults flatten out; note off-axis volcanism forming large volcanic edifices like Mt. Kenya. (D) Main Ethiopian Rift. The most advanced stage of continental rifting resulting in strongly thinned lithosphere; the style of rifting becomes more symmetric and rifting is assisted by pronounced magmatism.

the geometry and rate of lithospheric thinning (White et al., 1987). Partial melting can therefore, at least in part, be used as a proxy of the degree of maturity of a rift sector. We describe those differences from the most juvenile, primitive stage in the Western Branch and the southern tip of the Eastern Branch to the most evolved stage in the Ethiopian Rift of the Eastern Branch.

The Eastern and Western Rift Branches show marked differences in their igneous activity (especially its volume) and morphology. Extensive volcanism only occurs in the Eastern Branch, which is surrounded by a broad regional culmination, the Kenya Dome (Fig. 1). The Western Branch has only scattered volcanism and is not surrounded by a broad regional plateau, but shows great absolute rift subsidence. The differences in volcanism, uplift and subsidence probably reflect the way the mantle plume was channeled underneath East Africa.

3.2.1 WESTERN BRANCH

The Western Branch extends over a distance of more than 2000 km from Lake Albert in the north (Fig. 2b), to Lake Malawi in the south (Fig. 1). Regional doming/uplift is much less pronounced than in the Eastern Branch, though parts of the Western Branch show the greatest absolute subsidence on Earth as expressed by deep rift lakes whose bottom is at or below sea level. Furthermore, rift flank uplift is, at least in part, pronounced. The most striking example is the Rwenzori Mountains, which are a promontory of the eastern rift shoulder in Uganda and rise to more than 5 km above sea level (Pickford et al., 1993; Ring, 2008; Bauer et al., 2010, 2013) (Fig. 2a). The Rwenzoris are the highest rift mountains on Earth. The individual rift basins are long (~100-150 km) and narrow (~50-70 km) and are in the process of linking up.

Volcanism occurs in four isolated centres, which are from N to S the Toro-Ankole, Virunga, South Kivu and Rungwe volcanic fields (Fig. 1). There is no clear age trend and volcanism commenced, at least in the latter three provinces, around 10±2 Ma (Ebinger et al., 1993; Pasteels et al., 1993). The chemistry of most volcanics is strongly silica undersaturated and potash-rich (Rogers, 2006). The volcanic centres are confined to the rift zones proper and limited age data suggest magmatic activity occurs periodically rather than continuously (Delvaux et al., 1992; Ebinger et al., 1993; Ring and Betzler, 1995). It seems that volcanism predates or is concurrent with the onset of rift faulting (Ebinger, 1989).

Overall, the morphologic and magmatic evolution of the Western Branch suggests a relatively strong plate that has been very modestly thinned and border faults penetrate the entire lower crust, consistent with deep seismicity (Ebinger, 1989; Lindenfeld and Ruempker, 2011) (Fig. 3a).

3.2.2 TANZANIAN DIVERGENCE ZONE OF EASTERN BRANCH

In general, the Eastern Branch is volcanically much more active and produced distinctly greater volumes of magmatic rocks than the Western Branch (Fig. 1). The Eastern Branch shows a striking progression of magmatism (and rift evolution) from South to North.

The most juvenile rift sector is the Tanzanian sector, which marks the southern termination of the Eastern Branch (Fig. 1). The rift termination is structurally and morphologically expressed by a pronounced splay, the Tanzanian Divergence Zone (Dawson, 1992). The splaying of the Eastern Branch resembles the termination of ductile and brittle-ductile shear zones. In contrast to the narrow (≈50 km wide) and well-defined Kenyan rift sector, the Tanzanian Divergence Zone is ≈300 to 400 km wide and consists of three separate graben, which are from West to East the Eyasi Rift, the Manyara Rift and the Pangani Rift (Fig. 4). There are also normal faults in between those three graben showing how diffuse extension is accommodated in the Tanzanian Divergence Zone. It appears that the strong Archaean Tanzania Craton largely restricted fault slip and this resistance caused splaying of the major rift faults of the southward propagating Eastern Rift Branch (Ebinger et al., 1997).

As in the Western Branch, individual rift basins in northern Tanzania are half graben bounded by a faulted rift escarpment on one side and a flexural warp on the other (Foster et al., 1997). Each basin is ~100 km long and ~50 km wide (Ebinger et al., 1997). The rift basins contain only thin sequences of syn-rift volcanics and sediments (<3 km in thickness) indicating minor extension across the rift basins. This view is in line with geophysical data revealing a few kilometres of crustal thinning (Birt et al., 1997), and a narrow zone of thinned mantle lithosphere directly beneath the rift zone (Green et al., 1991) (Fig. 3b).

Volcanic activity began at ~8-4 Ma in the center of the Tanzanian Divergence Zone (Dawson, 1992; Foster et al., 1997). After ~4.5 Ma, volcanic activity was transferred to the outer graben of the Tanzanian Divergence Zone (Foster et al., 1997). In the Manyara Rift, volcanism appears to have migrated southward with ages of ~4.9 - 1.5 Ma for the northern Manyara Rift and of ~1.5 - 0.7 Ma for the southern part (Bagdasaryan et al., 1973). The chemistry of the volcanics is alkaline and silica-undersaturated. The composition of the lavas indicates small volumes of melt beneath a ~140 km thick lithosphere (Fig. 3b), and that the base of the lithosphere has been fundamentally altered by interaction with high-temperature fluids (Chesley et al., 1999). Seismic velocity information from refraction and tomography experiments both show low-velocity mantle lithosphere beneath the rift supporting the presence of a small melt fraction in the mantle (Birt et al., 1997).

Earthquakes are distributed throughout the entire ~35 km of crust (Foster and Jackson, 1998). Most rift basins in northern Tanzania are younger than 1-2 Ma (Foster et al., 1997; Ring et al., 2005; Schwartz et al., 2012). The age data for volcanism and graben formation fit into the general pattern for the Eastern Branch of magmatic activity predating tectonicsm.

3.2.3 CENTRAL KENYA RIFT OF EASTERN BRANCH

Further to the North, the main Kenya Rift has rift graben that are distinctly older and more mature. The basins are still asymmetric half graben. Extension is of the order of 10 km and the lithosphere has thinned to ~90 km (Mechie et al., 1997) (Fig. 3c).

The volcanics in the main Kenya Rift are distinctly more voluminous than in the Tanzanian Divergence Zone and show a marked trend from strongly alkaline and mafic to less alkaline and more evolved with time (Williams, 1970). Volcanism commenced by about 23 Ma in broad downwarps that subsequently became the sites of half graben (Keller et al., 1991). Between 14 - 11 Ma a period of intense phonolite volcanism filled and overflowed the rift basins. Another period of pronounced volcanism between 5 - 2 Ma produced noticeably more evolved lavas and trachytes and ignimbrites formed, overspilling the rift basins again. A stunning feature of young volcanism in the central Kenya Rift is the presence of large off-rift volcanic centres, e.g. Mt Elgon, Mt Kenya and Kilimanjaro (Figs. 1 - 3). Earthquakes are restricted to the upper 15 km of the crust (Ibs-von Seht et al., 2001).

Seismic and gravity data show a central rift zone of high velocity, high density material interpreted as upper crustal dikes. These dikes are probably connected to <2 Ma old volcanoes in the central rift, which are cut by a set of prominent, young faults (Ebinger, 2005). The lower crust is reflective suggesting solidified melt bodies at the crust/mantle boundary (Mechie et al., 1997).

All these data indicate a higher degree of lithospheric extension in the central Kenya Rift as compared to the Western Branch and the Tanzanian Divergence Zone. Therefore the lithosphere-asthenosphere boundary is shallower and the volume of decompression melting has increased, which led to the observed change in the chemistry of the rift volcanics. This change in chemistry was apparently associated with a narrowing in the width of the rift basins. The lower crust deforms in a ductile fashion suggesting that main rift faults attain a shallower inclination at depth, explaining off-rift volcanism (Bosworth, 1985) (Fig. 3c).

3.2.4 MAIN ETHIOPIAN RIFT OF EASTERN BRANCH

The review of the various rift segments of the east African Rift System shows that with increasing maturity of the rift sectors the lithosphere thins and the amount of decompressional melt increases (Fig. 3). This in turn created weaker lithosphere. In the East African Rift System these features should be best expressed in the Main Ethiopian Rift (Fig. 5), which represents the northernmost rift sector of the East African Rift system and links into the Afar Depression with the spreading centers of the Red Sea and Gulf of Aden.

Mohr (1983) estimated that Cenozoic volcanics amount to about 300,000 km^3 and produced the vast uplifted Ethiopian Plateau. Most of the volcanics erupted from 32 - 21 Ma (Wolde

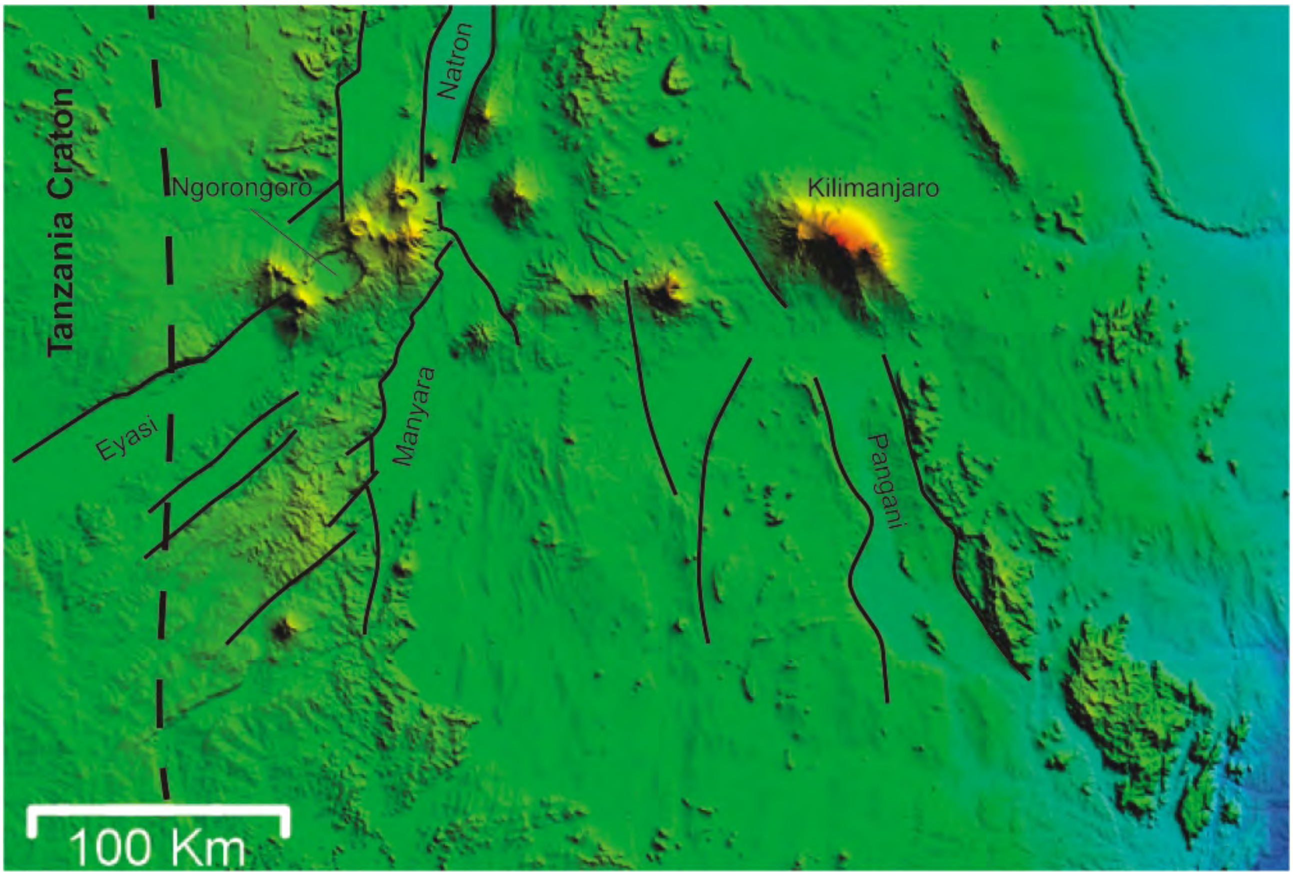

FIGURE 4: Digital elevation model of the Tanzanian Divergence Zone showing wide rifted area at the termination of Eastern Rift Branch. Most of the volcanic centers are near the long border fault segments with Kilimanjaro sitting outside the main rift. Note that some major shield volcanoes like Ngorongoro occur where two major border fault segments intersect.

Gabriel et al., 1991) with a short-lived period (~1 myr) of extensive and aerially widespread flood basalts at about 31 - 30 Ma (Hofmann et al., 1997; Corti, 2009), likely related to prior emplacement of a mantle plume beneath Afar (Ebinger and Sleep, 1998). Immediately after the peak of flood basalt emplacement, a number of large shield volcanoes developed from 30 Ma to ~10 Ma on the surface of the volcanic plateau (Kieffer et al., 2004). Basin formation and minor extension appears to have occurred from 24 - 11 Ma (Wolfenden et al., 2004). The volcanics were derived from enriched, subcontinental lithospheric mantle (Hart et al., 1989) and Pik et al. (2006) showed a mantle plume origin for the volcanics.

The main phase of extension in the Main Ethiopian Rift started at about 11 Ma (Ukstins et al., 2002), possibly related to the onset of seafloor spreading in the Gulf of Aden (Manighetti et al., 1997; Bosworth et al., 2005) and the initiation of extension in northern Afar (Manighetti et al., 2001). High-angle border faults are marked by volcanic centers aligning perpendicular to the regional extension direction (Boccaletti et al., 1998). The zone of active extension narrowed with time. Ebinger and Casey (2001) showed that this localization of the zone of extension became more pronounced to a ~20 km wide zone near the center of the rift since ~2 Ma (Wonji Fault System in Fig. 5). Volcanism since that time is silicic, in part bimodal (Le Turdu et al., 1999). This period of rifting may have been causally related to seafloor spreading in the Red Sea and a rearrangement in global plate motions at 5 - 3 Ma (Boccaletti et al., 1998; Calais et al., 2003).

Geophysical data show that the crust thins from about 40 km underneath the plateau to between 35-24 km underneath the Main Ethiopian Rift. Crustal thickness is higher in the South (33-35 km) than in the North near Afar (26-24 km) (Kebede et al., 1996; Dugda et al., 2005). Keranen et al. (2009) interpreted velocity anomalies along the crust-mantle boundary underneath the plateau to represent melt fractions of up to 20%, an interpretation that is supported by other geophysical data (electrical conductivity and bulk crustal Vp/Vs ratios, Whaler and Hautot, 2006). Crustal tomography and high Vp/Vs ratios are interpreted as indicating the presence of mid- to lower-crustal cooled mafic intrusions (Keranen et al., 2004; Daly et al., 2008) within the rift proper. Results of gravity analysis by Cornwell et al. (2006) suggest that these intrusions contain at least 40% gabbro. The magnitude of the Vp/Vs ratios and P-wave velocity anomalies along the rift axis could also indicate the presence of molten material in fractures within the solidified mafic intrusions (Dugda et al., 2005; Daly et al., 2008), as has also been suggested on the basis of petrological evidence (Rooney et al., 2005). Furthermore, shear wave velocity beneath the rift imaged by Keranen et al. (2009) indicates high temperatures and the presence of melt along the crust-mantle boundary. The lithospheric mantle underlying the Main Ethiopian Rift is either very thin or is entirely missing, especially in the northern part of the rift and in Afar (Dugda et al., 2005). There is also evidence of partial melts in the uppermost mantle (Mackenzie et al., 2005; Cornwell et al., 2006).

Collectively, these findings indicate that the crust beneath the rifted regions in Ethiopia has been extensively modified by magmatic processes and by the addition of mafic rocks in the mid- to lower crust (Fig. 3d). The drastic thinning of the lithospheric mantle is probably a combined effect of lithospheric extension and plume-related thermal erosion. Beneath Afar, the mantle structure is much akin of that of mid-ocean ridge systems and the crust has been highly modified by the emplacement of magmatic rocks (Corti, 2009).

4. TECTONIC DEVELOPMENT

In this section we try to link the above outlined magmatic features with rift basin evolution for better understanding the tectonic development of the East African Rift System. As previous syntheses (e.g. Ebinger, 2005), stages in the development of the East African Rift System will be presented from the young, pristine rift sectors towards the mature rift segments in Ethiopia.

4.1 GETTING STARTED - THE EARLY STAGES

The initial stages of rift development in East Africa are characterized by a series of strongly asymmetric graben, which are typically some 40 to 50 km wide and 60 to 120 km long and open at rates of ~3 mm/yr (Stamps et al., 2008). Graben dimensions are basically a function of plate strength and reflect early stages of extension of a rather strong lithosphere. As discussed in Ebinger et al. (2013), there are distinct variations in rift architecture and tectonic evolution, particularly in the degree of magma involvement. In rift sectors with more pronounced magmatism as the Manyara Rift in the Tanzanian Divergence Zone or the Rwenzori segment of the Albertine Rift in Uganda (Fig. 1), the rift appears to split into different rift arms and the graben with more pronounced magma involvement is the preferred choice for rift propagation (e.g. Manyara Rift vs Eyasi Rift and Pangani Graben in Tanzania, Lake George sector east of the Rwenzori Block in Uganda). This observation suggests that the magma involvement has a weakening effect and eases rift propagation (cf. Ebinger et al., 2013).

In the amagmatic Malawi and Tanganyika Rifts earthquake source depths are, at least in part, very deep and basically span the entire thickness of the extending crust and probably also the uppermost lithospheric mantle. The border faults are long and steep and, as noted by Ebinger et al. (2013), the depth extent of the border faults indicate that these basins achieved their maximum length and entire ~100/120 km long fault segments can rupture in single or coupled earthquake events (Jackson and Blenkinsop, 1997). The large border faults systems associated with a strong, thick lithosphere and limited thermal/magmatic activity appear to control the great subsidence in these rift graben filled by deep, narrow rift lakes (~2000 m deep Lake Tanganyika).

Especially the amagmatic, juvenile rift sectors allow tracing the early opening history of the rift. For the Malawi Rift, Delvaux et al. (1992), Ring et al. (1992) and Ring (1994) showed that the rift opening direction changed from ENE to SE, possibly as a result of plate boundary forces associated with the opening of the Red Sea (Bosworth et al., 1992). Ebinger et al. (2013) speculated that these kinematic changes on time scales of 10^6-10^7 years are associated with periods of tectonic quiescence and limited tectonic-magmatic activity.

4.2 Shifting up a gear – Advanced rifting

The Kenya Rift represents a more advanced stage of rifting in the East African Rift System. Changes in rift opening directions are still discernible. The central Kenya Rift also records an early ENE opening direction that changed to SE about 0.5 myr ago (Strecker et al., 1990). The rift basins still have a half-graben geometry. Likewise their geometry reflects the conditions of rift initiation. However, crustal stretching has now approached 10 km (Ebinger, 2005) and earthquakes are restricted to the upper crust. Crustal thinning has become a multifold process that includes horizontal ductile flow in the extending lower crust.

Widespread and voluminous igneous activity predated any tectonic movements on rift faults and caused pronounced areal uplift. Magmatic activity and subsequent extensional deformation thinned the lithosphere to less than 100 km and caused thermally driven uplift of the rift floor. Since about 2 Ma, volcanism and tectonic activity is in the process of becoming focused along the rift axis. There is still movement on the border fault segments, thereby retaining the initial asymmetry of the rift basins. However, this asymmetry is diminishing and will be lost in the near geological future.

The Kenya Rift is recording an advanced stage of rifting characterized by ductile flow in the lower crust and the fundamental change from an initial half-graben geometry to a stage where magmatic activity and deformation becomes localized along the central rift axis. Tectonomagmatic processes of the latter stages can be well demonstrated in the Main Ethiopian Rift.

4.3 Full speed - Transitioning to sea-floor spreading

The Main Ethiopian Rift marks the transition of continental rifting to incipient seafloor spreading in Afar. In Figure 6 the main differences in lithospheric properties accompanying this change are shown. The overall lithospheric strength is decreasing drastically from Kenya into Ethiopia as a result of increasing temperature in the lithosphere. The increase in

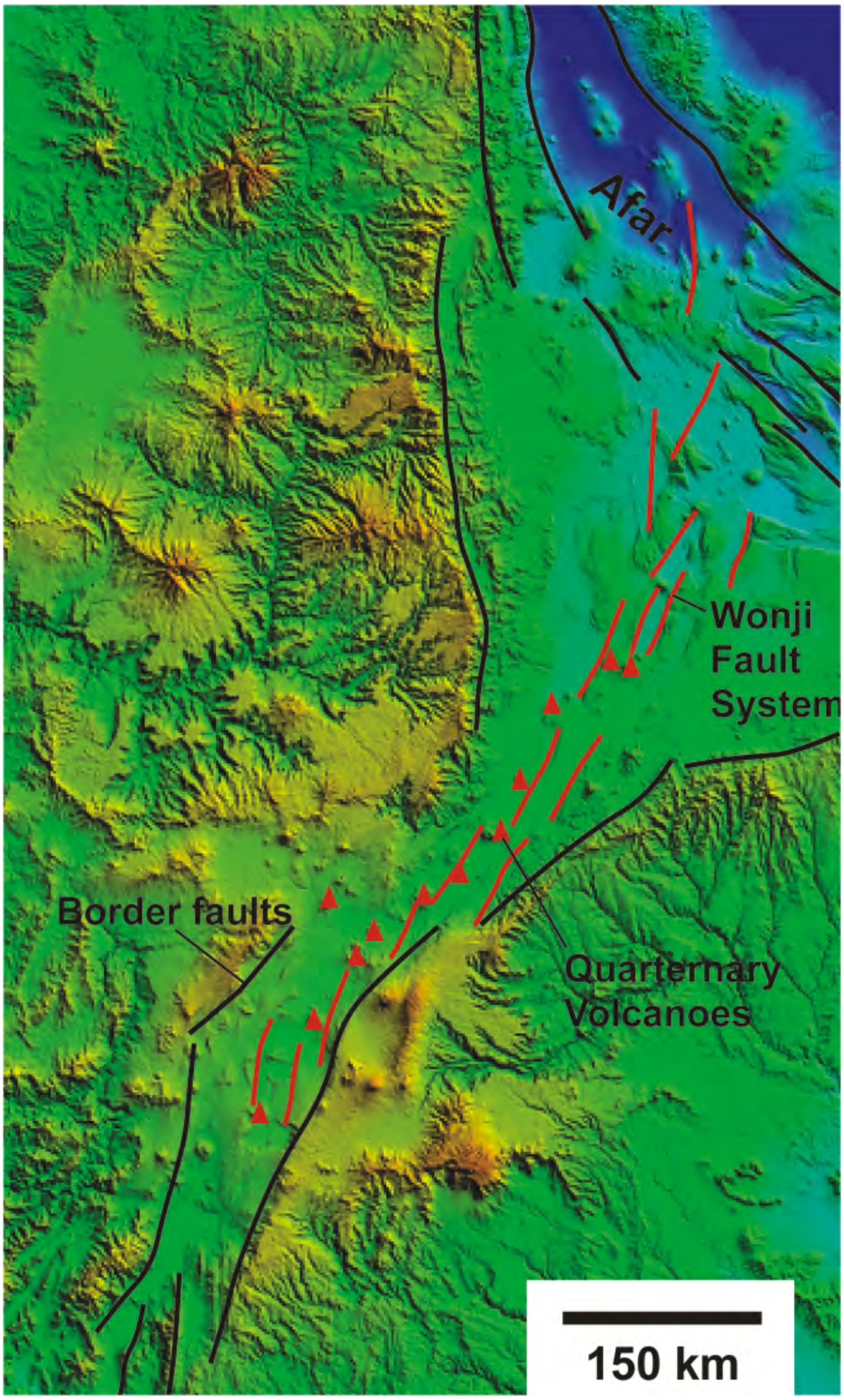

Figure 5: Digital elevation model of the Main Ethiopian Rift and Afar region showing the border faults in black. Note the intimate association of the Wonji Fault System and Quaternary volcanoes (in red). Also note that the Wonji Fault System developed oblique to the trend of the Main Ethiopian Rift.

temperature is manifest by a localization of deformation and magmatism into the central axis of the Main Ethiopian Rift (Wonji Fault System, Fig. 5) since about 2 Ma.

The early phases of rifting starting at about 24 - 11 Ma are still discernible in the south and led to the development of long, widely spaced, large-offset border fault systems forming major escarpments that separated the Ethiopian (west) and Somalian (east) plateau. The initial rift graben are asymmetric and up to 5 km of rift fill accumulated (Corti, 2009, and references therein). This initial phase of half graben development along the main border fault segments lasted until about 2 Ma (Bonini et al., 2005).

At about 2 Ma the style of deformation and rift tectonics changed markedly (Bonini et al., 2005; Corti, 2009). Deformation shifted from the border fault segments to the Wonji Fault System in the center of the rift (Fig. 5). The Wonji Fault System is a series of right-stepping faults, which strike slightly oblique to the main rift axis. Each segment of the fault system is 60 - 80 km long and about 20 km wide and consists of magmatic intrusion at depth and Quaternary dikes strongly coupled to faulting (Corti, 2009). The very strong link between magmatism and activity along the Wonji Fault System indicates that magmatic intrusions, diking and faulting fundamentally modified the lithospheric properties and let to the drastic reduction in yield stress (Fig. 6). The accommodation of deformation by magma intrusion and diking occurs at much lower stress levels than continued deformation along the border fault segments (Buck, 2006) and therefore it appears likely, that the magmatic process within the center of the rift caused the abandonment of the border faults.

The morphology and architecture of the Wonji Fault System has been compared to slow-spreading mid-ocean ridges, for instance Iceland (Ebinger and Casey, 2001; Keranen et al., 2004). Therefore, the Wonji Fault System is regarded to represent a precursor of seafloor spreading. However, as argued by Corti (2009), the uppermost mantle beneath the Main Ethiopian Rift has not yet organized itself into a series of punctuated upwellings characteristic for oceanic spreading centers. The latter stage of organized seafloor spreading occurs in Afar.

5. CRADLE OF MANKIND

Richard Leakey suggested in 1973 that the East African Rift

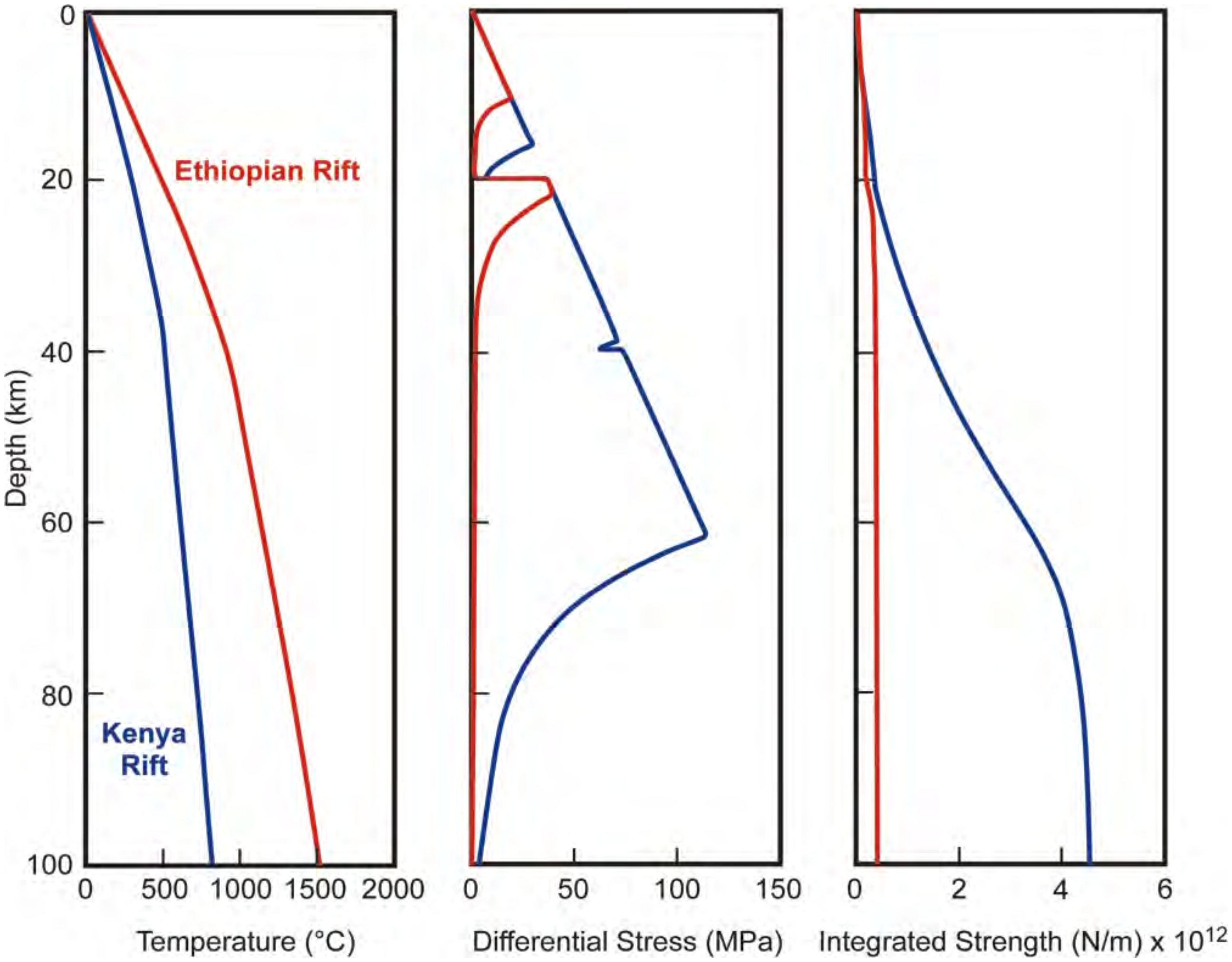

FIGURE 6: Comparison of thermal structure, strength and integrated strength of the lithospheres in the Kenya and Ethiopian Rifts (after Keranen et al., 2009). Note that there is no lithospheric mantle predicted under the Ethiopian Rift according to the calculations by Keranen et al. (2009) and that the integrated strength of the lithosphere in the Ethiopian Rift is an order of magnitude less than that in the Kenya Rift.

System is the “Cradle of Mankind” (Leakey, 1973) because most early hominid fossils have been found in rift sediments (Fig. 2c). All but a few hominid fossils are from the Eastern Branch (see summary in Bonnefille, 2010) with the northern part of the Malawi Rift being the only locality so far where hominid remains have been discovered in the Western Branch (Schrenk et al., 1993). Leakey’s proposition of the “Cradle of Mankind” finds support in the fact that the rift basins with their rivers and lakes are ideal sites for faunal and floral development. Widespread lake formation let to more diversified environments which have potentially influenced the evolution of hominids by altering their habitat. However, whether or not the basins of the East African Rift System were indeed the sites where our ancestors developed and evolved might be a semantic issue as it is basically in the rift basins where abundant sediments of the right age occur and where reasonable potential for preservation of hominid fossils exists. Meanwhile the oldest hominid found so far, Sahelanthropus tchadensis dated at about 7 Ma, is from Chad far away from the East African Rift System (see discussion in Brunet, 2010).

Paleoanthropologists and geologists widely believe that climate changes were the main drivers of early hominid evolution, including the development of bipedalism. The earliest hominids found in the Kenyan and Ethiopian Rift, and also in Chad, inhabited a mixed C3-C4 environment, which probably might have been wooded grassland with patches of woodland (Cerling, 1992). There is no record of closed-canopy forest at the time of deposition. A review of Cenozoic vegetation and climate in tropical Africa by Bonnefille (2010) concluded that an expansion of savanna/grassland occurred at about 10 Ma in East Africa. Another pronounced change in vegetation took place between 6.3 and 6 Ma and was marked by a decrease in tree cover across entire tropical Africa (Bonneville, 2010). In general, the trend towards more arid conditions coincides with the accepted timing for the chimpanzee/hominid split, and Sahelanthropus tchadensis in Chad and Orrorin tugenensis in Kenya.

The critical question is whether the climate changes driving and controlling hominid evolution can be linked to stages in the evolution of the East African Rift System. The development of pronounced topography of the rift shoulders appears to be a too young feature for explaining late Miocene climate shifts (Foster and Gleadow, 1993; Ring, 2008; Bauer et al., 2010, 2013). A more significant factor that may have influenced East African climate in the late Miocene appears to be the dynamic topography exerted by the development of the African Superswell. However, the timing of topography development is largely unknown due to the lack of quantitative markers of topography. This timing is crucial for constraining the role of the African Superswell in influencing seasonal moisture transport and regional climate change.

Moucha and Forte (2011) developed a backward running numerical simulation for reconstructing the amplitude and timing of topographic uplift above the African Superswell associated with changes in flow of the underlying mantle. Their results suggest that aerially extensive (of the order of 5×10^6 km^2) dynamic topography in excess of 500 m of elevation started to develop by 15 Ma and became pronounced by 10 Ma. This timing is in accord with the fact that plume-related activity caused topography and that the structuration of the rift graben occurred subsequently and transected an elevated plateau at about 10 Ma across most of the East African Rift System.

These findings make it likely that dynamic topography in East Africa has indeed influenced regional climate and a shift towards more arid conditions. However, numerical model simulations are no proof and evidence for the timing of pronounced topography is needed to better evaluate tectonic drivers of climate change in Africa in the Miocene. Furthermore, a deeper understanding of the cause(s) for climate shift(s) in Africa and their role in hominid evolution also needs to look at more global drivers like the Asian monsoon.

6. Summary and discussion

There appears to be widespread agreement that the East African Rift System developed above a mantle plume. Plume activity caused flood basalt volcanism in Ethiopia by about 31 - 30 Ma. Africa then slowly moved over that plume and extensive volcanism affected Kenya down to the border with Tanzania. Because of the northward drift of Africa, the Eastern Branch shows this distinct evolution from initial rifting stages in the South (Tanzanian Divergence Zone), via mature stages in the Kenya Rift to incipient continental break-up in the Ethiopian/Afar section.

Flood volcanism was preceded by heating and mantle metasomatism along the asthenosphere-lithosphere boundary, which led to the emplacement of kimberlites in Achaean cratons surrounding the rift in the Eocene. The differences in volcanism and uplift/subsidence in the Eastern and Western Branch, respectively, probably reflect different mantle temperatures with temperatures underneath the Eastern Branch probably 100 - 150°C higher than underneath the Western Branch (White et al., 1987). The plume activity obviously affected the two branches in a different fashion. A possible reason for this might be the pre-existing heterogeneities at the lithospheric level. The Eastern Branch developed in the Pan-African Mozambique Belt (Fig. 1b), which was a typical subduction/collision orogen in the Cambrian (e.g. Shackleton, 1986; Ring et al., 2002). Much of the Western Branch formed in older, early to middle Proterozoic Belts that, at least in part, were characterized by regionally widespread granulite-facies metamorphism, which cause regional dehydration of rocks and made the crust strong. It appears conceivable that the Mozambique Belt lithosphere was prone to delamination/gravitational removal or easier to thermally erode then the older lithosphere beneath large parts of the Western Branch. Therefore, thickness gradients underneath the Eastern Branch were greatest, channelizing the plume material along the rift axis and causing distinctly more partial melting.

It appears that thermal process can be linked more or less directly to the degree and time-scales of plume involvement in the rifting processes. The young rift sectors in the south have not been affected by plume-related heating, the entire lithosphere is still strong and has not been thinned to any significant extent. The further north one goes the longer the rift sectors have been affected by plume-related heating, there is more pronounced igneous activity, the lower crust is ductile and rifting is becoming more advanced.

Not only is the East African Rift System an (the?) archetypal rift system on Earth, it also seems to be an archetypal example of an active rift system (Şengör and Burke, 1980). In active rifts rising mantle plumes causes regional updoming and thermal erosion of the lithospheric mantle and these processes are the major drivers of plate divergence. These processes also drive dynamic topography and a fascinating corollary of this is that the dynamic topography may have been the most important cause for climate change in equatorial Africa, thereby influencing the development and evolution of mankind.

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Uwe RING
Department of Geological Sciences, Stockholm University, SE-106 91 Stockholm, Sweden;
uwe.ring@geo.su.se