Thematic set:
Tectonics and petroleum systems of East Africa

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Re-imagining and re-imaging the development of the East African Rift

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Abstract: The East African Rift (EAR) has fascinated and challenged the geological imagination since its discovery nearly a century ago. A new series of images showing the sequential development of faulting and volcanism along the Rift from 45 Ma to present offers a regional overview of that development. The EAR is the latest phase of the extensive Phanerozoic rifting of the East African continental plate, interwoven with the lithospheric fabrics knitted together during its complex Proterozoic past. South of 5° S, the EAR variously follows or cuts across the Karoo rift trends; north of 5° S, it is almost totally within new or reworked Neoproterozoic terranes, while the Karoo rifts are almost totally outside them. The compilations raise several aspects of rift development seemingly in need of re-imagining, including tight-fit reconstructions of the Gulf of Aden, and the projection of Mesozoic rifts from Yemen to Somalia. Overall, the rifting process does not accord well with a mechanistic paradigm and is better imagined within the Prigoginian paradigm, which accepts instability and disorder within natural processes such as mantle plumes. The structural complexity of Afar and its non-alignment with magnetic anomalies suggests that the seafloor spreading process is, in its beginnings at least, more chaos than order.

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The East Africa Rift System (Rift/EAR) has long fascinated the geological imagination, increasingly so since the mid-twentieth century, when its different segments were re-imagined as images of the plate tectonic process in its embryonic stages. The terms 'imagined' and 're-imagined', as used in this paper, do not carry any prejudicial implications, but refer simply to new or different ways of looking at the Rift, or thinking about it. Over the past decade, for example, the Rift has been re-imagined as an oil province. That is not to say that it isn't an oil province; only that this hasn't previously been the consensus view.

There is nothing new in this. Geologists have been re-imagining the Rift ever since it was discovered, based on the geological and geophysical data (images) available at the time, and always influenced by the received assumptions in the prevailing dogma of the day. In the early twentieth century, for example, many geologists imagined the EAR as a compressional structure. Wayland (1921) saw the apparent 'offsets' between the Lake Albert and Lake Edward rifts as 'demanding' a compressional explanation, as did the towering massif of the Rwenzori Mountains. A compressional origin was easier to imagine within the context of a contracting Earth, then the prevailing view. Mylonitic shear zones observed near the base of the escarpments were thought to be the detachment surfaces, and the rift 'margins' were imagined as gravity slumping at the leading edge of the converging thrust sheets (Mohr 2009). Bouguer gravity anomalies measured over the EAR were seen as supporting the compressional hypothesis (Bullard 1936).

The late twentieth century revolution in geological thinking installed 'global tectonics' or 'seafloor spreading' as the new dogma, and the EAR is now explained in terms of mantle plumes and intraplate stresses. There remains, however, considerable variation in how the Rift's form and forces of formation are imagined. For example, as Ghebreab (1998) pointed out, the Red Sea rifting has been imagined as both passive and active, controlled by uniform simple shear as well as by diffuse shear and normal faulting, with a crust almost entirely continental and almost entirely oceanic. The debate continues.

This project had its origins in a commercial study of possible relationships between Precambrian tectonic structures and minor rift segments, such as the Pangani Rift in Tanzania. Might rift segments located along Precambrian shear zones, for example, have formed or been reactivated earlier in the EAR history than was generally accepted? Might they contain older, previously unrecognized and potentially prospective synrift sequences? The final series of images showing the progressive development in both time and space of the widely separated Rift segments, and their relationship with the Proterozoic fabric, suggested that regional maps depicting sequentially the EAR faulting and volcanism might be of interest to other workers.

Detailed modern research on the rift provides a plethora of new geological and geophysical images that constantly change how geologists imagine the Rift's structure and origins, but that imagining can sometimes be influenced by what Eagles *et al.* (2002) called a 'restricted geographical focus'. This tension between detailed local observations and the compromises inherent in their integration into a 'panoramic whole' (Ksiazkiewicz 2012) is unavoidable, and both are essential. The mega-regional perspective presented here will hopefully prove useful to those working on a local scale, as well as those seeking a panoramic overview.

This paper presents new images of the EAR to illustrate its progressive development, and discusses several aspects of that development. These maps build on compilations by Saemundsson (2010) and Macgregor (2015), but have been expanded northwards to include Eritrea, Yemen, the Gulf of Aden and Somalia, and incorporate new research which has resolved some of the uncertainties regarding the age of volcanics in SE Ethiopia. The early stages of the Rift evolution, prior to 13 Ma, are analysed in more detail. The re-imagining ranges from the directly geological (the different locations of the Karoo and Tertiary rifting with respect to the Proterozoic fabric) to the more esoteric (the implications for the development of Afar of Ilya Prigogine's paradigm of nature as 'order out of chaos': Prigogine & Stengers 1984). Preliminary versions of these images were presented as 'Mapping the evolution

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of the East African Rift System – re-imaging and re-imagining' to the Geological Society of London (GSL) conference *East Africa: Research to Reserves* in April 2016.

Preparation of the East African Rift maps

This project involved the compilation of maps of the East African Rift faulting and volcanism, as well as the Proterozoic basement fabric and Karoo/Mesozoic rifting of Eastern Africa and Yemen. The project area extends from Eritrea in the north to Mozambique in the south, Socotra in the east, and Congo in the west. The maps were compiled manually at a scale of 1/3.5 mm, then reduced by 50% for final editing, simplification and drafting. Figure 1 presents the study area and all Phanerozoic rift localities referred to in the text. The offshore Kerimbas and Lacerda rift systems, extending sub-meridionally down the coast of Tanzania and Mozambique, are not included in the compilation or discussion. The EAR maps are discussed below; the Proterozoic fabric and the Pre-Tertiary rifting in a following section.

A relatively detailed map of the EAR, displaying the main rift-margin faults, was compiled from the references listed below, as well as the major regional compilations of Pilger & Rosler (1975), Chorowitz (2005) and Macgregor (2015). The rift segments were then block-filled so that minor features would remain visible at publication scale. The map series, showing the development of the Rift, commencing at 45 – 32 Ma, was then prepared by progressively adding the rift segments initiated during a particular period to the map showing the pre-existing rift segments. Except in the Afar/GOA/Red Sea region (and there only schematically), the maps are not 'reconstructions', and the rift elements are shown with their present-day form. The timing assigned to the initiation of individual rifts is biased towards rift onset, which is ultimately the start of rifting, rather than the main rift episode. This should be considered when comparing these maps with the map series of Macgregor (2015), which emphasizes the main periods of fault movement.

Significant location errors are evident on some early maps and, even on relatively modern maps, many rift features are plotted with slightly different shapes and locations by different authors. Compare, for instance, the rift faulting shown in southern Ethiopia by Bonini *et al.* (2005) and Vetel & Le Gall (2006), or the location of the Choke and Gona shield volcanoes in Kieffer *et al.* (2004) and Rooney (2017). Inevitably, this necessitated subjective decisions about the 'best' shapes and locations to incorporate into the compilation maps. Precedence has been given to more recent maps when plotting the faults and volcanic outcrops, and positioning relative to major topographical features, such as the rift lakes, has usually been preferred to coordinates. Plotting of 'single' faults along broad rift-margin zones is based, where possible, on the location of the main escarpments or the reported location of the largest faults (e.g. Juch 1975, along the southern Afar margin).

The progressive development of the faulting and volcanism along the Rift is shown on nine maps depicting the intervals 45 – 32, 31 – 29, 29 – 26, 26 – 23, 22 – 17, 13 – 10, 10 – 6, 5 – 3 and 2 – 0 Ma, respectively, and each interval is discussed briefly. This paper does not include a synthesis or critique of current concepts about the EAR and readers seeking additional comments on the timing of the EAR are referred to Macgregor (2015), which includes chronostratigraphic columns of the main rift segments and a useful summary of the various uncertainties inherent in dating East African rifts.

- Ethiopia: principal regional references for Ethiopia were Tefara *et al.* (1990), Corti (2009) and Abbate *et al.* (2015), with faulting and volcanism along the Main Ethiopian Rift (MER) composited from Ebinger *et al.* (1993, 2000), Wolfenden *et al.* (2004, 2005), Bonini *et al.* (2005) and Abebe *et al.* (2007, 2010). The distribution and age of Ethiopian volcanic rocks is also drawn from Berhe *et al.* (1987), Mohr & Zanettin (1988), Boccaletti *et al.* (1999), Kieffer *et al.* (2004), Mege *et al.* (2016), Rooney (2017) and unpublished ^{40}Ar/^{39}Ar dating by the author and colleagues.
- Afar: the geological framework of the Afar region is from the *Geological Map of Central and Southern Afar* (BEICIP 1975), with faulting along the southern Afar escarpment from Juch (1975) and Yihune & Haro (2010), and along the western Afar escarpment from Wolfenden (2005), Rooney *et al.* (2013) and Stab *et al.* (2016). The location of the fault zone separating Afar and the Danakil continental block is based on the Bouguer gravity gradient along this zone (Makris *et al.* 1975*a*). Details of the spreading zones on the Afar floor are from Manighetti *et al.* (1998, 2001).
- Gulf of Aden: the rift structure in the Gulf of Aden (GOA) coastal and near-shore areas has been composited from multiple sources, the principal reference being Leroy *et al.* (2012), with additional fault locations along the Somalia margin from Abbate *et al.* (1986), Bott *et al.* (1992), Fantozzi & Sgavetti (1998) and Ali (2015), and on the Yemen margin from Redfern & Jones (1995) and Ellis *et al.* (1996). The GOA crustal structure is derived from Manighetti *et al.* (2001), Fournier *et al.* (2010) and Leroy *et al.* (2012), but follows Bosworth *et al.* (2005) in imagining distinct steps in the westwards advance of seafloor spreading towards Afar. Volcanism in Yemen is from Grolier & Overstreet (1978), Ukstins *et al.* (2002) and Ukstins Peate *et al.* (2005), with details in the Aden region from Tard *et al.* (1991).
- Red Sea: faulting in the Red Sea is based on Crossley *et al.* (1992) and Mitchell *et al.* (1992), with Ghebreab (1998), Ghebreab *et al.* (2002), Bosworth *et al.* (2005) and Bosworth (2015) being the principal sources for timing of rift and drift development.
- Somalia: the rifting onshore northern Somalia and Somaliland is taken from the *Geological Map of Somalia* (Abbate *et al.* 1994), with modifications based on Fantozzi & Sgavetti (1998) and Ali (2015), and Granath (2001) for the Nogal Rift faulting.
- Kenya: the main rift faults are taken from BEICIP (1987), with details of faulting and volcanism in the Turkana area from Morley *et al.* (1999*d*), Wescott *et al.* (1999), Vetel *et al.* (2005), Vetel & Le Gall (2006), Africa Oil (2011, 2014), EHRC Energy (2015), Muia (2015), Brown & Jicha (2016) and Rooney (2017). The timing and extent of volcanism is also drawn from Baker *et al.* (1971), Pickford (1986) and Saemundsson (2010). Faulting in the Anza Graben is from Morley *et al.* (1999*a*).
- Tanzania: the rift faulting and timing in northern Tanzania is based on Ebinger *et al.* (1997), Foster *et al.* (1997), Le Gall *et al.* (2004, 2008) and Dawson (2008), with the southern extension through the Tanzania Craton from Macheyeki *et al.* (2008). The Usangu Basin details are from Harper *et al.* (1999) and Mbede (2002). Rukwa rifting and Rungwe volcanism is based on Morley *et al.* (1999*b*), Wescott *et al.* (1991), Roberts *et al.* (2004, 2010) and Fontjin *et al.* (2010).
- Uganda: the Western Rift faulting in Uganda is based on the Uganda Geological Survey (1961) map, Aanyu & Koehn, (2011), Karp *et al.* (2012) and Katumwehe *et al.* (2015), as well as industry sources (Tullow Oil plc 2012).
- Sudan: the rift framework and timing in South Sudan is based on Bouguer gravity data in Browne *et al.* (1985), McHargue *et al.* (1992) (who use the −40 mGal contour as a proxy for the basin outlines), Mohamed & Mohammed

Fig. 1. Locality map, eastern Africa. AA, Addis Ababa; Ab, Allia Bay Rift; AB, Abbai Basin; Ad, Ad Dali Rift; AF, Alula Fartak Transform; Af, Afar; Al, Albert Rift; Am, Amaro Horst; As, Aisha Block; Az, Anza Rift; Bf, Balhaf Graben; BN, Blue Nile Basin; Br, Berbera; CB, Chew Bahir Rift; CG, Cape Guardafui; Cm, Chama Rift; DB, Danakil Block; Do, Dolo; Dr, Darror Rift; Ed, Lake Edward Rift; Ef, Elegyo Fault; EO, Eastern Ogaden Sub-basin; Ey, Eyasi Rift; Ga, Galana Rift; G, Gatome Rift; Gm, Gambela; H, Harar; K, Kibish Rift; Ke, Kerio Rift; KG, Kenya (Gregory) Rift; Km, Klemmie Rift; Ki, Kilombero Rift; Ks, Kino Sogo Rift; Kv, Kivu Rift; Li, Livingstone Rift; Lk, Lokitipi Rift; LT, Lake Tana; Lr, Lapurr Rift; Lu, Luangwa Rift; M, Mogila Hills; Ma, Malawi Rift; MK, Malawi Karoo Rift; Me, Melut Basin; Mn, Manguela Rift; MF, Marda Fault Zone; Mg, Muglad Basin; ML, Mandera Lugh Basin; Mu, Muruanichok Rift; My, Manyara Rift; NER, Northern Ethiopian Rift; Ne, Negele; Nf, Ngurman Fault; NL, North Lokichar; No, Nogal Rift; Ny, Nyanza Rift; O, Omo Rift; ODS, Ogaden Dyke Swarm; Og, Ogaden Basin; Pa, Pangani Rift; Rb, Ririba Rift; Rc, Rhino Camp Rift; Rg, Rungwe; Ru, Ruhuru Rift; Rw, Rukwa Rift; Rz, Rwenzori Mountains; Se, South Afar Escarpment; Su, Selous Basin; SL, South Lokichar; Sr, Sagan Rift; SS, Shukra el Sheik Transform; T, Turkana Rift; Ta, Tanganyika Rift; Tg, Tendaho Graben; Us, Usanga Rift; We, western Afar escarpment; WO, Western Ogaden Basin; Yt, Yerer Tullu Welwel Rift.

(2008) and Dou *et al.* (2007), as well as unpublished oil company maps. Rift faulting in the Ilemi Triangle area between the Lokitipi and Muglad/Melut rifts is from Hutchinson (2009).

The locations of the EAR faults in southern East Africa are simplified from Bloomfield (1966), Zaire Service Geologique (1974), Instituto National de Geologica (1987) and Thieme & Johnson (1981). The analysis of lakes Tanganyika and Malawi/Nyassa follows that of Macgregor (2015), based largely on extrapolation of sedimentation rates, with an appropriate degree of uncertainty.

Gulf of Aden and Red Sea reconstruction

Reconstructing the Gulf of Aden (GOA) and the southern Red Sea region to the pre-rift locations, and depicting the subsequent stages of lithospheric extension and seafloor spreading have been the most challenging aspects of the map construction, and some comment is warranted prior to the discussion of the maps.

The similarities between Mesozoic sediments on the Somalia and Arabian shores of the GOA were first noted in the mid-nineteenth century (Mohr 2009), and the geological correlations and continuity between these regions is now well documented (Beydoun 1970; Fantozzi & Sgavetti 1998; Leroy *et al.* 2012). What is less clear and remains controversial is the pre-drift proximity of the modern shorelines. A tight-fit reconstruction has long been argued and is widely accepted. Leroy *et al.* (2012), for example, showed oceanic crust dated at 17.6 Ma east of the Shukra el Sheik Transform, with the current coastlines 'overlapping' east of Berbera. Regardless of their popularity, these tight-fit reconstructions are difficult to reconcile with the Precambrian outcrops onshore, and the identification by seismic reflection surveys of continental blocks and rifts offshore Berbera and Aden. Berhe (1986, p. 114) made this same point: 'plate reconstructions matching the coastlines cannot satisfactorily explain the geological constraints'.

Figure 2 shows the tight-fit reconstruction as proposed by Leroy *et al.* (2012) and others, but extended west to show the Precambrian and Mesozoic outcrops in Yemen and Somalia/Ethiopia. The Cretaceous outcrops in the Ali Sabieh region (Le Gall *et al.* 2010) overlie Jurassic limestones and serve as a proxy for the underlying basement complex. The point of juxtaposition of the Yemen and African Precambrian blocks would seem to be the closest-possible pre-drift location of the GOA 'coastlines', and even that makes no allowance for the continental crust in the adjacent offshore. Diagrams showing tight-fit reconstructions invariably solve the dilemma by omitting the Precambrian outcrops (e.g. Leroy *et al.* 2012) or terminate the model to the east of them.

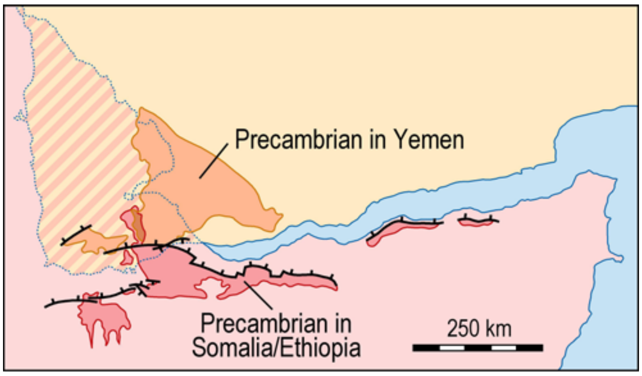

Fig. 2. Tight-fit reconstruction of the Gulf of Aden, showing overlapping Proterozoic terranes. Orange stripes show overlap of modern coastlines. Proterozoic outcrops on Danakil Block are not shown.

On the EAR maps, the GOA coastlines have been drawn schematically by 'closing' the GOA west of the Shukra el Sheik Transform until the reported continental domains offshore Yemen and Somalia are almost juxtaposed, and by adopting the 16 Ma coastline positioning of Fournier *et al.* (2010) adjacent to the Alula-Fartaq Transform. In the map series of Figures 3 – 11, the GOA has then been 'opened' progressively along the known transform-fault system to reflect the main periods of extension and seafloor spreading. This reconstruction has been done manually in map form and is schematic only. Because there are no data on the pre-oceanization rift structure, the central GOA is shown schematically as a zone of crustal extension and rifting. The Aisha and Danakil blocks are both considered to be relatively unattenuated continental crust: seismic velocity profiles have been interpreted in terms of some attenuation in southern Djibouti (Ruegg 1975) but gravity data (Makris *et al.* 1975*b*) suggest a crustal thickness of about 30 km. The Aisha Block is considered to be *in situ*, while the Danakil Block is shown as having rotated counter-clockwise in the so-called 'crank-arm' fashion.

Development of the East African Rift

The maps presented in Figures 3 – 11 show the progressive development of the EAR, and the inter-relationship of the rifting and volcanism. The nine maps cover the intervals 45 – 32, 31 – 29, 29 – 26, 26 – 23, 22 – 17, 13 – 10, 10 – 6, 5 – 3 and 2 – 0 Ma, respectively. The intervals have been chosen to illustrate progressive stages in the rift evolution and magmatism, but there is often overlap from one stage to the next, as well as evolutionary developments within a stage. Maps depicting a specific interval show the rift segments which formed during that interval as well as any pre-existing rift segments, so that the maps, when viewed sequentially, show the progressive development. Rift segments are shown at the time of rift onset rather than at the main rift phase, which can be considerably later, as in the South Lokichar Rift in the Turkana area, for example. Precise dating of many of the rifts is difficult because of the limited subsurface information available. Rift faults are shown as solid lines, while the hinge-side of half-graben rifts is shown without a demarking line. The drift of the African Plate is indicated on the maps by the changing position of the Equator, taken from Thackrey *et al.* (2017).

Areas of volcanism dating from the specific time interval of the maps are shown in bright red, while areas of older volcanics are merged and shown in pink. The extent of volcanism within each interval is not well defined in many areas. First, there are few age dates available, given the enormous area and its complex magmatic history. Secondly, many dates are based on potassium–argon analyses, and may be shown to be inaccurate by future ^{40}Ar/^{39}Ar dating, as has already been the case in many areas. Thirdly, the available dates show the local occurrence of volcanics of a certain age but do not always clearly define the original areas of volcanic activity. For example, were the 26 – 22 myr old volcanics on the southern and western Afar margins erupted only along these newly faulted margins? Or did the basaltic flows extend across what is now the Afar floor and are now buried under younger sediments and volcanics? In areas such as the greater Omo/Turkana Rift Complex, older volcanic units can be missing because of uplift and erosion (Davidson 1983) or can be downfaulted into younger rifts and buried. Hence, scattered outcrops in an area are considered to be erosional remnants of the original flow (e.g. on the Negele map sheet in Ethiopia: Yihunie & Tesfaye 1997), and existing thick volcanic outcrops are taken to indicate flows that originally extended beyond the current area. Accordingly, the volcanic sequences on the maps attempt to depict, based on the current outcrop areas, the possible original extent of the volcanism or flows. Areas of uncertainty because of younger sediment or volcanic cover, or removal by erosion, are indicated with a zigzag pattern.

45 – 32 Ma (Fig. 3)

This period spans the transition from the overall NW-trending Cretaceous–Palaeogene rift complexes in Sudan (Muglad, Melut) and Kenya (Anza Rift) to the sub-meridional trend of the EAR. Understanding this transition and the initiation of EAR magmatism and rifting in the Turkana area has long been hindered by the limited data available, but more recent information from the oil industry (e.g. Hutchinson 2009) and academic projects (e.g. Muia 2015) is providing new insights.

Extensive and thick volcanic sequences in the Turkana area, taken with the thinner sequences in the Southern Main Ethiopian Rift (SMER) and greater Omo areas, mark a major new magmatic episode at 45 – 32 Ma, referred to as the Eocene Initial Phase by Rooney (2017). The phase is commonly cited as 45 – 34 Ma but is extended here to 32 Ma to incorporate the newly dated basalt-capping rhyolites in the Mogila Range on the Sudan–Kenya border (Brown & Jicha 2016). Opinions differ as to whether the basal sediments and volcanic sequences predate or are synchronous with rifting. Some of this magmatism clearly predates extension: for example, in the SMER, there is no significant change in thickness of the basalts on or off the Amaro Horst between the Galana and Chama rifts, evidencing the absence of coeval rifting in this area (Ebinger *et al.* 1993). Conversely, the Eocene–Oligocene Balesa Koronto basalts in the Kojong area, east of southern Lake Turkana, thicken by 800 m across the Allia Bay Fault, and are clearly synrift (Vetel & Le Gall 2006). Slight thickening of Oligocene sequences into east-facing faults on seismic profiles across the Lapurr Range and Lake Turkana (Wescott *et al.* 1999) might also evidence coeval rifting, but detail is limited. The sediments and volcanics in the Lokitipi and Gatome basins are here considered a synrift sequence, but the alternative interpretation of a sag basin (Wescott *et al.* 1999) is acknowledged.

In Figure 3, the volcanic areas of the SMER, Omo and Turkana are shown as parts of a larger single volcanic province. This generalization is supported by the reported extensive erosional removal of older volcanics in the Omo region (Davidson 1983), and the recognition of the Oligo-Miocene volcanic sequence on seismic profiles in Lake Turkana (Wescott *et al.* 1999). Thin basaltic sills, considered to be Eocene extrusives, have been encountered in the subsurface in wells in the Melut Sub-basin in Sudan (Schull 1988) and Ethiopia's Gambela region, but their extent is unknown. These relatively thin layers contrast markedly with the thick volcanic sequences in the Turkana area.

This magmatism has been seen as probably the result of a very hot mantle plume (Ebinger & Sleep 1998), and might be imagined as an early pulse from the megaplume that would shortly thereafter break through the crust below the Ethiopian Plateau. The thinner crust of the Turkana region, a product of the Karoo and Mesozoic rifting along the Anza trend, might have been the attractor for this early pulsing plume.

A series of north–south-trending rifts, not all of them yet well-defined, developed west of Lake Turkana during this period, as shown in Figure 3. Bouguer gravity and seismic data (Wescott *et al.* 1999) show a more complex rift structure than commonly depicted: the Lokitipi Basin comprises two rifts separated by a basement horst, and originally extended west of the Mogila Hills, prior to their inversion. In Figure 3, this western rift is shown as stripes, and the bounding fault is set along the modern edge of the Precambrian outcrop. Recent FTG (full tensor gradiometry) data (EHRC Energy 2015) confirms the two Lokitipi rifts, and suggests rectilinear NW- and NE-trending rift-margin faulting, similar to the Chew Bahir Rift. The Gatome Rift is clearly indicated by gravity and magnetic data, and probably extended to the south to join the now inverted and extensively eroded Muruanochok Rift (Muia 2015), also shown as striped in Figure 3.

These north–south-trending Turkana rifts contrast markedly with the predominantly NW–SE-trending South Sudan rifts, and a broad data gap in the contested Ilemi Triangle area between them has long hindered investigations. Ebinger & Ibrahim (1994), Ebinger *et al.* (2000), Muia (2015) and others have noted that sub-meridional Palaeogene rifts are developed in eastern South Sudan and could be projected south into the Lokitipi area. However, proprietary gravity and magnetic data over the South Sudan–Kenya–Ethiopia border area now reveals a pronounced NW–SE trend to the rifting in this area (Hutchinson 2009).

South of the Lokitipi rifts and beyond the area of volcanic influence, the South Lokichar half-graben rift formed at *c.* 35 Ma (Vetel & Le Gall 2006), although substantial rifting may not have occurred before *c.* 30 Ma (Macgregor 2015). If this 35 Ma dating for rift onset is correct, then the South Lokichar Rift began to develop prior to the main Trap eruptions and marks the earliest rift faulting along the EAR.

31 – 29 Ma (Fig. 4)

Commencing at about 31 Ma, as 'an omen of crustal instability', to borrow Paul Mohr's (1975) term, the voluminous Trap Series basalts poured out over a vast area of Ethiopia, extending into Kenya, Sudan and Yemen. The volcanism covered an area of over 720 000 km^2 and is 1 – 2 km thick over much of that area (Rooney 2017). The scale of this outpouring in such a relatively short time span is considered evidence of a very-high-temperature mantle plume. The volcanism is aerially and volumetrically much larger on what is now the Ethiopian Plateau, relative to the Somalian Plateau to the SE, suggesting that the mantle plume responsible, despite the eponymous connection, was located more under the Ethiopian Plateau than under Afar itself. The initial eruptions were almost exclusively basaltic magmas but a major phase of silicic volcanism commenced about *c.* 30 Ma over much of Ethiopia and Yemen. Near the end of this period, the massive Simien shield volcano formed in northern Ethiopia, erupting basalts of similar composition to the underlying flat-lying main flows on which it rests unconformably.

Extensive rifting along most of the proto-Gulf of Aden had commenced by this time, with rifting in the east commencing several million years previously. The rift provided intermittent access for marine waters into the GOA from the proto-Indian Ocean to the east. Sabkha and marginal-marine deposits that are dated at 33 Ma occur in Dhofar (Leroy *et al.* 2012) and are recorded in offshore wells in the central GOA at 30 Ma (Hughes & Varol 1991), by which time a shallow-water carbonate shelf covered the Socotra area. The rift pattern shown in Figure 4 is a composite based on the references cited previously, and the remainder of the GOA area is shown schematically as a zone of extended and rifted continental crust. This rift episode is likely to have included the Nogal and Darror rifts onshore Somalia: no precise dating is available but wells drilled in, and on the shoulders of, the Nogal Rift show synrift thickening of the Oligocene (post-Karkar Formation) sequence (Granath 2001). Evidence for a Oligocene synrift sequence in the Darror Rift is less certain: about 600 m of predominantly carbonate sediments overlying the Middle Eocene Taleh Formation in a recent well in the rift is undated and, even if Oligocene in age, might not be synrift. Well data from offshore Eritrea indicate that rifting in the southern Red Sea had not yet commenced.

The East African Rift *sensu stricto* (i.e. the sub-meridional onshore rift) was still manifest only in the South Lokichar Basin, where rifting continued.

29 – 26 Ma (Fig. 5)

A period of relative magmatic quiescence followed, with more localized basaltic and silicic flows and dyking along the nascent

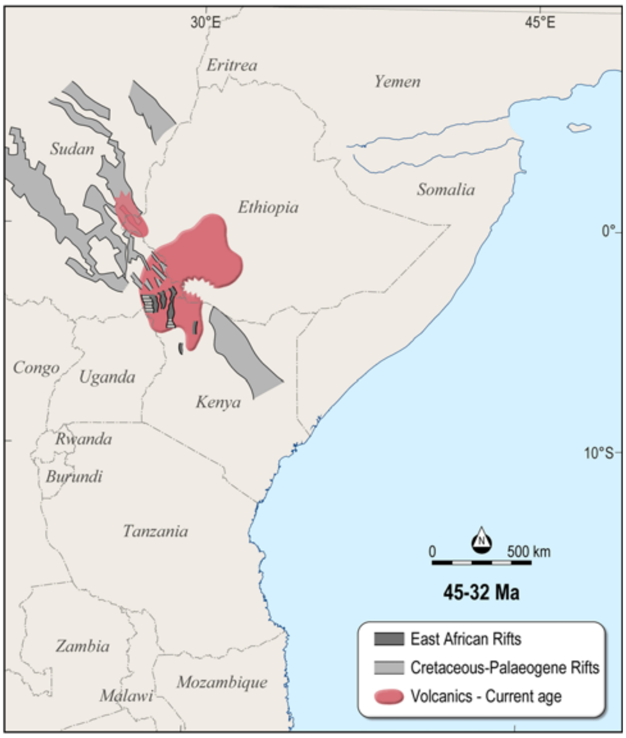

Fig. 3. East African Rift, faulting and volcanic areas, 45 – 35 Ma.

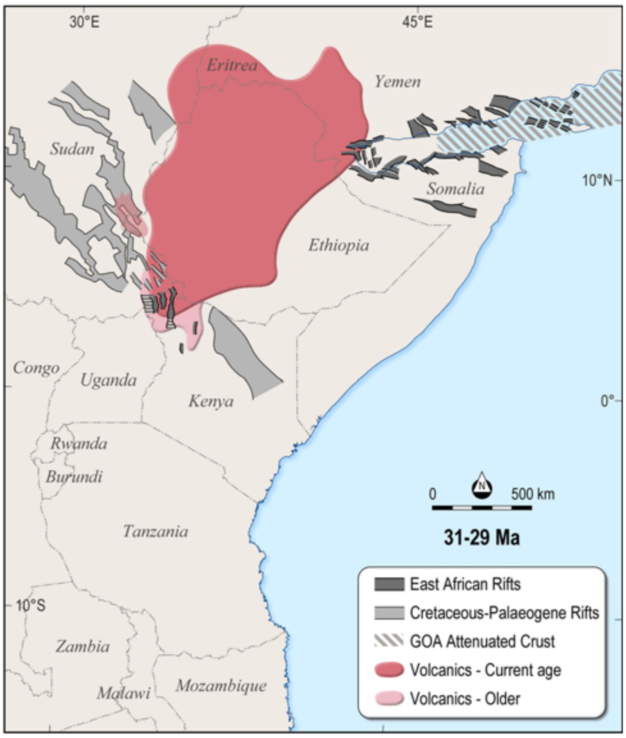

Fig. 4. East African Rift, faulting and volcanic areas, 31 – 29 Ma.

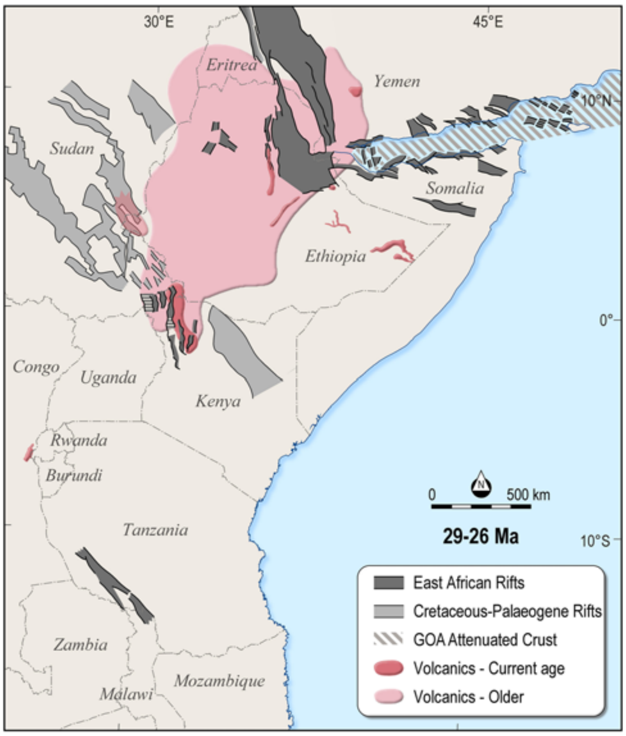

Fig. 5. East African Rift, faulting and volcanic areas, 29 – 26 Ma.

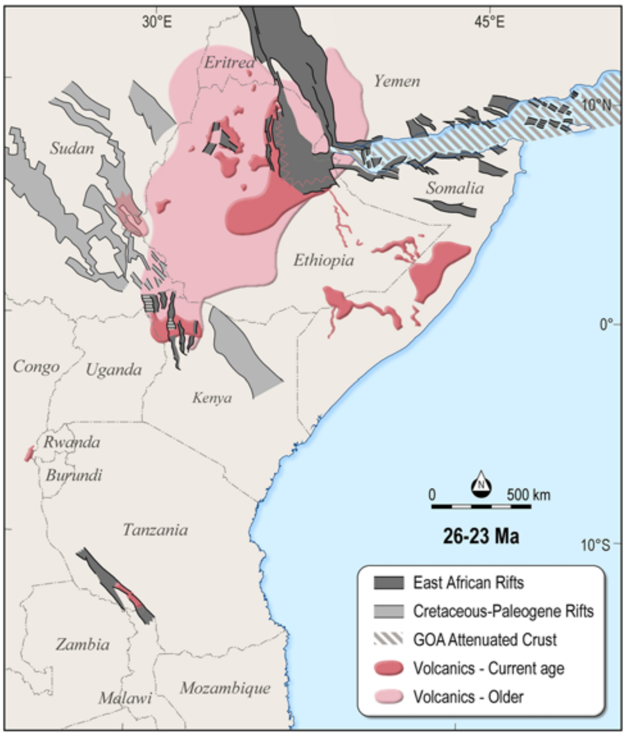

Fig. 6. East African Rift, faulting and volcanic areas, 26 – 23 Ma.

Afar margins: the extent of these bimodal flows beneath younger volcanics is not known and little dating has been done. Curiously, fissural volcanism commenced at this time in the far eastern Ogaden and on the north-central slopes of the Somalian Plateau, commonly filling ancient river channels, and presaging the increased far-field activity that followed (Mege *et al.* 2016). Cinder cones began to form in the monogenetic volcanic field east of Jijiga, at the intersection of the Marda Fault Zone and the southern Afar Margin (Mege *et al.* 2016). Basaltic and silicic flows in the Turkana area, previously considered of lowermost Oligocene age, also occurred during this period (Brown & Jicha 2016), and silicic ignimbrites and tuffs covered large areas of the northern Yemen Plateau (Ukstins Peate *et al.* 2005).

At about 27 Ma, rifting commenced along the western and southern Afar margins, defining a major expansion of the EAR activity. The western Afar faulting marks a continuation of the Red

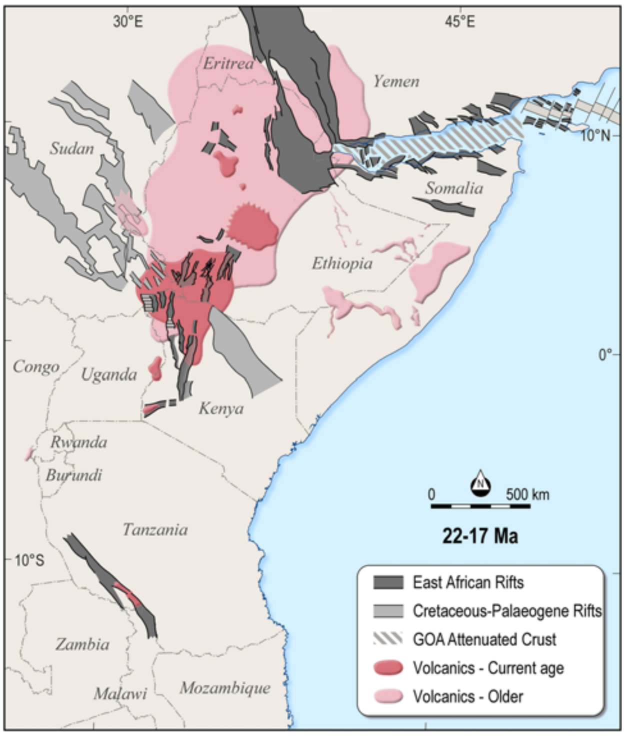

Fig. 7. East African Rift, faulting and volcanic areas, 20 – 17 Ma.

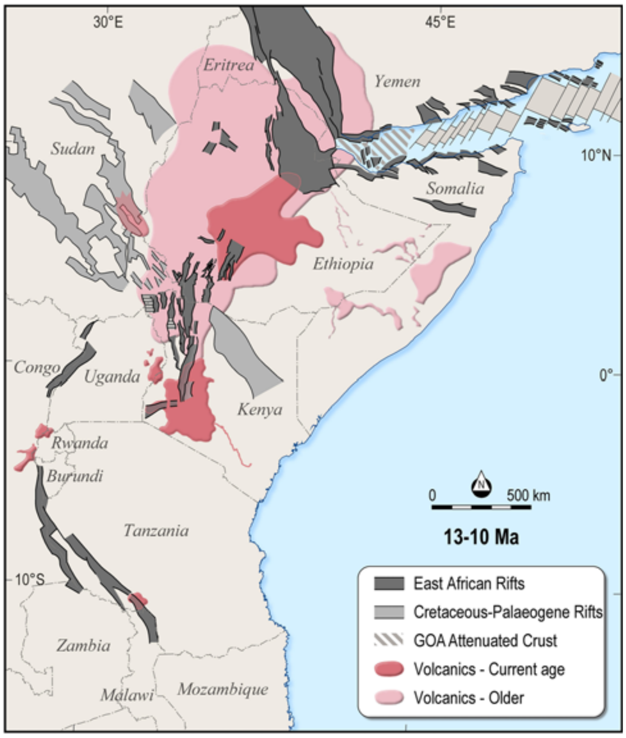

Fig. 8. East African Rift, faulting and volcanic areas, 13 – 10 Ma.

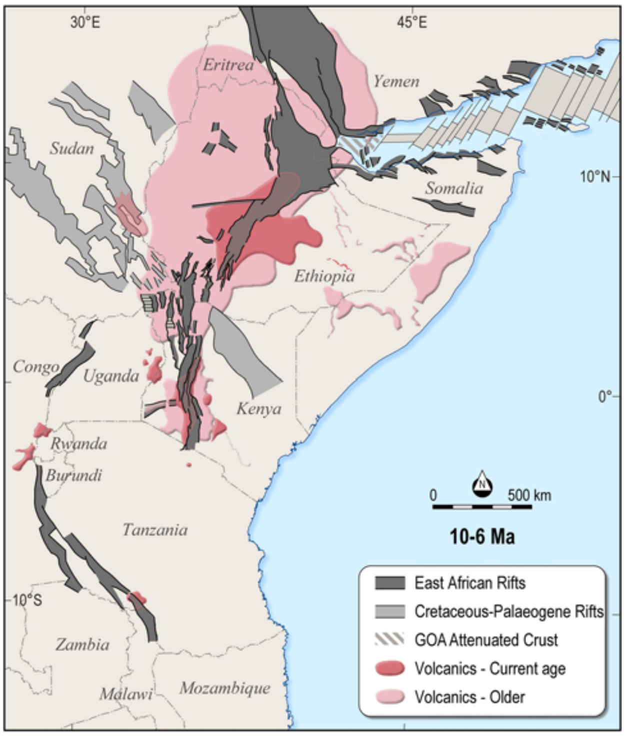

Fig. 9. East African Rift, faulting and volcanic areas, 10 – 6 Ma.

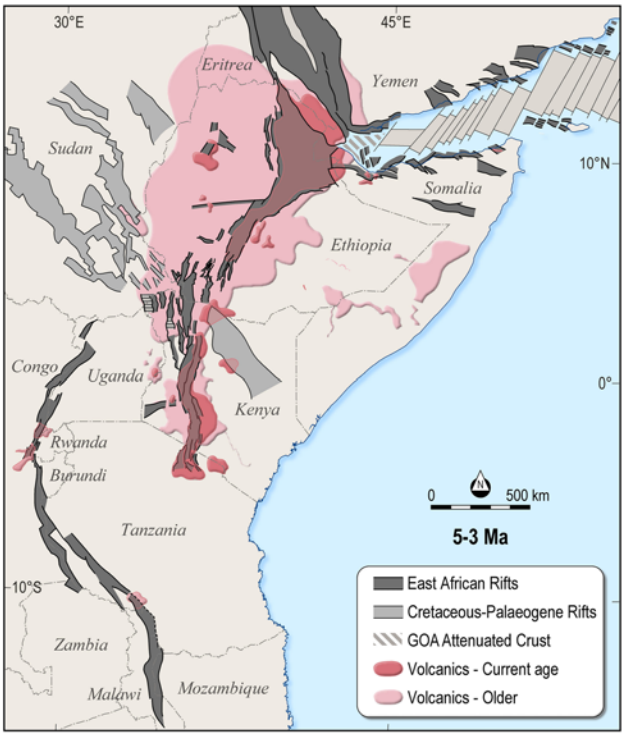

Fig. 10. East African Rift, faulting and volcanic areas, 5 – 3 Ma.

Sea rifting, while the southern Afar escarpment might be imagined as a westwards extension of the GOA rifting. The GOA rift system was deepening rapidly, causing a major transgression that had established deep-marine conditions in the central GOA area by the Middle Oligocene, *c.* 28 Ma (Hughes & Varol 1991), and extending across areas now onshore (Leroy *et al.* 2012). Palaeontological evidence indicates that rifting in the southern Red Sea was occurring contemporaneously, and had established a marine connection to the western GOA by 27 Ma (Hughes & Varol 1991). Rifting also occurred at Lake Tana during this time but is not normally considered part of the EAR.

Rifting in the Turkana area expanded slightly through this period. The South Lokichar Rift deepened: subsidence began to outpace sediment input and thin lacustrine beds were interbedded with coarser clastics, presaging the coming change in depositional environment. Basalts dated at *c.* 28 Ma in the inverted Lothidok Hills indicate that subsidence had commenced in the North Lokichar Rift, albeit as an east-dipping half-graben in this early phase. The Kerio Rift was probably also active by this time (sometimes called the South Kerio Rift, as is the rift further south along the Elgeyo Fault). The final phase of rifting in the South Sudan rifts continued through this period, although opinions differ on whether this was a rift or sag-basin phase.

Far to the south, the pre-Tertiary Rukwa Rift might have been reactivated near the end of this period, marked by the alluvial fan deposits of the Utengule Member of the Nsongwe Formation (Roberts *et al.* 2010, 2012).

Figure 5 shows that the tectonic activity during this period was still largely confined to the greater GOA/Afar area and along the Sudan and Anza rifts. The dominance of the NW–SE to NNW–SSE rift trends points to continuing continental-scale NE–SW-trending extension, presumably linked to slab-pull into the Zagros subduction zone. Extensional and magmatic forces causing the onset of EAR faulting at Turkana still appear to be a relatively local phenomenon.

26 – 23 Ma (Fig. 6)

A major resurgence in magmatic activity occurred during latest Oligocene time, and is widespread across the region (Rooney 2017), excluding Yemen. These outpourings are predominantly basaltic, in contrast to the previous bimodal volcanics on which they commonly rest, above angular unconformities or palaeosols. The Choke and Guguftu shield volcanoes were prominent features on the Ethiopian Plateau, and outpourings, both silicic and basaltic, occurred in Eritrea, northernmost Ethiopia and around Lake Tana. It is possible that this volcanism was relatively widespread down the eastern escarpment of the Ethiopian Plateau.

Volcanics dating from this period are also widespread along the rim of the Somalian Plateau and, while not the earliest outpourings in this area, appear to be the start of major magmatism to the SE/east of Afar/MER. This magmatic activity is predominantly fissural and major shield volcanoes did not develop. It is unclear if the magmatism was restricted to the Afar margins or extended some distance across the intervening area. An outcrop of 23 myr old granites intruding 29 myr old basalt on the Afar floor (Stab *et al.* 2016) offers some support for the broader distribution.

Major dyking occurred along the Red Sea Rift during this period and extended for over 600 km SE of the Afar margin across the Horn of Africa region by way of the Marda Fault Zone (Purcell 1976) and the Ogaden Dyke Swarm (Mege *et al.* 2016). Basaltic flows emanating from the dyke swarm and ranging to about 100 m in thickness covered vast areas of SE Ethiopia and Somalia (Purcell *et al.* 2011; Mege *et al.* 2012), akin to the extensive flows reported in the subsurface in the Melut Rift in Sudan. Several major flows appear to be filling river valleys, many of which were draining SE into central Somalia where a large subsurface basalt layer is known from intersections in water and oil wells (Faillace 1993). This flow is undated but is assumed here to be of the same age as the feeder flows and dykes. The source and significance of this far-field magmatism awaits further investigation.

The extensive volcanic tableland and flows in the Dolo region of south-central Ethiopia and the adjacent areas of Somalia are poorly documented but are now reliably dated in Ethiopia by the author and colleagues at 26.9 – 23.7 Ma. A flow down the ancestral Juba River is tentatively dated as Oligocene (Mohamed *et al.* 1987), and aeromagnetic data suggest a major flow extended from Dolo for over 500 km east along the ancestral Uddur River valley to the Somalia coast (Bosellini 1989; Purcell *et al.* 2011).

Rifting continued to be largely restricted to the Afar margins and in the GOA and southern Red Sea, with marine waters from the GOA funnelled into the Red Sea at least as far north as Eritrea. The South Lokichar Rift deepened during the period, and the lacustrine Loperot Shale was deposited. There does not appear to have been any substantial new rifting at Turkana or elsewhere along the EAR.

The reactivation of the Rukwa Rift continued through this period, with the synrift sediments of the Songwe Member of the Nsongwe Formation dated at 25.9 – 24.6 Ma (U–Pb and ^{40}Ar/^{39}Ar) from interbedded tuffs. These tuffs were derived from an alkaline magmatic source, probably a carbonatite volcano, and indicate volcanism coeval with rifting (Roberts *et al.* 2012). The reasons for this isolated reactivation at Rukwa are not clear, but it is imagined that future detailed work on nearby rifts will show that the Rukwa reactivation is less local than current data suggest. Gravity anomalies suggest that the Rukwa Rift is continuous below the Rungwe volcanics with the Livingstone Rift, the NW–SE-trending northern end of the Malawi Rift (Macgregor 2015), and, correspondingly, reactivation of the Livingstone Rift segment is also shown in Figure 6. Rifting also occurred in the Anza Graben at this time, at least in some rift segments such as at Hothori (Morley *et al.* 1999*a*).

22 – 17 Ma (Fig. 7)

Tectonomagmatic activity increased markedly during this interval. The most dramatic development was the initiation of seafloor spreading in the GOA at *c.* 18 Ma. The spreading axis was an offshoot from the Davie Ridge in the proto-Indian Ocean into the eastern GOA, where it appears to have been pinned at the Fartaq-Alula Transform (Bosworth *et al.* 2005).

Notable also is the beginnings of expansion of the EAR both north and south from the Turkana ‘seed point’. Within the Turkana area itself, the South Lokichar Basin deepened, possibly associated with changes in climate and sediment input, leading to the formation of a deep-water lake in which the Lokone Shale oil source rock was deposited. This Early Miocene lacustrine unit has sourced the many oil discoveries in the South Lokichar Basin.

North of Turkana, rifting commenced in the Galana and Chama/Abaya rifts in southern Ethiopia, with a northern limit possibly controlled by the Proterozoic Bongo-Goba Discontinuity (Bonini *et al.* 2005). This southern segment of the Main Ethiopia Rift (SMER) is offset by over 300 km from the Turkana rifting and a broad accommodation zone developed between them, variously referred to in general terms as a basin-and-range zone and a broadly-rifted zone, but which Davidson (1983) named the Gofa Basin-and-Range (GBR). Rift onset in the Chew Bahir segment may have commenced at this time, although the main rift phase did not occur until later. Other rifts extending west to the Kibish Rift are also shown in Figure 7 as developing through this period. This common dating of rift onset is preferred to the suggestion that the Chew Bahir and other rifts are much younger; that would require the juxtaposition of westwards-younging rifting across the GBR to the north of the Kenya–Ethiopia border, and eastwards-younging to the south.

South of Turkana, the rift extended south to the Baringo area, probably as a pair of east-facing half-graben, with the western side bounded by the Elegyo Fault. At Baringo, for reasons not yet clear, the rift branched to the west into the Tanzania Craton to form the Nyanza Rift. This rifting was coeval with the development of massive strato-volcanoes at Nyanza and Mt Elgon. Rifting continued in the Hothori and other segments of the Anza Graben, before major inversion and erosion in the lower Middle Miocene (Morley *et al.* 1999*a*, *c*)

Basaltic volcanics spread over a large area of southern Ethiopia early in the period, extending west into Sudan and south along the incipient Kenya Rift trend. Far-field magmatism largely ceased in SE Ethiopia but volcanic cones dated at 22, 18 and 16 Ma were emplaced east of Jijiga, near (even within) the Marda Fault Zone, and the residual magmatism apparently included mountain-forming intrusions such as Mt Abulcassim near the ancient Muslim settlement of Sheik Hussein. Possible volcanism has been reported in the Rukwa Rift at this time but the reliability of the dating is unclear (Fontjin *et al.* 2010).

13 – 10 Ma (Fig. 8)

At about 13 Ma, the onset of Macgregor's (2015) EARS 2 rift stage, the tectonic activity in the EAR increased markedly: the Western Branch of the EAR began to form early in the period, as did the northern segment of the Ethiopian Rift (NMER).

Rifting is thought to have commenced in the Albertine (or Lake Albert) Rift at 13 – 12 Ma, but an earlier rift onset at 17 Ma has been suggested (Brendan *et al.* 2017). Rift onset in the Semliki Rift segment, adjoining to the SW, has been dated at 15 Ma (Abeinomugisha & Kasande 2012). North of the Albertine Rift, the Rhino Camp Rift segment connects the Western Branch to the Proterozoic Aswa Shear Zone, the crustal dislocation along which strain was transferred from the Eastern Branch. Based on this tectonic hard-link, Figure 8 shows rift onset in the Rhino Camp Rift during this period, with the main rifting to follow during the upper Late Miocene. The Ivory Camp, Albertine and Semliki rifts are all located in the narrow Madi-Igisi Proterozoic fold belt, where Mesoproterozoic crust was deformed during Neoproterozoic tectonism (Westerhof *et al.* 2014).

Further south along the Western Branch, Na-alkaline lavas dated at 12.6 – 8.9 Ma evidence rift initiation at this time in the Kivu Rift (Kampunzu *et al.* 1998), co-incident with rifting in the Kigoma and Marungu segments of the Tanganyika Rift (Macgregor 2015).

The NMER also formed at this time, extending from the western Afar margin faulting south to the intersection with the Yerer Tullu Welwel (YTW) lineament (Abebe *et al.* 1998). This zone of rift faulting and volcanism, which is poorly defined because of its burial under Plio-Pleistocene flows and the Wonchi volcano, is now being re-imagined as an important element in the EAR history and structure (Keranen & Klemperer 2008; Adhana 2014). Volcanism commenced along the YTW Rift about 12 Ma (Abebe *et al.* 1998), slightly before the outpourings of plateau basalts from the Megezez volcano on the NMER margin.

Extensive volcanism at 12 – 10 Ma covered the CMER area, presaging the imminent collapse of that rift segment, and also covered large areas of the Somalian Plateau. Unpublished ^{40}Ar/^{39}Ar dating by the author and colleagues shows that these volcanic flows extended for over 500 km to the east of the MER, across the Somali Plateau. Major uplift of the plateau margins occurred at about 10 Ma (Gani *et al.* 2009).

In Kenya, the widespread outpouring of the Plateau Phonolites marks the imminent southwards advance of the main Gregory Rift. The impinging of the Eastern Branch on the thick lithosphere of the Tanzania Craton is generally accepted as the cause of the strain transfer to, and initiation of rifting in, the Western Branch. Given that the phonolite flows show no evidence for a sag or rift basin in southern Kenya at this time, it must be imagined that the subsurface crustal rupturing had penetrated further south than was manifest in the surface rifting.

In the Turkana area, major changes in the tectonic and volcanic activity occurred. Dyke swarms near the Lokichar and Kerio rifts sourced interbedded basalts encountered in the subsurface in these basins, and, further west, similar fissure-fed flows occurred along the proto-Suguta Trough (Vetel & Le Gall 2006). Subsidence slowed in the South Lokichar Rift but accelerated in the North Lokichar and Lothidok rifts, which underwent a polarity reversal as major east-facing faults developed (Morley *et al.* 1999*d*). The Lapurr and Murua Rith rifts formed on the west side of northern Lake Turkana and rift-onset faulting might have occurred in the Lake Turkana basins.

In the north, rifting and extension continued in Afar and the Red Sea, and seafloor spreading penetrated west along the GOA, before being 'pinned' at the Shukra el Sheik Transform (Bosworth 2015).

10 – 6 Ma (Fig. 9)

Volcanism along the Western Rift continued at Virunga and Kivu (Kampunzu *et al.* 1998), and also in the Rungwe Complex (Fontjin *et al.* 2010). These punctiform volcanic outpourings stud the offset nodes between rift segments in the Western Branch and contrast markedly with the extensive regional volcanism of the Eastern Branch. These different magmatic signatures between the Eastern and Western branches are reflected in their rift geometry and synrift fill: most rift segments in the Eastern Branch fill with volcanics, and deep sediment-filled basins are not commonly developed. Rifting might have been initiated in the Lake Edward Rift near the end of this period.

Volcanism continues along the central MER region, extending far onto the rift shoulders. Similar to the preceding period, the volcanism now appears more extensive on the eastern side of the MER. Major plateau-forming and valley-filling flows have been mapped and dated there by Mege *et al.* (2016), and additional dating will be published shortly.

The Central Ethiopian Rift (CMER) is thought to have formed about 8 Ma, joining the SMER and NMER segments (Abebe *et al.* 2010), although Bonini *et al.* (2005) argued for a later development at around 5 Ma.

At the end of the period, the Kenya Rift extended southwards, initially as a half-graben cutting through the Plateau Phonolite terrain, and reaching the Tanzania border at *c.* 7 Ma, based on Dawson's (2008) dating of the initial movement on the rift-bounding Ngurman Fault. Scattered areas of basaltic magmatism on the rift floor and shoulders may be part of a larger single province which probably extended into Tanzania, as evidenced by the Oldoinyo Sambu and Essimingore shield volcanoes dated at *c.* 8 Ma (Dawson 2008).

In the GOA, seafloor spreading advanced west of the Shukra el Sheik Transform, and Afar-like rifting was probably occurring in the area of what is now the Gulf of Tadjura.

5 – 3 Ma (Fig. 10)

The main rift phase of Macgregor's (2015) EARS 2 stage occurred during this period, as many rifts that formed initially in the Mid to Late Miocene underwent maximum subsidence. Rifting in most of the lakes of the Western Branch reached the main rift stage during this period.

The Eastern Branch of the EAR encountered the thick lithosphere of the Tanzanian Craton and the so-called Tanzanian Divergence Zone began to develop, splitting into eastern, western and central segments. Sediments at the northern side of Lake Manyara are interbedded with basalt dated as 4.86 Ma (Dawson 2008) and have been interpreted as indicating rift onset in the central branch (Foster *et al.* 1997). Faulting along the eastern margin of the southern Kenya Rift converted this into a graben structure.

To the north, widespread volcanism occurred in the Turkana area, and is recognized both in outcrop and in the subsurface. This volcanism included the Gombe Group that formed the Kino Sogo plateau south of Chew Bahir, and the fissural-type lavas that flowed over an extensive area of the Anza Rift region. The Anza layer, ranging to about 30 m in thickness, resembles the widespread flows of the eastern Ogaden in Ethiopia. Rifting accelerated in the half-graben Lake Turkana basins and the Suguta Trough collapsed, extending this rift trend to the south and downfaulting the Miocene volcanics which had earlier marked this developing line of weakness (Vetel & Le Gall 2006). The increased tectonic activity, probably linked to changing stress conditions, is also expressed by the development of dense and multidirectional fault systems in the Kerio and other rift basins.

Rifting and volcanism increased markedly in the Afar and NMER as seafloor spreading continued in the Gulf of Aden and commenced in the southern Red Sea. The Danakil Block continued its counter-clockwise rotation as Afar underwent further extension. The Afar Stratoid Series of transitional basalts erupted over most of Afar, commencing at about 4 – 5 Ma and coeval with increased oceanization of spreading centres such as Manda Inakir and Erta Ale/Tat Ale. A final phase of uplift of the Ethiopian and Somalian plateaus commenced about 6 Ma (Gani *et al.* 2009).

2 – 0 Ma (Fig. 11)

The East African Rift has expanded further over the past 2 myr and, in so doing, created the spectacular modern landscape of this region.

In northern Tanzania, the east and west rift segments of the Tanzanian Divergence Zone developed rapidly: in the west, the Pangani Rift formed along a Proterozoic shear zone; and in the east, the Eyasi and other rifts exploited the NE–SW grain of the Tanzania

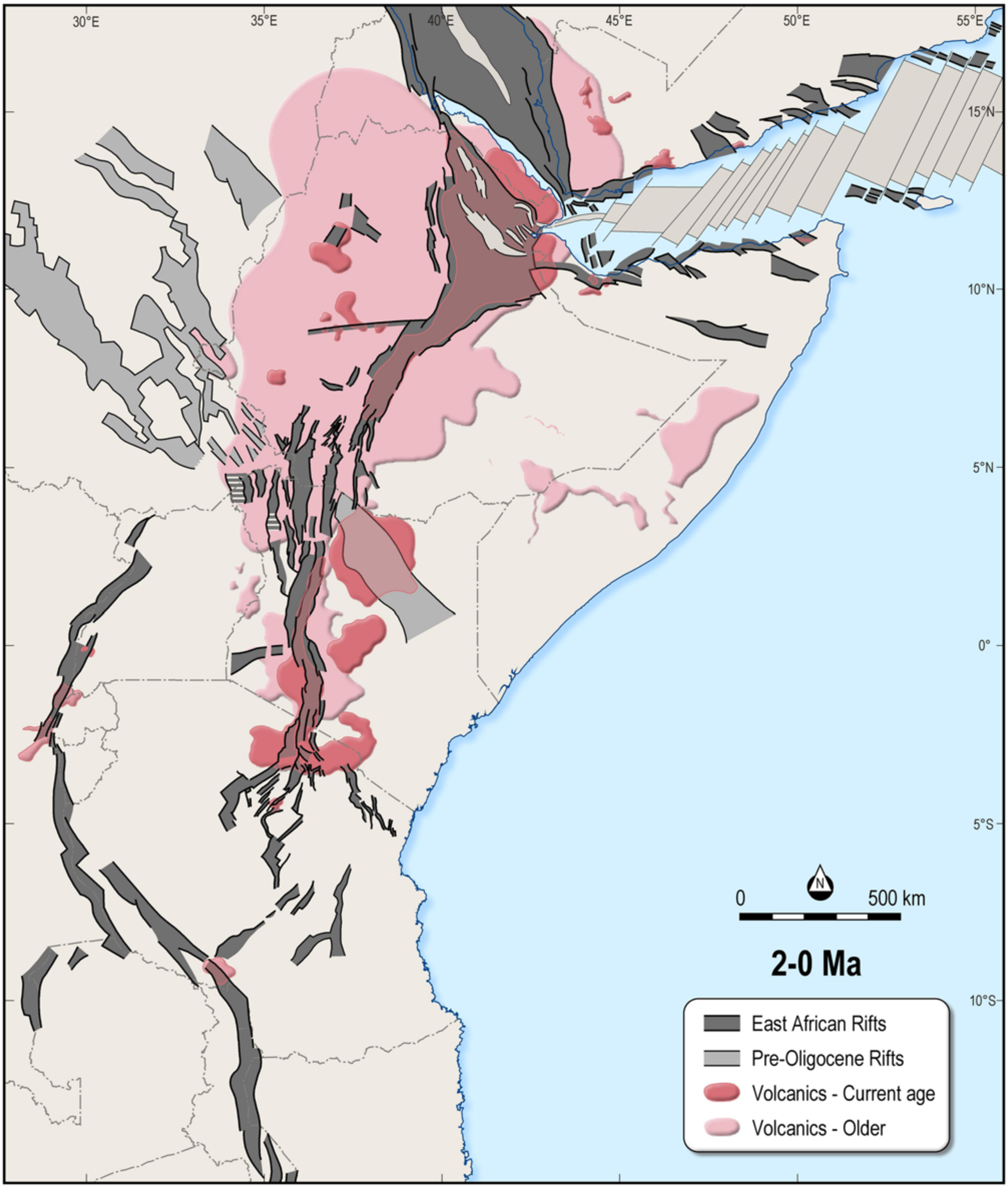

Fig. 11. East African Rift, faulting and volcanic areas, 2 – 0 Ma.

Craton. The central Manyara Rift extended south, associated with extensive volcanic activity, best known for the crater at Ngorongoro and the carbonatite peak of Oldoinyo Lengai (Masai for 'Mountain of God'). East of the rift, the towering Kilimanjaro (Swahili for 'shining mountain') formed from the coalescing of the Shira, Kibo and Mawenzi volcanoes, and remains, in its relative height, the highest mountain on continental Earth.

Over the past 1 myr, a broad rift zone involving both the Eyasi and Manyara 'arms' and with numerous, frequently narrow, NE–SW- and NW–SE-trending graben and half-graben has been progressively breaking south through the Tanzania Craton (Macheyeki *et al.* 2008). This rifting is in the process of linking with the reactivated NW–SE-trending Usanga and Ruhuhu Karoo rifts, and, ultimately, with the Rukwa and Malawi rifts of the Western Branch at the Rungwe triple junction. Rift activity is currently spreading southwards and westwards beyond the map area, as far as the Chissenga Graben offshore Mozambique and the Okawango swamps in Botswana. Major uplift occurred along the shoulders of many rifts, creating the steep-walled rift valleys of the modern landscape. Major uplift of the Rwenzori Mountains beside the Lake Edward Rift also occurred at this time.

In the Turkana/Omo region, the rifting shifted east again, with the narrow Ririba Rift connecting north to the Sagan Rift and furthering the incipient southern extension of the SMER. The faulting in the Kino Sogo volcanic plateau, an embryonic rift, connected the Chew Bahir Rift to the Suguta Rift System, while the Kerio and Turkwel rifts were inverted (Vetel & Le Gall 2006).

In the MER, the Wonji Fault Belt (Mohr 1967; Bonini *et al.* 2005) formed as a rift-in-rift structure, with dextrally offset magmatic segments on the rift floor, along which tectonic and magmatic activity was localized. This activity extended into Afar in the Tendaho Graben, linking the MER and Red Sea spreading system in western Afar. The GOA spreading axis broke through into eastern Afar, where the Asal Ghoubbet and Manda Inakir rifts are considered the incipient edge of the Arabian continent (Manighetti *et al.* 1998).

Phanerozoic rifting in relation to the Proterozoic fabric

The relationship between the Proterozoic crustal framework and the pattern of Phanerozoic rifting in eastern Africa has attracted considerable debate over the decades, much of it influenced by, and changing with, the prevailing dogma of the day. The EAR's continent-spanning scale and linearity, with its soaring escarpments and deep lake-filled graben, prompted early twentieth century geologists to imagine that it must have been formed by reactivation of a fundamental zone of crustal weakness in the Earth (McConnell 1951; Boutakoff 1952). By the 1950s, as the alignment of many rift segments with the encasing Proterozoic basement grain became more widely recognized, that image in the geological imagination changed from a re-torn crustal seam to a rectilinear tear in the Proterozoic fabric (e.g. Furon 1963). This concept of fixed vertical crustal zones, reactivated from epoch to epoch, would soon pose a threat to the emerging plate tectonic paradigm and, by the 1970s, that orderly tear had been re-imagined as a ragged rip across the fabric. There was no denying that the Rift 'followed Precambrian structures in a few places', as Baker *et al.* (1972, p. 44) put it, but this was only because the older structures were 'favourably located or oriented': 'the rift system as a whole was formed by the imposition of new structural lines across the heterogeneous pre-existing fabric' (Baker *et al.* 1972, p. 44). Alignment was happenstance.

Today, 'plate tectonics' is the unchallenged dogma, and the dominantly north–south-, NE- and NW-trending Proterozoic structures are, again, seen as controlling the location of the Phanerozoic rifts. This applies on a regional scale (e.g. Hetzel & Strecker 1994; Morley 1999: regarding the EAR in Kenya) and in local detail (e.g. Katumwehe *et al.* 2015: regarding rift polarity reversal in the Albertine Rift). The late twentieth century concepts of irreversibility, chaos and chance (Prigogine & Stengers 1984; Gleick 1988), challenging the 'machine' paradigm that has long driven Western science, are yet to have a significant impact on the geological imagining of the Earth processes driving the rifting in East Africa.

Some of the emphasis on the alignment of Proterozoic fabric and Phanerozoic rifting in eastern Africa might well be a 'revenge of geography' (Kaplan 2012): the relationship between them has been mostly studied south of about 5° S, where Karoo, Mesozoic and Tertiary rifts are often superimposed. A detailed analysis of this superposition is beyond the scope of this review, but several aspects bear noting. First, the superposition is constructed in some areas: inversion and erosion associated with the Tertiary rifting has altered the original Karoo basin framework and some current rifts are downfaulted relicts of formerly larger basins (Castaing 1991). Secondly, the Tertiary rifting both exploits and cuts across Karoo rift trends (Delvaux 2001*a*, *b*), recalling Baker *et al.*'s (1972) caution about overstating the coincidences. North of 5° S, the Karoo and Mesozoic basins are not as well known, but considerable differences in the respective locations of the Tertiary and pre-Tertiary rifts are, nonetheless, quite clear.

Figure 12a and b shows, respectively, the Karoo–Mesozoic rifts and the EAR superimposed on a simplified map of the Proterozoic terranes of eastern Africa. The Proterozoic map draws heavily on Fritz *et al.* (2013), notably for the reclassification of the Neoproterozoic Mozambique Belt (MB) and the Arabian Nubian Shield (ANS), and Westerhof *et al.* (2014), notably for the recognition of Neoproterozoic reactivation along the Madi-Igisi suture zone underlying the Albert Rift. Other key references for the Proterozoic geology and history were McConnell (1972), Daly *et al.* (1989), Whitehouse *et al.* (2001), Collins & Windley (2002), Kroner & Stern (2005), Begg *et al.* (2009) , Alemu & Hailu (2013) and Saalman *et al.* (2016).

The crustal fabric of (what is now) eastern Africa began to form during a series of Wilsonian cycles between *c.* 2.5 and 1.0 Ga, when Palaeoproterozoic and Mesoproterozoic fold belts were wrapped around the central cratons. About 850 Ma, a major continental rift system, opening northwards into an oceanic basin, had formed in the region. Subsequent multiphase collision at *c.* 800 – 600 Ma between the proto-African Plate and the Azania microplate closed the oceanic basin in the north to form the Arabian–Nubian Shield and remobilized the rifted Proterozoic fold belts in the south to form the Mozambique Belt (Fritz *et al.* 2013; Westerhof *et al.* 2014).

Figure 12a is primarily displaying the Permo-Triassic rift systems, commonly grouped as 'Karoo', but also showing Mesozoic rifts in South Sudan and Yemen. The locations of the Karoo rift faults south of Kenya have been simplified from the respective national geology maps for Congo (Zaire Service Geologique 1974), Malawi (Bloomfield 1966), Mozambique (Instituto National de Geologica 1987), Tanzania (Geological Survey of Tanzania 1959) and Zambia (Thieme & Johnson 1981), and combined with data from Chorowitz (1989), Delvaux (1991, 2001*a*, *b*) and Macgregor (2017). The well-known alignments of the Karoo rifting with the Proterozoic fabric south of about 5° S (present day) is clear: for example, the influence of the Ubendian and Irumide fold belts on the location of the Tanganyika and Rukwa rifts; and the Mwembeshi Shear Zone (MSZ), part of the Trans South Africa Shear Zone (TSASZ), facilitating the opening of the Luangwa Rift and, to the NE, controlling the location of the Selous Rift (Delvaux 2001*a*).

The Karoo rift structure in Kenya, Ethiopia and Somalia is less well known, especially in its details. The Karoo rift extending north through Kenya into Somalia is wholly located within the Palaeoproterozoic crust of the Azania continental block. The rift

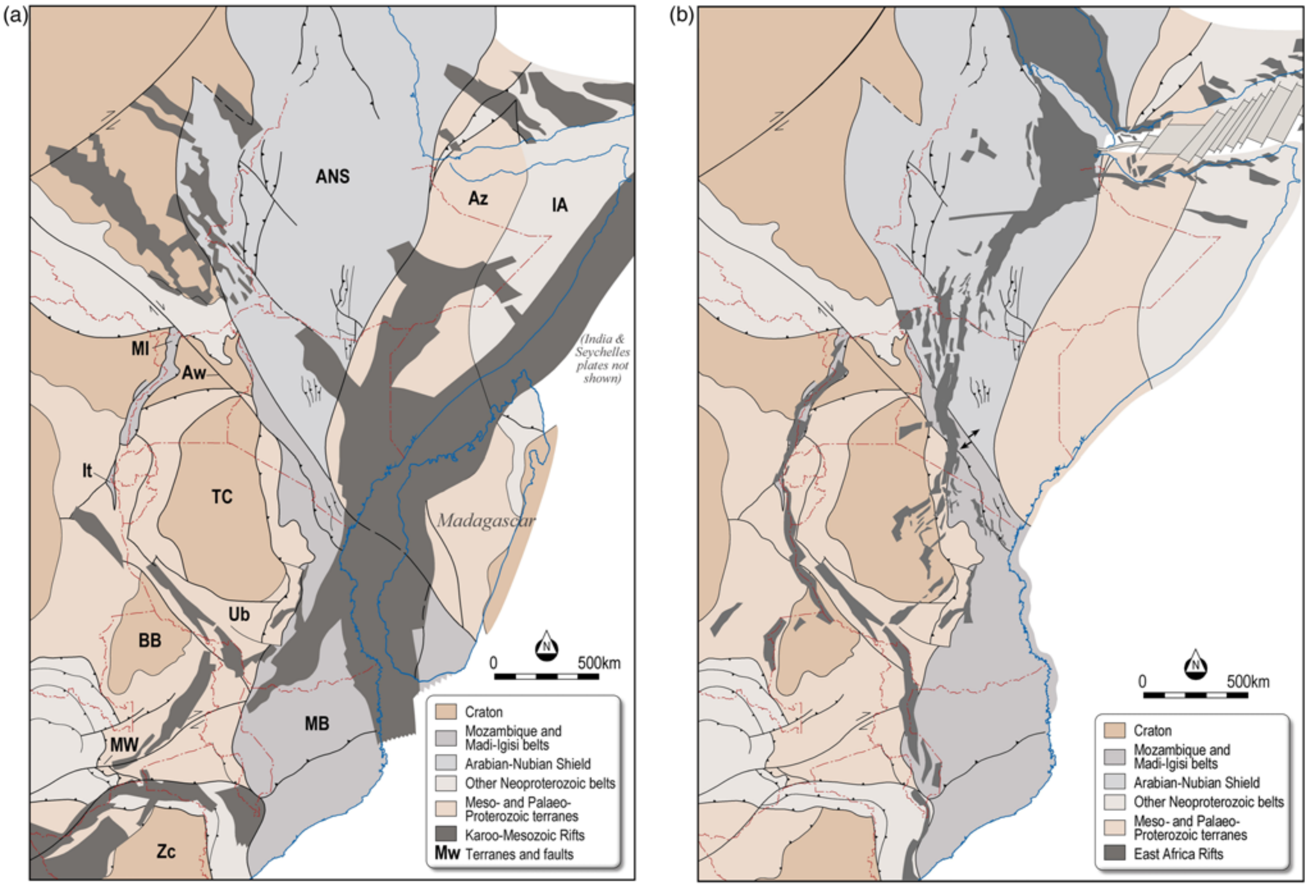

Fig. 12. (**a**) Karoo/Mesozoic rifts superimposed on the Proterozoic terrane map of East Africa, showing features and locations mentioned in the text. Crustal structure in the Indian Ocean is not shown. ANS, Arabian–Nubian Shield; Aw, Aswa Shear Zone; Az, Azania microcontinent; CA, Central African Shear Zone; IA, Inda Ad Belt; Ir, Irumide Fold Belt; It, Itombwe Belt; Ka, Kibaran Belt; MB, Mozambique Belt; MI, Madi Igisi Belt; MW, Mwembeshi Shear Zone; TC, Tanzania Craton; Ub, Ubendian Fold Belt. (**b**) The East African Rift superimposed on the Proterozoic terrane map of East Africa.

bifurcates at the intersection with the Anza Rift trend, thought to be located along a major Proterozoic suture/shear, with over 2000 m of Permian sediments along trend in Ethiopia (Davidson & McGregor 1976; Davidson 1983). The interior rift, comprising the Mandera Lugh and West Ogaden segments which contain over 4000 m of Karoo synrift sediments (Beltrandi & Pyre 1973; Hunegnaw *et al.* 1998), remains largely within the Azania microcontinent. A NW-trending branch of the Western Ogaden Rift fails to penetrate very far into the ANS, while a NE-trending branch extends into the Inda Ad terrane (Utke *et al.* 1990), and might then extend SW along the Marda Fault Zone (Purcell 1981; Bosellini 1989). The main rift, which ultimately defined the NE edge of the African continental plate, is thought to be controlled by a reactivation of the NE extension of the MSZ/TSASZ (Visser & Praekelt 1996); it cuts abruptly out of the Azania Block and into the Neoproterozoic Inda Ad terrane.

In South Sudan, the Mesozoic–Palaeogene rift complex is located partly within the Saharan Megacraton (Abdelsalam *et al.* 2011), where it is constrained to the NW by the Central African Shear Zone, and partly within the ANS, where alignment with NW to NNW shear zones is manifest. In Yemen, the Mesozoic rifts cut across the sutures defining the contact of the Azania Block and the ANS, and are generally considered to be a reactivation of elements within the Neoproterozoic Najd Shear Zone (Stern 1985).

Figure 12b shows the EAR's very different location within the Proterozoic fabric. For the greater part of its 3000 km north–south span from the Red Sea to 5° S, the EAR is predominantly within new Neoproterozoic crust, such as the ANS, or older crust reworked during the Neoproterozoic Pan-African Orogeny, such as the Mozambique and Madi-Igisi fold belts. In marked contrast, the Karoo and Mesozoic rifts, except for South Sudan, have pointedly 'avoided' these same Neoproterozoic terranes. In Ethiopia and northern Kenya, where the EAR is almost entirely within the Neoproterozoic ANS, the sub-parallel Mandera Lugh and south Western Ogaden Karoo rifts are located totally outside it. These differences might be seen to invite questions about the rifting processes. Why did the Tertiary rifting exploit the north–south fabric of the MB/ANS, whereas the Karoo rifting did not, given that the rifts are sub-parallel and thought to be caused by similarly orientated stress fields? Why did the ANS seemingly facilitate the Tertiary rifting when it had previously 'resisted' any significant penetration by the Permian or Mesozoic rift forces?

Implicit in these questions is the traditional or Newtonian paradigm that emphasizes order and predictability in a mechanistic natural world. Earth forces, such as occur associated with a mantle plume, are viewed as closed predictable systems, and answers are sought in terms of differences in rheological stratification, underplating, temperature profiles, intra-plate stress and other such parameters. The alternative is to view Earth processes within what has been called the Prigoginian paradigm (Toffler 1984), emphasizing disorder, disequilibrium and unpredictability. In this unstable and evolving world, Earth processes are dynamic non-linear systems, with multiple complex interactive variables and instability bred of pervasive impacting heterogeneities (Prigogine 1997).

As Keranen *et al.* (2009) have argued, mechanistic models predicting a crustal response based solely on factors such as temperature, rheological stratification and lithospheric thickness, amongst others, will not usually be satisfactory long-term predictors of rift behaviour, either in time or space. They will successfully model short-term stable developments but they deny the role of chance inherent in the nature of evolution (Gould 1994). Mantle–plume processes, involving massive and turbulent exchanges of energy and matter, are better imagined as open and unstable systems that will fluctuate rapidly between relative order and disorder. In the Prigoginian paradigm (Prigogine & Stengers 1984; Prigogine 1997), the rift development would have an inherent unpredictability, being controlled less by orderly Earth processes than by the disorder that develops when those forces encounter crustal discontinuities and local heterogeneities. Long periods of relative stability within the rifting process might occur, but cross-cutting lithospheric discontinuities would provoke unpredictable outcomes as far-from-equilibrium conditions develop, and chaos and chance come into play.

Viewed on either a regional or a local scale, the EAR shows the unpredictable consequence of interaction between rifting forces and lithospheric discontinuities. In southern Kenya, for instance, when the EAR encountered the Aswa Shear Zone (Katumwehe *et al.* 2016), it deflected eastwards and continued southwards along a Proterozoic thrust zone and, coincidentally, initiated a new rift (Lake Albert) within the Madi-Igizi Fold Belt. Conversely, when the Ethiopian Rift encountered the Yerer Tullu Welwel suture, the rift reactivated the lineament and extended WSW along it, while stalling for about 5 myr before continuing southwards. Both developments are readily explainable in terms of these discontinuities, but neither was predictable. In Afar, Manighetti *et al.* (2001) described the 'dense network of cross-cutting active faults' that creates the disorderly deformation that precludes the application of rigid plate tectonics.

Discontinuities aligned with the direction of rift propagation can serve as zones of crustal weakness along which, more predictably, the rift can be channelled. The MER, for instance, long seen to be located within the dominantly sub-meridional fabric of the Arabian Nubian Shield (or the Mozambique Belt under earlier terrane classifications: Asrat *et al.* 2001), is now seen more precisely to be located along a major suture zone within the ANS, evidenced by the different crustal thickness detected on the eastern and western rift shoulders (Keranen *et al.* 2009). Berhe (1986) suggested that the Red Sea rifting occurred along a Proterozoic lineament. Such lineaments might be instrumental in facilitating periods of relative order within the rifting process. It is the cross-cutting lithospheric discontinuities, be they suture zones or craton margins, that become the catalyst for dynamic change within the system (Prigogine 1997). The slowing or blocking of the advancing rifting forces creates disorder at the interface and the far-from-equilibrium conditions that ensue will have unpredictable outcomes. When the EAR impinged on the Tanzania Craton, it abruptly split into eastern, western and central branches, with the Western Branch striking into the craton, while the Eastern Branch opened along an on-trend Proterozoic suture. Attributing this divergence solely to the greater lithospheric resistance of the craton invites the question as to why the Rift didn't just take the path of least lithospheric resistance along the eastern (Pangani) trend. But the question is only relevant within the mechanistic paradigm, where the rift process is seen as predictable!

Re-imagining the development of the EAR within the Prigoginian paradigm, seeking an overview of the order and chaos created by the lithospheric fabric awaits another time. Suffice here to follow Gould (1994), and suggest that the location of the EAR is 'the fortuitous and contingent outcome of thousands of linked events, anyone of which could have occurred differently', and sent the Rift on an alternate pathway. If the Earth forces that formed the EAR were imagined anew, the role of chance in its evolving would have the Rift cleave a different path through the African continental plate.

Observations and speculations

A number of questions and speculations arising from this compilation project or previous work in the region have been alluded to above; others are discussed below. These range in scale from the continental (why didn't the Karoo and Mesozoic rifting exploit the Neoproterozoic crust of the Arabian–Nubian Shield?) to the regional (why did the EAR begin in the 'gap' between the Muglad and Anza rifts?) and the local (did the Yemen rifts extend into Somalia?). The GOA reconstruction was a major challenge for the compilation but also an important stimulus, since it raised many issues, not simply regarding the mechanics of map construction but also regarding the mechanistic view of Earth inherent in the prevailing imagining of seafloor spreading.

The EAR's evolving complexity

The compilation of a regional image of the many segments of the EAR, both Eastern and Western branches, highlighted the evolving complexity of our imagining of the Rift's form. This evolution over recent decades owes much to both the detailed geological and geophysical local mapping, and the increasingly sophisticated satellite-based imagery of the Rift's mega-form. During the author's early work in Ethiopia in the mid-1970s, the image of the EAR was relatively simple, with a Gregory Rift offset from the Main Ethiopian Rift along an ENE-trending 'transform', and other local transform faults offsetting rift margins. Many new features of the rift complex were being seen for the first time on the then-revolutionary Landsat ERTS-1 imagery (e.g. Mohr 1974*a*; Pilger & Rosler 1975), and mapping in areas such as the Afar and Omo regions had begun to reveal the complexity. The EAR was thought to be 'unzipping' from north to south, as the African continental plate drifted northwards above the mantle-derived hotspot, and the Western and Eastern branches were considered synchronous. The detailed satellite imagery and detailed surface maps available today are far beyond the simplicity of those early images. The EAR is now seen to open both northwards and southwards, from beginnings in Afar and Turkana, and with early movement far to the south in the reactivated Rukwa Rift. Similarly, the Eastern Branch, once thought to fade out as it intersected the Tanzanian Craton, is now seen as a rectilinear filigree in the Craton fabric.

At the same time, the vast dimensions of the Rift and the local detail now available make the display of anything except the main rift elements very difficult in publications. This applies at all map scales, but the larger the overview, the fewer the details it is possible to display. Inevitably, regional maps can only present the EAR in a very simplified form and small location maps inset into larger figures commonly bear little relationship to geological reality. The corollary is that the more local the map area, the closer the detail to that reality. This dilemma is clearly manifest in the maps presented in this paper. It is simply not possible, for instance, to show in any detail the junction of the Red Sea, Danakil Block and GOA at the publication scale available, and the results are unavoidably schematic.

This tension between the local observed details and the simplified regional map has long been at play in geological enquiry. Ksiazkiewicz (2012) characterized them as the historical and the ideal: the local geological details testify to changes in the crust, but only when they are idealized ('simplified') and integrated do they provide a comprehensive vision of that Earth structure. 'Correct in all the generalities, wrong in all the details' is not just a throw-away line, it applies to most regional maps, including those presented here. This suggests there is value in our reminding ourselves from time to time that the EAR is far more complex than our images show and our imagination needs to hold that complexity to the fore.

Is it possible, for instance, that older and simpler images of the rift might colour the modern imagining? It is now clear that the rifting in the greater Omo/Turkana region of Ethiopia and Kenya is a complex system, which has expanded to the east, south and north, and now extends across nearly 400 km. This is comparable in scale with the

Afar complex. The EAR began in this area, with the initial faulting of the South Lokichar Rift. Yet, the Gofa Basin-and-Range complex is always imagined as the accommodation or transfer zone between the main rift systems of Kenya and Ethiopia. Inherent in this concept is the primacy of the main Kenya and Ethiopia rift segments, relative to the Gofa accommodation zone. An alternate view might see the broad rift zone of the Turkana/Omo/Chama complex as the more likely location for increased faulting and magmatism as the next stage of separation of the Somalia Plate evolves. Are the Gofa and Afar complexes connected by the central and northern MER, where renewed separation is now occurring along the Plio-Pleistocene Wonji Fault Belt?

Trendology and the Muglad–Anza connection

The end-to-end trend of the Muglad and Anza rifts prompted early speculation about a connecting rift segment that had been partly uplifted and eroded, and partly downfaulted into the Tertiary rifts. Subsequently, the absence of any supporting Mesozoic outcrop or corroborating subsurface data led to the concept of an east–west-trending transfer zone connecting the Sudan and Kenya rift segments (Bosworth 1992). More recently, a series of sub-meridional rifts extending south from the Melut Basin in eastern South Sudan to link with the Lokitipi rifts in Kenya has become the preferred concept (Ebinger & Ibrahim 1994; Ebinger *et al.* 2000).

This 'gap' between the Muglad and Anza rifts has become of special interest because the EAR *sensu stricto* started there, with the South Turkana and, perhaps, Lokitipi rifts. Unfortunately, political uncertainty about the contested Ilemi Triangle area on the Sudan–Kenya–Uganda border served to limit research and oil exploration activity there. However, a proprietary aeromagnetic and gravity survey in 2009 has provided important new insights into the area, revealing a complex of mainly NW–SE-trending rifts extending SE from the Muglad/Melut rifts in Sudan and seemingly continuous with the Lokitipi rifts in Kenya (Hutchinson 2009). The age of these rifts is unknown but is presumed to be Palaeogene, with a possible Late Cretaceous rift onset. The rifts are narrow, more akin in scale to the Kenya rifts, but more data will be needed to clarify whether they are better viewed as part of the Sudan rifting, part of the EAR or as some bridging complex between them.

This leaves unanswered the relationship between the Muglad and Anza rifts. Both may be located along the same Proterozoic zone but they have quite different tectonic and sedimentary histories, indicating reactivation at different times. Hutchinson (2009) suggested that the Anza trend extends further NW than is generally accepted, reprising the older view that the Cretaceous rift has been masked by the Tertiary uplift and rifting. Future publications of oil exploration results in the area, especially the Ilemi Triangle area, would be a valuable contribution to the study of this region.

It remains unclear why the EAR began to form at this time and, curiously, in the enigmatic 'gap' between the Anza and Muglad rifts. The Lokitipi and Gatome rifts might be seen as part of a transfer zone between the Muglad and Anza rifts, but the South Lokichar Rift is clearly an initiating element of the EAR. Why here? Between, and contemporaneous with, the older NW-trending rifts? And with a totally different orientation? Certainly, a change in the stress field was at play, but why would an ESE–WNW-directed stress field initiate this sub-meridional rifting instead of transtensional shear and rifting along the Muglad/Anza trend. It appears inconsistent with a mechanistic view of Earth processes but accords well with the Prigoginian concept of the role of chance in a rifting process driven by the chaotic interaction of mantle plume dynamics and lithospheric heterogeneity.

Otherwise, the uncertain correlations along the Anza/Muglad trend reprise the warning that trendology can sometimes be very misleading, no less in East Africa than elsewhere. A NW–SE-trending trough in the western Ogaden Basin appears on maps to line up with sediments in the Abbai Basin in central Ethiopia and the Blue Nile Basin in Sudan (WO, AB and BN in Fig. 1). This has led to the concept of a (greater) Blue Nile Rift, despite the very different ages of the Ogaden (Karoo) and Blue Nile (Cretaceous–Palaeogene) sequences, and the fact that the so-called Abbai Basin is not a geological basin *per se* but an erosional basin cut by the Abbai (Blue Nile) River in the thick Trap Series volcanics, 'locally' exposing the Mesozoic sediments that are widespread over central and northern Ethiopia.

The Afar triple junction as construct

A tri-radial triple junction is commonly seen by petroleum exploration geoscientists as a fundamental framework element in continental rift systems, with the Afar triple junction as the accepted model. Inherent in this model is an assumption of contemporaneous formation of the three rift arms. This is clearly not the case in the Afar. Rifting began in the Gulf of Aden at *c.* 30 Ma, in the southern Red Sea at *c.* 27 Ma, in the Southern Ethiopian Rift at *c.* 18 Ma and in the Northern Ethiopia Rift at *c.* 10 Ma. The Afar Triple Junction has an elegant tri-radial geometry today, at least when viewed in schematic form, but this symmetry is a relatively recent construct. Despite this, references to the three rift arms having emanated from Afar remain common (e.g. Gummert *et al.* 2016).

If an Afar-like symmetrical triple junction was not present during the early stages of Afar rifting, then caution is warranted in viewing the tri-radial triple junction as a fundamental framework element in early rift development. Explorationists searching for the initiating segments of a rift system, reasoning that lacustrine oil source shales might have developed there, ought not to focus attention exclusively on the rift segments proximal to the triple-junctions in that rift system. The lesson of the EAR and Afar is that the rift probably began in some far-flung and quite unpredictable segment, analogous to the EAR's Turkana area, where the South Lokichar Basin remains the most petroliferous rift segment yet drilled in the Eastern Branch.

Extension of Yemen rifts across the GOA

The continuation of the Jurassic–Cretaceous rifts in Yemen to the SW into Somalia is a fundamental aspect of most reconstructions of the GOA. It bears noting, therefore, that there does not appear to be any clear evidence for this concept, despite its wide acceptance and commercial exploitation. The key elements of the highly productive petroleum system in Yemen are of Upper Jurassic–Lower Cretaceous age (Ellis *et al.* 1996) but neither the Darror nor the Nogal rifts have synrift sequences of that age (Granath 2001). The Nogal and, perhaps, the Darror do contain Upper Cretaceous and Oligocene synrift sequences, but that does not support the analogy to the petroliferous Yemen rift basins. Pre-Aptian sediments in NE Somalia were formerly part of the greater Ogaden sag-basin prior to the uplift of the Nogal Arch in the Aptian.

One possibility is that a major Proterozoic shear zone is coincident with the GOA. Enigmatic ENE-trending lineaments are common in Ethiopia (Mohr 1974*b*), and are reflective of deep Proterozoic structures. These ENE structures include the Yerer Tullu Welwel Precambrian shear zone, a major lithospheric discontinuity marking a change in crustal thickness below the Ethiopian Plateau (Keranen *et al.* 2009), and manifesting a curious near-alignment with the southern Afar escarpment (Williams 2016). A companion feature to the Yerer-Tullu Welwel Fault Zone extending ENE through the GOA region, might have acted as controlling edge for the Yemen rifts, in like-fashion to the control exerted by the Central African Shear Zone on the formation of the Muglad and Melut rifts in Sudan. Redfern & Jones (1995) suggested that GOA was a major transform fault zone during the Early Triassic, separating the Lut Block from the northern edge of (what is now) the Indian continent.

The Yemen ‘connection’ has significant implications for peace and security in Somalia. The conflict between Somaliland and Puntland over control of the Nogal Valley area has its origins in widely believed local myths about major oil discoveries by Conoco in the late 1980s (Purcell 2014). Local clans have recently rejected the authority of both those governments and seek control of the ‘oil fields’ as the property of their self-declared Khatumo State. This conflict and the underpinning mythology are regularly revitalized by company announcements of Yemen analogues for northern Somalia basins, with potential reserves in the billions of barrels.

GOA reconstruction

The ‘penetration’ of the SW ‘heel’ of Arabia deep into the Afar is inherent in any tight-fit reconstruction of the GOA/Red Sea, and the resultant overlap with the Precambrian basement blocks of the Danakil Alps and Aisha Horst has long bedevilled tectonicists (e.g. Le Pichon & Francheteau 1978). The solution was to imagine the Danakil and Aisha blocks as either independent mini-plates, as part of the Arabian Plate, or hinged in the north (Gulf of Zula) and south (Bab el Mandeb) to the Nubian and Arabian plates, respectively (Eagles *et al.* 2002). Counter-clockwise rotation of the Danakil and Aisha blocks from a pre-rift location against the western Afar escarpment was common to most of these models, albeit with the Aisha rotation sometimes described as clockwise – the difference being one of the observer’s perspective not the imagined motion. The rotation of these continental ‘chips’ was considered to be the result of lithospheric stretching across Afar, driven by fault-block rotation and dyke injection. In recent decades, it has become more popular to rotate only the Danakil Block and to view the Aisha Block as being *in situ* (Manighetti *et al.* 2001), or having itself rotated on its own axis (Kidane 2016). The contrary view, illustrated by Garfunkel & Beyth (2006), is that an *in situ* Aisha Block is inconsistent with a tight-fit reconstruction. The term ‘Aisha Block’ is used in this discussion for the Precambrian block between the Gulf of Tadjura and the southern Afar margin, and includes the Ali Sabieh Block of Le Gall *et al.* (2010) and Kidane (2016).

At the same time, there are several fundamental issues with any attempt to imagine a westwards displacement of the Aisha Block, as envisaged by Garfunkel & Beyth (2006). First, such a displacement would seem to be located along the southern Afar escarpment zone, and there is no evidence for over 200 km of Miocene–Recent strike-slip movement along that zone. Nor is there evidence in the southern Afar tectonic fabric for any such event, whereas the counter-clockwise rotation of the Danakil Block appears more readily accommodatable within the central and northern Afar tectonic evolution. Thirdly, the Aisha Block is an integral part of an extensive Precambrian block extending for over 400 km east into Somalia, and there is no surface evidence that the Somalia and Aisha blocks have recently been juxtaposed.

The oceanic crustal structure in the GOA is based on the interpretations of magnetic anomalies measured in the Gulf during research surveys. It would appear, however, that the interpretation of the magnetic lineations in the western GOA is not unequivocal. Magnetic lineations in the western GOA have been interpreted as showing that oceanic crust first formed there around 30 Ma as part of a two-stage spreading process (Styles & Hall 1980), at 10 Ma as a single spreading process (Cochran 1981), and more recent explanations give dates of 16 Ma (Fournier *et al.* 2010) and 17.5 Ma (Leroy *et al.* 2012). Cochran (1981) noted that magnetic anomalies based on modelling continuous spreading for the past 15 myr were very similar to anomalies from a model starting at 25 Ma but with a gap from 15 to 5 Ma. Conversely, much of this area was considered to be a magnetic quiet zone by Courtillot (1980), associated with diffuse stretching of continental crust. Similar magnetic anomalies in the Red Sea have also been the subject of very different interpretations, having been cited as evidence for coast-to-coast oceanic crust (Girdler & Styles 1974) and, more recently, for predominantly continental crust (Cochran & Karner 2007).

Reconciliation of the age and extent of oceanic crust in the GOA crust, as derived from the magnetic data, with the constraints imposed by onshore Precambrian outcrops and offshore continental rifts is beyond the scope and capacity of this study. This will need further investigation by others with appropriate databases and resources.

The enigma of the Afar magnetic lineations

The ordered linearity of the GOA spreading centre is based largely on the magnetic lineation pattern, as discussed above. Similar linear magnetic anomalies are present in Afar and would intuitively be thought to reflect a similar injection of magmatic material into the upper crust. In reality, there is little consistent correlation between the magnetic anomalies and the various Afar rifts, including the Erta Ale magmatic rift in northern Afar, commonly considered to be ‘nearly’ oceanic crust.

Figure 13 shows the axes of total magnetic intensity anomalies over the Afar area, superimposed on the main rift elements. The magnetic anomalies are based on two surveys: a regional survey in 1969 (United Nations 1973) and a high-resolution oil exploration

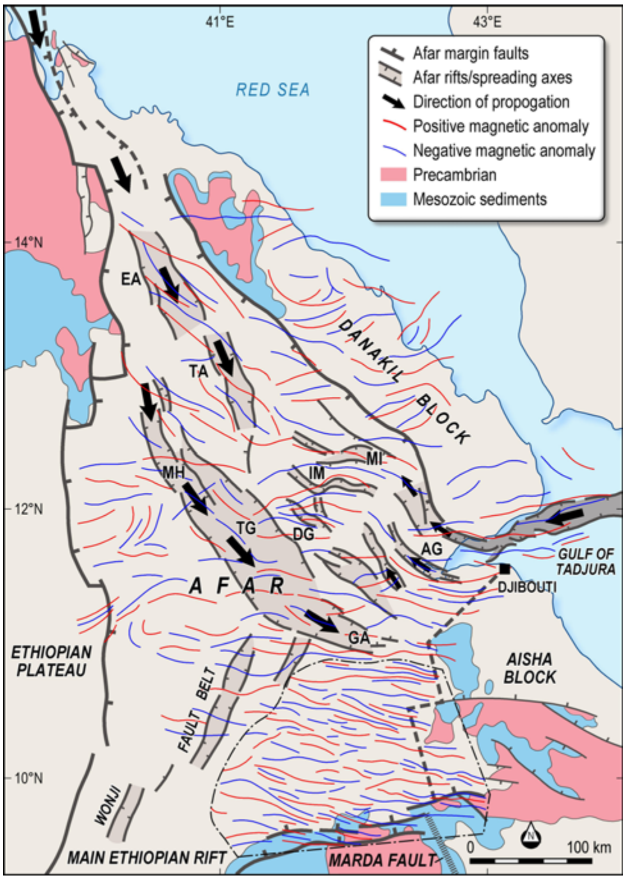

Fig. 13. Magnetic lineations and main structural features of Afar. AG, Asal Ghoubbet Rift; AL, Alayta Rift; DG, Dobi Graben; EA, Erta Ale; GA, Goba‘ad Rift; IM, Immino Rift; MH, Manda Hararo Rift; MI, Manda Inakir Rift; TA, Tat Ale; TG, Tendaho Graben. The New Age data are located within the dashed area in SE Afar.

survey in 2008. The 1969 regional survey data were discussed in several papers by Ron Girdler and colleagues, (e.g. Girdler 1970) but the maps and detailed interpretation referred to therein were never published. The reasons for this are not known, nor is it clear why there has been so little attention paid to these data since. The New Age African Global Energy data were released to the author by the company in 2015 as part of a magnetic data compilation to help map volcanic areas in SE Ethiopia. Both datasets are available to this project only as contoured maps.

The linear magnetic anomalies, ranging up to about 100 km long and with maximum amplitudes of about 700 nT, show a predominantly west to WNW trend in southern and central Afar, and a NW trend in the north. The regional data have 10 km line-spacing and some aliasing is clear in the contours, but the overall trends are clear, as is the contrast with the main Afar structural trends. There is local – and arguably coincidental – correlation of magnetic anomalies and fault trends in parts of the Goba'ad, Manda Inakir and Immino rifts, but overall there is little orderly correlation. Barberi & Varet (1977) interpreted the lineations at Erta Ale and Tat Ale as indicative of seafloor spreading, but this overlooks the distinctly different trends of the magnetic lineations (305° – 310°) and the magmatic rifts (340°). It is also significant that the magnetic anomaly pattern over the Afar rifts is indistinguishable from the anomalies over the Danakil and Aisha blocks, and even the Somalia Plateau margin. Wohlenberg & Bhatt (1972, p. 143) reported a similar conflict between the trends of rift faulting (north–south and NNW–SSE) and magnetic anomalies (NW–SE) over areas of the Kenya Rift, with no magnetic evidence of 'extended intrusive bodies in the upper part of the earth's crust beneath the rift floor'.

Mohr (1976, p. 18) concluded that:

> the near perpendicularity of (magnetic) lineations and faults in southern Afar signifies either that the lineations were developed in an earlier tectonic episode than the faults, or that if penecontemporaneous then each reflects a different structural level in the lithosphere, tectonism deriving from deeper than the magnetic lineations.

Could the deep crustal structure be on a different orientation to the shallow structure? Robertson *et al.* (2016) proposed precisely that in the Kenya Rift, based on observations of rift faulting misalignment with magma chambers below intra-rift elliptical calderas.

Bridges *et al.* (2012) reported that ground-surveyed magnetic anomalies across the northern Tendaho Graben show good alignment with the rift. The linear anomalies are similar in dimensions and amplitude to the magnetic 'stripes' associated with oceanic spreading centres and, given the crustal thickness at Tendaho of nearly 30 km, carry the obvious implication that the magnetic stripes observed along magmatic rifted margins 'are not necessarily indicative of the timing and location of the onset of seafloor spreading' (Bridges *et al.* 2012, p. 2013). Comparison of these ground profiles with the regional magnetic data shows, however, that the observed correlation with surface structure at the northern Tendaho Graben is a local phenomenon, which is not manifest immediately north or south. That local correlation aside, the linear anomalies observed in Afar are clearly not related overall to the tectonic pattern manifest at the surface and raise doubts about the interpretation of magnetic anomalies along continental margins such as in the GOA.

If the linear magnetic anomalies in the GOA are deemed indicative of the orderly Earth process of seafloor spreading, then similar anomalies in Afar are pointing to a more chaotic Earth structure.

Order and chaos in Afar and the GOA

Images of the crust in the GOA all show an elaborately ordered linearity: discrete linear segments of oceanic crust are offset along sub-parallel transform zones and are pushing apart the rigid continental plates. This is a very mechanistic view and sets the seafloor spreading process firmly within the 'machine' paradigm for the natural world.

In contrast to this, the detailed work by Manighetti *et al.* (1998, 2001) and others has shown that rigid plate tectonics do not apply in Afar, at least not at present. Seafloor spreading zones, overlapping with opposing polarities and propagating in opposite directions, have created an extremely complex lithospheric dynamic (Fig. 13). Such 'misgivings' about rigid plate dynamics in Afar date from early work there (Barberi & Varet 1977; Le Pichon & Francheteau 1978). The tectonomagmatic pattern observable today along the Mid-Atlantic Ridge in Iceland shows a similar complexity, manifesting as much chaos as order.

The Afar development does not conform to the mechanistic or Newtonian paradigm that emphasizes order and predictability, and is better seen within the Prigoginian paradigm (Toffler 1984), emphasizing instability and disequilibrium. Certainly, the order and organization interpreted in the crust of the GOA can emerge from the disorder and chaos of Afar. Self-organization evolving from the chaos is a fundamental point of the Prigogine's (1997) concepts, and has implications for our imagining of the seafloor spreading process, at least in its early stages.

In the first instance, a Prigoginian model would foresee Afar-like chaos in the GOA before seafloor spreading would emerge with any semblance of order – although it might emerge very quickly in geological terms. This would caution against imposing an ordered linearity on the early stages of the seafloor spreading process. Intuitively, a more complex oceanization process would be imagined. Perhaps, rather than discrete linear segments of new oceanic crust pushing the continental plates apart, the initial oceanization process may be more chaotic, with the injected magma consuming existing crust, rather than physically displacing it, until the order of spreading emerges. If this is so, then tight-fit models for the GOA are not needed to accommodate the newly formed oceanic crust, and Afar may be less extended than is currently thought.

Concluding remarks

A compilation project such as this is inevitably what the sixteenth century English poet and diplomat Henry Wotton called 'a gathering and disposing of other men's stuff'. This gathering has provided the gatherer with an insight into, and a humbling admiration of, the many and varied efforts to explain the form and formation of this spectacular and fascinating Earth structure.

The fascination is not limited to the geological fraternity, of course; the East African Rift is also sharply etched in the popular imagination. Beheld as Eden-like, it is at once the animal kingdom of the world and the cradle of mankind. These images have their origins in the tectonic and magmatic development of the rift. It was, for instance, the ash falls from Ngorongoro, Oldoinyo Lengai and other volcanoes that created the Serengeti grasslands that now host that animal kingdom and that, long ago, helped lure *Homo erectus* to stand on his/her hind legs.

Long before that, the Neoproterozoic collision that formed the Mozambique Belt and Arabian–Nubian Shield may well have caused the oxygenation event that led to the development of higher organisms and, ultimately, life on Earth (Fritz *et al.* 2013). That the East African Rift then developed there 600 myr later and became the founding home for *Homo sapiens* is a coincidence to delight our imagination and encourage our further exploration of its origins.

Many of the questions and speculations arising from this compilation likely have been asked and even answered previously by others, but a few may yet provoke useful new imaginings about the East African Rift.

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