The East African Rift System: Does It Have Oil and Gas Potential?

Bernard Kipsang Rop, Seroni Anyona and Michael Kinyua

Abstract – The East African Rift System (EARS) is one of the most extensive rifts on the Earth's surface, extending from Afar in Ethiopia, southward through Kenya, Tanzania up to Mozambique. The system is 4,000 miles (6,400 km) long and 30–40 miles (48–64 km) wide. The EARS and its associated sedimentary basins, is one of the most active rifts in the world. Recent oil and gas discoveries in Kenya and Uganda have increased the impetus of prospecting within the extensive rift by international oil companies. Understanding the rift genesis and its evolutionary tectonic setting will help unearth the full hydrocarbon (oil and gas) potential of the EARS. This paper is premised on the rift formation history and its impact on oil and gas prospects.

Keywords: Rift system, sedimentary, hydrocarbon (oil and gas), tectonic setting, prospects.

I. INTRODUCTION

When continents break up they often break-up parallel to ancient orogenic belts. The easiest way to initiate this breaking up of continents is to reactivate long-lived crustal scale weakness zones by trans-current movements (Vauchez et al., 1997). The determination of the rifting process and associated uplift is key to unraveling the evolution of East Africa Rift System (EARS). The shape and appearance of EARS was hugely influenced by tectonic activities which begun in early Tertiary. This marked the beginning of uplift and warping which was followed by volcanism and faulting of the African Metamorphic basement; this continued in severally phases from early Tertiary until Pleistocene (Baker et al., 1972; Rop, 2012). The upper Paleozoic and Mesozoic sediments are mostly found preserved in the tectonic troughs.

The EAR system is still an active system where the Earth's tectonic forces are presently trying to create new plates by tearing old ones apart. These splitting forms a new plate (Somali plate) while the Nubian and the Somali plates continue to move from each other and also further from the Arabian plate (Figs 1, 2 and 3). All the three plates join to form the triple junction (Afar region) at the Red Sea. The oldest part of the rift is at the Afar triple junction region in Ethiopia and Eritrea where the EARS is considered to have originated, moving downward through the Ethiopian Dome (Afro-Arabian Dome). The Turkana depression abuts both the Ethiopia and the Kenya domes but to the south is the Tanzania Divergence where the rift meets the Tanzania Craton. The rift splits further into Western branch starting from Lake Victoria, though the two rifts do not join at the top. Klemse et al. (2010) opined that ancient dense rock shield underlying the Lake Victoria resisted the faulting and caused the rift to produce the East and West branches. The two rifts continued to propagate downwards, one through Kenya and the other from Lake Victoria, before they both join and die out in Malawi.

The tectonic rifting in the region has continued to create a series of asymmetric grabens and half-grabens along the EARS since the Late Permian up to Tertiary period. These grabens have over the time continued to subside due to continental separation and compounded by increased rapid sediment loading, with input from sediments from the Highlands. The orientations of the rift basins and grabens are controlled by the tectonic regimes.

The EARS is an active continental rift zone with elongate morphology. The complete rift system extends 1000's of kilometers in Africa alone and several 1000 km more if we include the Red Sea and Gulf of Aden as extensions. The rift system is dominated by extensional block faulting (Bloom, 2009) and characterized by two main rifting trends. These trends are defined as the Eastern and Western Branches, with several phases of superimposed rifting having occurred (Girdler, 1983; Green et al., 1991; Michael Hall et al., 2011). The rifting is estimated to have started in Early Tertiary in the north and propagated south with time. Using U-TH thermo chronology however Raphael et al.(2008) concluded that rifting could have probably started not later than 20 Ma during the Neogene to Early Miocene, although this has however been disputed by some scholars (Davidson and Rex, 1980).

The EARS is considered as having provided an excellent opportunity to investigate plume-driven continental rifting. The eastern branch of the EARS extends over 2000 km from the Red Sea southward to Mozambique (Fig 2). It crosses two regions of topographic uplift, the Ethiopian and Kenyan domes, both regarded as the surface manifestation of mantle plumes; between the two domes lies the Turkana Depression overlying the older Anza graben which is a zone of NW–SE extension that developed in the Early Cretaceous (Winn et al. 1993).

The Turkana Depression is considered anomalous in that it is a site of Quaternary volcanism yet displays no uplift attributed to a mantle (Walsh and Dodson, 1969;Tanya Furmanet al., 2004).

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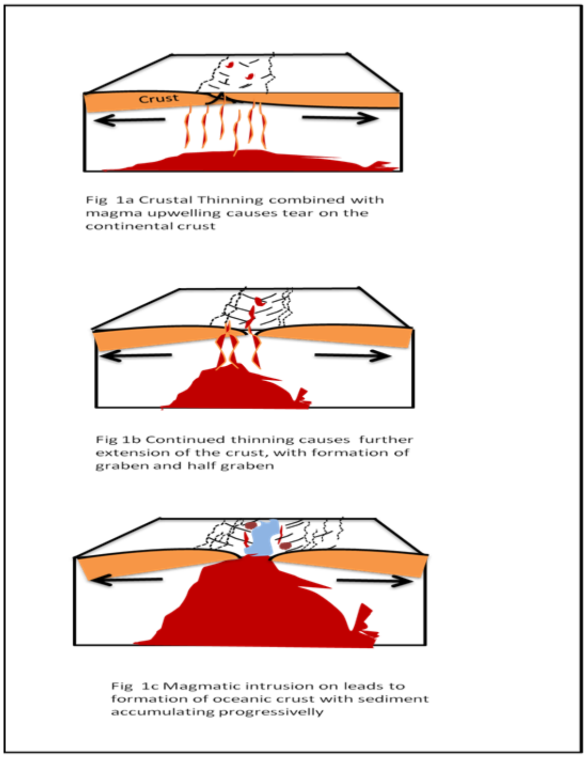

Fig. 1: Map showing crustal thinning and magmatic intrusion causing rifts

Two models have pointed into the evolution of the EARS. The first model indicates presence of Hotspots in the mantle causing massive crustal uplift (Fig. 1a) in early Miocene. This swelling and thinning of crust created highlands of thousands of meters and continued to swell, expanding eastwards, creating cracks that opened up along weak fault lines (Klemes et al., 2010). This is theory is complimented by studies conducted by Davis and Slack (2002) where in comparison of S-wave delays and P-wave tomography, they characterized the rising Limb and melt zone of an inferred mantle convection cell beneath the Kenyan dome and Ethiopian dome. They suggested that East African rifts resulted from separation of deeper mantel upwelling into three currents that impinged and eroded the base of the lithosphere, their thermal buoyancy drove the domal uplift and brittle failure of the upper lithosphere forming the rift grabens (Fig. 1a-c).

The second model proposes that tension caused by the crustal plate sinking under the Iranian plate pulled the Arabian plate, and subsequently pulled open the Red Sea thus tearing Africa plate part (Klemes et al., 2010). Some Geologists describe the rift as a failed rift, evident by the fact that as the Arabian plate moved eastward and outward creating the Red Sea and initiating the tear of the Africa plate, African plate remained relatively immobile as the Arabian plate broke away. It should be noted however that the EARS is still active to date.

The most significant control on the current rift morphology is the Tertiary to Quaternary rifting, manifested in the general north-south orientation of the rift structures (Rop, 2012; Barker et al., 1972). This dominant trend truncates structures formed during previous rifting events, namely the Late Permian to Early Jurassic 'Karoo' events and the Cretaceous event. Karoo rift basins are concentrated in the south of the EARS, predominantly in Mozambique and Tanzania; and include the NNE-trending Luangwa rift and the Selous graben, trending NE to SW (Michael Hall et al 2011). Both the Eastern and Western branches exhibit different structural trends with the former having a general trend of NE-SW in the north, then NNE to SSW at the Ethiopia-Kenya border, before deflecting N-S at Lake Baringo. A series of small rifts branch off from the main structure at Lake Turkana, before terminating directly north in southern Ethiopia (Fig. 2).

The main difference between the Eastern branch and the Western arm of the EARS system is that the Eastern part is dominated by volcanic activities with two dominant uplift in Kenya and Ethiopia forming the two main domes, this arm also has frequent micro seismic activity. The western part is associated with low volcanic activity but has generally higher thickness; large scale earthquake activities are also frequent in this arm. The higher volcanic activities in the Eastern arm generates higher geothermal gradient within the basins.

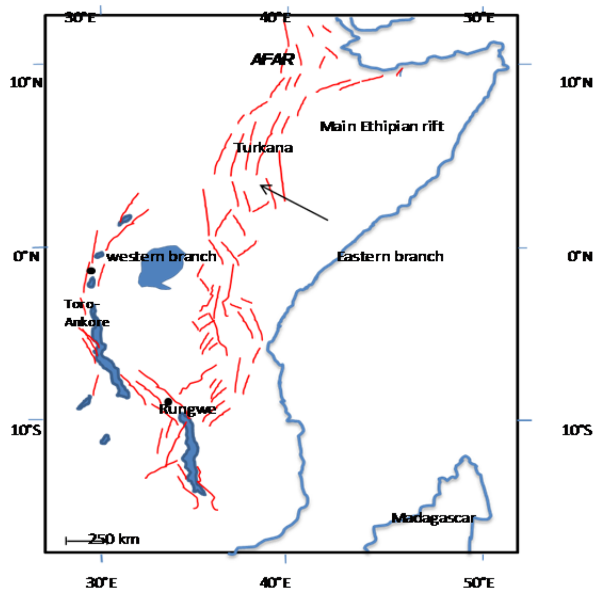

Fig. 2: The East African rift systems, the main Branches of the rift and the general trend

However, the western rift arm is bounded by high angle normal faults system of a spoon shaped basins (Fig. 2). This rift stretches from the border between Uganda and Sudan in the north, to the major rifts of Lake Tanganyika and Lake Nyasa (Malawi) - predominantly trending north-south except where it diverts around the Tanzanian Craton near Lake Tanganyika.

II. RESULTS AND DISCUSSIONS

The Glaciers of East Africa roughly divides the EARS into 5 major sections namely: The North Afar depression, Main Ethiopian rift, Turkana depression, The Gregory rift and Kavirondo rifts and North Tanzania divergence.

The Afar Rift and the Main Ethiopian Rift sectors are believed to contain grabens of variable sizes, some of which have high hydrocarbons potential. The Afar rift at the triple junction of the Red sea, Gulf of Aden and the East African rift systems is bordered to the north by Danakil horst, to the west by the Plains of Djibouti republic to the southwest by the Ethiopian Plateaus with varying thickness between 1500 to 300 m. The Afar rift has experienced varied sequential phases of arching in its evolutionary development. The early Tertiary marked series of rifting and subsidence of the crust with repeated sequence for a long period produced what's now a series of horst and graben structures conducive for hydrocarbons exploration.

The rifting extended from the southern end of the Afar Rift southward, along the axis of the eastern branch of the East African Rift System (EARS), up to the northern tip of the Southern Rift Basins. The Main Ethiopian Rift (MER) broadens towards north into the Red Sea and Gulf of Aden rifts (Fig. 4). The development of most of Ethiopia sedimentary basins is related to the extensional tectonic events that have taken place intermittently since the Late Paleozoic and continued up to Tertiary. The Ogden, Abay and Mekele basins are presumed to be intracontinental rift basins formed as a result of extensional stresses that brought out continental rifting as a part of the major Gondwanaland breakup in the Late Paleozoic time and continued in the Mesozoic and Tertiary. This movement was accompanied by a stupendous outpouring of the lava flows (Rop, 2012).

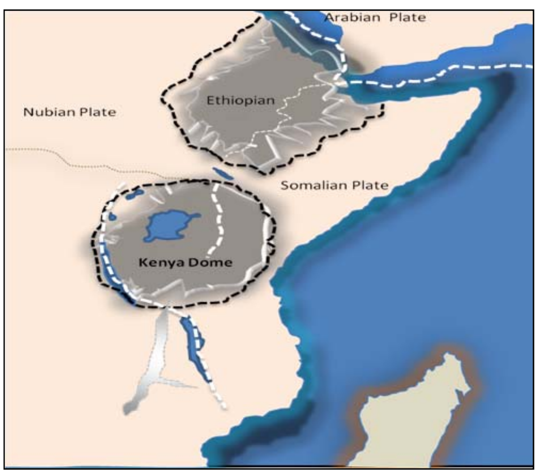

Fig. 3: Colored Digital Elevation Model showing tectonic plate boundaries outlines of the elevation highs demonstrating the thermal bulges and large lakes of East Africa. The base map is a Space Shuttle radar topography image by NASA. Delvaux (2000)

The Main Ethiopian rift extends between the Kenyan dome and the Ethiopian dome (Barker et al 1972). The rift was formed by repeated warping of the crust preceded and accompanied by faulting and volcanism. Visible divergent faults characterize the margins of the domed uplift of the Kenyan dome. Lake Victoria forms a shallow depression in a broad field of Precambrian metamorphic and igneous rocks that span across Kenya, Uganda, Tanzania and Sudan (Fig. 3).

The main Ethiopian rift is a result of a large scale down warping of the entire East African continent which is suggested to have taken place during Upper Triassic to Lower Jurassic time and the subsequent fluvio-deltaic sediments deposited over a large area, which extends from western to northern regions of Ethiopia. The basin is covered with marine sediments, varying from shelf to deep basin types, deposited over a large area. It is noted that Lateral variation on the sedimentary facies was controlled by the sub-basins that formed by recurrent faulting and tilting of the main fault block during Jurassic age. The regression of the sea from the region began in Late Jurassic as the result of arching and doming of the Arabian- Somalian massif, and sediments of varying facies (restricted marine, lagoonal and supertidal to inter-tidal) were deposited in structurally controlled domains. By Late Cretaceous, the sea completely withdrew leaving behind regressive continental clastics, consisting mainly of sandstones, with some intercalation of shales (Rop, 2013).

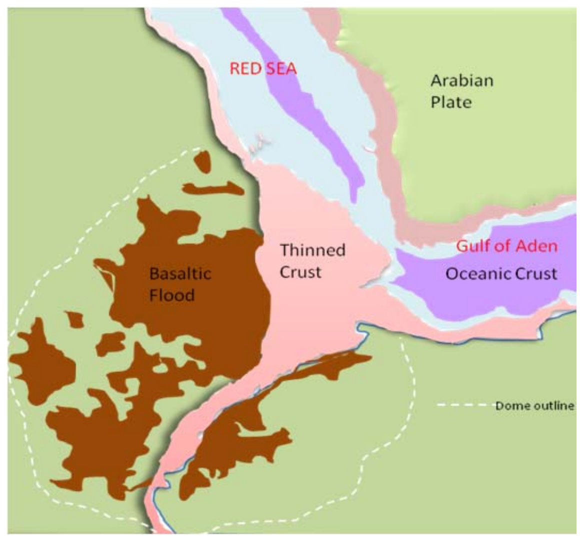

Fig. 4: Triple Junction in the Afar region of Ethiopia. Image shows areas of stretched and oceanic crust as well as areas of exposed flood basalts that preceded rifting. Areas unshaded or covered by flood basalts represent normal continental crust. As the crust is pulled apart you end up with thinned crust with a complex mixture of continental and volcanic rock. Eventually the crust thins to the point where oceanic-type basalts are erupted which is the signal that new ocean crust is being formed. This can be seen in the Gulf of Aden as well as a small sliver within the Red Sea. The original extent of the flood basalts would have been greater, but large areas have been buried within the rift valley by other volcanic eruptions and sediments. The basemap is a Space Shuttle radar topography image by NASA. Delvaux (2000).

The southern Ethiopian rift developed from late Oligocene to Early Miocene and has continued periodically to the present day. Southern Ethiopia contains the South rift basin which extends from Kenya as a continuation of the Oligocene rift systems of the northern Kenya, the southern rift basins are characterized by N-S striking Omo and Chew-Bahir basins that lie within the broadly rifted zone of southwest Ethiopia. There is high possibility of existence of sediments of Jurassic-Cretaceous rift system underneath the Tertiary rift strata. This suggestion is based on Bouguer gravity data which indicates E-W-striking structures in the area that correlate exactly with E-W striking strike-slip faults (or an EW fault zone) linking the Southern Sudan rift (which includes the Muglad Basin) with the Anza Graben of northern Kenya (Rop, 2012). The southern Sudanese Mesozoic (Late Jurassic-Cretaceous) rift basins are known to be petroliferous (Schull, 1988), with large oil field discoveries mainly in the Muglad and Mulet Basins; it appears likely that the suggested Mesozoic sediments beneath the Tertiary strata could be potentially attractive for oil/gas exploration in the Omo and Chew Bahir Basins as well.

The Eastern branch of the EARS roughly bisects Kenya, north-to-south, on a line slightly west of Nairobi (Fig. 2). Lake Victoria sits between these two branches. It is thought that these rifts are generally following old sutures between ancient continental masses that collided billions of years ago to form the African Craton; the split around the Lake Victoria region occurred due to the presence of a small core of ancient metamorphic rock comprising the Tanzania Craton that was too hard for the rift to tear through (Fig. 2). Because the rift could not go straight through this area, it instead diverged around it leading to the two branches that can be seen today.

Similar to Ethiopian dome is a topographically elevated dome situated in central Kenya (Fig. 3) which is considered a hot spot. This is almost exactly analogous to the Ethiopian dome, and in fact, some geologists have suggested that the Kenya dome is the same hotspot or plume that gave rise to the initial Ethiopian rifting. However there is a clear cause that the two rifts are separated enough to justify giving them different names, but near enough to suggest that they are genetically related. The Cenozoic rift basins of the EARS in East Africa are generally superimposed on Paleoproterozoic mobile belts surrounding the Tanzanian Craton (McConnell, 1972). They were formed mostly by extensional processes, but largely reactivated older basin systems. In the Ubende belt, along the western margin of the Tanzanian Craton, sedimentary basins formed as early as in the Mesoproterozoic, apparently in a strike-slip context (Klerkx et a, 1998). Tanzanian Basins that fall within the EARS include the Tanganyika-Rukwa-Malawi (TRM) segment. This segment is a good example of a long-lived weakness zone that was repeatedly reactivated, even after long periods of tectonic quietness. It was shown that the Permo-Triassic Karoo rift system developed in response to intraplate transpressional deformations (Fig. 2) induced by stress transmission from both the southern (Paleo-Pacific) and the northern (NeoTethys) margins of the Gondwana continent (Delvaux, 2000). In this context, the Karoo rift system in western Tanzania is a precursor of the late Cenozoic rifting. During the Late Paleozoic to recent times, the TRM segment of the western branch of the EARS was affected by repeated rifting cycles (McConnell, 1972).

The Rukwa rift basin (Peirce and Lipkov, 1988) is located in the relay zone between the Tanganyika and Malawi (Nyasa) rift valleys (Fig. l), which together form the NW-trending Tanganyika-Rukwa-Malawi (TRM) lineament. The TRM lineament is interpreted as an intracontinental transform fault zone, along which the Rukwa rift basin opened as a pull-apart basin in response to oblique, NW-SE extension (Kazmin, 1980). In contrast, Morley et al. (1992) favoured an opening of the Rukwa rift basin in a NE-SW direction, sub-orthogonal to its general trend, while Sander and Rosendahl (1989) suggested a sub-orthogonal opening of the Tanganyika and Malawi rift basins.

However, all these models may not have adequately considered explicitly the possible existence of older rift basins along the TRM trend, although their occurrence has been demonstrated that they largely influenced the geometry and location of the Late Cenozoic rift basins by the classical process of tectonic reactivation. It was shown recently that the NW-trending Ubende belt is a zone of repeated reactivations since the Palaeoproterozoic, controlling successive stages of sedimentary basin formation (Delvaux, 2000). During the Late Carboniferous to Permian, the NW-trending Karoo rift basins developed in response to compressional and transpressional deformations in East-Central Africa. Recent workers have suggested the probable existence of an Early Tertiary rifting stage (Specht and Rosendahl, 1989; Damblon et al., 1998; Vauchez et al., 1997). The Late Cenozoic rift system in the Rukwa-Malawi area started 8-9 Ma ago by semi-radial extension and evolved locally to strike-slip deformation since the mid Pleistocene (Ring et al, 1992; Delvaux & Hanon, 1993).

III. PROGNOSTIC EVALUATION AND CONCLUSION

Regions within the EARs have been known to contain hydrocarbon accumulations (e.g. Uganda, Kenya Ethiopia). A number of oil slicks have been identified in Lake Turkana and there have also been reports of good quality source and reservoir rocks in the adjacent Lokichar and Kerio Basins (Michael Hall et al 2011; Rop, 2012). Similarly, recent oil discoveries in Lokichar basin, and Albertine graben confirm a working petroleum system within the EARS rift system (Rop and Patwardhan, 2013). Oil generation and accumulation within this rift system may have been driven by a number of factors with regional tectonic activities setting the stage for basins as well as sediment accumulation. Deep basins with 3,000-10,000 m sediment loads have provided excellent opportunity for hydrocarbon generation. The infilled rift sediments are predominantly non-marine but it is possible that there is some marine influence during the initial sediments filling, such as those of the Lake Turkana Lapurr Range Formation (Cretaceous) part of the EARS basin. The geothermal gradients of the Cretaceous basins and those of the Tertiary should have been different, consequent to the non-uniform mantle upwarping as revealed by the gravity anomaly profiles. The structural profiles also revealed that the basins could have attracted potential petroliferous sedimentary sequences which are deposited on basement rocks of Precambrian age underneath the horst- and graben-like structures (Rop, 2012).

Similarly lakes in the Western Branch, including Lakes Albert, Edward, Nyasa (Malawi) and Tanganyika have a significant number of oil seeps which have been identified from Radar imagery, with the potential for associated good quality source rocks (Michael Hall et al, 2011). In comparison, Kenya Tertiary and Ethiopia rifts have remarkable similarities owing to their mutual origins; even though the Eastern and Western branches were developed by the same processes, they have very different characters. The Eastern Branch is characterized by greater volcanic activity while the Western Branch is characterized by much deeper basins that contain large lakes and lots of sediment; including Lakes Tanganyika which is the seconded deepest lake in the world, and Lake Malawi. Southern rift basins have high thermal activity with volcanic eruption occurring intermittently though Tertiary with the above threshold sediment thickness, which is a good factor in hydrocarbon maturation. The southern basin as well as the rest of EARS system has extensive fluvial and lacustrine sedimentary rocks of Quaternary age occupying low-lying areas formed by numerous small grabens and half graben structures (Rop, 2012). Tertiary fluvio-lacustrine deposits within the rift grabens and older Karoo Supergroup deposits are the main onshore Petroleum Systems.

Branching of the EARS provides further interesting and yet contrasting characteristics of the Eastern and Western Branches of the rift. The Western Branch, initiating in the Albertine Graben in western Kenya, displays a high level of seismic activity, but has less active volcanism and generally a greater thickness of sediment in comparison to the Eastern Branch, excluding the rifts of the Turkana Depression. These factors are likely to have a corresponding influence on hydrocarbon prospectivity. However, previous studies of the Turkana Depression region have also emphasized hydrocarbon opportunities in the Northern and Central Kenya Rifts of the Eastern Branch. These are thought to be the oldest and longest-lived sedimentary basins of the Tertiary-Quaternary EARS because they represent an overlap area with the Cretaceous rifts.

Oil seeps have been identified and documented by various studies within the rift system such as in the rift lakes of Lake Tanganyika, Edward and Nyasa (Malawi). These oil seeps generally indicate the presence of a similar petroleum play involving the Tertiary sections, as discovered recently at Lake Albert and Kenyan Turkana region. It is however worth noting that oil seeps in the Southern Lakes of EARS which directly overly the common Karoo sediments may have been derived from the Karoo sediments. Recent exploration on the Karoo basins such as the Ruhuhu and Upper Zambezi Grabens has revealed large reserves of Gondwana coals within the lower part of the Karoo Supergroup (Damien Delvauxi 2001). Studies conducted and special researches indicate that these coal seams may yield commercial amounts of coal-bed methane as well as reasonable quality coals for future exploitation.

Rifting process is a process associated with high thermal activity. High geothermal gradient is known to allow maturation and/or generation of hydrocarbons especially in young and shallow sediments. However hydrocarbon prospects within the EARS has to be looked together with other factors which contribute to a working petroleum system. Possibility of early migration to early structural or stratigraphic entrapment has to be considered. In addition there are several well-defined but definitely smaller structures, called grabens that have rift-like character and are clearly associated, geologically, with the major rifts. Thus, what people might assume to be a single rift, somewhere in East Africa, is really a series of distinct rift basins which are all related and produced the distinctive geology and topography of East Africa. These rifts exhibit different characteristics and provide interesting opportunities for oil and gas exploration rationale.

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