Presented at Short Course VI on Exploration for Geothermal Resources,
organized by GRÓ GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 13- Dec. 4, 2022

INFLUENCE OF PRE-EXISTING CRUST IN THE EVOLUTION OF EAST-AFRICAN RIFT SYSTEM (EARS) AND ITS IMPACT ON GEOTHERMAL EXPLORATION STRATEGY OF WESTERN RIFT

Ermias Yohannes Berhane
Ministry of Energy and Mines, Department of Mines
P.O. Box 272, Asmara
ERITREA
ermias_yohannes@yahoo.com

ABSTRACT

Geothermal exploration in the western arm of the East African Rift System (EARS) has been a matter of concern. There is a need for understanding the crustal structure to come up with a suitable approach of geothermal exploration strategy. In this case it is imperative to think about the regional dynamics of the crustal evolution of the EARS. The East African Rift System is a well-developed continental rift that separates the Somali Plate from African (Nubian) Plate. Volcanism initiated in the north, in Ethiopia in Mid Oligocene, in Kenya at 25 Ma followed by episodic rifting. Volcanism in the Western Rift is confined to four volcanic provinces, the Tore-Ankole, Virunga, South Kivu and Rungwe that began 12 Ma in the north and 7 Ma in the south. Pre-existing structures have controlled the location and rifting of the EARS. The dynamics of the EARS preferentially splits the African Nubian Shield (ANS) part of the East African Orogen. This selection of the East African crust rifting can be attributed to the nature of juvenile crust of ANS and rheologically acted as relatively incompetent compared to the thick and rigid crust of predecessor orogenies. The Western Branch of EARS follows preferentially Proterozoic Ubendian and Kibaran belts and avoids Archean craton. The less evolved western rift, which is characterized by thick crust, less volcanism and thick sedimentation requires a different approach in geothermal exploration than the eastern arm of EARS. The region from Ruwenzori through Kivu to Rusizi and finally to the south should be handled separately in relation to its site specific tectonic development to outline strategy of geothermal exploration.

1. INTRODUCTION

The East African Rift System (EARS) is a late Eocene to recent rift system, which has been splitting the African continent. The EARS (Figure 1) consists of a series of connected continental rifts separating the main African (Nubian) Plate from the Somali Plate, and the Indian Ocean. The rift valleys form two main lines, the eastern and western branches of the EARS. A third, southeastern branch is in the Mozambique Channel (Chorowicz, 2005). The EARS propagates from the northern Afar Depression and Main Ethiopian Rift and bifurcating farther southwards and this forms (Figure 1): Eastern branch which extends from the Kenyan rift to central Tanzania and western branch which runs through Lake Albert, Lake Edward, Lake Tanganyika, and Lake Malawi, and dies out in southern Mozambique.

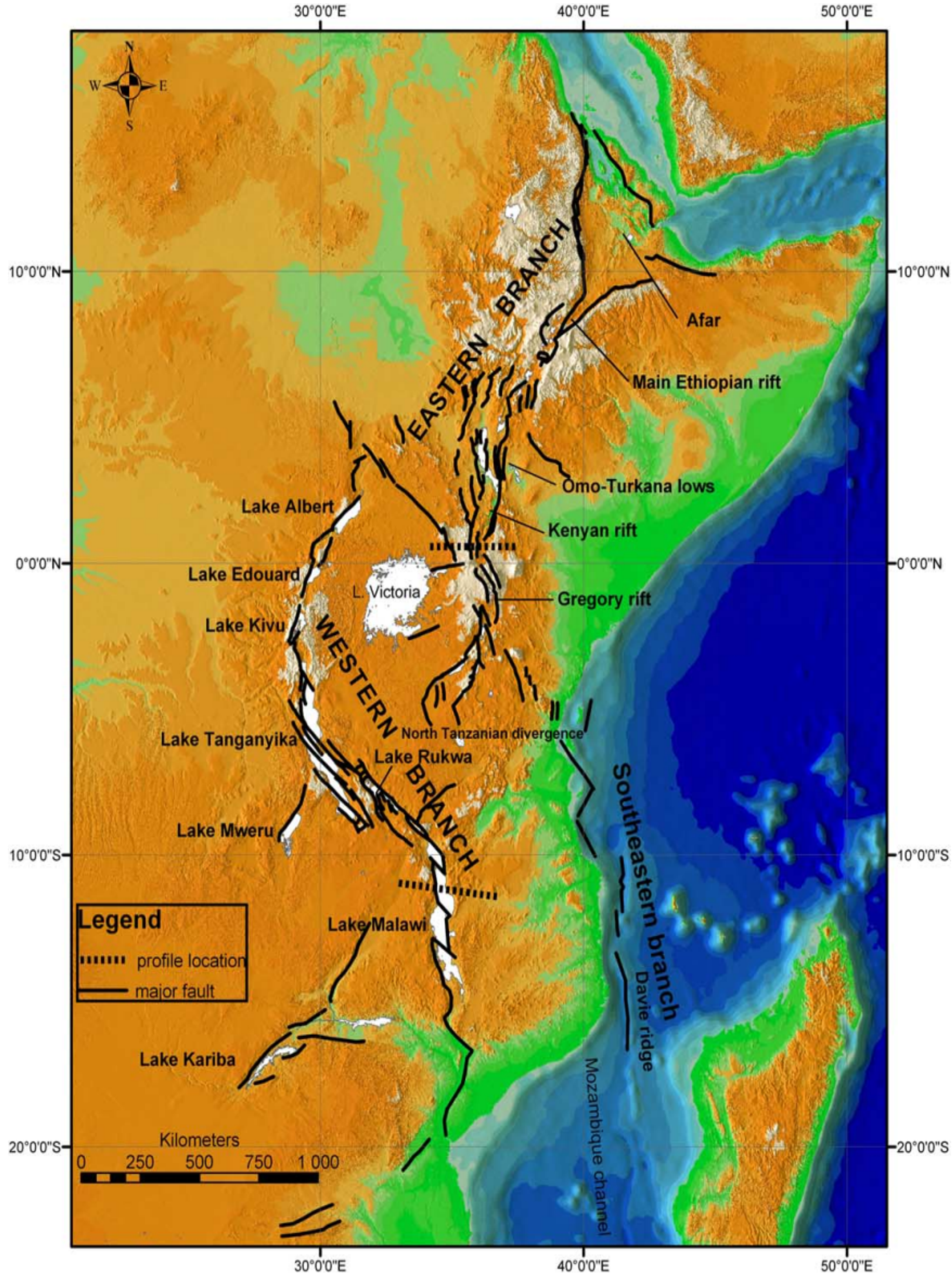

FIGURE 1: Location of the East African Rift System. The EARS is a series of several thousand kilometers long aligned successions of adjacent marginal basins and hilly terrain of faulted blocks bordered by uplifted shoulders.

For many years, the EARS has received a lot of interest from the scientific community. Extensive literature on research into the geology, structure and geothermal potential of the area are available from the work of Chorowicz (2005), Chorowicz et al. (1987), and Hardarson (2015). The EARS is an active magmatic centre and so has a significant potential for geothermal energy exploration.

The EARS remained attractive for geothermal investigation with the recent advances of power generation in Kenya from geothermal resources. The Olkaria geothermal field alone has recently added about 400 MWe. Aggressive exploration activities are ongoing in Eburru, Suswa, Longonot, Baringo, Korosi and others. In Ethiopia, the 7.3 MWe Aluto pilot binary plant is recently refurbished and exploration is active on Tendaho and other known surface manifestations. Contrary to the eastern rift, no successful results on exploration for power generation as well as direct use applications have been achieved in the western rift of the EARS. The main reason for this failure is that the same approach of geothermal exploration is followed as the eastern arm. Rifting in the western arm of the EARS is at its initial stage, thus needs different way of geothermal exploration than the eastern arm. Therefore, it is vital to characterize its dynamics of tectonism with respect to its crustal development. Hence, in this paper, lithospheric thickness and the pre-rift development of the crust of the EARS will be assessed to come up with a suitable approach on strategy of geothermal exploration in the western rift in relation to its specific tectonic development.

2. EVOLUTION OF THE EARS

Rift-related volcanism, faulting and topographic relief are well-exposed in the EARS, this makes it to be a classic continental rift. Variety of tectonic styles, reflected in grabens and half-grabens, transverse fault zones and accommodation zones, and influences of pre-existing geologic structures, are present in the rift system. The evolution of the rift system can effectively be considered in three parts; Afar and the main Ethiopian rift in the north, which collectively are categorized as northern rift, the southern rift of the eastern branch and the western branch of EARS.

2.1 Northern rift

The northern rift comprising of the Afar and the main Ethiopian rift, is characterized by bi-modal magmatism, transitional basalts that straddle the tholeiitic-alkaline boundary and younger (Upper Miocene-Pliocene to Recent) trachyte-pantellerite ignimbrites and lavas. The volume of its volcanism totally reaches about 300,000 km^3.

In the main Ethiopian rift and its flanking plateaus, volcanism began in the mid-Oligocene or earlier. WoldeGabriel et al. (1990) found evidence for six episodes of volcanism but no evidence for lateral migration of volcanism from the flanks to the centre of the rift as observed in Kenya.

Beginning about 4 Ma, extensive basaltic volcanism covered most of Afar and obscured the geologic record of events (Braile et al., 2006). Since that time, the history of the Afar rift is more of sea-floor spreading than continental rifting.

2.2 Eastern (Kenya) rift

A general migration of volcanism from north to south and from west to east and progressions from strongly alkaline to less alkaline magmatism and from mafic to more evolved and felsic compositions are remarkable aspects of Kenya rift magmatic evolution. The volume of volcanism reaches about 230,000 km^3 (Williams, 1982) with the main phase of uplift taking place during the period of 40-21 Ma (Smith, 1994). A pre-rift depression formed in the early Miocene, but clear development of half grabens did not occur until about 12 Ma (Smith, 1994).

2.3 Western rift

The western rift generally appears to be younger than the Kenya rift. Doming began at about 20 Ma and volcanism began at about 12 Ma in the north and at about 7 Ma in the south (Ebinger, 1989). This indicates that volcanism evolved progressively from north to south and continued to the present. Volcanism in the Western rift occurs in four isolated Miocene to recent volcanic provinces including, from north to south, the Toro-Ankole, Virunga, S. Kivu, and Rungwe regions. The development of the many basins in the Western rift began concurrently with or prior to the volcanism. Through time, the border faults propagated to both the north and the south resulting in the linkage of many basins which were initially separate features. The basins have tended to narrow with time due to hanging wall collapse (Ebinger, 1989).

Apart from the graben of the western rift, the transverse structure and faults play an important role in shaping the rift. The main troughs are linked or cut by transverse structures, generally striking NW-SE. There are two types of NW-SE transverse structures (Chorowicz et al., 1987): 1) Large lineaments linking the main segments of the rift; and 2) fault zones dividing the main rift segments into minor parallelogram-shaped basins. The major fault zones bordering the main grabens, linked by the transverse faults inside these grabens, along with the Tanganyika-Rukwa-Malawi lineament and, to a lesser extent, with the Aswa and Zambezi lineaments, form the principal directions of fracturing in East Africa (Chorowicz, 2005).

3. CHARACTERISTICS OF LITHOSPHERE BENEATH THE EARS

The structure and evolution of the lithosphere and upper mantle provide the continental wide structural background for the seismotectonic map of Africa based on seismic wave tomography and gravity anomaly studies (Meghraoui, 2016). The lithospheric and crustal structure is addressed through the P and S waves' anisotropy tomography and the results of receiver functions (Adams et al., 2012; Meghraoui, 2016).

The East African rift and related plume extending from Malawi to the Red Sea illustrate the geodynamics of the mantle below Africa and the underlying mantle convection (Meghraoui, 2016; Figure 2). In comparison with the cratons, the plume corresponds to the signature of hot materials and testifies for the volcanic activities with continental deformation in accord with the seismicity distribution visible in the map (Meghraoui, 2016; Koptev et al., 2016).

An attempt has been made to relate earthquake depths with the lithospheric thickness of the East African rift (Craig et al., 2011; Fagereng et al., 2013). Along the northern sections of East Africa, the lithosphere is too thin (< 110 km). The off-rift lithosphere is expected to be of a thickness consistent with the maximum stable thickness of the lithosphere in the oldest oceans, limited by the development of convective instabilities to about 100 km (McKenzie et al., 2005).

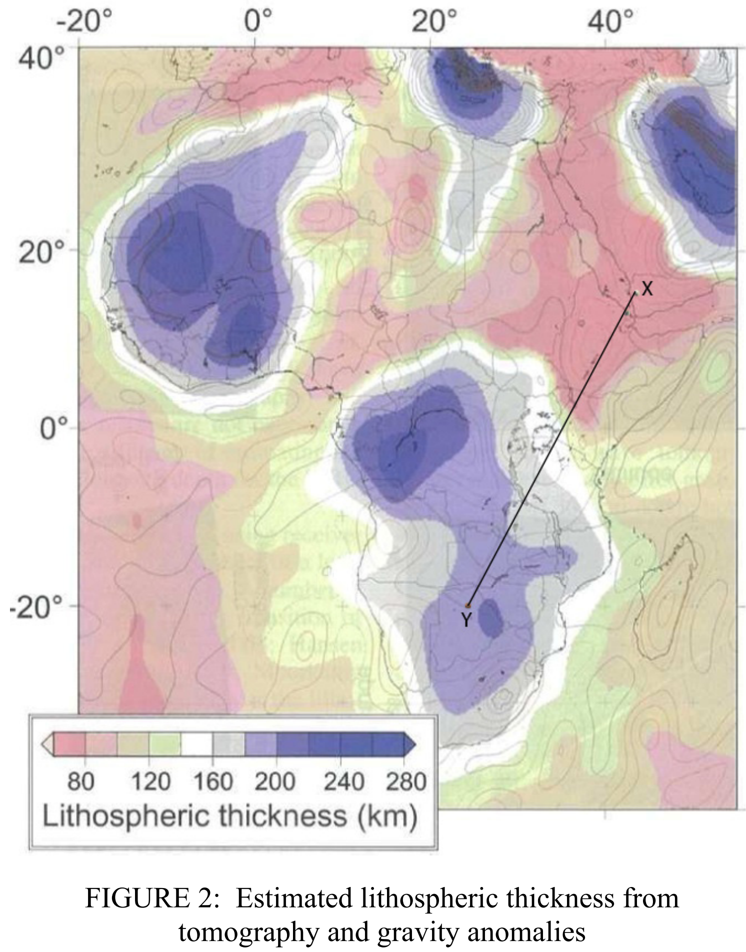

FIGURE 2: Estimated lithospheric thickness from tomography and gravity anomalies (Meghraoui et al., 2016)

Studies of lithospheric thickness along the northern rift, main Ethiopian rift indicate that, under the northern-most sections of the rift near Afar, where the extension factors are highest, and rifting has progressed furthest, the lithosphere has been thinned appreciably from its pre-rift, steady-state thickness (Craig et al., 2011). All regions in Afar where such thinning has taken place demonstrate seismogenic thicknesses of 15–20 km or less corresponds to the area where the upper layer changes from continental to oceanic crust. The contrast between upper-crustal seismicity in regions of thinner lithosphere and whole-crustal seismicity in regions with thicker lithosphere is seen particularly clearly in northern Tanzania (Craig et al., 2011).

Typical values place the Moho at 40-44 km beneath the western branch and 37-42 km beneath the eastern branch (Craig et al, 2011; Tigume et al., 2012). Crustal thicknesses in Afar of 13-28 km (Figure 3) are consistent with higher extension factors and thinner crust at the northern end of the main Ethiopian rift (Craig et al, 2011). Crustal thickness along the rift is presumed to increase with decreasing extension factor southwards along the main Ethiopian rift through Turkana, up to the 40 km values as seen in places around southern Kenya and Tanzania (Craig et al, 2011; Tigume, 2012).

The southern part of the EARS including the western rift broadly has similar lithospheric thickness. There is also similar crustal thickness between the Archean and Proterozoic terrains, but has no influence in the rifting of the EARS according to the findings from Moho depth and Poisson's Ratio ranges (Tigume, et al, 2012). However, rifting in western arm is selective on the Proterozoic belts rather than Archean, and may be attributed to the presence of crustal structure such as shear-zones that favours position of rifting.

Therefore, from the above observation it can be deduced, the underlying lithospheric thickness of EARS exhibits thinner on the northern part compared to western arm and the southern part of the eastern rift. These characteristics influence the activity of volcanism to be common on the eastern arm of the EARS.

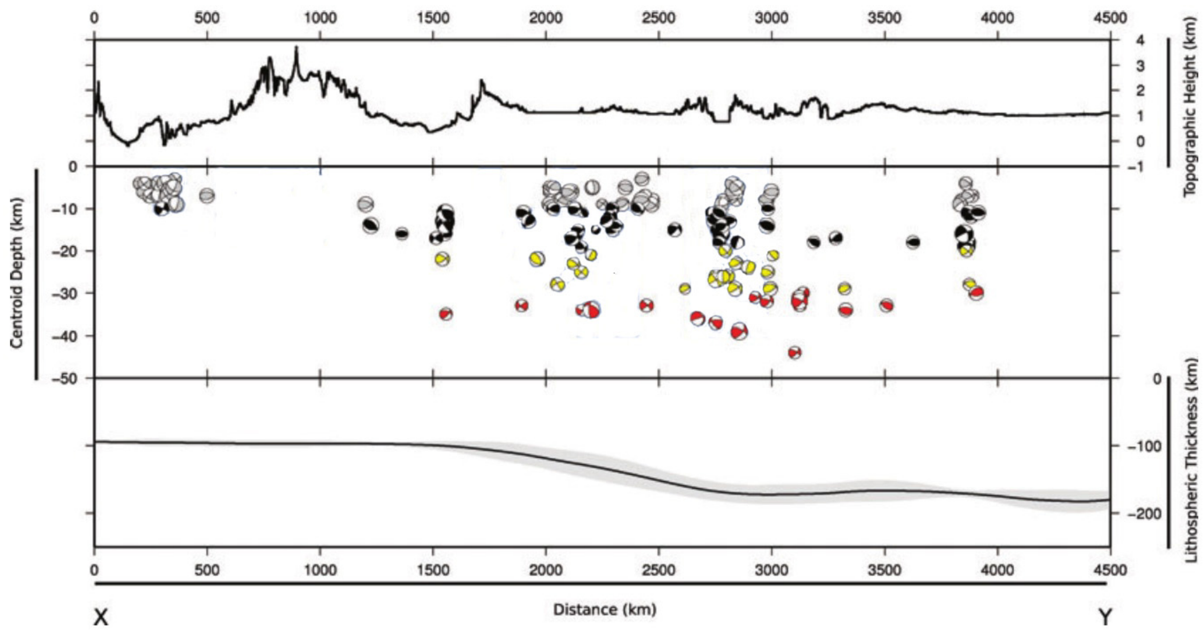

FIGURE 3: Cross-section taken N–S along the grey line on Figure 2 similar to the line of Craig et al. (2011). Top panel is topography. Central panel shows focal mechanisms as east-hemisphere projections at locations based on profile-perpendicular projection, plotted at the centroid depths denoting grey < 9 km, black 10-19 km, yellow 20-29 km and red > 30 km. Bottom panel is a swath track of lithospheric thickness calculated from the earthquake (Graig et al., 2011).

4. PRE-RIFT CRUSTAL DEVELOPMENT OF THE EARS

Pre-existing structures have controlled the location and the initial stages of rifting in the north of the East African Rift System specifically the Northern Rift (Keranen and Klemperer, 2008). There are two distinct Proterozoic basement terranes, one of which strongly underplated beneath its northern part and created rheological boundaries that localized extension and permitted the Main Ethiopian Rift (MER) to propagate (Keranen and Klemperer, 2008).

Experimental modelling and field work have shown that segments of the East African Rift System are controlled by pre-existing fabrics and it inherited its trend from the older zones of weakness between the cratons, and belts (Aanyu and Koehn, 2011). Many authors agree that there is a strong basement control at various parts of the East African Rift initiation (Tiercelin et al., 1988; Theunissen et al., 1996). Since the East African splitting of the rift began during Oligocene, understanding the pre-Tertiary development of the crust is necessary to characterize and visualize the evolution of the EARS. It is also imperative that there has not been any persistent crustal development during the post-Neo-Proterozoic orogeny, except for the structures related to the major event of the Early Cretaceous extension attributed to the separation of Africa from South America. Therefore, in this paper the crustal creation orogeny mainly during Precambrian time will be explained.

4.1 Orogenies of the East African region

The East African Rift zone mainly occurs in the crustal basement of the East African Orogen (EAO). Formed by the EAO (Stern, 1994) is a Neoproterozoic–early Cambrian mobile belt that today extends south along eastern Africa and western Arabia from southern Israel, Sinai and Jordan in the north to Mozambique and Madagascar in the south. It constitutes the Arabo-Nubian Shield in the north and the Mozambique belt to the south comprising mostly pre-Neoproterozoic reworked crust with a Neo-Proterozoic-early Cambrian tectonothermal overprint, and consolidation of the orogeny was achieved between c. 850 to 550 Ma (Fritz et al., 2013). It likely incorporates multiple phases of collision and accretion and defines one of the largest and most continuous orogenic belts within Gondwana. It formed during the waning stages of the Proterozoic when Gondwana was nearing the final stages of its formation.

The Congo and Tanzanian Cratons are the earliest stable rocks of Archean basement composed mainly of granitised formations which suffered a prolonged period of tectonic activity (Aanyu and Koehn, 2011) and has been superposed on old cratonic blocks spanning the period c. 3000–2500 Ma (Figure 4), and constitute the area of the western rift flanks. Rocks of these Archean gneissic granulitic complexes made up the oldest rock formations that stratigraphically underlie younger cover formations.

The Paleoproterozoic Ubendian orogeny occurred between 2100 and 1800 Ma and resulted high-grade metamorphic lithologies through two deformational phases. The early (more regional) deformational phase (2100–2025 Ma) marked by an E–W to WNW–ESE foliation and granulite-facies metamorphism, has been interpreted as a product of collisional orogeny along the southwestern margin of the Tanzania, and possibly Congo cratons (Aanyu and Koehn, 2011). The second phase (1950–1850 Ma) is characterised by large NW–SE trending dextral shear zones and was restricted to the Ubendian belt (Theunissen et al., 1996). Within this period at about (~1.9 Ga) the northeast trending Usagaran Belt abuts the northwest trending Ubendian Belt to the south–southeast of the Tanzanian craton (Adams et al., 2012). The second phase resulted from a N-ward compressional stress regime that also caused N-ward directed thrusting of rocks of the Usagaran belt immediately south of Tanzania Craton and intrusion of late- to postkinematic calc-alkaline granitic batholiths dated at c. 1860 Ma. Hence, the upper time limit for the second event is placed at c. 1860 Ma, as the late stage of the main deformation phase (Lenoir et al., 1994).

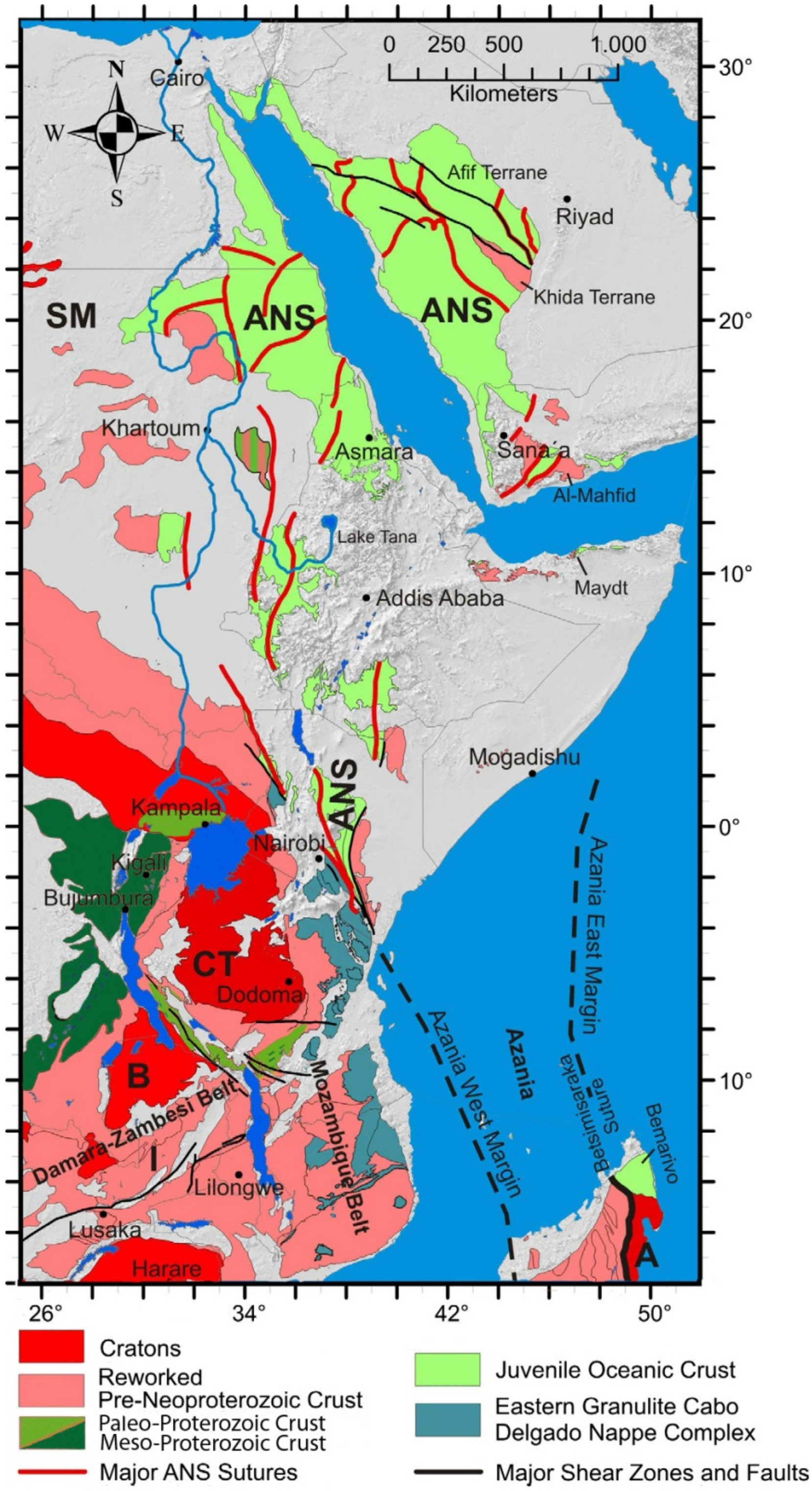

FIGURE 4: Relative location of cratons and mobile belts constituting the basement structure of the East Africa Orogen and adjacent areas prior to rift development (modified from Fritz (2013) and Aanyu and Koehn (2011)). Except for Ubendian and Kibaran, other Pre-NeoProterozoic crust are all labelled as Reworked Pre-Neoproterozoic Crust. ANS denotes Arabian-Nubian Shield, CT; Congo-Tanzania craton, B; Bangweulu craton, and SM, Sahara Metacraton

The Mesoproterozoic Kibaran orogeny is a short-lived but prominent c. 1375 Ma tectono-magmatic event (Aanyu and Koehn, 2011). The northeast trending Kibaran Belt lies north of the Ubendian Belt and west of the Tanzania Craton, and was formed at about 1300 Ma (Cahen et al., 1984). The rocks of this orogeny form the Karagwe–Ankole belt northeast of the Ubende belt-Rusizian basement extension and east of the western rift; and the Kibara belt which is the domain occurring southwest of the Ubende belt-Rusizian basement extension (Aanyu and Koehn, 2011). It is indicative of intra-cratonic regional-scale emplacement under extensional stress regime and the mantle-derived magmas penetrated a zone of weakness at the rheological boundary between the Archean Tanzania Craton and the adjacent Paleoproterozoic basement (2100 Ma mobile belt) to the left, both of which were overlain by Mesoproterozoic meta-sedimentary rocks.

As observed by many researchers the EARS avoided dissecting the cratonic and older crust, but follows orogenic belts (eg. the western rift of the EARS (Ebinger, 1989)). Since rocks of both the Paleoproterozoic Ubendian and Mesoproterozoic Kibaran belts in the region of western rift are strongly deformed with polyphase faults and ductile shear zones, they must have a profound effect on the younger deformational episodes including rift formation and evolution. The direction of the western rift from north to south follows the above orogenic belts. The pre-existing Kibaran Belt being weaker and preferentially reactivated (Craig et al., 2011), supports the idea that the localization of the rifting is dominated by the structure of the crust (Jackson at al., 2008).

The Neo-Proterozoic EAO however is the most influential orogeny in defining the present day configuration of the EARS rift. Traditionally, the EAO is subdivided into the Arabian–Nubian Shield (ANS) in the north, composed largely of juvenile Neoproterozoic crust (e.g. Stern (1994)) and the Mozambique Belt (MB) in the south comprising mostly pre-Neoproterozoic crust with a Neoproterozoic–early Cambrian tectonothermal overprint (Fritz et al., 2013). Part of the MB is later termed as Eastern Granulite – Capo Dolgado Nappe Complex (CDNC, for eg. Fritz et al. (2013)).

The dynamics of the EARS preferentially splits the ANS part of the EAO. It can easily be traced from the Afar Depression in the north to the northern part of the Tanzanian Divergence Zone (TDZ), remarkably following only the crustal segment of the Arabian-Nubian Shield. This selection of the East African crust rifting can be attributed to the nature of juvenile crust of ANS and rheologically acting as relatively incompetent compared to the thick and stiff crust of predecessor orogenies. The EARS was unable to pass as a narrow belt to the south rather diverged in Tanzania in TDZ. The rigidity of the Eastern Granulite – Cabo Delgado Nappe Complex presumably is explained due to the presence of reworking crust and the superimposing of Kuunga Orogeny. This is justified by the geophysical signature which interpreted as strong crust in Lake Magadi in the south, compared to Lake Baringo in the relative north of the Eastern Rift (Albaric et al., 2009).

5. THE WESTERN RIFT – IMPLICATION FOR GEOTHERMAL EXPLORATION STRATEGY

The western branch of the EARS is an arcuate narrow rift characterized by a series of elongated and deep half-graben basins, developed in a Precambrian basement, and separated from each other by transfer zones. The volcanic activity in the western branch of the EARS is less well-developed compared to the eastern branch and the rift development is also at its initial stage. Therefore, approach of the geothermal exploration programme is rather different from the well-developed Eastern branch of the EARS. Besides, the rift basins are filled with thick detrital sediment deposits compared to the thin cover of that of the eastern arm. Based on the above facts and the inception stage of the rift development, the geothermal exploration strategy should be considered distinctly based on the specific local geodynamic properties of the area of interest rather than outlining an approach on a regional perspective. In this paper, therefore, each region of the Western Branch of the EARS, from north to south is emphasized mainly based on its tectonic development.

5.1 Ruwenzori region

The 5000 m high Rwenzori Mountains in Uganda are situated within the Albertine rift (Figure 5), which is part of the western branch of the EARS. They represent a non-volcanic basement block composed of rocks of Proterozoic and Achaean age (Sachau et al., 2011).

Since most of the geothermal surface manifestation of Uganda and possibly some of Congo occurs surrounding the Rwensori Mountains, an investigation and characterization of tectonic evolution of Rwenzori block is necessary for exploration of geothermal resource.

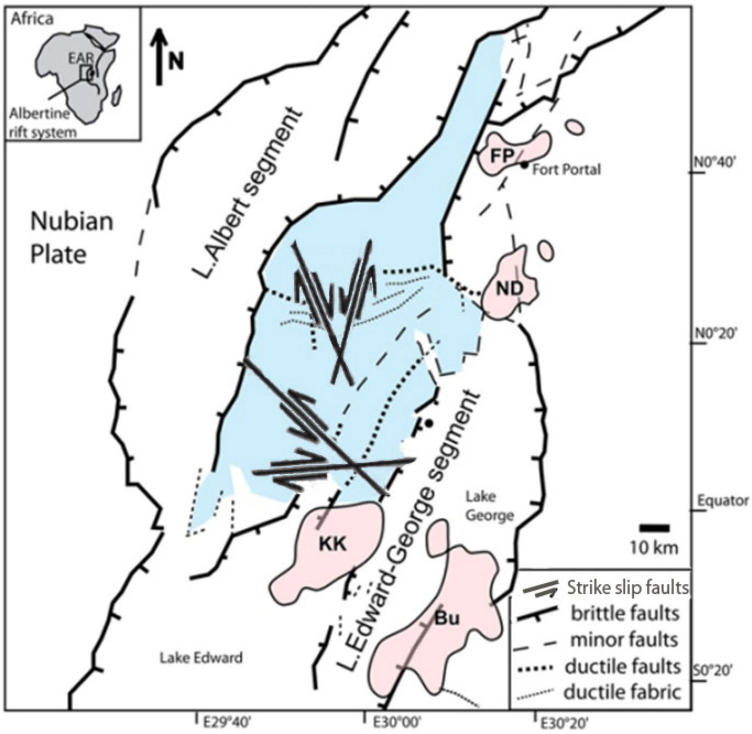

FIGURE 5: Tectonic map of the Rwenzori area (modified from Lindenfeld et al. (2012) and Sachau et al. (2011)). The Rwenzori mountains (light blue area) are surrounded by two rift segments, with the exception of a region in the NE, where they are connected to the Victoria plate. Volcanic fields are marked by red areas (FP: Fort Portal; ND: Ndale; KK: Katwe-Kikorongo; Bu: Bunyaruguru). The strike-slip systems indicate roughly N–S and E–W compression, respectively (Sachau et al., 2011). Normal faults illustrate the NW–SE oriented rift opening.

Most of the studies conducted so far indicate that the tectonic regime of Rwenzori is attributed to tectonic uplift within extension regime. But recently (Sachau et al., 2011) deduced a strike-slip faulting with rotational component (Figure 5). The stress field resulting from the computer simulations explains previously unexplained key structural features of the Rwenzori mountain block. These structures are N-ward oriented thrust faults and two different sets of strike-slip structures indicating a rotation of the stress-field with N–S and E–W compression, respectively, in the central block.

The observed earthquake swarms in the Rwenzori area have been interpreted to originate from crustal fluid migrations and/or CO_2 emanations rising from a magmatic body in the upper mantle (Figure 6). The compositions and isotope ratios of the mineral waters and their incorporated gases also point to a mixing with a magmatic or mantle related gas flow and water source (Bahati et al., 2005; Lindenfeld at al., 2012).

Geothermal manifestations occur both to the north and south surrounding the Ruwenzori mountain blocks. Accompanying all these studies, it is presumably preeminent to relate the geothermal exploration with the tectonic development of Ruwenzori mountains blocks. Thus, the extension coupled with the rotation which assumed to be an accommodation zone should be taken into consideration.

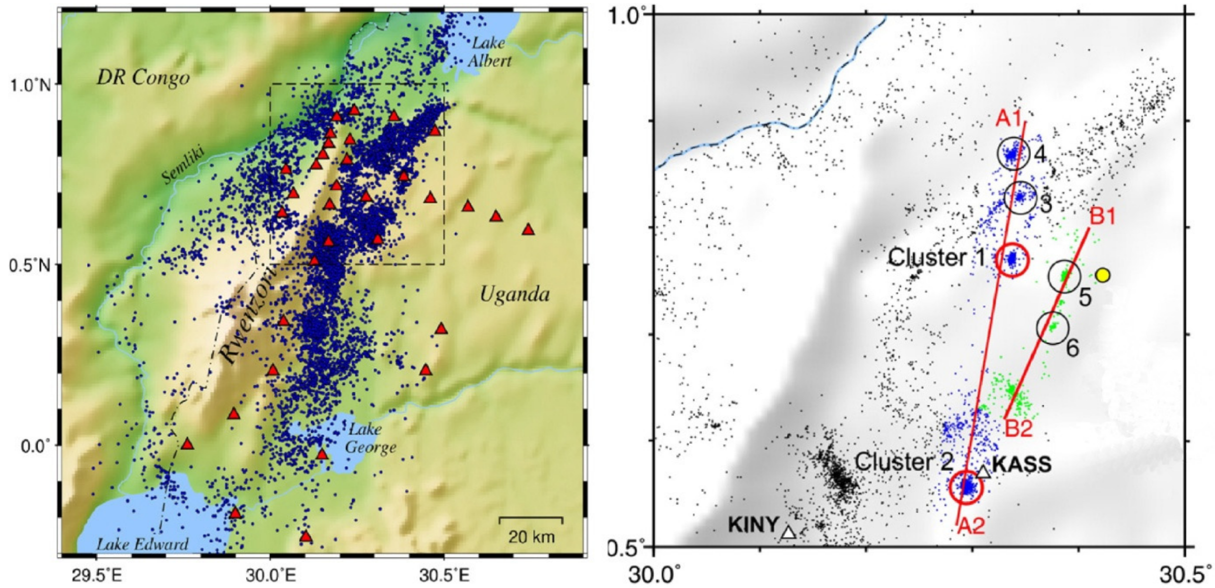

FIGURE 6: Left (a): Seismic station network (triangles) and recorded local seismicity from February 2006 to September 2007 (from Lindenfeld et al. (2012)); Right (b): The central region, inset in (a), for which earthquakes are relocated by the HypoDD method, yellow circle is the location of detected mantle earthquakes (h = 53-60 km)

5.2 Regions of transfer zone and volcanism

As explained above, the volcanic activity in the western branch is at its incipient stage and is restricted to four transfer zones (Ebinger, 1989). These include Toro-Ankole and Virunga volcanic provinces from north, up to South Kivu and Rungwe in the south (Figure 7). The resulting patterns of magma emplacement and deformation may offer insights for explaining the correspondence to the volcanic provinces with major transfer zones in the Western Branch of the East African Rift System (Corti et al., 2003). Thus, these transfer zones may contribute to the rifting process by sourcing upper crustal dikes that propagate laterally into the tips of rift basins.

A detail study on the relationship of transfer zone and magmatism is presented by Muirhead et al. (2015). They developed a conceptual model on magmatic architecture of the transfer zone with implication of the magma-driven rifts, which is quite important in geothermal exploration (Figure 8). According to this conceptual model, stress fields induced by magma reservoirs produce radial dikes, whereas extension-oblique dike intrusions form

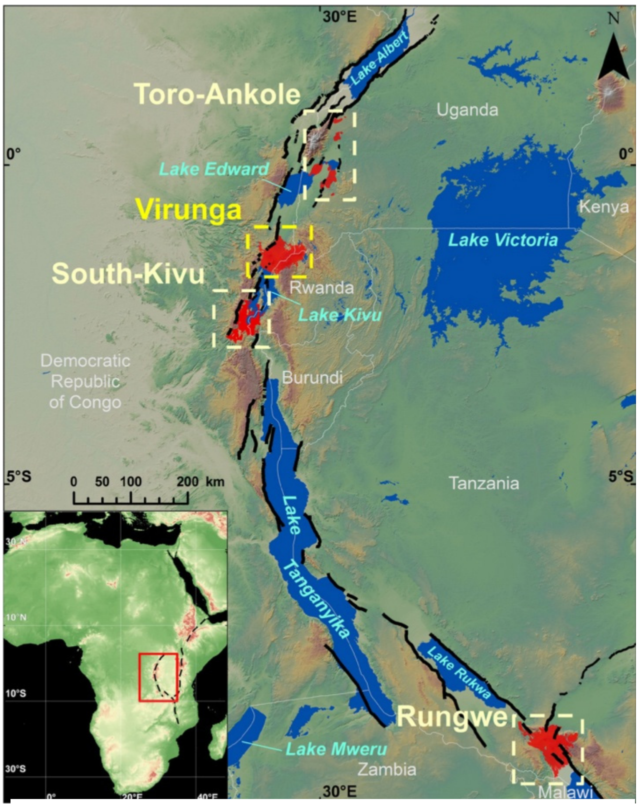

FIGURE 7: The western branch of the East African Rift system and its four volcanic provinces. The inset shows the location of the EARS in Africa (after Smets et al. (2015)).

from the mechanical interaction between segmented rift basins. Extension-normal dikes occur at the boundary between transfer zones and the ''distal ends'' of rift basins, where their orientations are controlled by the regional extensional stress field. The orientation of transfer zones follows mostly Precambrian structures. These transfer zones control the storage and conduits of volcanism. Therefore, it will play a vital role in exploration of geothermal resources.

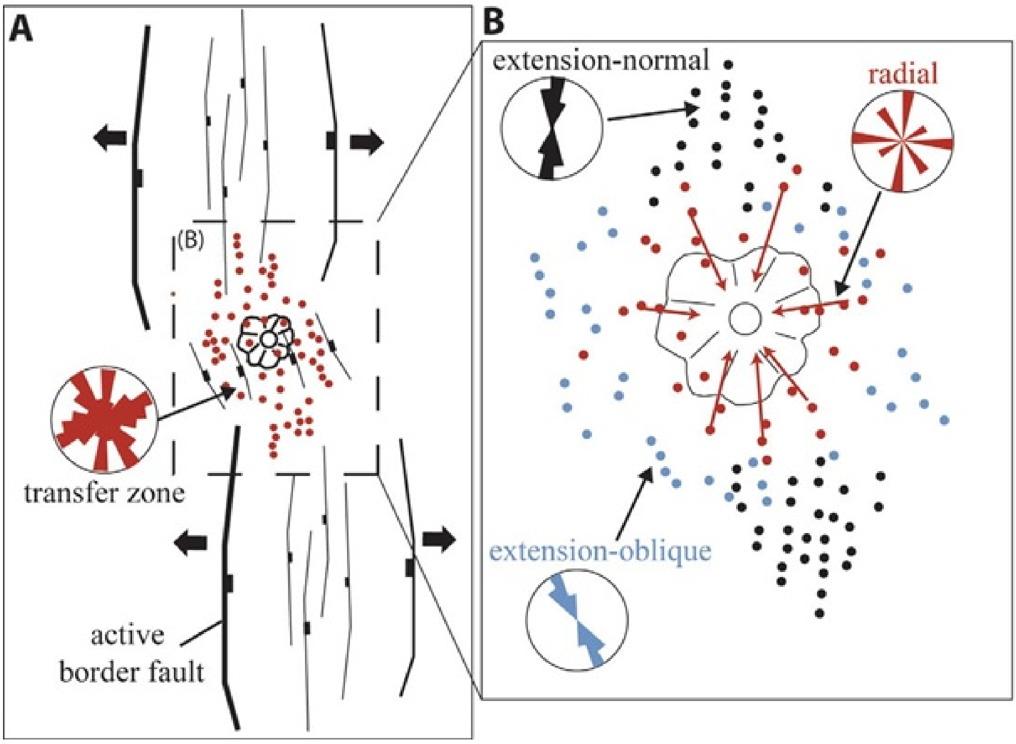

FIGURE 8: A) Schematic representation of the trend of transfer zone and distribution of cones in immature magmatic rift and magma poor rifts (Muirhead et al., 2015). Rose diagrams provide a conceptual example of the expected cone lineament trends in the different structural settings. Black arrows represent the regional extension direction (E-W in this example). Cones (red dots) focus in transfer zones and the distal tips of basins. B) shows the range of cone trends distributed within transfer zones in immature magmatic rifts and magma-poor rifts

As explained above, almost all the volcanism in the western branch of the EARS is localized within the transfer zones. Thus, detailed study of the tectonism of the transfer zone is necessary to outline and explore targets of geothermal resources present if any. In this context, it is conceivable to observe the relationship between the structural set up of the rift, the transfer zone and the geothermal manifestation to pinpoint favourable geothermal sites.

The Virunga Volcanic Province (VVP) is one of the four volcanism provinces, corresponding to the transition between the basins of Lake Edward and Lake Kivu, which are two half-graben basins with the main rift faults forming the western border. Rifting in this part of Kivu basin has reactivated NE-SW oriented weakness structures of the Mesoproterozoic Karagwe-Ankole Belt, which represent the Precambrian basement in which the rift propagated.

This observation suggests that the cone alignment in the VVP might represent, for this section of the rift, the trace at ground surface of the main active faults located at depth (Smets et al., 2016). Except for the 1938-1940 eruption, atypical eruptions consistently occur 15 km north of the caldera centre, at the northern or southern ends of the N50°E cone alignments (Figure 9). This is in line with the direction of the transfer zone, which also follows the Precambrian basement structure.

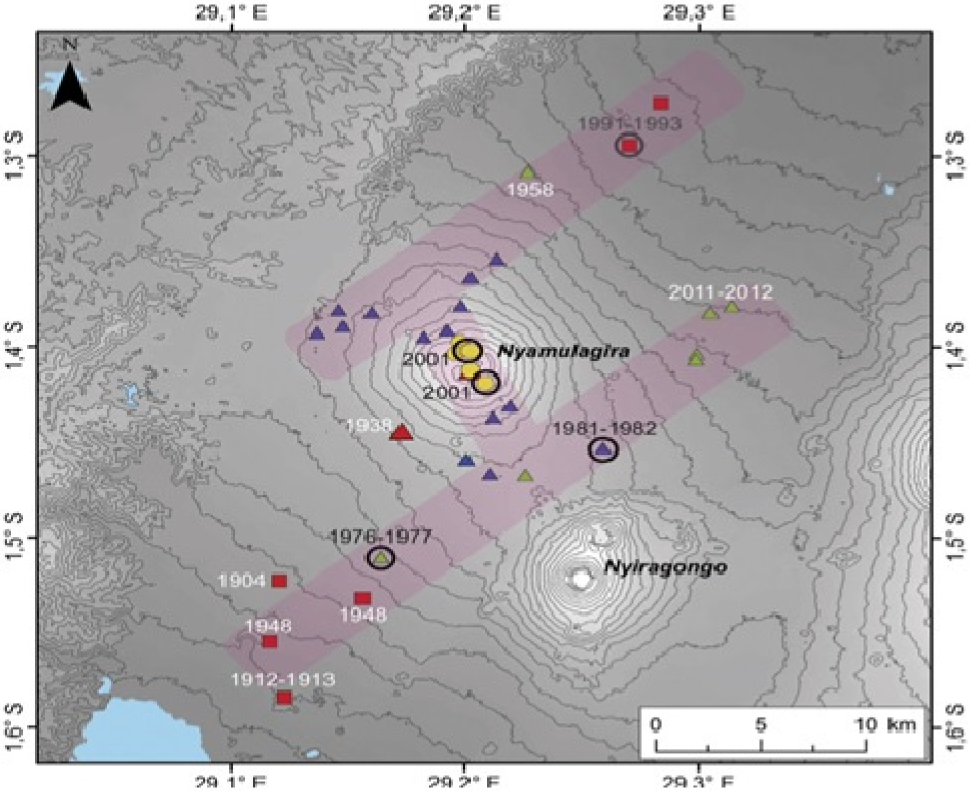

FIGURE 9: Precambrian structures also promote the preferential location of some eruptive vents along N50°E oriented axes located north and south of the main edifice of VVP (Smets et al., 2016)

The continuity between the VVP and South Kivu Volcanic Province (SKVP), characterized by volcanic cones extending into Lake Kivu, strongly suggests that volcanism in this region has a common origin (Smets et al., 2016). This observation is consistent with the hypothesis of magma underplating below the Kivu region (Corti et al., 2003).

Extension-normal cones (Figure 10, black circles, black rose diagram) occur near the boundary between the transfer zone and the distal tip of the basin. A potential implication is that the injection of extension-normal, upper crustal dikes laterally extending from transfer zones into the rift axis may facilitate magmatic rifting in both magma-poor of the Western Rift, albeit localized to the distal ends of these basins. This indication of the presence of dyke is in agreement with the concentration of hydrothermal springs on roughly the same spot, suggesting that the area presumably be positioned at the intersection of the N-S alignment of the cones and the transfer zone of the VVP. Thus enhances the possibility of resource target for geothermal exploration.

In the SKVP, the NE-SW orientation lineament corresponds to fault escarpments, inherited from the faulted fold axis located west of the volcanic province in the Meso-Proterozoic basement (Ebinger, 1989) and the main dyke direction. Thus, the presence of old structures as weak-zones also influence the orientation of volcanic edifice. Therefore, it is important for geothermal exploration to consider regional geological mapping including basement geology, in deciphering the relationship of old structures, volcanism and geothermal manifestation to pinpoint area of interest.

Similar approach can be drawn for Bugarama-Rusizi basin and areas of the North Tanzanian Divergent Zone (NTDZ). In the earlier, the Upper-Miocene basalt flows cover the accommodation zone between the Kivu and Rusizi extensional basins, where transfer faults link basins bound by border faults (Ebinger, 1989). In the NTDZ, the presence of NW-SE, extensional oblique cone lineaments may be the result of dykes intruding pre-existing transverse structures (Muirhead et al., 2015). This view was also generalized for the Tanzanian and Kenyan regions of the EARS, which contain NW-SE striking shear zones, acting as transfer zones, which are aligned locally with recently active transverse faults (Smith and Mosley, 1993).

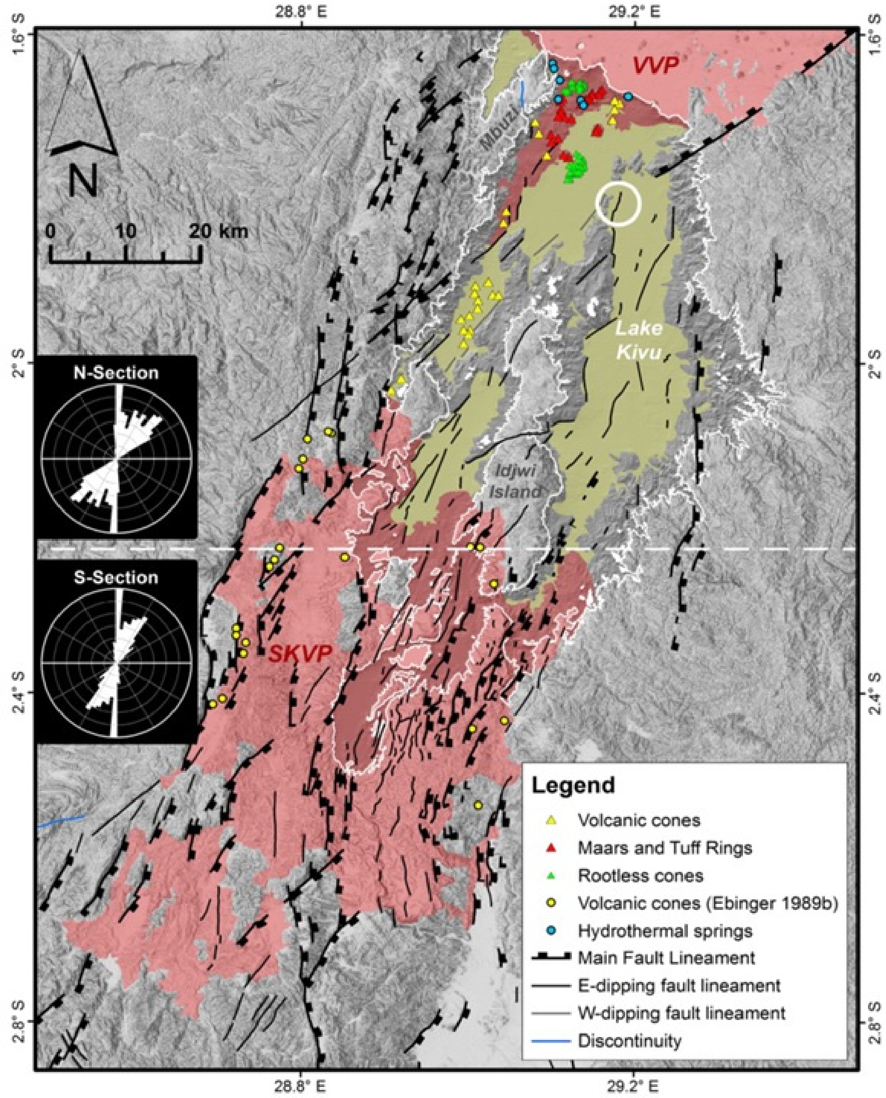

FIGURE 10: Simplified geological map of the Lake Kivu basin realized in this work. Areas coloured in grey, red and yellow are Precambrian rocks, lava fields and lacustrine sediments, respectively (after Smets et al. (2016). The location of the blue coloured hydrothermal springs, close to the VVP, could be influenced by dyke underneath, which is responsible for the basalt flow.

6. CONCLUSION

The EARS is well developed in the part of the crust of the Neo-Proterozoic Arabian Nubian Shield assembled during the East African Orogeny. This preferential splitting is mainly due to the inherent characteristics of the crust pertinent to its thickness and juvenile crust.

Thick sedimentation and crustal structure, meager volcanic activity and the incipient stage of the western rift make it different than that of the eastern arm of EARS, one should follow different procedures in outlining plans for geothermal exploration. Therefore, the following approach is indispensable in setting up geothermal exploration strategy:

- Geological mapping not only of the Recent volcano-sedimentary rocks but also the Precambrian basement adjacent to the surface manifestations.
- Defining weak-zones related to transfer zones, or accommodation zones, such as in the Ruwenzori block, as surface breaching dykes are confined to areas in and around transfer zones.
- Find out the relationship between the surface manifestations, transfer zones, and volcanism if any. Define extension from the transfer zone into the rift axis, as upper crustal dikes laterally from transfer zones into the rift axis may facilitate magmatic rifting in both magma-poor and immature magmatic rifts of the EAR (Muirhead et al., 2015).

Where volcanism occurs, likely to be in a dyke form, a high temperature reservoir for power generation is expected; otherwise a low temperature geothermal energy prevails in western rift of EARS.

REFERENCES

Aanyu, K. and Koehn, D., 2011: Influence of pre-existing fabrics on fault kinematics and rift geometry of interacting segments: Analogue models based on the Albertine Rift (Uganda), Western Branch - East African Rift System. *Journal of African Earth Sciences, 59*, 168-184.

Adams, A., Nyblade, A., Weeraratne D., 2012: Upper mantle shear wave velocity structure beneath the East African plateau: Evidence for a deep, plateau-wide low velocity anomaly. *Geophys. J. Int., 189*, 123-142.

Albaric, J., Déverchère, J., Petit, C., Perot, J., and Le Gall, B., 2009: Crustal rheology and depth distribution of earthquakes: Insights from the central and southern East African Rift System. *Tectonophysics, 468*, 28-41.

Bahati, G., Pang, Z.H., Ármannsson, H., Isabirye, E.M., Kato, V., 2005: Hydrology and reservoir characteristics of three geothermal systems in Western Uganda. *Geothermics, 34*, 568–591.

Braile, L., Keller, G., Wendlandt, R., Morgan, P., and Khan, M., 2006: The East African Rift System. In: Olsen, K.H. (editor), *Continental rifts: Evolution, structure, tectonics*. Elsevier Science B.V., Amsterdam, Netherlands, 466 pp.

Cahen, L., Snelling, N., Delhal, J., and Vail, J., 1984: *The geochronology and evolution of Africa*. Clarendon Press, New York, United States, 512 pp.

Chorowicz, J., 2005: The East African Rift System. *Journal of African Earth Sciences, 43*, 379–410.

Chorowicz, J., Le Fournier, J., and Vidal, G., 1987: A model for rift development in Eastern Africa. *Geological Journal, 22*, 495–513.

Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., Sokoutis, D., 2003: Analogue modelling of continental extension: A review focused on the relations between the patterns of deformation and the presence of magma. *Earth Sci. Rev., 63*, 169–247.

Craig, T.A., Jackson, J., Priestley, K., and Kenzie, D., 2011: Earthquake distribution patterns in Africa: Their relationship to variations in lithospheric and geological structure, and their rheological implications. *Geophys. J. Int., 185*, 403–434.

Ebinger, C.J., 1989: Geometric and kinematic development of border faults and accommodation zones, Kivu-Rusizi Rift, Africa. *Tectonics, 8*, 117–133.

Fagereng, Å., 2013: Fault segmentation, deep rift earthquakes and crustal rheology: Insights from the 2009 Karonga sequence and seismicity in the Rukwa–Malawi rift zone. *Tectonophysics, 601*, 216-225.

Fritz, H., Abdelsalam, M., Ali, K., Bingen, B., Collins, A., Fowler, A., Hauzenberger, C., Johnson, P., Kusky, T., Macey , P., Muhongo, S., Ghebreab, W., Stern, R., Viola, G., 2013: Orogen styles in the East African Orogen: A review of the Neoproterozoic to Cambrian tectonic evolution. *Journal of African Earth Sciences, 86*, 65-106.

Hardarson, B., 2015: The Western Branch of the East African Rift: A review of tectonics, volcanology and geothermal activity. *GRC Transactions*, 39.

Jackson, J., McKenzie, D., Priestley, K., and Emmerson, B., 2008: New views on the structure and rheology of the lithosphere. *J. Geol. Soc. Lond., 165*, 453–465.

Keranen, K. and Klemperer, S.L., 2008: Discontinuous and diachronous evolution of the Main Ethiopian Rift: Implications for development of continental rifts. *Earth and Planetary Science Letters, 265*, 96– 111.

Koptev, A., Burov, E., Calais, E., Gerya, T., Guillou-Frottier, L., Cloetingh, S., Leroy, S., 2016: Contrasted continental rifting via plume-craton interaction: Applications to Central East African rift. *Geoscience Frontiers, 7-2*, 221-236.

Lenoir, J., Liégeois, J., Theunissen, K., Klerkx, J., 1994: The Paleoproterozoic Ubendian shear belt in Tanzania: Geochronology and structure. *American Association of Petroleum Geologists Bulletin, 19*, 169–184.

Lindenfeld, M., Rümpker, G., Link, K., Koehn, D., Batte, A., 2012: Fluid-triggered earthquake swarms in the Rwenzori region, East African Rift – Evidence for rift initiation. *Tectonophysics, 566-567*, 95-104.

McKenzie, D., Jackson, J., and Priestley, K., 2005: Thermal structure of oceanic and continental lithosphere. *Earth and planetary science letters, 233*, 337-349.

Meghraoui, M., 2016: The seismological map of Africa. *Episodes, 39*, 9-18.

Muirhead, J.D., Kattenhorn, S.A., and Le Corvec, N., 2015: Varying styles of magmatic strain accommodation across the East African Rift. *Geochem. Geophys. Geosyst., 16*, 2775–2795.

Sachau, T., Koehn, D., and Passchier, C.W., 2011: Lattice-particle simulation of stress patterns in a Rwenzori-type rift transfer zone. *Journal of African Earth Sciences, 61*, 286-295.

Smets, B., Delvaux, D., AnnRoss, K., Poppe, S., Kervyn, M., d'Oreye, N., and Kervyn, F., 2016: The role of inherited crustal structures and magmatism in the development of rift segments: Insights from the Kivu basin, western branch of the East African Rift. *Tectonophysics, 683*, 62-76.

Smets, B., Kervyn, M., d'Oreye, N., and Kervyn, F., 2015: Spatio-temporal dynamics of eruptions in a youthful extensional setting: Insights from Nyamulagira Volcano (D.R. Congo), in the western branch of the East African Rift. *Earth Science Review, 150*, 305-328.

Smith, M., 1994: Stratigraphic and structural constraints on mechanisms of active rifting in the Gregory rift, Kenya. *Tectonophysics, 236*, 3-22.

Smith, M., and Mosley, P., 1993: Crustal heterogeneity and basement influence on the development of the Kenya Rift, East Africa. *Tectonics, 12*, 591–606.

Stern, R.J., 1994: Arc assembly and continental collision in the Neoproterozoic EastAfrican Orogen — implications for the consolidation of Gondwanaland. *Annual Reviews of Earth and Planetary Sciences 22*, 319–351.

Theunissen, K., Klerkx, J., Melnikov, A., Mruma, A., 1996: Mechanisms of inheritance of rift faulting in the western branch of the East African Rift, Tanzania. *Tectonics, 15-4*, 776–790.

Tiercelin, J., Chorowicz, J., Bellon, H., Richert, J., Mwanbene, J., and Walgenwitz, F., 1988: East African Rift System: Offset, age and tectonic significance of the Tanganyika Rukwa-Malawi intracontinental transcurrent fault zone. *Tectonophysics, 148*, 241–252.

Tigume, F., Nybalde, A., and Juli, J., 2012: Moho depths and Poisson's ratios of Precambrian crust in East Africa: Evidence for similarities in Archean and Proterozoic crustal structure. *Earth and Planetary Science Letters, 355-356*, 73-81.

WoldeGabriel, G., Aronson, J.L., Walter, R.C., 1990: Geology, geochronology and rift basin development in the central sector of the main Ethiopia Rift. *Geological Society of American Bulletin 102*, 439–458.

Williams, L.A.J., 1982: Physical aspects of magmatism in continental rifts. In: Pálmason, G. (editor), *Continental and Oceanic rifts*. American Geophysical Union, Geodynamic Series, 8, 193-222.