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History of the development of the East African Rift System: A series of interpreted maps through time

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ABSTRACT

This review paper presents a series of time reconstruction maps of the 'East African Rift System' ('EARS'), illustrating the progressive development of fault trends, subsidence, volcanism and topography. These maps build on previous basin specific interpretations and integrate released data from recent petroleum drilling. N–S trending EARS rifting commenced in the petroliferous South Lokichar Basin of northern Kenya in the Late Eocene to Oligocene, though there seem to be few further deep rifts of this age other than those immediately adjoining it. At various times during the Mid-Late Miocene, a series of small rifts and depressions formed between Ethiopia and Malawi, heralding the main regional rift subsidence phase and further rift propagation in the Plio-Pleistocene. A wide variation is thus seen in the ages of initiation of EARS basins, though the majority of fault activity, structural growth, subsidence, and associated uplift of East Africa seem to have occurred in the last 5–9 Ma, and particularly in the last 1–2 Ma. These perceptions are key to our understanding of the influence of the diverse tectonic histories on the petroleum prospectivity of undrilled basins.

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1. Introduction

The East African Rift System ('EARS') represents the world's best example of an active rift system, although its deep origins remain poorly understood. The objective of this review paper is therefore to integrate the voluminous literature on the EARS with partially released subsurface well data, in order to compile a series of maps showing the progressive development of the system through time. These maps will remain dynamic as more data is released on drilling in the region and further studies are undertaken.

There is widespread confusion in the application of the term 'East African Rift System' ('EARS'). Multiple ages of rifting in East

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Africa are recognised (Fig. 1), including extensive systems of Permo-Triassic and Cretaceous age, in each case themselves consisting of several stacked rift phases (Kreuser, 1995). The term 'East African Rift System' ('EARS') tends to be applied only to rifts of Cenozoic age (e.g. Chorowitz, 2005), but even here there may be confusion, as there are three overlapping subsets of Cenozoic rifts (Figs. 1 and 2), namely (a) those of Early Paleogene age, which usually represent a continuation of rifting from the Late Cretaceous (e.g. Anza Graben, (Morley et al., 1999c)), (b) those of ?Eo-Oligocene to Early Miocene age, and (c) the currently active set of rifts, dating, according to this work, back to the Mid Miocene. This paper is confined to the study of the two youngest of these phases, i.e. those which are not continuations of the NW–SE Cretaceous rifts, though it is realised that some of the EARS rifts may be reactivations of earlier rifts (e.g. Rukwa Basin, Fig. 2). The EARS rifts show a general N–S trend, except over the long-lived Ubendian line of basement weakness through the Rukwa Basin (Klerkx et al., 1998), where they swing to follow NW–SE basement trends (Figs. 1 and 2, Delvaux, 2001). The limited number of rifts active from? Eo-Oligocene through to the Early-Mid Miocene boundary, of which the type example is the South Lokichar Basin (Morley et al., 1999b), are referred to in this paper loosely as 'EARS 1' rifts, while the more extensive Late Neogene (Mid Miocene to Recent) rifts, typified by the Albertine Basin (Pickford and Senut, 1994), are referred to as 'EARS 2' rifts. In most cases, in the onshore, these two phases seem to be geographically distinct, as is illustrated on Fig. 1, and the distinction has been historically emphasised in northern Kenya, where Vetel (1995) and Morley et al. (1999b) document a major shift eastwards through time in the location of rifts. The Mid Miocene division between the two phases also seems to mark the onset of Neogene rifting in the Western Branch, within the Semliki extension of the Albertine Basin (see below), although determining whether this initiation is truly synchronous with the rifting shift in the Turkana Area needs better biostratigraphic control than is available at present. This division is therefore useful for descriptive purposes, but is likely to be refined in the future as more precise dating becomes available. Offshore rifts active during this timescale are also presented and discussed in this paper, though these are of doubtful direct affinity to the onshore rift systems and less easily follow the EARS 1/EARS 2 division. Essentially, therefore, this is a paper which assimilates our current state of knowledge on Oligocene-Recent rift activity in East Africa. The names applied for each of the basins described are shown in Fig. 2.

Data and interpretations assimilate previous regional and semi-regional evaluations of the EARS (e.g. Chorowitz, 2005; Morley et al., 1999a), published outcrop-based studies, particularly of volcanic dating and geometries related to faulting (e.g. Wichura et al., 2011) and lakebed lithological studies (e.g. Tiercelin et al., 1992). Geophysical contributions include gravity modelling to identify deep rifts (e.g. Ebinger et al., 1989), published subsurface seismic studies (e.g. Scholz/Project Probe, 1989) and new seismic mapping by the author of the PROBE seismic over Lake Tanganyika, Lake Malawi (including Surestream Petroleum reprocessed data) and Lake Turkana. Public domain seismic data and mapping by other authors have also been incorporated from various sources over the Lake Albert, Rukwa, South Lokichar, Turkana, Omo, Chew Bahir, Anza and Kerio basins (as listed in Table 1).

Available well information, with the fullest datasets from pre-2005 wells, is shown in Table 1. There has been a recent spate of drilling of Ugandan, Ethiopian and Kenyan EARS basins, though only sparse data is available on post-2005 wells through

Table 1
Published well and seismic data, plus source of mapped faults, over the East African Rift System.

Well	Basin	Reference	Key points
Kingfisher 1,2,3	Albertine	Logan et al. (2009)	Thick Plio-Pleist. Late Miocene over Basement. Tie to seismic. Published biostrat
Turaco wells	Albertine/Semliki	Abeinomugisha and Kasande (2012), Lukaye (2009)	1400 m thick Mid-Late (and ? Early) Miocene section
Ngassa 2	Albertine	Sserubiri and Scholz (2012)	Early Pliocene source rocks described at 3000–3250 m close to Basement surface
Waki 1	Albertine	Karp et al. (2012)	Undated section with source rocks over Basement
Nyuni 1	Lake Edward	Dominion (2011)	Late Pliocene over Basement
Ruzizi 1	Ruzizi	Morley and Wescott (1999)	Undated section
Buringa 1	Ruzizi	Morley and Wescott (1999)	Undated section
Ivuna 1	Rukwa	Morley et al. (1999d)	Latest Miocene-Pliocene over top Oligocene unconformity
Galela 1	Rukwa	Morley et al. (1999d)	As above
Syracuse Borehole A	Lake Malawi	Scholz et al. (2011), Lyons et al. (2011)	TD at 390 m at date of 1.2 Ma
Loperot 1	South Lokichar	Talbot et al. (2004), Morley et al. (1999b)	Early Miocene reservoirs and source rocks, Eo-Early Olig close to mapped Basement
Eliye Springs 1	Turkana	Morley et al. (1999b)	Tie for thick Plio-Pleistocene and thinner ?Late Mio section in Turkana rift
Ngamia 1	South Lokichar	Africa Oil (2013)	Early Miocene reservoirs and source rocks
Twiga 1	South Lokichar	Africa Oil (2013)	As above
Seismic programme	**Basin**	**Reference**	**Mapping of faults in this paper by**
Project PROBE	Lake Tanganyika	Rosendhal (1988)	Author
Project PROBE	Lake Malawi	Scholz/Project Probe (1989)	Author
Project PROBE	Lake Turkana	Dunkelman et al. (1989)	Author
Amoco Seismic Rukwa Basin	Rukwa	Morley et al. (1999d)	Morley et al. (1999d)
Amoco Seismic South Lokichar, Kerio and Turkana Basins	South Lokichar	Morley et al. (1999b)	Morley et al. (1999b)
Early Academic Seismic Lines	Albertine	Karp et al. (2012)	Karp et al. (2012), Abeinomugisha and Kasande (2012)
Recent Commercial Seismic Lines	South Omo, Chew Bahir, Ethiopia: Turkana and South Kerio, Kenya	Africa Oil (2013)	Africa Oil (2013)

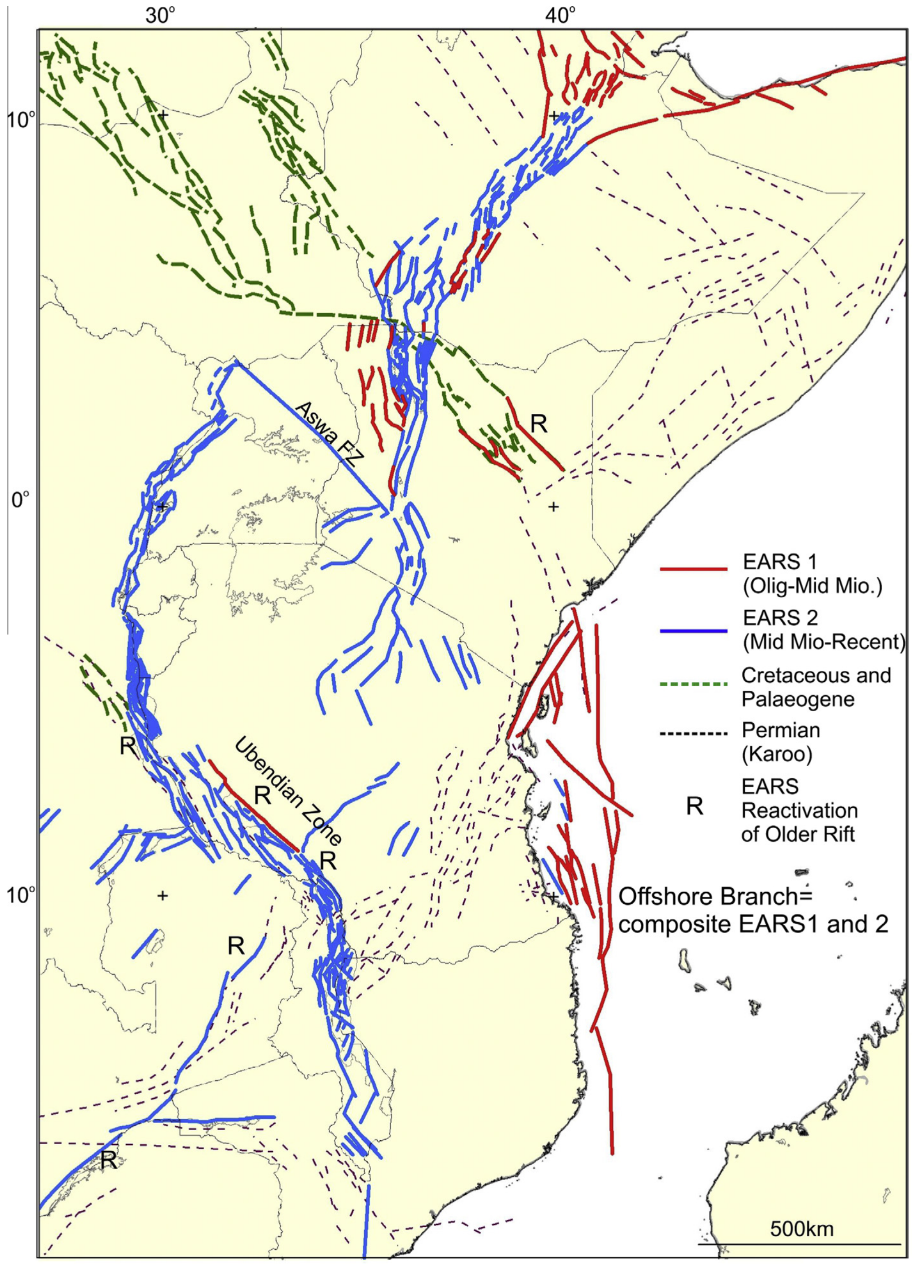

Fig. 1. Assignment of rifts in East Africa to Permo-Triassic ('Karoo'), Cretaceous-Palaeogene, Eo-Oligocene to Mid Miocene (EARS 1) and Mid-Late Miocene to Recent (EARS 2) phases. Latest rift phase forms basis of classification. Rifts active in both EARS 1 and EARS 2 phases are located in the offshore, in northern Kenya/southern Ethiopia and in the Rukwa Basin of Tanzania and are shown here in the EARS 1 phase. R = Neogene reactivation of a pre-EARS rift, Cretaceous/Palaeogene in the case of the Anza rift, Karoo in the case of rifts along the Ubendian trend from Tanganyika to Malawi. For the colour version of this and other figures, see the electronic version of this paper.

conference and investors presentations. However, the maps and chronostratigraphic charts in this paper are consistent, to the author's knowledge, with all wells drilled as of January 2014.

2. Pre-EARS rifts

An interpretation of the respective ages of the various Phanerozoic rifts across East Africa is shown in Fig. 1, based on interpretations in the literature, mainly the ages of their thickest stratigraphic fills. While there is some evidence for Neoproterozoic rifting along the Ubendian trend of Tanzania (Klerkx et al., 1998), the oldest regionally extensive rift phase is the so-called 'Karoo' or Permo-Trias phase. The NE–SW trending Ruhuhu rift of Tanzania (Figs. 2 and 3) has been subdivided into three main rift phases in the Early Permian, Mid Permian and around the Permo-Triassic boundary (Kreuser, 1995). The younger Karoo rift phases seem to be less well represented within the NE–SW trending rifts of this age, such as those exploited by the Western Branch of the EARS. The 'Karoo' rifts are again reactivated in eastern and coastal areas by Early Jurassic rifts, some of which evolved into the successful rifts of the Indian Ocean.

In the earliest Early Cretaceous, a series of rifts developed across Central Africa, related to plate re-organisations in the Atlantic ocean, generally referred to as the 'Central Africa Rift System' or 'CARS' (Genik, 1992). NW–SE trending members of this population of rifts, including the Anza Basin and Sudan rifts,

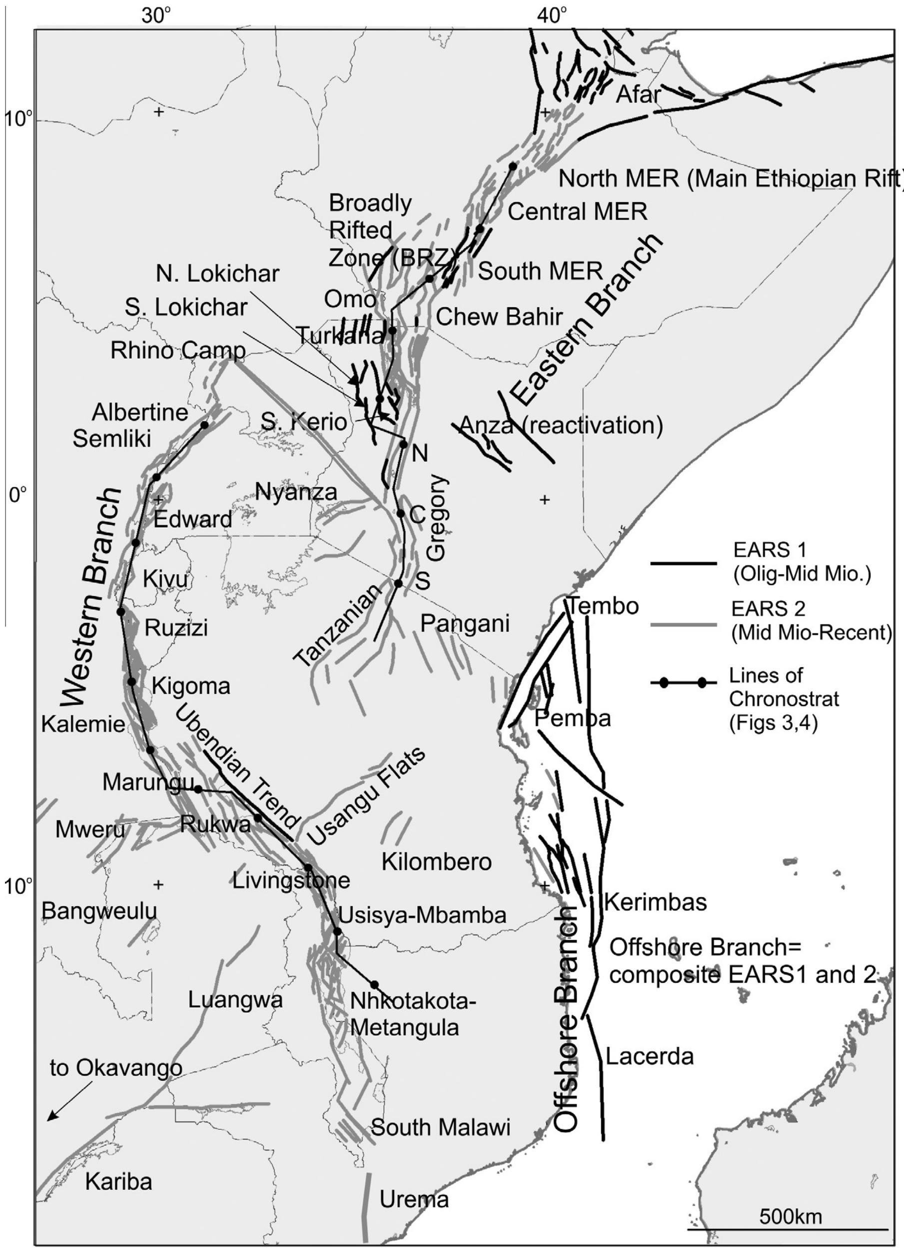

Fig. 2. Key basin names applied in this paper. The lines of chronostratigraphy shown as Figs. 3 and 4 are located here.

experienced multiple rift phases extending into renewed Late Cretaceous and Eocene–Oligocene phases, with intervening inversions in the case of the Anza Basin (Bosworth, 1992; Bosworth and Morley, 1994; Morley et al., 1999c), where activity is generally younger than in the Sudanese rifts. Apatite Fission Track Analysis from surrounding basement outcrop (Foster and Gleadow, 1996) and vitrinite reflectance data on the Elgal wells (Bosworth and Morley, 1994) evidence that the Anza Rift shoulders experienced severe erosion in the Late Cretaceous-Palaeogene. Such erosional events are not seen in the basin or surrounding area, suggesting that the shoulders were topographically high, similar to modern EARS rift shoulders. Many EARS rifts of the Western Branch exploit these earlier rifts (such cases are labelled on Fig. 1 and are illustrated on Fig. 3), particularly along lines of basement weakness, though this seems rarely to be the case for the Eastern Branch (Fig. 4).

3. Construction of time reconstruction maps for EARS 1 and EARS 2 Rifts

The key product of this paper is a series of sequential maps illustrating a developing understanding of the progressive development of the EARS (Figs. 5–12). The maps show rift faults evidenced to have be active during the intervals labelled, an illustration of relative palaeo-topography (unquantified) and active volcanism. The periods covered by the maps span approx. ±10% of the ages concerned to allow for uncertainties in the dating and to enable the illustration of the full series of events. Fault locations and timings shown are taken from the author's mapping of the PROBE seismic in the various lakes and from the mapping of other authors on seismic data, listed in Table 1. Further interpretations of fault locations and timing are taken from: Africa Oil, 2013; Bonini et al., 2005*; Chorowitz, 2005; Cohen et al., 1993; Dawson, 2008; Delvaux,

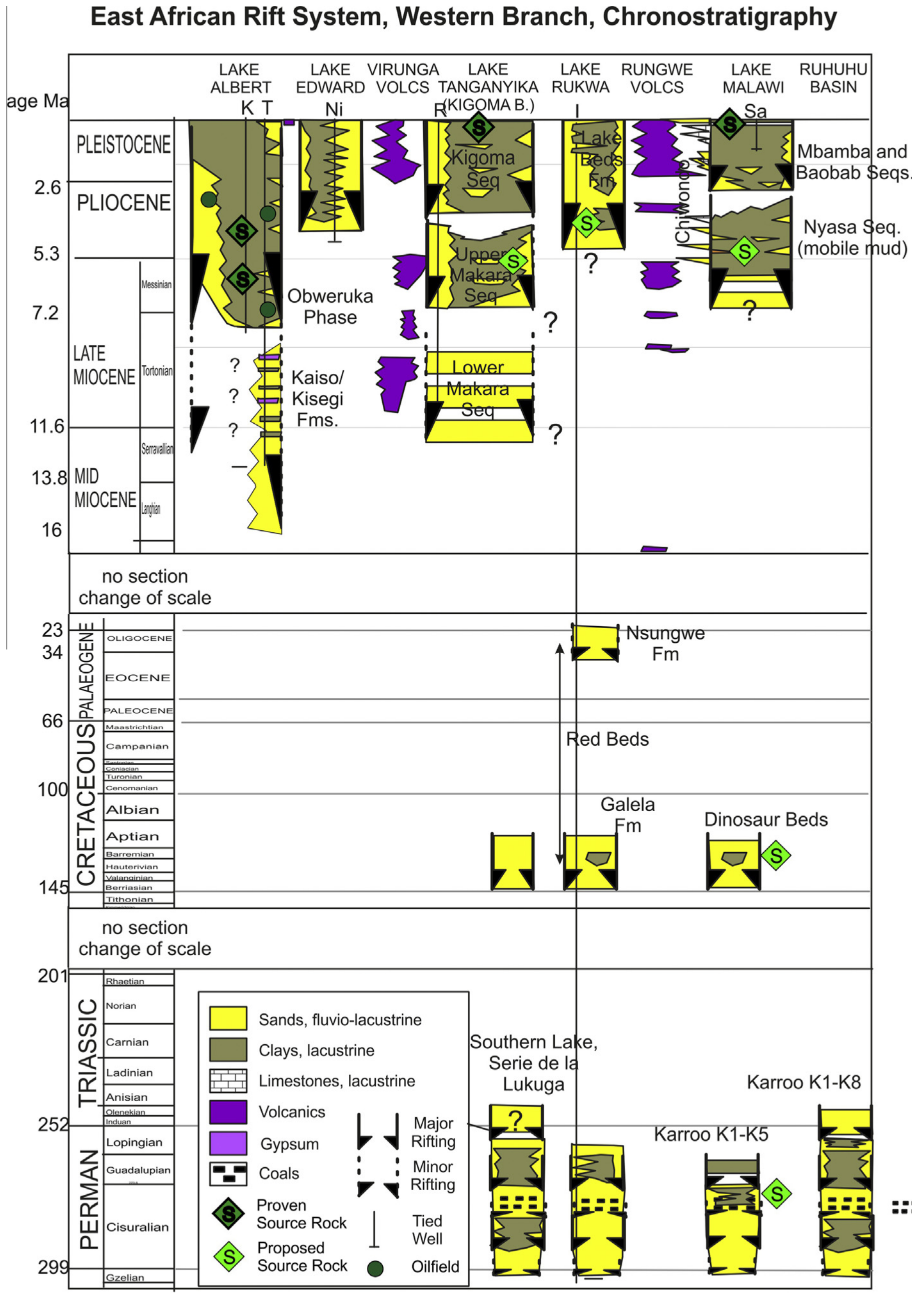

Fig. 3. Chronostratigraphy of the Western Branch of the East African Rift System. Scale amended to accommodate the Cretaceous and Permian rift phases on which many of the EARS 2 rifts are reactivated. Only the Rukwa Basin shows evidence for (mild) EARS 1 rifting. The Albertine Basin is the best controlled of the EARS 2 rifts, with parts of Lake Tanganyika being conceivable time analogues: other basins, particularly to the south, seem to be slightly younger, as indicated by biostratigraphic data discussed in the text on wells in the Rukwa Basin and in exhumed outcrop adjacent to Lake Malawi. See Fig. 2 for line of section. References are listed in the text. Line of section in Fig. 2. Wells : K = Kingfisher, T = Turaco, Ni = Nyuni, R = Ruzizi, I = Ivuna, Sa = Syracuse A.

2001; Ebinger, 1989; Ebinger et al., 2000; Foster et al., 1997; Le Fournier et al., 1985; Lezzar et al., 1996*; Morley, 1999*; Morley et al., 1992; Pickford and Senut, 1994; Ring and Betzler, 1995; Saemundsson, 2010*; Vetel, 1995*; Woldegabriel et al., 1990. Those asterisked above contain time reconstruction maps for restricted regions of the EARS that are integrated into this paper. Baker, 1986; Ebinger et al., 1989, 1993; Kampunzu et al., 1998; McDougall and Brown, 2009, are the main sources for the age of volcanism.

The interpretation of the timing of rifting in this analysis uses a number of techniques, which can be listed in approximate order of confidence below:

a. Biostratigraphic or volcanic dating within well penetrations in the rifts concerned, tied wherever possible to seismic.
b. Biostratigraphic or volcanic dating of exhumed outcrop sections of rifts, usually on uplifted flexural margins.
c. Dating of volcanics in outcrops, combined with analyses of their thickness patterns relative to rift-bounding faults.
d. Dating of volcanics that are believed to have compositions (e.g. rhyolites) that correlate to periods of likely extension.
e. Extrapolation of measured modern sedimentation rates to a mapped basement horizon.
f. Jump correlations of intervals of similar seismic character between basins.

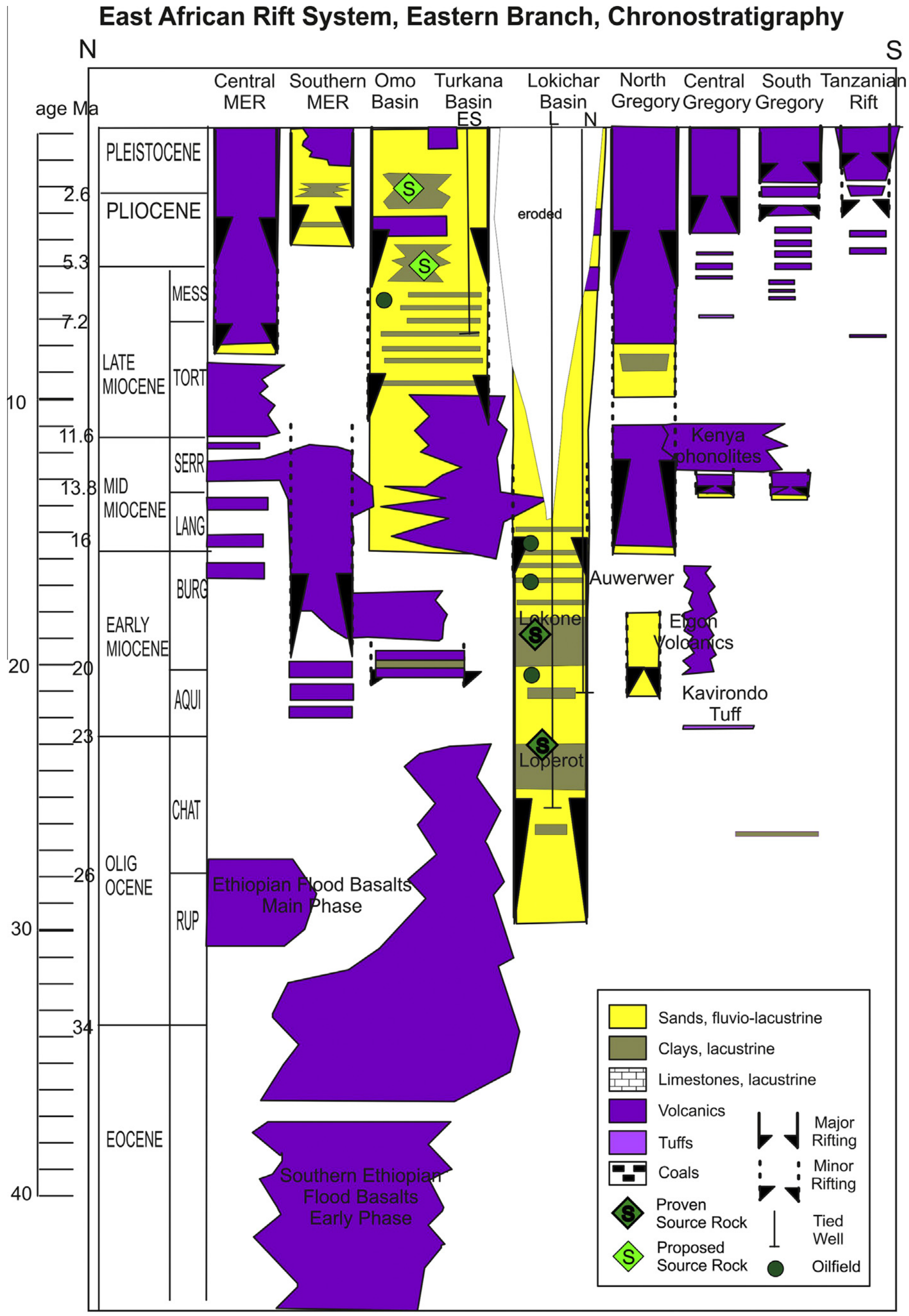

Fig. 4. Chronostratigraphy of the Eastern Branch of the East African Rift System. Timescale limited to EARS 1 and EARS 2 rifts as older sedimentary sections (e.g. Turkana Grits) are of limited development and affinity. Note distinction between EARS 1 rifts initiated in Oligocene with peak rifting in Early Miocene and EARS 2 rifts initiated as depressions with minor rifting at various times in Mid-Late Miocene with peak rifting in Pliocene-Present Day. References are listed in the text. Line of section in Fig. 2. Wells : ES = Eliye Springs, L = Loperot, N = Ngamia.

g. Labelled seismic correlations within investors presentations that cannot be fully audited by the author.

In the context of the above and the wide variations in databases, confidence in the interpretation of the precise timing of rifting events clearly varies regionally. Confidence is high over the portion of the Eastern Branch in Kenya and Tanzania, where techniques a. and c. can be employed, but is diminished somewhat over Ethiopia, where there are some conflicting interpretations from technique c. and little published drilling control. In the Western Branch, confidence is high in the analysis of the well-drilled Albertine Basin but low in Lake Tanganyika, where low confidence techniques such as technique e. need to be used. A level of moderate confidence applies to the Rukwa-Malawi trend of the Western Branch where there is one well fully penetrating the rift section tied to seismic (technique a.) and outcrop control in Malawi of an exhumed rift section (technique b.). Based on a lack of published well data at this stage, confidence is also low in the precise nature of timing of rifting offshore, with the interpretation shown inferred from a number of conference papers and diverse seismic images within investors presentations (technique f.).

The interpretation of palaeotopography is based on an extrapolation of current topography backwards in time. This extrapolation essentially assumes that (a) maximum topographic variation and amplitude across the region is achieved at Present Day, and (b) the rough level of rift shoulder topography was achieved at the

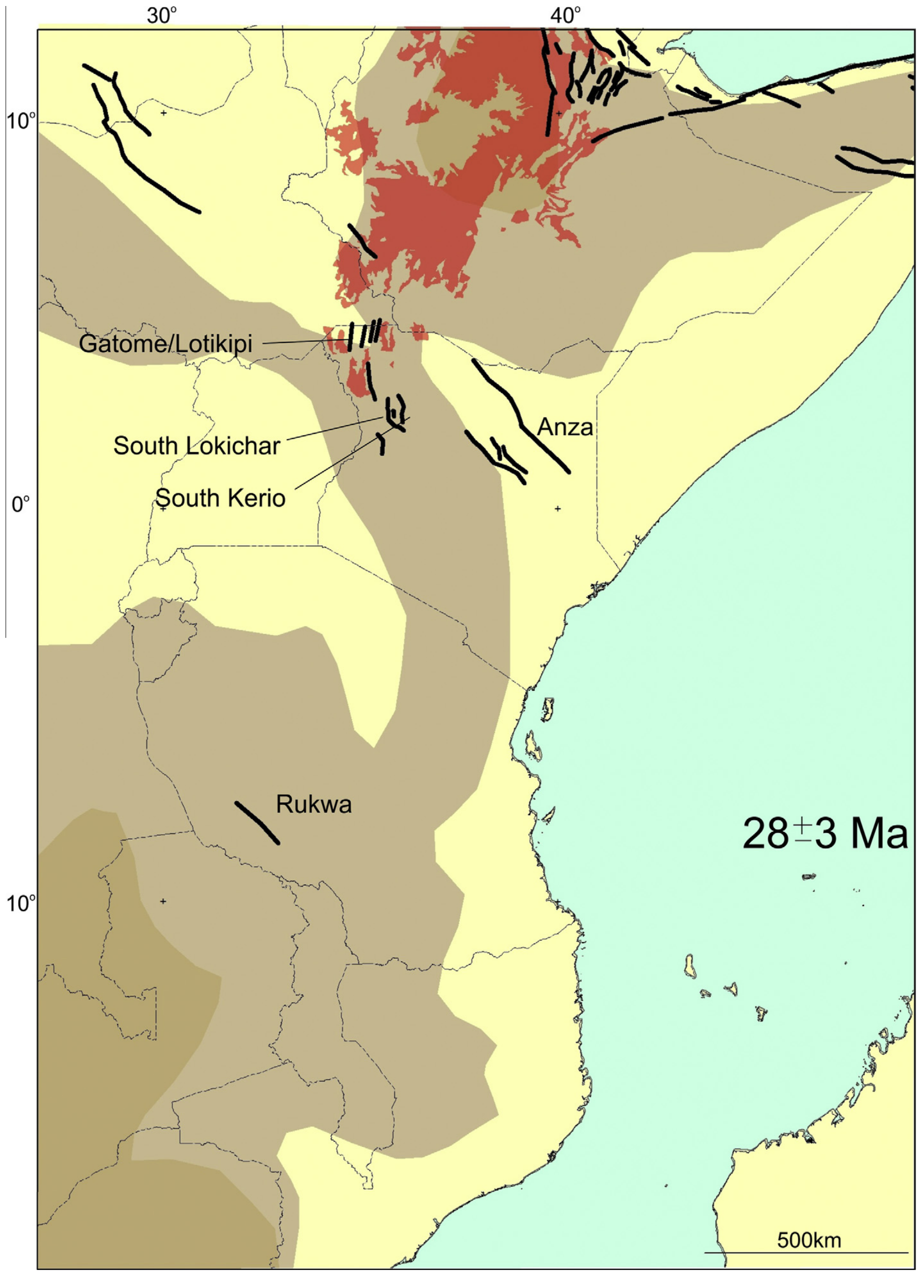

Fig. 5. Time reconstruction at 28 ± 3 Ma, Rupelian, Initiation of EARS 1 rifts. Key events include: (1) first N–S trending Cenozoic rifts are initiated in N Kenya ? around 35 Ma. (probable Oligocene strata in Loperot 1 well), (2) large volume of trap basalts erupted from 28–25 Ma in Ethiopia, associated relief of Afar plume around 1 km, (3) rifting in Afar around 25 Ma (Bosworth et al., 2005), (4) earlier Melut and Anza basins remain active, (5) Nsungwe Fm. of Rukwa Basin indicates mild reactivation of Permian/Cretaceous rift (Roberts et al., 2012). Topography prior to EARS development based on Moore et al., 2009, in south, AFTA data of Noble (1997) and Foster and Gleadow (1996) in Tanzania, plus Oligocene sedimentation rates offshore East Africa (Morley, 1999, Fig. 13 of this paper). Darker shades on all maps indicate relatively higher topography. Volcanics in red.

time of maximum rift faulting, as interpreted in the paper. The critical interpretation that topography is at a maximum in the Plio-Pleistocene is supported by a number of lines of evidence, including (a) the peak of sedimentation rates in the Plio-Pleistocene in depocentres charged from rivers which drain the EARS rift shoulders (Fig. 13), (b) the immaturity of river profiles across the region (Paul et al., 2014; Gani et al., 2007) and (c) interpretations of the age of the main throws on the rift bounding faults, as is discussed below for the basins concerned. For example, the rise of the 5 km high Rwenzori mountains, which represent the highest non-volcanic, non-orogenic topography in the world, is dated as Plio-Pleistocene by folding of Pliocene strata in outcrop (Pickford and Senut, 1994). High altitude taxa associated with that uplift are not seen in spore assemblages within the Kingfisher Wells in the Albertine Basin until around 1 Ma (Shaw et al., 2009). Volcanic geometries and dating illustrate that the Gregory rift shoulders (technique c.) also did not rise till 1–2 Ma (Baker, 1986; Dawson, 2008).

The topography around rifts is assumed to have been reduced in magnitude for periods prior to maximum rifting, following a model of rifts developing initially as gentle depressions with low throw bounding faults apparent on Present Day analogues (Modisi et al., 2000) and developed on seismic over Lake Tanganyika by Tiercelin and Mondeguer (1991) (Fig. 14). Many, though not all, rifts investigated in this paper show increased structural growth into bounding faults through time, i.e. greatest isochron variations

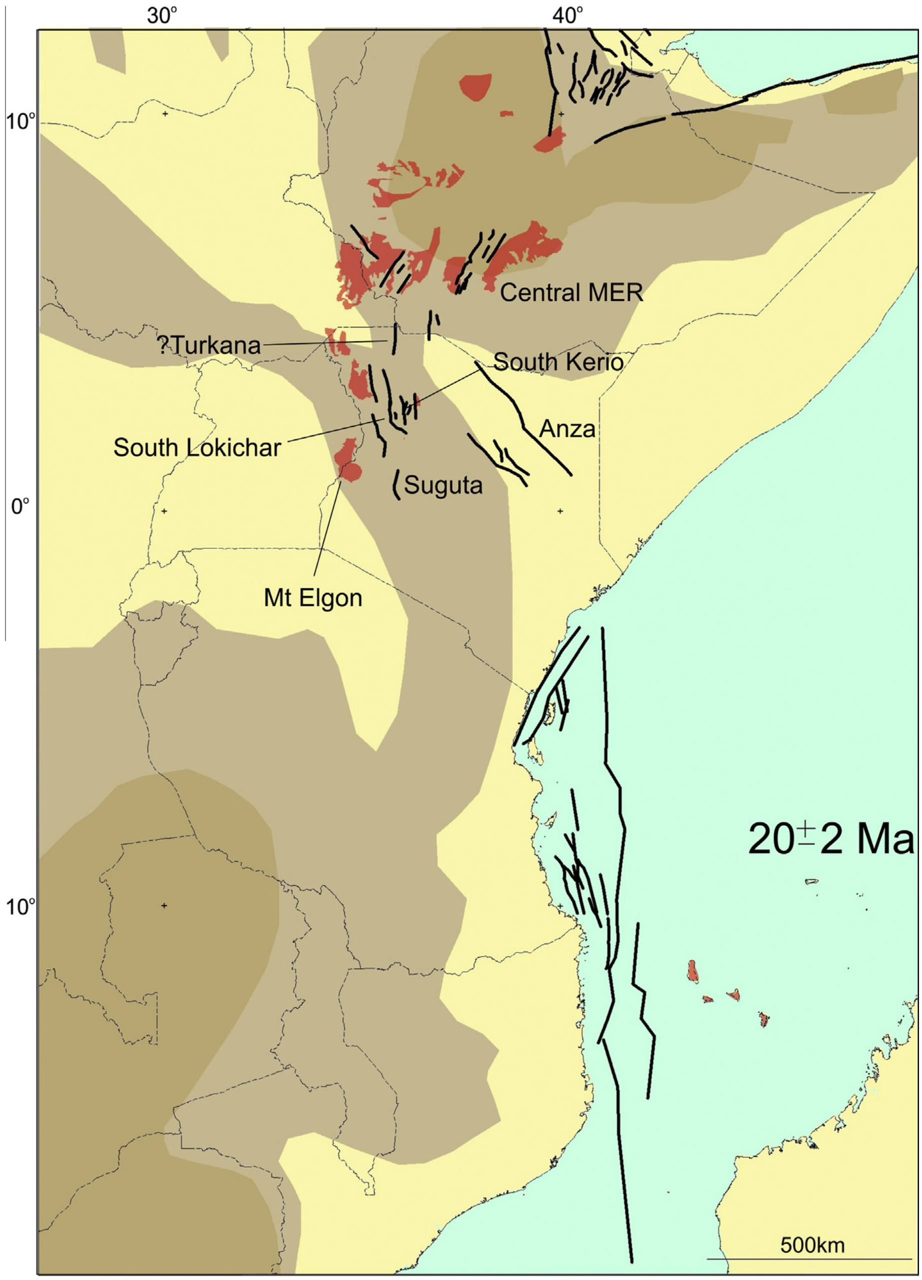

Fig. 6. Time reconstruction at 20 ± 2 Ma, Aquitanian, Acme of EARS 1 rifting. Key events include: (1) deep lacustrine shale (source rock) development in South Lokichar Basin, (2) rifting in Broadly Rifted Zone of Ethiopia commencing between 25 Ma and 21 Ma (Levitte et al., 1974; Bonini et al., 2005), (3) some activity in Suguta Basin (Morley, 1999), where Early Miocene section present, (4) Ethiopian dome developed along with peak of Red Sea rifting and shoulder uplift (Bosworth et al., 2005), (5) offshore rifting active from latest Olig-Early Miocene (Danforth et al., 2012; Jeans et al., 2012; Parsons et al., 2012).

in Recent times. Prior to rifting, interpretations are made of the development of broad domes with reliefs as suggested by Wichura et al. (2011) for the Kenya dome, based on the observed geometries of lava flows. The interpretation is eventually tied for the Oligocene to a broad interpretation of pre-EARS topography based on Apatite Fission Track Analysis, drainage analysis and offshore sedimentation rates analysis. This essentially assumes some residual palaeotopography around the Anza Rift shoulder (as discussed earlier) and Tanzanian Craton in a region of Late Cretaceous-Palaeogene Apatite Fission Track ages and high topography in the northern part of the South African plateau as proposed by Moore et al., 2009: such topography is also required to explain a peak in sedimentation rates and turbidite sand supply in e.g. the Rovuma Delta (Fig. 13). The palaeotopographical patterns shown through time are similar to those independently derived by Paul et al. (2014) on the basis of river profile studies, though differ from the assumption used in that paper that African topography was essentially flat at the start of the Oligocene.

4. EARS 1 Rifts (?Eo-Oligocene to Mid Miocene), Figs. 5–8

A new set of rifts were created in the Palaeogene in northern Kenya that do not exploit earlier trends and show, for the first time in Africa, a distinct N–S orientation, thus marking a significant change in stress direction (Fig. 5). There are many basins in this region and most are undrilled, but the only basin at this time established from drilling and seismic interpretation to contain a

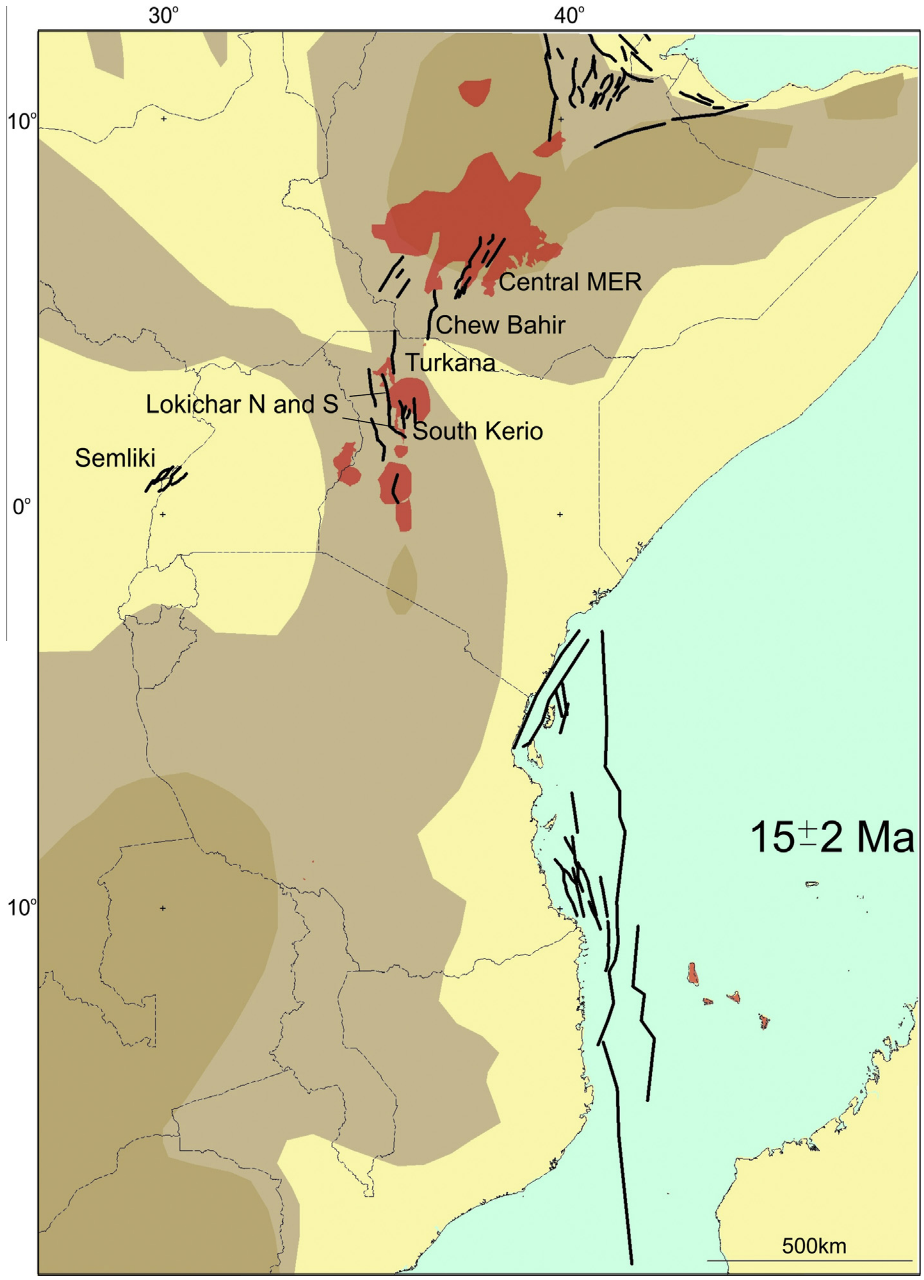

Fig. 7. Time reconstruction at 15 ± 1 Ma, Langhian, late milder stage of EARS 1 rifting in Eastern Branch and possible earliest EARS 2 rifts in Western Branch. Key events include: (1) volcanism fills up rift topography in northern Kenya, (2) rifts active in southern MER (Bonini et al., 2005), (3) Semliki Sub-Basin of Albertine Basin probably initiated close to this time, based on stratigraphy of Turaco well, (4) assumed continuation of rifting offshore based on sparse published seismic coverage.

thick (6–7 km) stratigraphic section of this age is the South Lokichar Basin.

The South Lokichar Basin has now been drilled by a large number of recent wells (Africa Oil, 2013). Results of the earlier Loperot 1 well have been published in detail (Figs. 4 and 14, Morley et al., 1999b; Talbot et al., 2004). The well penetrated a deep lacustrine shale (the 'Loperot Shale'), dated as 'Early Oligocene to possible Eocene', some 300 ms TWT above the predicted basement surface at a central point within the rift (Fig. 14). The earliest rift units show a planar geometry on seismic, without significant thickening to the bounding fault. Peak rift subsidence was probably attained at the time of deposition of a younger deep lacustrine shale unit termed the 'Lokone Shale', which shows a distinct wedge shaped geometry on seismic, and is dated in recent wells as Early Miocene (Africa Oil, 2013). This is overlain by a sandy rift infilling unit of Early to earliest Mid-Miocene age ('Auwerwer Formation') before the basin was uplifted in the Late Miocene-Pliocene on the shoulder of the later EARS 2 Turkana rift (McDougall and Brown, 2009). Vetel (1995) proposes that the initiation of the basin was around 35 Ma, which is consistent with the available data.

Two adjoining rifts in the Turkana complex, the South Kerio (Fig. 14) and North Lokichar rifts, have established EARS 2 sections observable on seismic and tied to outcropping arkoses below the regional mid Miocene volcanics (Morley et al., 1999b; Vetel, 1995). Their sections seem to be thinner than in South Lokichar, at up to 2 km in North Lokichar and perhaps up to 5–6 km in South Kerio where seismic definition is however poor. Vetel (1995) speculated these basins may have been initiated later, perhaps in the Early Miocene, partly due to their thinner nature and partly to follow a trend of younging volcanism to the east. Drilling is

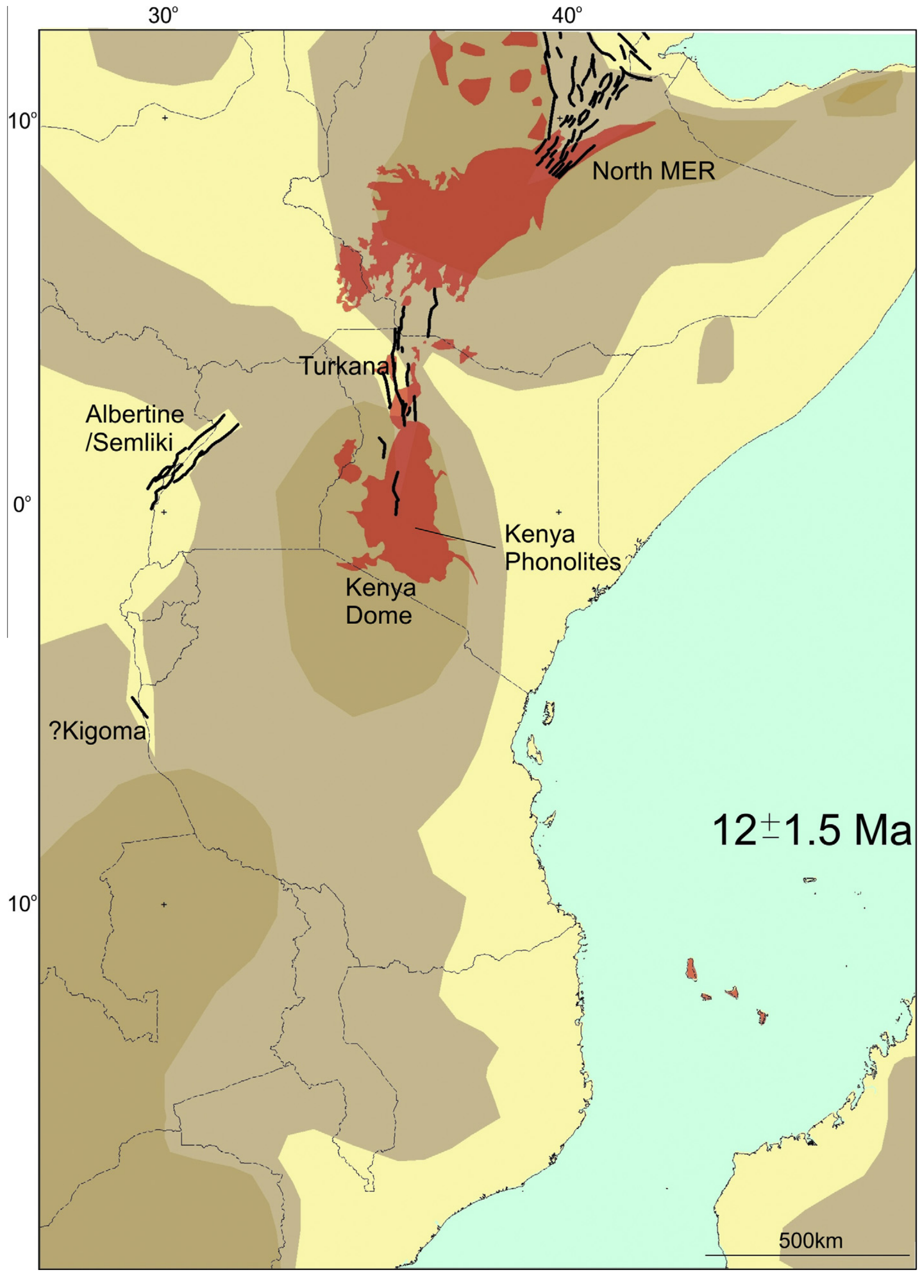

Fig. 8. Time reconstruction at 12 ± 1 Ma, Serravallian, transitional phase between EARS 1 and initiation of early sag phases of EARS 2 rifts, with migration of rifts. Key events include: (1) jump of rift activity from South to North Lokichar Basin and to Turkana Basin around end mid Miocene (Morley et al., 1999b), (2) lack of rifting (Elgayo escarpment excepted) but existence of circa 1400 m high dome evidenced by volcanic geometries of Kenya phonolites at 13.5–11 Ma. (Wichura et al., 2011), (3) continued rifting of Semliki portion of Albertine Basin (e.g. Pickford and Senut, 1994) and commencement of subsidence below Lake Albert, (4) a best case assessment of Lake Tanganyika rifts suggests in the most likely case that they have not been initiated by this time, though this cannot be excluded, (5) poorly controlled period of relative quiescence offshore between rift phases (e.g. Jeans et al., 2012).

planned later this year (2014) to analyse whether the critical Early Miocene source rock and reservoir section seen in the South Lokichar wells is present and should resolve this issue.

Elsewhere in northern Kenya, sparse evidence suggests the existence of only thin sedimentary sections of Early Miocene age. An Early Miocene sandy section is uplifted along the Elgayo Escarpment in the northern Gregory rift (Bosworth and Maurin, 1993) while thin shallow lacustrine deposits have been dated at around 20 Ma by interbedded tuffs east of Lake Turkana (Ebinger et al., 2000). These sections, as shown by the maps of Morley et al. (1999b), are indicative of fluvial and shallow lacustrine deposition, perhaps in localised small and slowly subsiding rifts. It can be noted that pre mid-Miocene volcanism is sparse in the region around and east of Lake Turkana (Vetel, 1995), which suggests that rifting was concentrated around South Lokichar. The existence of EARS 1 rift sections below the mid Miocene volcanics below Lake Turkana, and therefore beyond seismic definition, cannot however be ruled out.

In the main part of the Gregory Rift, Mid-Miocene volcanic flow geometries are generally unsupportive of the presence of any pre-existing rift topography (Wichura et al., 2011), suggesting the EARS 1 rifts did not propagate any further to the south. Rifting also seems to have also continued from Palaeocene times in the earlier Anza Graben, extending up to an unconformity in the Hothori 1 well, roughly dated as intra-Early Miocene (Morley et al., 1999c). It is also possible that the gravity-defined Gatome and Lotikipi rifts

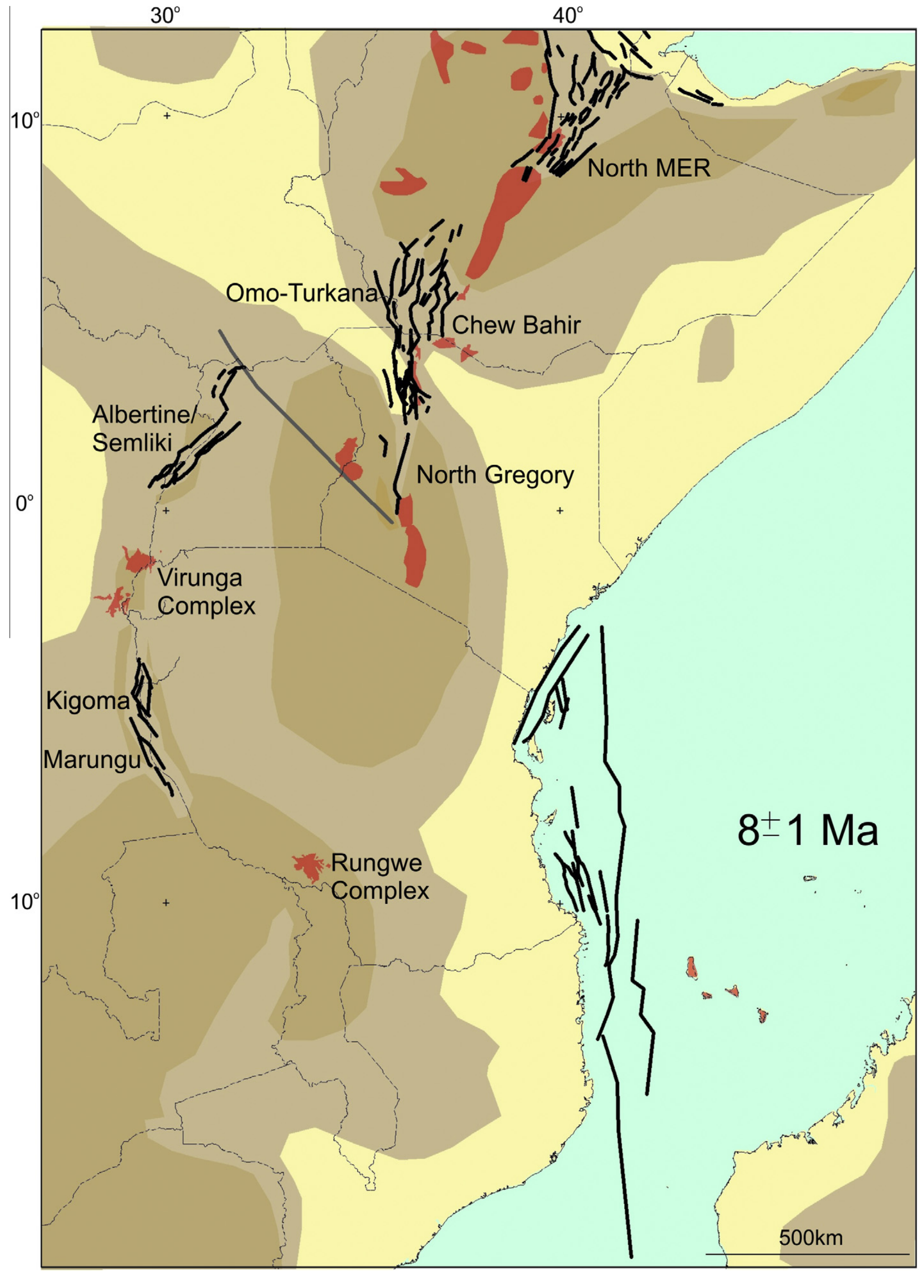

Fig. 9. Time reconstruction at 8 ± 1 Ma, Tortonian, mild EARS 2 rifting. Key events include: (1) rifting now propagating southwards into Central MER (Bonini et al., 2005), volcanic geometries suggest no rifting to south of that shown, (2) rifting active in Turkana/Omo/Chew Bahir area, but not yet in main subsidence phase, (3) Albertine (Lake Albert) Basin in early part of syn-rift (e.g. Pickford and Senut, 2004), (4) block faulting phase in Lake Tanganyika around this time according to sedimentation rate extrapolations, (5) renewed rifting offshore (Danforth et al., 2012; Parsons et al., 2012).

of Wescott et al. (1999) could at least in part be active rifts at this time period: these are capped by Oligocene volcanics and the interpreted rift section below these could be anywhere between Cretaceous to Oligocene in age.

In Ethiopia, evidence for Palaeogene to Early Miocene rifting is largely confined to the 'broadly rifted zone' of southern Ethiopia (Ebinger et al., 2000). Levitte et al. (1974) and Zanettin et al. (1978) indicate rifting started here in the late Oligocene-Early Miocene, at around 21–25 Ma. (Fig. 4), based on volcanic geometries and dating, with dating of fluvio-lacustrine deposits suggesting well established rifting by 17–15 Ma. (Fig. 7). Vetel (1995) suggests that the Chew Bahir rift became active in the Early Miocene on the basis of volcanic associations and chemistry, but acknowledges that the main fill to this basin is undoubtedly much younger.

In the Western Branch of the EARS, a >300 m thick sandy Oligocene section has been described in the Rukwa Basin (Roberts et al., 2010, 2012, Fig. 3 of this paper), suggesting a minor pulse of rifting at this time and it is possible by step correlation from here that the undated Sungwe Beds (Dixey, 1927) of Malawi could be of this age. Early Miocene rifting within the Semliki valley area of the Albertine Basin of Uganda has been suggested by Abeinomugisha and Kasande (2012), though no rocks of this age have been penetrated and early interpretations of exhumed Early Miocene strata in outcrop have now been revised to younger dates (see discussion below in Section 5.2). The low level of tectonic activity in this region is emphasised by a paucity of volcanic dates in the Western Branch older than 10 Ma. (Kampunzu et al., 1998). Small exceptions are some isolated Early Miocene dates from the Rungwe complex (Rasskazov et al., 2003).

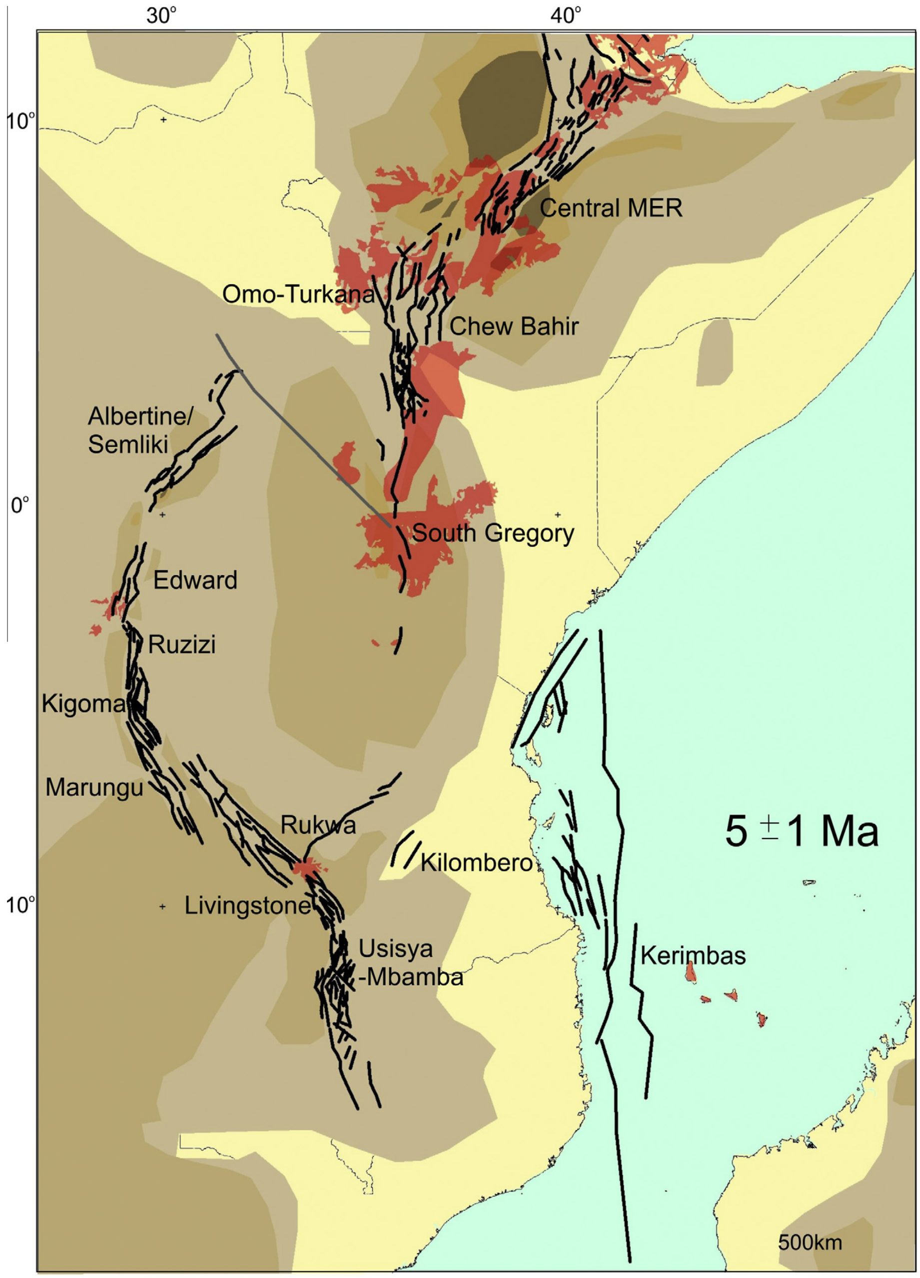

Fig. 10. Time reconstruction at 5 ± 1 Ma, Zanclean, entering main phase of EARS 2 rift subsidence and topography development. Key events include: (1) major topography development in Ethiopia, indicated by river incision analysis (Gani et al., 2007) and surge in Nile sedimentation (Macgregor, 2012a), associated with southwards rift propagation, (2) Turkana, Omo and Chew Bahir rifts now in main subsidence/sedimentation phase according to picks on seismic sections illustrated at conferences, (3) propagation into Gregory and formation of half graben on western shoulder (Saemundsson, 2010), (4) active rifting of Albertine and Kigoma Basins, (5) Rukwa Basin reactivating – near base of section according to biostrat in wells (Wescott et al., 1991), (6) livingstone Basin of Malawi initiation constrained between 8 and 4 Ma as constrained by outcrop data, while sedimentation rates in Usisya Basin borehole extrapolate to unconformity at 7 Ma.

5. EARS 2 Rifts (Mid-Late Miocene to Recent and ongoing)

Onshore rifts with demonstrated or interpreted rifting in the last 13 My are illustrated in Figs. 8–12 and can be seen to be grouped into two branches, the Eastern and Western branches. The onset of the EARS 2 rifts is taken at the apparent migration of rifting from South Lokichar to the Lake Turkana area in Kenya and at the onset of the first rifts in the northern part of the Western Branch. Offshore activity is discussed in Section 6 of this paper. An overview of these much more widespread EARS 2 rifts is obtained on the chronostratigraphic charts compiled for the eastern and western branches in Figs. 3 and 4.

5.1. Eastern Branch

The EARS 2 Eastern Branch rifts extend continuously from the Afar of Ethiopia to northern Tanzania, which, given that Afar rifting commenced in the Oligocene, has led to generalisations that the system can be interpreted as unzipping from north to south. However, more detailed study of the Ethiopian rifts (Bonini et al., 2005) suggests that the central Main Ethiopian Rift ('MER') did not form till the earliest Pliocene, at around 5 Ma. This interpretation is based largely on dating of volcanics and the geometries of flows relevant to the present rift, but is supported by Gani et al. (2007)'s river profile analysis, that suggests that the main uplift

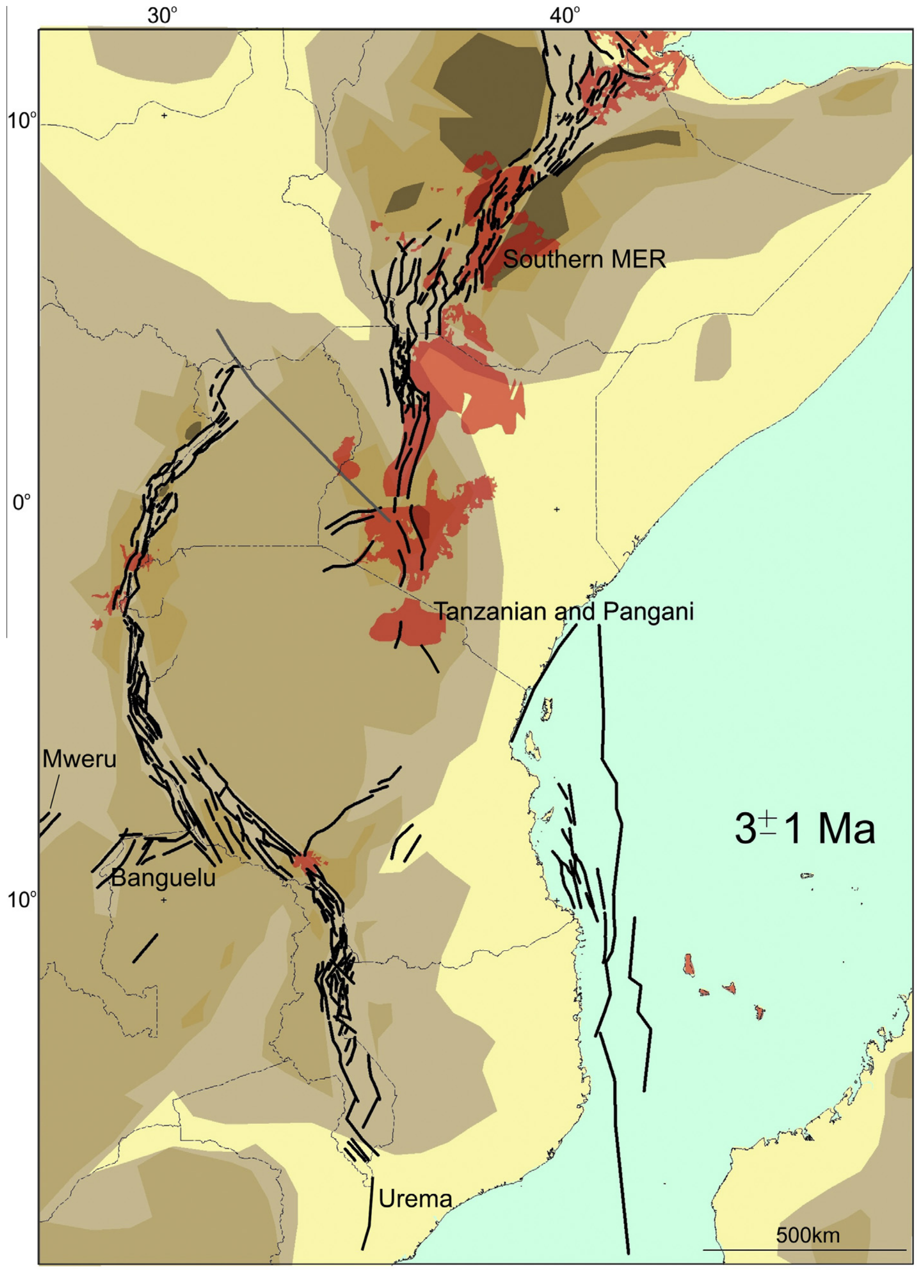

Fig. 11. Time reconstruction at 3 ± 1 Ma, Piacenzian, within main syn-rift phase of EARS 2 basins in most cases. Key events following on from previous map, but additionally: (1) southern MER rifting active (Bonini et al., 2005), (2) full graben now formed in southern Gregory (Saemundsson, 2010), (3) rift shoulder uplift in Albertine area, including Rwenzori mountains (Pickford and Senut, 1994), (4) assumed further rift propagation southwards and eastwards from Lakes Malawi and Tanganyika into basins that seem at Present Day to be still in early rift phase, (5) seismic lines in papers (e.g. Danforth et al., 2012) plus earthquake data (Craig et al., 2011) suggest recent activity offshore concentrated in southern Tanzania and Mozambique.

of the shoulders was not till the Pliocene and also by an Early Pliocene sediment surge to the Nile river containing Ethiopian-derived minerals (Fig. 13; Macgregor, 2012a). This timing is preferred here rather than the rift initiation date of 10 Ma previously published by Wolfenden et al. (2004). The Southern MER is proposed by Bonini et al. (2005) as a Late Pliocene–Pleistocene reactivation of the easternmost EARS 1 rifts, thus making the Ethiopian EARS 2 rifts of younger initiation than those further south in Kenya. It would seem therefore that, in addition to very young propagation southwards from the Afar, a further initial centre of rifting was formed in the Mid-Miocene in the Lake Turkana area and that rifts propagated both north and south from here during the Pliocene.

Multiple rifts in the Lake Turkana area show thick syn-rift geometries that can be tied back to the Plio-Pleistocene of the Eliye Springs 1 well (Vetel, 1995; Morley et al., 1999b; Hendrie et al., 1994, Fig. 14). This well drilled around 2000 m of Plio-Pleistocene rift strata above a volcanic level dated at 5 Ma, with an underlying 900 m of sandy section of indeterminate age, terminating some 500 ms above a reflector assumed to be top of the Mid Miocene volcanics. Seismic correlations extrapolated from this well (Dunkelman et al., 1989) indicate that the Plio-Pleistocene section expands to 4 s TWT below Lake Turkana, with considerable structural growth into the rift bounding faults. Further correlations can be made from this data to the South Omo rift of Ethiopia into seismic data illustrated by Africa Oil (2013), which again suggest

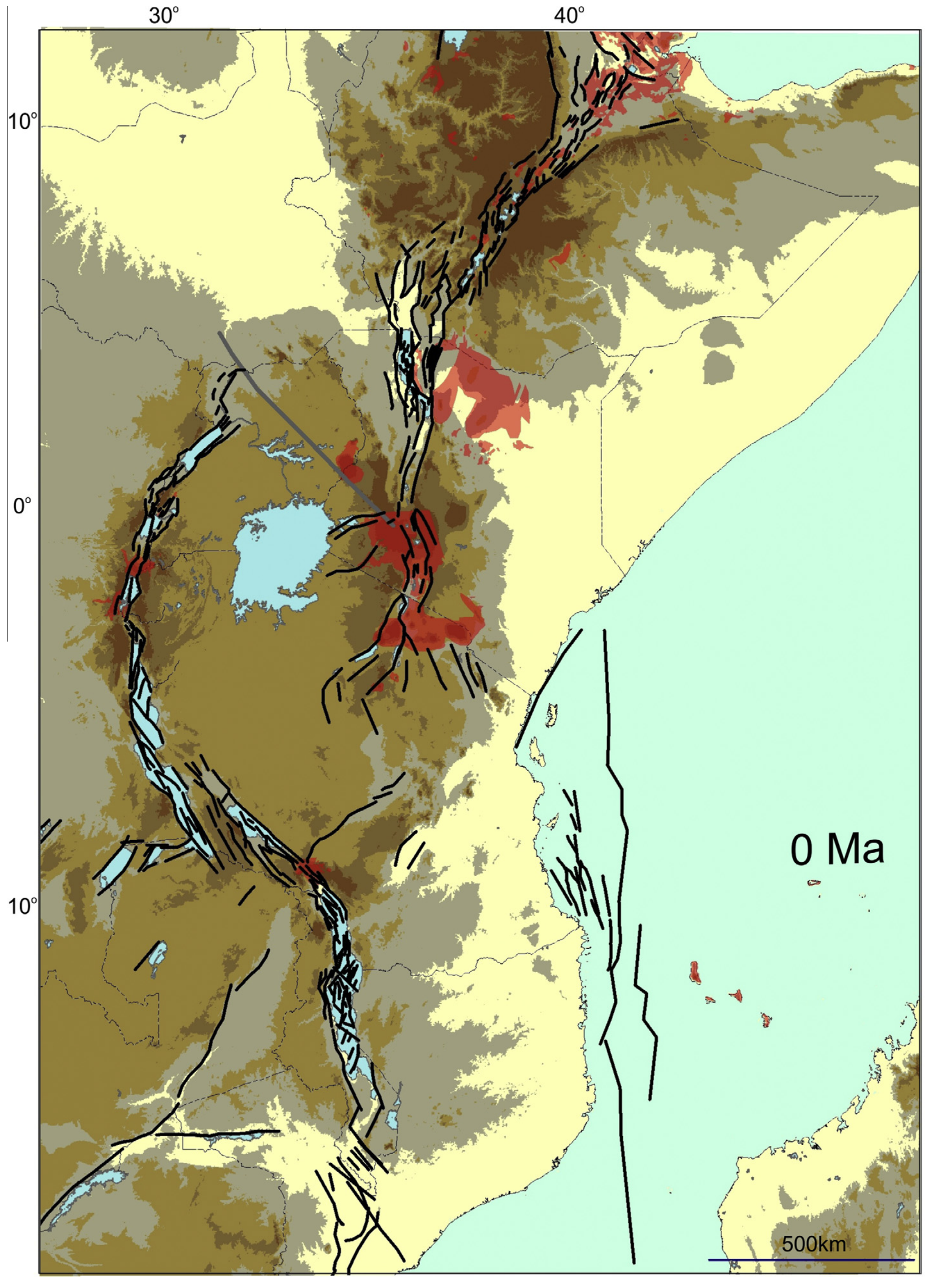

Fig. 12. Time reconstruction at 0 Ma, Present Day. Continued acceleration of subsidence, fault movements and formation of high topography within EARS 2 syn-rift phase. Topography shown in darkening 500 m segments. Active faults based on observed faulting to surface and earthquake occurrence (Craig et al., 2011; Nusbaum et al., 1993). Volcanism as at Present Day. Organic shales widespread below 100 m water depth in Present Day lakes.

that the bulk of the visible seismic section and structural growth is Plio-Pleistocene in age. Seismic correlations between the South and North Lokichar Basins indicate a shift between the sections of greatest thickness and structural growth from pre-Mid Miocene in South Lokichar to Late Miocene and younger in the North Lokichar Basin, with an unconformity marking this switch tentatively tied to near top Mid-Miocene by Morley et al. (1999b). On the basis of these interpretations, most authors (e.g. Morley et al., 1999b; Vetel, 1995) believe that the Turkana and other EARS 2 rifts represents an eastwards migration of the EARS 1 South Lokichar Rift, in which case rifting should have migrated sometime around the Late Middle Miocene.

The section in the isolated Chew Bahir Basin to the east of the Turkana complex is assumed here to again be filled primarily by Plio-Pleistocene section. Vetel (1995) interprets the main subsidence phase to be associated with the Plio-Pleistocene Kinu-Sogo fault belt (Fig. 14) to the south, which itself seems to reflect a further eastwards migration of rift activity.

Further south, a progressive younging southwards of both the ages of initial and maximum rifting is interpreted by Mechie et al. (1997) and Saemundsson (2010). The key evidence controlling the age of rifting in the Gregory Rift is the age and geometry of the well-known 13–11 Ma. Kenya phonolites (Wichura et al., 2011). With the possible exception of some onlap against the Elgayo escarpment of the northern Gregory rift, the phonolite flows show no evidence of thinning over the current rift-bounding faults, being instead suggestive of a low relief domal geometry centred over the Present Day rift area, as might be developed from a plume developed prior to rifting. This indicated topography was high but low angle at the time. Similar concepts are applied by the other

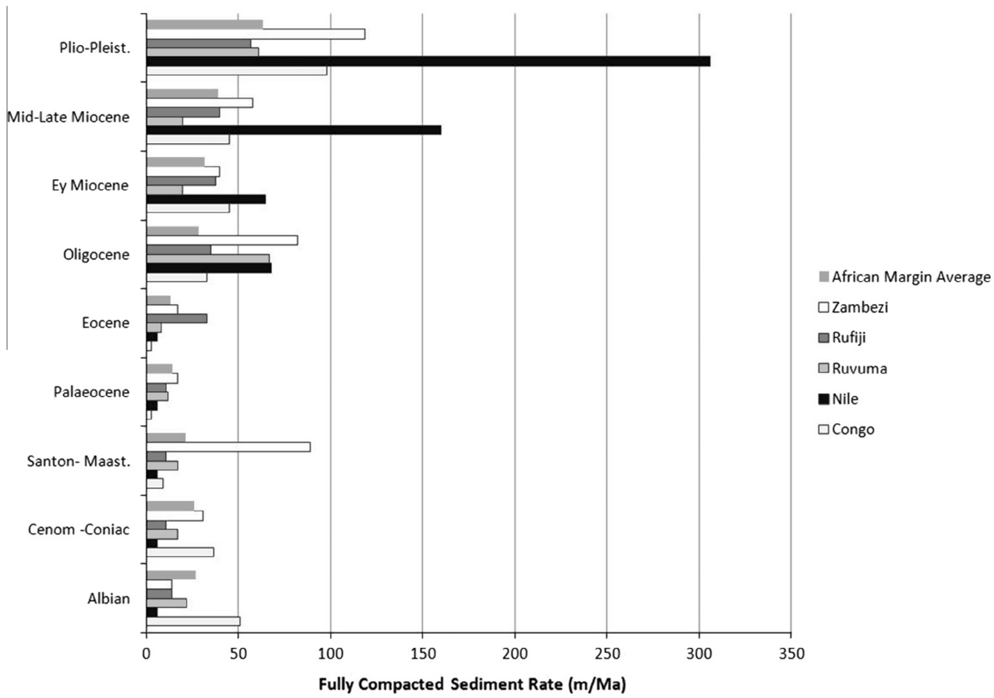

Fig. 13. Sedimentation Rates, corrected for compaction, in depocentres fed by east African rift shoulders. Note peak in Oligocene tied to northern South African plateau uplift of Moore et al. (2009), and thereafter a progressive buildup to modern times, which is proposed to be tied to increasing rift activity and vertical movements throughout the Neogene. For example, note major surge in Nile in Pliocene, which is tied to Ethiopian rift shoulder uplift as assessed independently by Gani et al. (2007) and Bonini et al. (2005). Methodology of calculations as presented in Macgregor (2012b). Data from cross-sections published by Abdel Aal et al. (2001), Cope (2000), Law (2011), Leturmy et al. (2003), Walford et al. (2005). African average calculated by author from circa 100 offshore cross-sections around Africa.

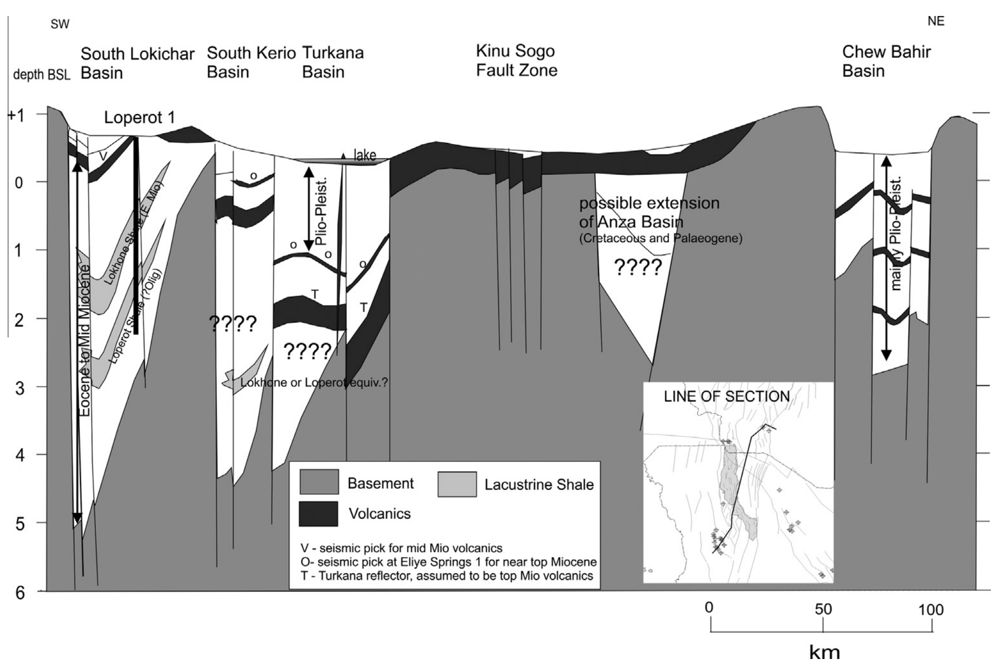

Fig. 14. Schematic cross-section through northern Kenyan and southern Ethiopian EARS 1 and EARS 2 rifts, based on seismic data and analyses within Morley et al. (1999b), Dunkelman et al. (1989) and Africa Oil (2013), plus authors review of public domain seismic. South Kerio and Chew Bahir Basin interpretations are speculative and await results of 2014 drilling.

authors listed below to date the formation of escarpments, which suggest that a half graben formed in northern/central Gregory around 7 Ma. (first seen in Fig. 10), evolving into a full graben by 4 Ma. (Fig. 11), but with peak rifting not taking place till the last 2 Ma, (Baker et al., 1971; Baker, 1986). In southern Gregory, faulting was not initiated until around 2 Ma and in north Tanzania not till around 1 Ma. (Foster et al., 1997; Dawson, 2008) These interpretations are summarised in sequential form by Figs. 10–13 of Saemundsson (2010), which are in agreement with the interpretations presented in Figs. 9–12 of this paper.

5.2. Western Branch

The Western Branch of the EARS 2 rifts extends from close to the Uganda/Sudan border, where it is linked to the Eastern Branch through the Aswa Fracture Zone (Fig. 1), to the Indian Ocean at Beira in Mozambique (Ebinger et al., 1989). The trend of rifts is less continuous than in the Eastern Branch, with a number of gaps apparent, e.g. in northern Burundi/southern Rwanda, together with some clear offsets (e.g. between the Rukwa and Lake Tanganyika rifts), that are still poorly located and understood. Contrasts with the Eastern Branch include the relative paucity of volcanics, which is clearly seen in a comparison of Figs. 3 and 4, and the greater depths of many of the rifts, particularly those below Present Day lakes. Examples of basement/base Neogene relief between outcrop on rift shoulder and maximum basin depth in the Western Branch are the Albertine Basin at circa 8 km, Lake Tanganyika at circa. 6 km., the Rukwa Basin (Neogene only) at circa 3 km., Lake Malawi at circa 5 km., whereas the Turkana Basin at 3.5 km. is the only Eastern Branch EARS 2 rift that is estimated to reach close to such magnitudes. It can be proposed that most extension in the Eastern Branch is taken up by dyke injection, with crustal addition of magma preventing the extremes of subsidence seen in the Western Branch (D.Delvaux, pers.comm., 2013).

With the exception of the Albertine Basin, the manners in which the timing of basin evolution can be interpreted in the Western Branch are less precise than in the Eastern Branch, and necessarily use some of the lower confidence techniques listed earlier. It is less often possible to link sedimentation and rift movements directly to volcanic ages and geometries and much of the sedimentary section is below water and thick Holocene sediment piles. The most confident correlations are between basins which have wells which penetrate the entire Neogene stratigraphy and/or have exhumed outcrop sections, namely the Albertine, Rukwa and Livingstone (Malawi) basins (Fig. 3). Constraints imposed by biostratigraphic and other forms of dating in the Rukwa and Livingstone Basins, as are summarised below, do appear to confirm that the initiation of the southern rifts is younger than the Albertine Basin. While peak rifting may be synchronous across the Western Branch in the Plio-Pleistocene, it would appear that the initiation of the milder underlying Miocene rift sections does young from north to south and indeed, for some of the rifts in the extreme southwest of the trend, rifting is only just commencing at Present Day (Modisi et al., 2000).

5.2.1. Albertine Basin

The Albertine Basin is the best controlled Western Branch rift, with an exhumed outcrop section present against the Plio-Pleistocene Rwenzori uplift and four published wells Table 1), two of which are tied to published seismic lines (see Fig. 5 within Logan et al. (2009), sketched as Fig. 15 here, and Fig. 9 within Karp et al., 2012). A small pre-Neogene precursor basin is mentioned by Davis et al. (2012) and by Abeinomugisha and Kasande (2012), which is probably Permian in age, as a small Permian graben outcrops to the west in the DR Congo.

There has in the past been some controversy between industry biostratigraphers and academics over the age of the Albertine Basin, which is best resolved by considering two areally distinct rift phases covering respectively the onshore southern part of the basin (the 'Semliki Basin') and the region around and below Lake Albert. The Turaco wells in the Semliki Basin contain a 1400 m thick Mid-Late Miocene section, comprising fluvial and lacustrine margin deposits, with a further second of TWT of section possibly present below the well (Abeinomugisha and Kasande, 2012). Lukaye (2009) dated this section as ranging down into the Early Miocene, though more recent publications quote Mid Miocene for the oldest sediments penetrated (Lukaye et al., 2012; Abeinomugisha and Kasande, 2012). Previous interpretations of Early Miocene dates from outcrop, which were based on mammalian fossil ages from the outcropping basal unit in DR Congo (Lepersonne, 1949), now seem to be discredited due to redating of these taxa to the Late Miocene (Yasui et al., 1992). Such dates support earlier work on the outcrop by Pickford and Senut (1994), who dated the earliest sediments at around 13 Ma. The combined well and outcrop data appears to evidence a rift in this region of Mid-Late Miocene, and possibly Early Miocene, age. The basin is currently shown as being initiated on the base Mid-Miocene map in this paper (Fig. 7) to accommodate the range of possibilities. It should be noted that this is the only direct evidence in the Western Branch at present for a Miocene section more than a few hundreds of metres thick.

A series of publications based on seismic tied to the Kingfisher 1 and Waki-1 wells, interpret a more dramatic Late Miocene-Recent (and predominantly Plio-Pleistocene) rift phase centred below the current lake (Fig. 15). Biostratigraphy on 30 wells around the lake has identified an age range of Late Miocene to Holocene (Shaw et al., 2011). An age of 8.5 Ma has been reported by Tullow for the base of the syn-rift succession below the lake in the

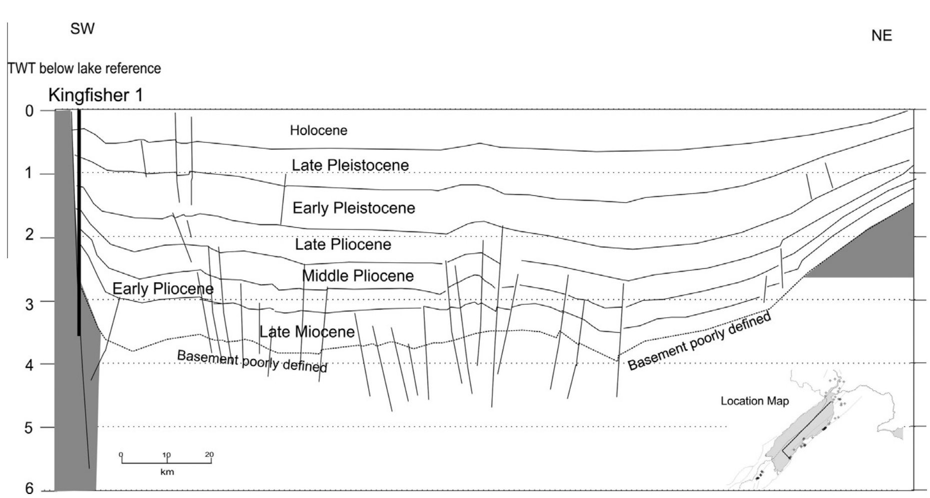

Fig. 15. Sketch of seismic line through Lake Albert, based on data within Logan et al. (2009) and seismic tie to biostratigraphic data in Kingfisher well (Shaw et al., 2009). Note extremely young nature of main rift fill and increasing sedimentation rates throughout Late Neogene section.

structurally deepest well at Ngassa 2 (McFerran and Ochan, 2011), which is more or less consistent with the onshore macrofossil-based dating of a major subsidence episode at 9 Ma interpreted from outcrop data by Pickford and Senut (1994). Stratigraphic ties on seismic lines suggest a thin Late Miocene section and then progressively increasing sedimentation rates and wedging into the border faults (Logan et al., 2009; Karp et al., 2012; Fig. 14) through the Pliocene and Pleistocene. The main rise of the rift shoulders, including the 5 km high Rwenzori mountains, are not thought to have taken place until around 2.6–2.3 Ma by Pickford and Senut (1994) (Fig. 11), with high altitude taxa not appearing in the Kingfisher wells until 1 Ma (Shaw et al., 2009).

5.2.2. Lake Edward to Lake Tanganyika

A well drilled in the Lake Edward Basin by Dominion (2011) reports a basal section dated as Late Pliocene. There is no dating possible on the Lake Kivu grabens, though Kampunzu et al. (1998), suggest rift initiation ages of about 4 Ma, based on changes in volcanic chemistry.

Lake Tanganyika overlies at least three discrete basins separated by highs where basement comes to or near to lakebed, each of which can be further separated into a switching set of half grabens. These are the most poorly dated basins in this study. With limited outcrop on the basin margins and only two wells drilled on the Burundi shoreline, which are composed entirely of undatable Neogene sands, there is near to no biostratigraphic control aside from cores a few metres thick. Carbon dating is available on these sections, indicating sediments at most, tens of thousands of years old (Baltzer, 1991). The lake is covered by the PROBE seismic programme (Rosendahl/Project Probe, 1988), with definition on these lines varying from very poor to excellent. Three seismic sequences have been identified on the best quality lines through the Kigoma Basin (Tiercelin and Mondeguer, 1991; Rosendhal (1988)), namely a basal, seismically transparent, near to planar, parallel bedded early rift or 'sag' unit ('Lower Magara Sequence' of Rosendahl/Project Probe, 1988), a block faulted, high frequency, high amplitude unit ('Upper Magara Sequence') and a thick more transparent deep lacustrine unit ('Kigoma Sequence'), the latter two sequences separated by an unconformity marking throw on the border fault and the formation of high rift shoulders. Three seismic sequences of similar character can be identified in the Marungu Basin in the southern lake (Fig. 16), though no seismic tie is possible due to intervening basement blocks and an intervening basin potentially dating to the Permian (see below). Dating of the sequences identified can be attempted in the Kigoma Basin through an extrapolation of Recent sedimentation rates, based on the carbon dating of lakebed cores ranging up to 10 m in penetration (Cohen et al., 1993) and relating these to calculations of sediment thickness from seismic mapping through the application of decompaction algorithms. As might be expected, a wide range of results is obtained, both by Cohen and from the author's own remapping and calculations, though estimated dates of the base of the sedimentary sections group around 9–12 Ma., those for the age of the top of the Lower Magara Sequence around 6–11 Ma, and those for the 'rift shoulder' unconformity at the base of the Kigoma Sequence ('Kigoma Sequence Boundary') between 2–5 Ma. Such dates would suggest a broad correlation of events to that of the Albertine Basin, to which there is some similarity in seismic facies and character. However, these estimates need to be considered together with an assessment as to how sediment rates in the subsurface may relate to those measured in the Holocene. Baltzer (1991) describes Holocene core sections as rich in biogenic material and high in organic content (e.g. laminated diatomites), facies that would normally be taken as indicative of a low clastic sediment supply. It is therefore possible that sediment rates were higher in the past, which would imply the dates above are overestimates, in which case the base of the Neogene section could be younger than that estimated by this technique. No firm estimate can thus be reached and two dating models remain possible, representing either a similar age of basin initiation to the Albertine Basin (i.e. circa. Mid Miocene) or to the Rukwa Basin (Latest Miocene?, Fig. 16). An intermediate case between these two models is shown on the figures of this paper.

Part of the southern part of the lake (Kalemie Province of Rosendahl/Project Probe, 1988) is suggested to contain an

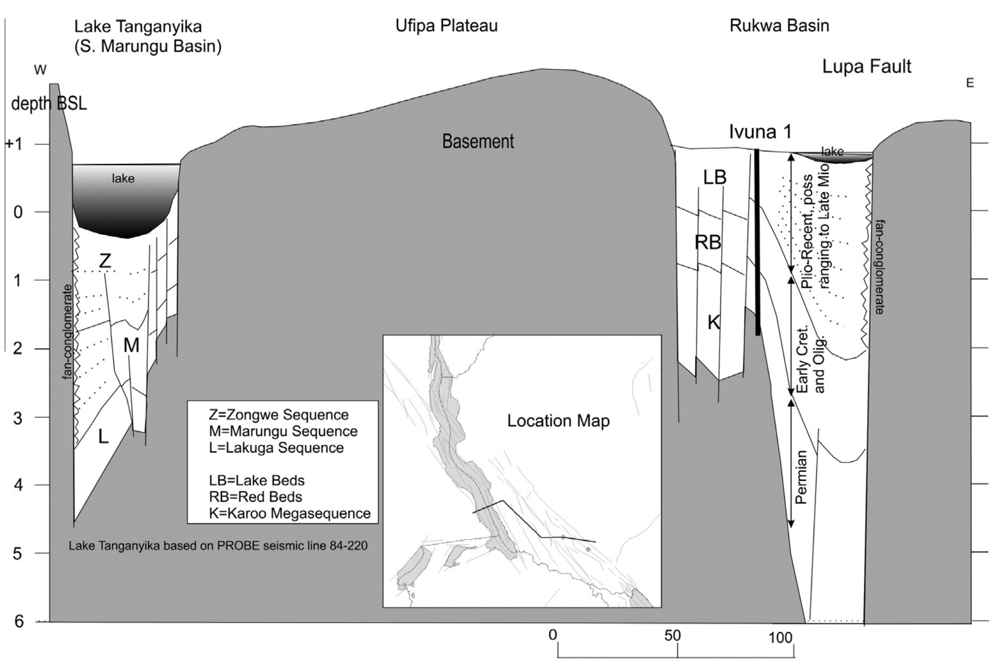

Fig. 16. Schematic cross-section through southern Lake Tanganyika and Rukwa Basin EARS 2 rifts, based on seismic data and analyses within Rosendahl/Project Probe (1988), Morley et al. (1999d), plus authors own mapping. Lake Tanganyika ages are speculative but Rukwa Basin ages are well controlled by biostratigraphy (Wescott et al., 1999; Roberts et al., 2012).

underlying Karoo (Permian) rift by two of the PROBE lines (lines no 214 and 216 in Rosendahl/Project Probe, 2008), which terminate a few kilometres from Permo-Triassic exposures onshore in DR Congo and show an angular unconformity that most reasonably can interpreted as one between Permo-Trias and Neogene section. This Karoo rift is likely offset by a transform into the Rukwa Basin, which also contains a thick section of this age. It seems unlikely that the Karoo section extends into the extreme south of Lake Tanganyika (Marungu Basin, Fig. 16), where mud diapirism is apparent in the basal part of the section, which seems unlikely to be rooted in section of Permian age.

5.2.3. Rukwa to Mozambique

The Rukwa Basin is a multiphase half-graben developed along the NW–SE Ubendian line of weakness, with non-marine sections dated in wells and outcrop of Permian, Early Cretaceous, Oligocene and ?Latest Miocene to Recent age (Roberts et al., 2012; Wescott et al., 1991, Fig. 3 of this paper). Interestingly, the main depocentre seems not to have moved significantly between rift phases (Morley et al., 1999d). The EARS 2 section dating is based on palynological evidence from two vintage Amoco wells. Section of Pliocene age is confirmed while the presence of Late Miocene spores is doubtful (Wescott et al., 1991), thus the range of dates seen is narrower and younger than that in the Albertine Basin. Neogene basin initiation is thus estimated at around the Mio-Pliocene boundary. As the onset of the Neogene Rungwe volcanics on the continuation of this basin to the south is about 8 Ma, some 2 My younger than the oldest dates in the Virunga complex (Kampunzu et al., 1998; Ebinger et al., 1989), a diachronicity seems to be evident in both estimated rift initiation and volcanic dates. The two wells encountered a mixed lithology EARS 2 section, respectively 700 and 969 m thick, though this is interpreted to reach over 3000 m in the deepest parts of the half graben, though with no significant additional section appearing by onlap between the wells and basin deep. The published seismic through the basin deeps indicates a uniform thickening of the rift section without major vertical facies variations.

Lake Malawi, like Lake Tanganyika, is best viewed as a composite of basins (Flannery and Rosendahl, 1990; Scholz/Project Probe, 1989). On the basis of the outcrop geology studied in a number of narrow onshore rifts in northern Malawi (Dixey, 1927), there seems little doubt that the NW–SE trending Livingstone Basin will, like the Rukwa Basin, contain a composite rift section of Permian, Cretaceous and Late Neogene (EARS 2) age (Delvaux, 2001). The size of the Bouguer gravity anomaly measured by Ebinger et al., 1993 over the northern extension of the basin suggests that the total section exceeds 6 km, with the majority being low density sediments, which when compared with sediment densities onshore in rift sequences of different ages, suggests the majority of the section in the offshore deep is Neogene EARS 2 section. Recent Heritage Oil seismic data (R. Downie, pers comm., 2013) in the onshore Tanzanian extension of the basin, indicates a 4–4.5 km section, mainly Neogene in age. The PROBE seismic (Scholz/Project Probe, 1989) in Lake Malawi has less penetration than in Lake Tanganyika, possibly due partly to higher structural dips and partly to the presence of a thick transparent mobile shale unit that further south is expressed as mud diapirism. As such, it is not currently possible to confidently identify any seismo-stratigraphic subdivision of the rift section.

The tectonic history of the Livingstone Basin is likely to be similar to that of the Rukwa Basin (Delvaux, 2001). Indeed, recent gravity acquisition and analysis by Heritage Oil suggests the two basins may be connected below the Rungwe volcanics (R. Downie, pers. comm., 2013). Offshore seismic lines indicate that there has a series of uplifts towards the western shoreline, with a dipping Pliocene outcrop section exhumed below a Pleistocene unconformity. This geometry should expose sediments close to the base of the Neogene section. Macrofossil dating in the Neogene section of a small onshore extension of the Livingstone Basin extends to somewhat older than 4 Ma. (Bromage et al., 1995; Ring and Betzler, 1995). Between these datable horizons and the underlying Cretaceous lies a thin series of fluvial sands, which in the Tanzanian part of the basin also overly a 8.5 Ma old tuff. This seemingly constrains the onset of the basin to between 4 and 8.5 Ma.

Further south, as Lake Malawi turns to a N–S trend to follow Mozambiquan rather than Ubendian basement trends, the Usisya-Mbamba half-graben is developed. While PROBE seismic definition at depth remains unclear over much of the basin, there is a region around the 390 m deep Syracuse A Borehole where definition improves substantially. As shown on Line 828 in the PROBE Seismic atlas (also Fig. 4 of Scholz et al., 2011), three main seismic units seem to be present in this area, from top to bottom: a banded interval ('Mbamba-Baobab Sequence' of Scholz/Project Probe, 1989), which ties to interbedding of shallow organic poor and deep lacustrine organic rich muds in the borehole (Lyons et al., 2011), a transparent sequence underneath ('Nyasa Sequence'), which can be assumed to be composed of mobile deep lacustrine mud, based on the observable rooting of several diapirs in this section, and a lower planar banded sequence (unnamed) separated from the mobile mud by an angular unconformity. This lowest unit can be speculated to be either an early rift-sag unit or perhaps a Cretaceous sandy section, as seen in outcrop in the Livingstone Basin. The base of the Syracuse A Borehole within the Mbamba-Baobab sequence has been dated at 1.2 Ma (C. Scholz, pers comm., Fig. 3), and using the same sedimentation rate and decompaction techniques as in Lake Tanganyika (with a rather lower degree of uncertainty as the sedimentation rate is here measured over a 390 m section), the base of the Nyasa Sequence, assumed here to be the basal rift section, would be calculated at 7 Ma, which is within the range of dates interpreted from outcrop data for the onset of the Livingstone Basin to the north. On the combined evidence, the initiation of the first mild faulting in northern Lake Malawi is predicted at around Messinian in age, with most subsidence and rift activity again occurring in the Plio-Pleistocene (Fig. 3). This also suggests a synchronous section with the Lake Rukwa Basin.

A clear basement reflector appears in the southern part of Lake Malawi marking a thinning of section southwards. There are no indications of pre-Neogene rifts in this region. The South Malawi half graben, on the border with Mozambique, is however again clearly of composite Permian, Cretaceous and Late Neogene age (Castaing, 1991), as demonstrated by the outcrop on its flexural margin. Moving further south into Mozambique, if the slight younging trend continues, the Urema Graben can be assumed to contain a Plio-Pleistocene section exploiting the trends of former Permo-Triassic and Early Cretaceous rifts. The Western Branch finally peters out in the offshore waters south of Beira in Mozambique.

It should finally be mentioned that new NE–SW splays of the system are now forming through the DR Congo, Zambia, Zimbabwe and Namibia, extending to the Okavango (Fig. 12), and often exploiting Permian rifts. These incipient basins are of similar widths to the Western Branch rifts but of much lesser depth and often show sag-like shapes with minor bounding faults. (Modisi et al., 2000; Mondeguer et al., 1989). They are generally filled with fluvial sands and possibly form models for the Late Miocene, planar, seismically transparent, basal sequences described in the Kigoma and Marungu Basins of Lake Tanganyika. Similar basal seismic sequences may also be interpreted in the Albertine and Turkana Basins, though are not recognised in the Rukwa Basin. These Namibian and Zambian basins have yet to enter the main syn-rift stage, as represented by the Kigoma and Zongwe Sequences of the Lake Tanganyika rifts (Mondeguer et al., 1989).

6. Offshore branch

The so-called offshore branch was first described by Mougenot et al. (1986), who described the Pemba, Mafia, Kerimbas and Lacerda basins as Neogene rifts. There has unfortunately been no subsequent data published in peer reviewed publications and there is no publically available seismic dataset. Recent seismic offshore illustrated in oil industry conferences and articles has however delineated these further, extending the trend to the north to the southern Lamu Basin. This assessment is heavily based on a few seismic lines and well ties (Simba 1, Maridadi 1, Windjammer 1) accessible in such publications (see for instance PanContinental Oil and Gas, 2003; Danforth et al., 2012; Law, 2011).

The authors interpret two phases of rifting in the Oligocene-Early Miocene (onset circa. 22 Ma) and Late Miocene (circa 10.5 Ma) to Recent (Parsons et al., 2012; Jeans et al., 2012; Danforth et al., 2012). These two phases could be speculated to correspond to the periods of peak rifting of the EARS 1 and EARS 2 rifts onshore, though more precise stratigraphic control is required. The EARS 2 rift section reaches 1800 ms TWT thickness on seismic in the Pemba Rift and over 4000 ms TWT in the Kerimbas Rift (Danforth et al., 2012). In the latter case, there is also 1500 m of relief on the seabed, which indicates much of the fault movement is very young. The continued activity of such lineaments in southern Tanzania and Mozambique is also demonstrated by recent earthquake activity (Craig et al., 2011).

While it could be possible to broadly relate the timing of events in the Offshore Branch to those in the Western and Eastern Branches, it should be pointed out that these offshore rifts have very different characteristics. In particular, they lack kilometre scale relief rift shoulders (the largest being Pemba Island), are more symmetrical in form than the typical half grabens onshore, do not seem to have any significant igneous association and are associated with some significant and still active transpressional features such as the Davie and Seagap Fault Zones. They can also be expected to differ in their stratigraphic fills, which are expected to be entirely marine. Rifting is also interpreted to have commenced much earlier than in the geographically closest parts of the Eastern Branch, e.g. the Pliocene Pangani Rift, and they cannot therefore be part of any progressive rift unzipping trend from the onshore. Their formation can perhaps be more readily linked to wrench tectonics along the nearby Davie Fracture Zone. As such, given the lack of clear fault linkages between the two systems on most of the maps illustrated here, a direct genetic link between the onshore and offshore EARS rifts remains uncertain at this time, The similarities in timing however suggest that they may well be indirectly linked in the greater scheme of regional plate tectonics.

7. Petroleum implications

At the time of writing (2014), two diverse petroleum systems have been established within the EARS system, within the South Lokichar and Albertine Basins. The former is thought to be charged from an Early Miocene lacustrine source rock (Fig. 4), which shows a distinct wedge-shaped geometry on seismic reflection data (Morley et al., 1999b), and is thought to have been deposited during the peak of the EARS 1 rift cycle, which as pointed out in this paper, affects only this and a few adjoining basins. Reservoirs are also mainly of Early Miocene age. The Albertine Basin petroleum system is representative of the more widespread EARS 2 rift cycle, with a source rock thought to be of Late Miocene-Early Pliocene age (Fig. 3; Sserubiri and Scholz (2012)) and oil bearing reservoirs ranging from Late Miocene to Late Pliocene age (Abeinomugisha and Kasande, 2012). Both petroleum systems seem to show evidence of an active Present Day charge system with thin siltstones acting as effective top seals and fault planes, upthrown basement juxtaposition and fault plane conglomerates as side-seals (e.g. Lays, 2013). This is a marked contrast to older African rift systems such as Sudan, where fault planes generally do not seal (Idris and Yongdi, 2005) and this difference seems to be largely responsible for the existence of substantial oil columns and thus economic scale reserves.

Many of the attempts to analyse prospectivity elsewhere are based on trying to extend analogues from these two proven petroleum systems. This paper suggests that perfect analogues are rare in terms of the timing of the structural events controlling the elements of the petroleum system, with different basins active at different times. A preferred approach to assessing prospectivity is to use these two analogues as guides to where source rocks and reservoirs are likely to be developed in relation to the structural history of the basin concerned, e.g. deep lacustrine source rocks are most likely to be developed during underfilled conditions during peak rifting, conditions which are suggested in this paper to be concentrated in the Early Miocene and Latest Miocene to Recent. Additional complexity and opportunities are imposed in basins which have underlying pre-Neogene rift sections rich in reservoirs which could possibly be charged from overlying Neogene source rocks. Volcanism and its detrimental effects on clay mineralogy and reservoir quality is a clear issue in Eastern Branch basins (Tiercelin et al., 2004; Tiercelin, 2009).

In summary, the East African Rift System is a diverse set of rifts and this diversity will be reflected in its petroleum systems. There are likely further petroleum systems to be discovered in these basins but they may not be perfect analogues to those already established. The explorationist may thus need to apply elements of analogue from several rifts of different ages to identify new plays in these basins.

8. Conclusions

It is suggested here that 'EARS' Cenozoic rifting can be broadly split into two cycles, one peaking in the Late Oligocene-Early Miocene and confined largely to northern Kenya and southern Ethiopia (EARS 1), and the more widespread 'EARS 2' system, which originates as low relief depressions and shallow rifts in a few nucleation centres in the Mid-Late Miocene. There seems to be a broad southwards younging trend of the initiation of EARS 2 rifting in the Western Branch, from Mid-Miocene in Uganda to Latest Miocene in Rukwa and Malawi, as well as southwards across Kenya in the Eastern Branch and at the extreme southern ends of both these systems, rifting has only been initiated in the last few million years. There are however other regions, e.g. southern Ethiopia and Lake Tanganyika, where the initiation of rifting seems to have propagated northwards. This complex pattern on rift initiation is however accompanied by the observation that peak rifting, subsidence and sedimentation in the majority of basins is Plio-Pleistocene, with many of the most significant events such as rift shoulder uplift not taking place until the last 1–2 My. More data continues to be required to develop these maps and models and it is hoped more precise data will shortly become available from the ongoing drilling, whereby these maps will undoubtedly need revision.

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