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CHARACTERISTICS AND IMPORTANT FACTORS THAT INFLUENCE THE DEVELOPMENT OF GEOTHERMAL SYSTEMS IN THE WESTERN BRANCH OF EAST AFRICAN RIFT SYSTEM

P. Omenda[1], C. Ebinger[2], W. Nelson[3], D. Delvaux[4], W. Cumming[5], L. Marini[6], S. Halldórsson[7], J. Varet[8], K. Árnason[9], G. Ruempker[10], K. Alexander[11], M. Zemedkum[12]

[1]Geothermal Consultant, Nairobi, Kenya, [2]University of Rochester, USA, [3]Towson University, USA , [4]Royal Museum for Central Africa, Belgium, [5]Consultant, USA, [6]Consultant in Applied Geochemistry, Italy, [7]University of Iceland, [8]Consultant, France, [9]ISOR, Iceland, [10]Goethe University, Germany, [11]Consultant,
New Zealand, [12]UNEP, Nairobi, Kenya
Email: pomenda@gmail.com

ABSTRACT

The workshop was funded by ARGeo-UNEP and ICEIDA and organized at the request of countries of the western branch of East African Rift System (EARS) arising from poor results from previous geothermal projects. The main objectives of the workshop were to discuss the geologic setting and conditions that support the development of geothermal systems in the countries of the western branch of East African Rift System (EARS). Further, the workshop was geared to understanding the occurrence, nature and characteristics of the geothermal systems in the western branch and to discuss the appropriate exploration methods. Some of the key findings were that it is likely that medium to high temperature geothermal systems exist at several localities within the western EARS and that majority of the systems can be described by fault controlled model. It is believed that some localities that are associated with volcanoes may have magmatic geothermal systems. It was recommended that exploration of fracture controlled geothermal systems should incorporate drilling of TG wells in the programme. It is further suggested that the classification for the entire EARS geothermal systems (divergent plate boundary) should be modified from that used for convergent plate boundaries as chloride levels are naturally lower in the former due to low values in volcanic gases. It is also demonstrated that K-Mg and chalcedony/quartz geothermometers are the most reliable for most prospects in the western EARS. From B&R experience, it is clear that exploration for fracture controlled systems must be led by detailed geology and structural/fault analyses followed by drilling of temperature gradient wells and where necessary slim holes.

1. INTRODUCTION

1.1 About the Workshop

The workshop was organized as part of the activities of the African Rift Geothermal Development facility (ARGeo) under UNEP on request by countries of western branch of EARS. The countries include Burundi, Rwanda, Uganda, Zambia, Tanzania, Malawi and Mozambique. The need for the workshop arose from the fact that despite enhanced exploration activities in the countries transected by the western branch of EARS, no successful geothermal project has been developed. This was thought to be partly contributed by the poor understanding of the relationship between the local geologic setting of western EARS and their geothermal occurrences. This had resulted in exploration methods that have been successfully applied in eastern EARS geothermal prospects being used to evaluate prospects in western EARS.

The workshop was held at Lemigo Hotel in Kigali, Rwanda on 9-11 March 2016 where a total of 75 invite-only participants attended from countries of EARS and international resource persons from Belgium, Italy, France, Germany, USA, New Zealand, Iceland and Africa. The workshop was sponsored by UNEP, MFA, Iceland and NDF, Energy Development Corporation Limited of Rwanda (EDCL) and Rwanda Energy Group (REG). From the presentations and discussions thereto, the meeting resolved that there are some issues that are now better understood which would lead to better implementation of geothermal exploration programmes in the western EARS with some impacts on the eastern EARS prospects.

1.2 Regional Geologic Setting

The East African rift system is widely recognized as a classical example of a continental rift system. It is part of the Afro Arabian rift system that extends from the Red Sea to Mozambique in the south. As the rift extends from the Ethiopian segment southwards it bifurcates at about 5^{o}N into the Eastern and Western branches. The two branches of the rift skirts around the Tanzania craton and formed within the Late Proterozoic belts adjacent to the margins of the craton. However, the Eastern Branch that comprises the Ethiopian and Kenya rifts is older and relatively more volcanically active than the western branch that comprises Albert–Tanganyika-Rukwa-Malawi rifts (Figure 1).

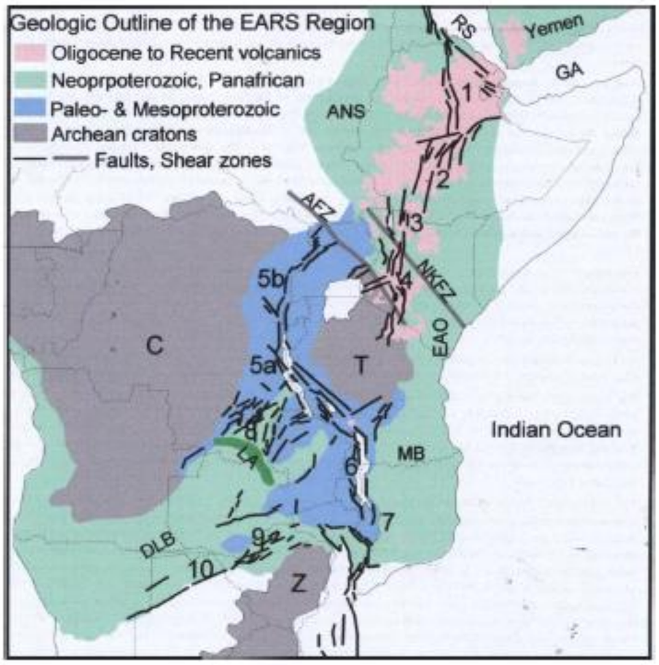

Figure 1: Tectonic map of East Africa

Asthenospheric upwelling of the African superplume formed two arms with one centred under Ethiopia (Ethiopian Dome) and the other Lake Victoria region (Kenya Dome) (Figure 2). Further brittle extension of the crust resulted in down faulting and formation of the graben. In the case of the EARS, extensions is more active in the north being more than 2cm/year in the Red Sea – Gulf of Aden, 1 mm/year in the Main Ethiopian Rift, and further less than 1mm/year in the Kenya Rift and southwards. In response to the increased extension in the EARS, the Moho is shallow under the rift and occurs at between 5 and 35 km along the axis of the rift.

The northern EARS sectors (MER and Afar) developed in the Arabian-Nubian shield (ANS), the northern sector which is made up of mechanically weak, newly formed crust. On the other hand, the Kenya rift developed in terrain occupied by the Mozambique Belt (MB). The MB is made up of reactivated pre-existing terrains having mechanical characteristics which were partially modified by the Panafrican tectono-thermal processes but are still partially retained (Fig. 1). These differences may be partly responsible for the fact that rifting and volcanic activity have evolved further in the north. Mantle plume impact appears to be greater in the region of the northern sectors than in that of the Kenya Rift, as reflected in the dimensions of domal uplift and the differences in the extent of rift opening: 30km in Ethiopia, 10km in Kenya and 2-4km in Northern Tanzania. The initiation of rifting and volcanism in Turkana region (45 Ma) predated those in the above rift sectors and had been plume independent. Turkana rift zone is not yet linked with the MER but in its south, it has merged with the main Kenya rift at the site of Barrier volcano.

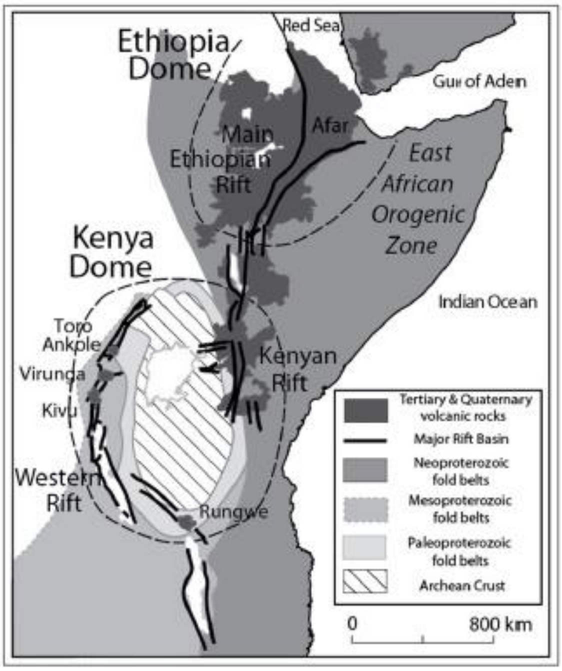

Figure 2: Mantle plumes of the Kenya and Ethiopian domes

2.0 TECTONIC DEVELOPMENT OF WESTERN EARS

The Western Branch of the East African Rift System (EARS) extends from South Sudan to Mozambique in a general S-shape, with, from North to South, the NE-trending Kivu and Albertine rift segments, the N-S northern half of the Tanganyika rift, the NW-trending South Tanganyika-Rukwa-North Malawi (TRM) rift segment, and the N-S Malawi rift segment and its prolongation into Mozambique (Fig. 3). It developed with relatively discrete basin initiation and volcanism at various times since the since the Mid Miocene, widespread rifting in the Late Miocene (5-9 Ma) and a last phase of accelerated rifting during the Quaternary (last 2 Ma) (Ebinger, 1989; Chorowicz, 2005; Roberts et al., 2012; McGregor, 2015). The Western Branch is one of the two branches of the EARS which separate the eastern coastal Africa (Somalian plate) from the rest of Africa (Nubian plate). These two branches surround and isolate the Tanzanian craton in the North (Victoria microplate) and the Mozambique part of the East African Orogen in the South (Ruvuma microplate plate) (Fernandes et al., 2013; Saria et al., 2014).

Different kinematic models have been proposed for the opening of the EARS (Fig. 3). Based on remote sensing interpretation and fault-slip data, Chorowicz (2005) suggested a NW-SE opening in a pull-apart mechanism guided by transcurrent wrench fault zones. In this model, the NW- trending central portion of the Western branch (TRM zone) acted as an intracontinental right-lateral fault zone. Conversely, Delvaux et al. (2012) show after detailed neotectonic and fault kinematic analysis that the TRM segment is currently opening in pure normal faulting, with principal extension orthogonal to the fault trend. Evidence for right-lateral faulting has been also found along the major border faults, but this is related to an earlier, pre-Cretaceous tectonic stage.

The Western branch has a long-lived tectonic evolution, with frequent reactivations, first in ductile conditions and then in brittle conditions since the late Neoproterozoic - early Palaeozoic (Delvaux, 2001). The brittle faults recorded along the TRM rift segment (Delvaux et al., 2012) and also in the Kivu rift segment suggest that thrusting and reverse faulting occurred in the area of the future Western branch during the Late Pan African amalgamation of Gondwana, as a consequence of the E-W convergence and collision of the eastern and western Gondwana along the eastern margin of the Tanzanian craton. Later, probably during the Triassic, the same area was affected by strike-slip reactivations in response to far-field ~N-S oriented compressional stresses generated at the southern margin of Gondwana which was in the situation of an active compressional margin at that time.

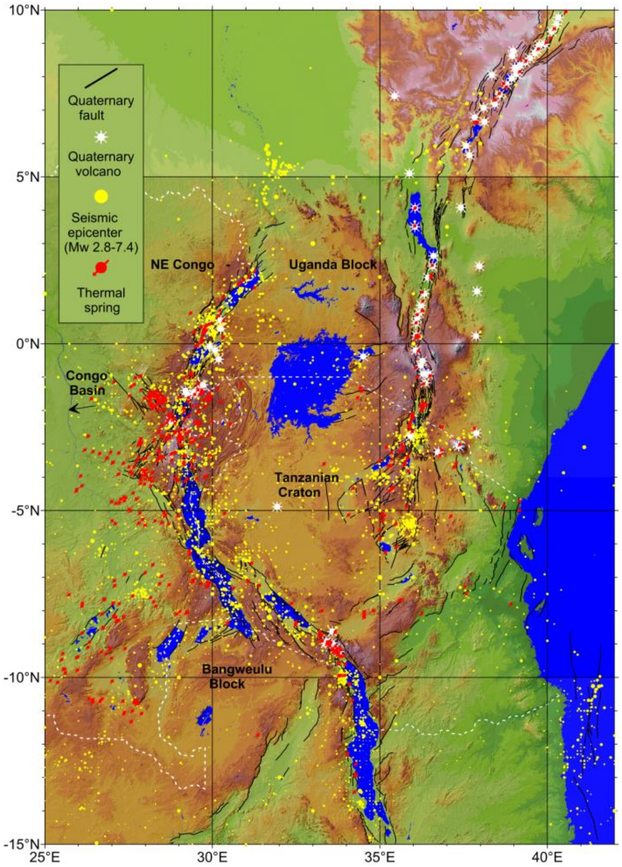

Figure 3: Distribution of Quaternary neotectonic faults, volcanoes and thermal springs (After Delvaux, 2015)

3.0 MAGMATISM IN EARS

Magmatism in the EARS was a product of active rift formation that involved lithospheric extension accompanied by upwelling of the underlying ashenospheric mantle followed by melt formation due to decompression of the asthenosphere (Fig. 4). Further brittle extension of the crust resulted in down faulting and formation of the graben. In the rift axis of the eastern branch occurs numerous central volcanoes of Quaternary age overlying products of Miocene and Pliocene volcanism. The shield volcanoes are built largely of basalts, intermediate lavas (trachytes) and rhyolites and the associated pyroclastics. The evolution of the basalt – tracyte-rhyolite suite has been modelled as being a product of fractional crystallization of mafic lavas and crustal assimilation. However, some volcanic fields show products of crustal anataxis, e.g. Olkaria comendites. Fractional crystallization process occurred within shallow magma chambers which resulted in the formation of large size caldera volcanoes that are a common feature of the east African rift axis from MER to Kenya. Style of magmatism changed along the from north in Afar where MOR is literally on the surface through MER and Kenya rift where the Moho is less than 25km to northern Tanzania where the crust thickens to more than 40km is exemplified by change from basalt-trachyte-rhyolite to carbonatitic types in northern Tanzania, e.g. Ol Doinyo Lengai volcano.

However, metasomatized lithospheric mantle does not behave like fertile or depleted peridotite mantle and therefore, Elkins-Tanton (2007) proposed lithospheric drip melting to explain melting of metasomatized lithologies which are unstable compared to peridotite and can founder into the underlying asthenosphere via ductile dripping. In this model, a drip descends the easily fusible metasomatized lithospheric mantle, heats conductively and melts at increasing T and P (Fig. 5). Ambient peridotite mantle can melt as it convectively fills the space left by the descending drip and thereby melts via decompression. If the descending drip has significant volatile contents, those volatiles can be driven into the surrounding peridotite mantle, forcing it to melt as well. Together, these processes constitute lithospheric drip melting.

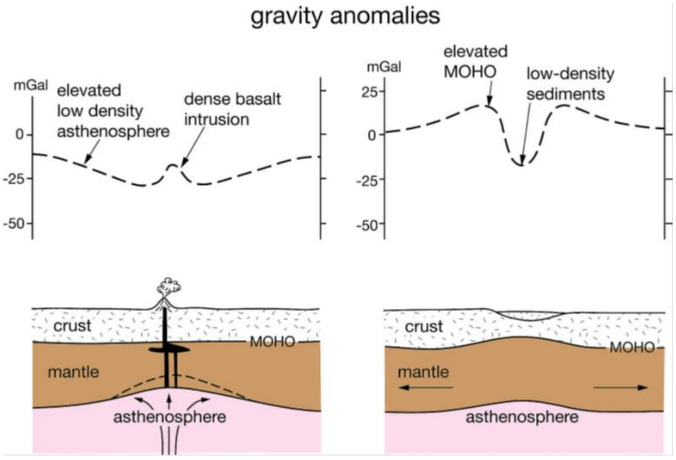

Figure 4: Active model of rift formation

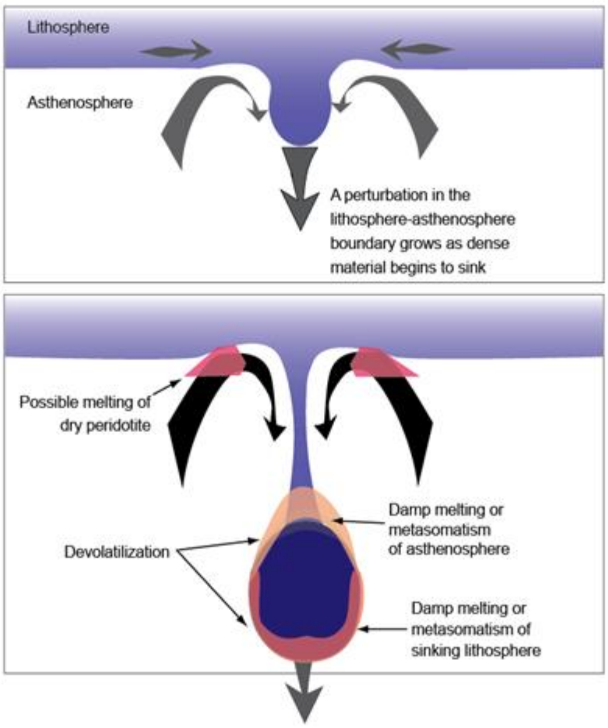

Figure 5 Schematic model of lithospheric drip melting (After Furman et al., accepted)

Lateral flow within weakened lithosphere feeds the growing instability. As the instability begins to sink, lateral flow lags behind and an annulus of high topography forms around the drip; some adiabatic melting can occur here. The sinking drip heats conductively in the asthenosphere and can devolatilize or melt producing magmatism or generating additionally metasomatized asthenosphere or lithosphere. After the neck of the instability thins to disappearing, a downward-facing cusp can remain in the lithosphere, along with remaining frozen-in dense material (Elkins-Tanton, 2007). The width of the drip is dependent upon the thickness of the unstable layer that is sinking, and multiple instabilities can occur adjacent to each other simultaneously or sequentially.

Evidence for lithospheric drip magmatism can be seen in pre-flood basalt volcanism in Turkana (>35 Ma), Miocene shield volcanism on the eastern Ethiopian Plateau and in Turkana (22-26 Ma), and Quaternary volcanism in Virunga and Chyulu Hills (Eastern Rift). In contrast, there is, at best, limited evidence for drip magmatism in Miocene volcanism in S. Ethiopia, or Quaternary within-rift lavas in Ethiopia and Turkana. The evidence for widespread lithospheric removal across eastern Africa coincides with the timing of dome uplift (e.g. Gani *et al.*, 2007; Wichura *et al.*, 2015) and further demonstrates the controls of lithospheric mantle on volcano- tectonic processes throughout the evolving EARS. Lithospheric drip magmatism has potentially important implications for geothermal exploration. In this model, the descending lithospheric drip is relatively localized, meaning it can supply low-volume melts to a volcanic field but not to an entire region. Additionally, as the drip descends, it will eventually be exhausted and the major source of magmatism and, by extension geothermal energy, will cease.

4.0 CASE STUDIES: BASIN AND RANGE GEOTHERMAL AREA, USA

The Great Basin region, USA, hosts ~425 known geothermal systems ≥37° C (Fig. 6), of which more than 150 resources have temperatures ≥100° C and 72 systems have temperatures ≥150° C (Faulds et al., 2014). Currently, 31 resources in the Great Basin region are in production or have had successful flow tests, and total installed capacity is nearly 1,000 MWe. Individual systems range from 0.5 to 275 MWe capacity. Twenty-seven systems of the 31 total productive systems are < 50 MWe in size and the median installed capacity of all 31 systems is 18 MWe. The ~425 known geothermal resources in the Basin and Range region are dominantly amagmatic with less than 2% of the systems associated with upper crustal magmatism. Instead of magmatic heat, these resources are associated with active extensional and transtensional faulting within a broad region of high crustal heat flow (Sass et al., 1971; Koenig and McNitt, 1983; Lachenbruch and Sass, 1978; Wisian et al., 1999; Blackwell and Richards, 2004; Kennedy and van Soest, 2007; Faulds and Hinz, 2105). Another key characteristic of geothermal systems in the Basin and Range is that ~40% of the known resources are blind, having no active surface manifestation such as hot springs or fumaroles (Ball et al., 1979; Coolbaugh et al., 2007; Faulds and Hinz, 2015). Estimates are that blind geothermal systems probably make up at least 75% of the total resources in the Great Basin with many new systems yet to be discovered (Coolbaugh et al., 2002; Faulds et al., 2016).

For several decades, high angle normal fault zones have been recognized as a key control on individual geothermal fields in the Great Basin region such as at Dixie Valley (Blackwell et al., 1999; Johnson and Hulen, 2002; Wannamaker, 2003), Rye Patch (Waibel et al., 2003), Brady’s and Desert Peak (Benoit et al., 1982; Faulds et al., 2010), Lee-Allen (Hinz et al., 2008), San Emidio (Rhodes et al., 2011), Neal Hot Springs (Edwards and Faulds, 2012), Tuscarora (Dering and Faulds, 2012), and Salt Wells (Hinz et al., 2014). More recently it has been recognized that the geothermal resources in the Great Basin region are associated not with just any random fault segment, but with specific fault patterns or structural settings. These settings include terminations of major normal faults, accommodation zones (belts of intermeshing, oppositely dipping faults), step-overs in range-front faults, displacement transfer zones along strike-slip faults, pull-aparts along strike-slip faults, major bends in normal faults, and fault intersections (Fig. 7; Faulds et al., 2006, 2011; Faulds and Hinz, 2015). In striking contrast, the central segments of major normal faults with maximum displacement contain relatively few geothermal systems in the Basin and Range.

The consistent correlation between geothermal systems and specific structural settings (Fig. 7) is in agreement with Micklethwaite and Cox (2004), who found that zones of high permeability in fault systems correspond to paleo-rupture arrest areas at the ends of fault segments. In normal fault systems, these rupture arrest regions commonly correspond to discrete step-overs in fault zones or reversals in the dominant dip direction of systems of faults (Faulds and Varga, 1998).

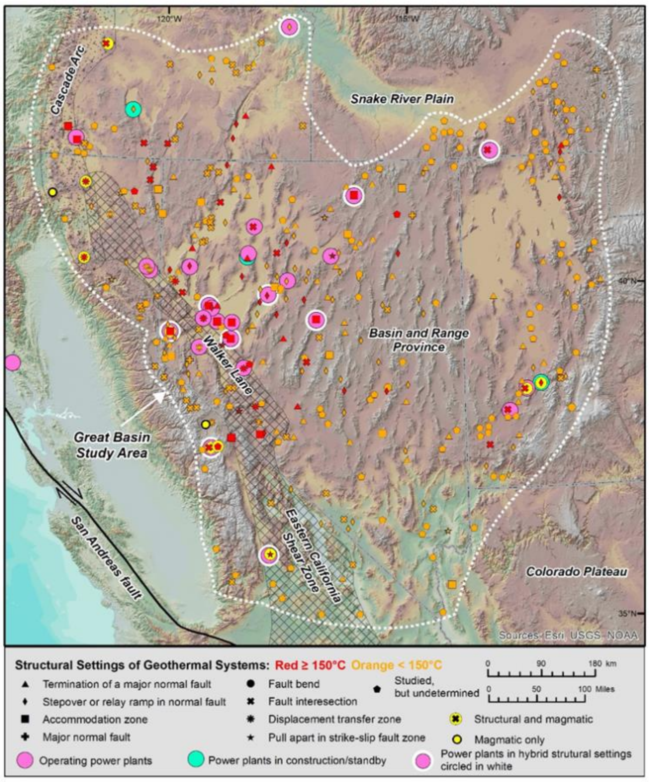

Figure 6. Structural setting of geothermal systems in B&R Province, USA

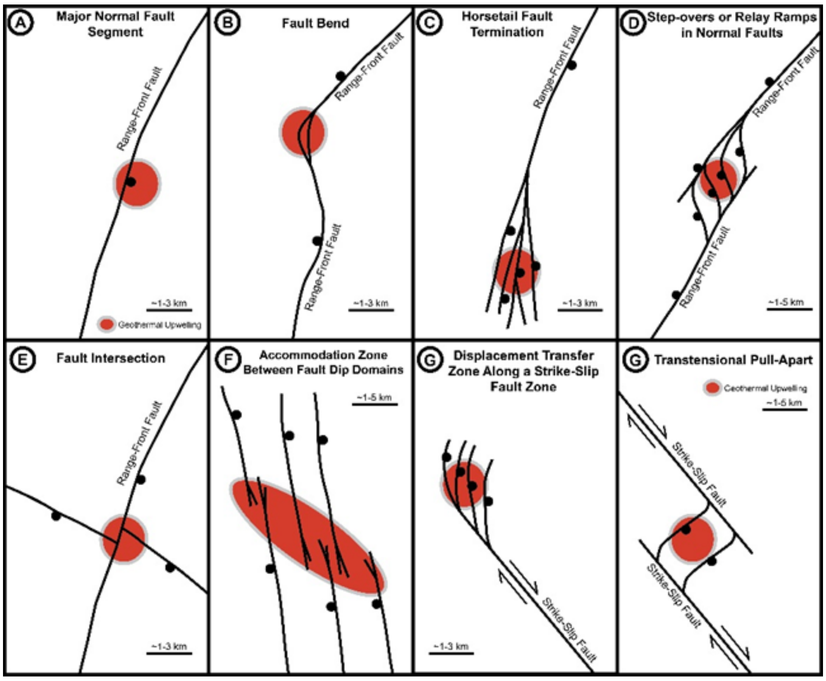

Figure 7. Characteristic structural settings for geothermal systems in the B&R Province (Reproduced from Faulds and Hinz, 2015).

Such rupture arrest regions may also account for high-permeability flow paths occurring in spatially discrete but negligible overall fractions of individual faults, as documented in the Borax Lake geothermal field in southern Oregon (Fairley and Hinds, 2004). The fault zones associated with these structural settings tend to be dominated by fault breccia with greater permeability whereas the centers of normal faults with maximum displacement tend to be dominated by impermeable clay-rich fault gouge.

The vertical architecture of fault and fracture intersections associated with these structural settings (Fig. 7) facilitate fluid convection from 2-5 km deep for all the power capable resources (Coolbaugh et al., 2005). Many production wells in the Great Basin region produce from 1 to 2 km depth. Analysis of feed zones in production and injection wells reveals two primary patterns that include: (1) intersections with high angle faults or (2) specific stratigraphic units with high primary and/or secondary permeability. Examples of high-angle fault dominated feed zones for production wells include Tuscarora (18 MWe; Dering and Faulds, 2012), Neal Hot Springs (30 MWe, Edwards and Faulds, 2012), and McGinness Hills (72 MWe), where feed zones are limited to intervals of <10 m, with focused fluid flow in intervals of <0.5 m per well along single fault planes. Stratigraphic permeability has been encountered in both sedimentary and volcanic units (e.g., Soda Lake, 23 MWe; McLachlan et al., 2011). Competency contrasts between stratigraphic units favor broadly distributed tectonic fractures throughout the more competent units and produce productive horizontal reservoirs connected to primary deeply rooted fluid flow conduits (e.g., Bradys, 26 MWe; Siler et al., 2016).

The catalogue of structural controls of geothermal systems in the Basin and Range can be used both as a guide for exploration of undiscovered systems and for development of known resources. Numerous structural settings capable of hosting blind geothermal resources remain unexplored (Hinz et al., 2015; Faulds et al., 2016). Structural settings can be identified and ranked for relative favorability to host a geothermal resource (e.g., play fairway analysis; Faulds et al., 2016; Shevenell et al., 2015; Coolbaugh et al., 2015). For example, recency of faulting, earthquake seismicity, and extensional strain rate have all been shown to statistically correlate with economic hydrothermal systems in the Great Basin region, USA, and globally (Faulds et al., 2016; Hinz et al., 2016). Structural settings can then be tested with shallow temperature surveys to see if a hydrothermal resource is present, and if so a systematic exploration approach can be employed to further evaluate the resource potential and develop the resource if commercially viable (e.g., Hinz et al., 2013).

5.0 HEAT SOURCES FOR WESTERN EARS

The similarity in He/Ne ratios between EARS samples and many OIBs that display high $^3He/^4He$ ratios suggested a deep-seated plume component that has preserved noble gas characteristics distinct from the upper-mantle, and which currently supplies the EARS with primitive volatile components. In this way, the Ethiopia and Kenya domes represent two different heads of the common plume source which pervasively influences magmatism throughout eastern Africa. The similarity in He/Ne ratios between EARS samples and many OIBs that display high $^3He/^4He$ ratios suggested a deep-seated plume component that has preserved noble gas characteristics distinct from the upper-mantle, and which currently supplies the EARS with primitive volatile components. In this way, the Ethiopia and Kenya domes represent two different heads of the common plume source which pervasively influences magmatism throughout eastern Africa. Such a model involving a common mantle plume source underlying the entire EARS effectively rules out other plume models that advocate either different styles of mantle convection along the EARS or multiple plumes impinging the African lithosphere, such as an oceanic HIMU-type mantle plume to explain low $^3He/^4He$ ratios evident in the Kenya rifts. Finally, the model shows that the SCLM plays the key role in generating the low $^3He/^4He$ ratios along the EARS, effectively ruling out DMM involvement in petrogenesis in the region surrounding the Kenya Dome. This conclusion argues against the concept of a globally homogeneous upper-mantle, supplying volatiles to both mid-ocean ridges and continental rifts.

Compared to the Main Ethiopian Rift and the Eastern Rift, the Western Rift is considerably amagmatic. With four recognized zones of recent volcanism – Toro Ankole, Virunga, Kivu, and Rungwe – there is a significant portion of the rift that lacks volcanism entirely. Apart from Rungwe, much of the volcanism in this region has unusually high potassium abundances. In contrast, the Eastern Rift is marked by alkaline to highly sodic volcanism from Turkana through southern Tanzania (though activity is not temporally continuous). The Main Ethiopia Rift is marked by alkaline lavas (not enriched in either sodium or potassium extremes) and transitional lavas associated with the 30 Ma flood basalt episode. Therefore, the sources and dynamic processes associated with volcanism in the Western Rift are geochemically distinct from those operating in both the Main Ethiopian and the Eastern Rifts. Additionally, variations in spreading rates within and between rift segments (Stamps *et al.*, 2008) impact crustal structure and, consequently, magma generation, transport, and ultimately volcanic productivity. This means that the factors influencing volcanism are not uniform across the EARS. Therefore, each region must be evaluated separately to determine ultimately whether or not shallow magma chambers can form and support geothermal activity.

Productive shallow to intermediate geothermal fields associated with magma chambers in other locations (e.g. Italy, Kenya, Ethiopia, etc.) are typically associated with intermediate to rhyolitic volcanic fields because the magma chambers responsible for generating silica-rich lavas are contained within the crust (e.g. Wohletz & Heiken, 1992; Carlino *et al.*, 2012). The scarcity of evolved volcanism suggests crust-level magma chambers are not common or at least not long-lived in the Western Rift. Instead, dikes of mantle-derived magma actively feed volcanoes such as Nyiragongo and Nyamuragira. Carlino *et al.* (2012) suggest that the presence of silicic magma chambers generate more productive geothermal fields that can be tapped from a larger distance from the magma chamber. These authors also suggest that dike-fed volcanoes can produce geothermal fields, but note that those fields do not have a large radius of influence.

There are a number of geodynamic factors responsible for produce alkaline mafic magmas with little to no more evolved melts. First, eastern Africa is composed of an amalgamation of terranes assembled during the Pan-African orogeny (~950-500 Ma). During this orogenic event, the Tanzania craton served as a nucleus upon which other material was accreted. As a result, the lithosphere underlying the EARS is geodyamically heterogeneous and these inherited heterogeneities provide a viable explanation for geochemical difference in the nature of volcanism in each of the rift sections. While numerous geochemical and geophysical papers support the presence and contribution of at least one mantle plume beneath the EARS, the majority of the Western Rift lacks compelling elevated 3He/4He (> 8Ra and ≤ 20Ra; Marty *et al.*, 1996; Scarsi & Craig, 1996) signatures attributed mantle plume contributions. Only at Rungwe do the mafic lavas preserve elevated 3He/4He (up to 14Ra; Hilton et al. 2011). Interestingly, Rungwe also records the fastest spreading rate in the Western Rift (Stamps et al. 2008). Instead, many geochemical investigations conclude that the ambient upper asthenosphere mantle and the lithospheric mantle are the major contributors to volcanism in the Western Rift (Rogers *et al.*, 1992; Furman, 1995; Rogers *et al.*, 1998; Furman & Graham, 1999; Rosenthal *et al.*, 2009; Tedesco *et al.*, 2010).

Lithospheric mantle xenoliths from the Toro Ankole (Katwe-Kikorongo) and Virunga (Bufumbira) regions are dominated by pyroxenite, phlogopite-rich pyroxenite, glimmerite, and olivine-bearing pyroxenite lithologies (e.g. Lloyd, 1981, W. Nelson, unpublished data). These unusual mantle lithologies have been linked experimentally to the potassium rich volcanic products in this region (Lloyd *et al.*, 1985). Additionally, these olivine-poor lithologies are considerably more fluid-rich than peridotite, which enables melting at lower temperatures and can thereby produce smaller volumes of magma. These melts may be generated by conductive heating (upwelling ambient mantle or plume material), decompression melting due to lithospheric extension, or even lithospheric drip melting (Furman *et al.*, accepted). Regardless of the mechanism, geochemical analyses demonstrate that crustal contamination of the mafic lavas occurs only minimally (e.g. Rogers *et al.*, 1998; Furman & Graham, 1999; Chakrabarti *et al.*, 2009; Rosenthal *et al.*, 2009). This observation, in turn, demonstrates that these mantle-derived melts do not pause at crustal levels. In fact, unlike recent (<1 Ma) volcanism in Ethiopia, Kenya, and Tanzania, Western Rift volcanism is dominated – roughly 75% (Demissie, 2010) – by mafic volcanism. There is little geochemical evidence to support sustained magma chambers within the continental crust whereby more intermediate to silicic magmas can be generated by fractional crystallization and crustal assimilation.
Therefore, from a petrologic perspective, there is not abundant evidence for crust-level magma chambers in the Western Rift, and magma chambers may not be the best focus for geothermal exploration. Instead, mafic dikes feeding volcanism may be a more viable alternative but have a limited reach from the volcanic edifice. Understanding faulting and groundwater flow near the

volcanoes may provide the best insight into potential geothermal reservoirs in association with magma production.

6.0 FLUID GEOCHEMISTRY

6.1. Water classification

The geochemical framework of geothermal systems situated along subduction zones has been established long ago through extensive exploration, at the surface and at depth. Mature chloride waters hosted in geothermal reservoir migrate laterally and discharge at the surface at considerable distance from the geothermal field. Fumarole activity and steam-heated acid-sulfate waters mark the upflow zones. Peripheral bicarbonate waters occur at relatively shallow depths at some distance from the geothermal field. Acid chloride-sulfate volcanic waters are found in crater lakes. Consequently, the terms mature chloride waters, steam-heated acid-sulfate waters, peripheral bicarbonate waters, acid chloride-sulfate volcanic waters have been suggested by Giggenbach (1988). Only the Giggenbach's triangular diagram of major anions is often used for water classification in geochemical investigations carried out in convergent-plate settings although a more comprehensive approach is needed.

The high-temperature geothermal reservoirs of the Eastern branch of the EARS (e.g., Olkaria and Menengai in Kenya, and Aluto-Langano in Ethiopia) host not only mature chloride waters but also mature bicarbonate-chloride and mature bicarbonate waters. To try to explain why, we recall that in volcanic-magmatic regions, deep geothermal liquids are assumed to be produced through neutralization of initially acidic meteoric-magmatic aqueous solutions (e.g., Giggenbach, 1988). The few available data for volcanic gases indicate that subduction-zones volcanic gases are enriched in Cl relative to hot-spot and divergent-plate volcanic gases (e.g., Symonds et al., 1994; Sawyer et al., 2008). Therefore, the comparatively small supply of Cl-bearing magmatic gas species (chiefly HCl) in the root of the Eastern EARS geothermal systems might be responsible of the comparatively low Cl contents of related geothermal liquids (Marini and Pasqua, 2014). Irrespective of the reasons controlling the presence not only of mature chloride waters but also of mature bicarbonate-chloride and mature bicarbonate waters in the Eastern EARS, it is evident that the terminology of subduction-zone geothermal systems cannot be used in other frameworks. The situation might be even more complicated in the Western EARS. Therefore, more comprehensive approach to water classification is needed to distinguish mature waters from immature waters (Marini, 2016).

6.2. Water geothermometers

All the thermal waters of Northern Thailand have Na-HCO_3 composition and are here considered analogs to the western rift waters. Most of these thermal waters are more or less directly related to a mainly granitic basement, from which they rise up towards the surface along active faults, sometimes of regional importance. Northern Thailand thermal waters plot in the fields of the partially equilibrated waters and of the immature waters in the Na-K-$Mg^{0.5}$ triangular plot of Giggenbach (1988, modified). In most cases there is also a large Na-K/silica disequilibrium that might be due to the absence of albite and K-feldspars as hydrothermal minerals in the geothermal reservoirs. In some cases there is also a considerable K-Mg/silica disequilibrium. Relying on the K-Mg geothermometer, apparent equilibrium temperatures vary from 128 to 153°C for the boiling waters and from 86 to 116°C for the non-boiling thermal waters. These temperatures compare or are somewhat higher than those found in boreholes drilled at maximum depths of 1.3 km in San Kamphaeng and 250 m in Pai - Ban Muang Paeng (Singharajwarapan et al., 2012).

Recent investigations in western rift show that: (i) the Kibiro hot springs exhibit substantial Na-K/K-Mg and Na-K/silica disequilibria; (ii) all the hot springs of the Ngozi prospect and nearby areas have considerable Na-K/K-Mg disequilibrium and most of them have also a significant Na-K/silica disequilibrium. The hot springs of the Ngozi prospect and the Kibiro hot springs have a moderate K-Mg/silica disequilibrium. By analogy with the Northern Thailand case history, K-Mg and silica temperatures are probably representative of the portions of the geothermal aquifers reachable through drilling.

The CO-geothermometer can be used without specifying redox conditions being based on the assumption of full equilibrium among the three carbon-bearing gas species. This assumption is unlikely for CH_4 (due to its slow rate of equilibration, especially at relatively low temperatures) but CH_4 has a small influence on the computed equilibrium temperature. Geothermometers based on H_2 and CO are very effective as H_2 and CO are fast-reacting gas species. However, CO must be measured in dry gases, not in Giggenbach's bottles, since CO reacts with excess NaOH to give formate (Giggenbach and Matsuo, 1991). Geothermometers based on CH_4 work at very high temperatures, where the kinetics of CH_4 re-equilibration is appreciable. Geothermometers based on CO_2 work only for the portions of the geothermal systems flushed by small CO_2 fluxes. Under these conditions CO_2 mineral buffers are effective. If the CO_2 fluxes are too high, CO_2 mineral buffers cannot keep up and the geothermometers involving CO_2 do not work. Geothermometers based on H_2S may be affected by near-surface oxidation of H_2S.

7.0 GEOPHYSICS

Because the western branch of the EARS may have geothermal systems with either volcanic or non-magmatic heat sources and reservoirs may be hosted in sedimentary, volcanic or intrusive formations, the approach to geophysics in geothermal exploration of the western EARS will differ from practices in the mainly volcanic systems of the eastern EARS. On the other hand, crucial elements of the conceptual models of different types of geothermal systems are similar enough the most cost-effective geophysical methods of characterizing them are often similar. For example, because almost all commercial geothermal reservoirs are capped by smectite clay, either through alteration in volcanic cases or deposition in sedimentary cases, resistivity methods like MT and TEM that can image low resistivity smectite clay will have a similar role in East Africa.

Methods like gravity and magnetics, on the other hand, tend to be less cost-effective for geothermal exploration on volcanoes where the largest contrasts in density and susceptibility are typically at or near the surface. Magnetic data are sometimes used to detect sulfate water destruction of magnetite in volcanic rocks but resistivity methods typically provide more reliable images of similar alteration. In sediments, on the other hand, gravity commonly provides effective resource constraints. For example, where relatively uniform sediments unconformably overlie old dense metamorphic rocks, the structure of the interface can sometimes be reliably inferred to several 1000 m depth. Depths can also be estimated by modeling the magnetic responses of isolated magnetic bodies within the metamorphic rocks buried below sediments, albeit with more ambiguity. This highlights the need to reconsider the relevance and reliability of geophysical methods for each situation.

For over 30 years, passive seismic surveys have been routinely used to monitor deep geothermal injection and they have also been effectively used to characterize suspected magma movement in exploration prospects. Seismological methods have provided unique and detailed evidence for ongoing magmatic processes in the crust and upper mantle beneath the Rwenzori region as part of the western branch of the EARS. The relatively high seismic activity favors studies based on passive recordings of local earthquakes. The travel time tomography based on crustal earthquakes reveals evidence for a low velocity anomaly beneath the Rwenzori range (Jakovlev et al. 2011, 2013). The inversions for P and S wave velocity anomalies were performed independently and agree well. The interpretation of the results is based on a synthetic model that reproduces the same pattern of anomalies as that obtained after inversion of the real data. Our models exhibit a significant negative velocity anomaly (up to 8%) beneath the central Rwenzori Mountains. This is interpreted as an indication for active magmatic intrusions beneath the mountains in relation to the rifting. The presence of low velocities in the northwest of the range, within the rift, may be related to magmatic processes beneath the Buranga hot springs. Higher velocities are found elsewhere beneath the eastern rift shoulder and are thought to be related to cratonic crust. Joint local and teleseismic tomography provides information on upper mantle velocity anomalies (probably in relation to partial melt) down to a depth of about 90 km (Fig. 8; Jakovlev et al. 2013).

Active seismic reflection surveys directed at geothermal exploration in volcanic rocks have not produced useful data. The tendency of geothermal systems to degrade seismic data quality makes its application to sedimentary geothermal targets risky. However, because of the particularly promising conditions for acquiring reflection seismic in the sedimentary basins of the western EARS, reflection seismic may play a larger role in geothermal applications, especially if investments in the exploration for petroleum can be leveraged.

The approach used to interpret the geophysical results in geothermal assessments is as important as the specific geophysical methods and analyses used. In mineral exploration, for instance, it is common practice to set a threshold to define an anomaly using the values of one or more types of data. This method, called anomaly hunting, is low cost and works well for low value decisions, such as targeting core holes for mineral assays. However, geothermal wells are much more expensive. To avoid the shortcomings of anomaly hunting, best practice publications in the geothermal industry emphasize integrating geophysics with the other geoscience data to build geothermal resource conceptual models consistent with all available data. Typically, three or more models are prepared that are representative of the uncertainty in the data and analyses. Conceptual models in the western EARS are expected to differ significantly from those in the eastern EARS, probably a greater difference than the type of geophysical data likely to be used.

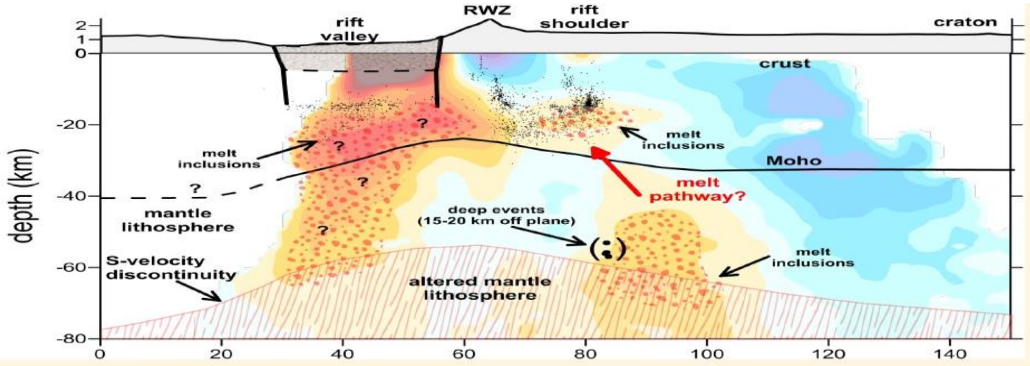

Figure 8: MEQ interpretational sketch of Ruwenzori. From Jakovlev et al (2013).

8.0 TEMPERATURE GRADIENT WELLS

The drilling of temperature gradient holes (TGHs) is a relatively low cost exploration tool compared with slim holes or full size wells, and are accomplished using light truck-mounted rotary or diamond core rigs. Temperature gradient holes are typically drilled <150 m deep, with some ranging up to 500 m. Pipe is installed, plugged at the bottom, and then is filled with water and left to equilibrate with the subsurface temperature profile before obtaining a detailed, down-hole temperature log. The ability to collect numerous temperature measurements over varied terrane without having to develop large drill pads has made this a widely used tool in the Basin and Range. The results from TGHs primarily serve two purposes: (1) regional exploration for new undiscovered resources and (2) guiding detailed development of individual resources. In the case of regional exploration, where magmatic heat is not present, temperature gradient anomalies point towards shallow to mid-level convection anomalies (geothermal systems). TG wells have also proved to be very useful for identifying blind systems. There are many blind systems discovered in Kenya (Chepkoiyo, Baringo), Ethiopia and B&R province in USA (McGinness Hills (72 MWe capacity) and Don A. Campbell (19MWe net production, Orenstein and Delwiche, 2014) through shallow water well drilling which intersected high temperature fluids.

9.0 SUMMARY

- Volcano hosted geothermal activity requires magma chamber development within the continental crust. Indicators of sustained crust-level magma chambers include: Silica-rich volcanism (rhyolites, trachytes, and phonolites), Caldera formation, Stratovolcano formation, Tuff and pyroclastic deposits, evidence for hydrothermal alteration
- Shallow to intermediate magma chambers are not common in the Western Rift since Most volcanism is likely fed by dike systems that do not stall in the crust and therefore only (potentially) deep magma chambers occur.
- Paucity of shallow magma chambers in western branch could be due to lithospheric drip magmatism which generates small volumes of melt pockets of altered lithospheric mantle which may not form large size magma chambers in western rift volcanoes. Other reasons include slow rates of extension – volcanism is fed through dikes that do not stall in shallow crust, and composition of magma source material
- Geothermal reservoirs in the western branch are likely localized to dike networks beneath active volcanoes and along faults.
- Geothermometers that are reliable for western branch are K-Mg and chalcedony/quartz. Na-K is not reliable for many cases. H2 based geothermometers needs to be recalibrated before being used. CO_2, CH_4 and CO data can be used. Other gas geothermometers are less effective.
- A suitable Classification of geothermal waters in EARS should be used as what is in literature was developed for convergent regions. E.g. some bicarbonate waters in EARS are “mature” and not immature as would be read from old classification plots. Reliable classification should be based not only on triangular plots of major anions but also on triangular plots of major cations and salinity plots.
- Effective exploration of geothermal resources in the western branch require detailed geological mapping accompanied by structural studies and fault kinematics since most of the resources are anticipated to be fault controlled medium temperature. Fault controlled systems are also common in eastern EARS between the volcanoes and along rift flanks.
- Effective exploration of fault controlled geothermal systems requires use of TG wells to supplement the common surface methods used for exploration.

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