Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Mantle Influence, Rifting and Magmatism in the East African Rift System (EARS): A Regional View of the Controls on Hydrothermal Activity.

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Keywords: EARS development, Afar, Main Ethiopian Rift, Kenya Rift, Western Rift, Southwestern EARS branches, plume impact, magmatism, hydrothermal features.

ABSTRACT

The most energetic hydrothermal features in Africa occur in the EARS region. EARS development is controlled by the magnitude of the in-field extensive stresses, the fabrics of rifting terrains and, during its later stages, by mantle plume impact. The African Superplume has installed an anomalously high subsurface temperature regime in the South-central, Eastern and Northeastern Africa regions. On this background is superimposed an anomalous temperature regime caused by two focused mantle plumes, one rising under Afar and the other from underneath the Tanzanian craton and spreading to the north and west. There is a strong correlation between high energy hydrothermal activity and these two temperature structures. Passive rifting, where the deep seated Superplume drives crustal extension is associated with the occurrence of hydrothermal features which are due to heating of meteoric water by circulation in the upper crust which is itself heated conductively by the tumescent mantle. Active rifting, where the focused plumes are involved in crust mantle interactions, is associated with hydrothermal activity which is attributed to the heating of the upper crust by mass and heat transfer from the upper mantle. To better understand the occurrence and development potentials of the variety of geothermal resources which the surface hydrothermal features may indicate, it is useful to account for the wide diversity in the modes of occurrence and characteristics of the features in the various EARS sectors. This is achieved by viewing the settings and characteristics of the features in light of rifting as an evolutionary continuum, amagmatic during its early stages, and later, engendering magmatism which itself evolves in stages from the initial eruption of primitive effusives to that of evolved volcanic products. Based on this, it is proposed that the above diversity arises from the different modes of hydrothermal fluid heating which prevail during the different stages of the evolving rifting process.

1. INTRODUCTION

Hydrothermal features are the most obvious and direct indicators of the probable existence of exploitable geothermal resources in the subsurface. Thus, exploration for the resources in new regions, as is the case in most of Africa, would begin with the study of these features. Geothermal fluids occur on the surface and are also encountered in drill holes in all of the tectonic settings which characterize the continent. The exposition of the geothermal resources potential of Africa has to date been limited to the presentation of summary country reports and descriptions of individual resource areas. The known continent-wide inventories of hydrothermal features are incomplete and lack information on their geologic associations. There is need for the regional scale characterization of these activities in the context of the geologic conditions which engender and sustain them. This can contribute to the better understanding of the fundamental bases of geothermal resource occurrence, the transfer of knowledge and experience between analogous settings and, where differences are recognized, to the adoption of appropriate exploration and development strategies. Exploration and academic research are generating useful knowledge which encourages attempts in such a regional scale characterization.

This contribution deals with one geologic regime comprising the EARS sectors that may or may not host Quaternary volcanism but exhibit hydrothermal activity. The EARS region is broadly unified in its tectonic development and regional geothermal character, but also has internal diversity. The paper does not aim discuss the very numerous individual hydrothermal occurrences except in illustration. It follows a top-down approach starting with dealing with presently accepted overarching principles: mantle crust interactions, the progression of rifting through its successive stages and the initiation and evolution of magmatism and ends with a discussion of their resulting geothermal associations. This is hoped to enable the better understanding, as well as the prediction, of the occurrence and characteristics of the geothermal resources of the region which can be followed up by observation and experimental testing in the field. The available information is used to relate the different elements of these overarching themes to the conditions which prevail in the region and to determine their gross geothermal associations. The region's global tectonic setting is outlined as background and its internal tectonic and, where they occur, magmatic developments are described to provide an understanding of the large scale controls on the occurrence and characteristics of the known hydrothermal features. Hydrothermal activity is referred to, in illustration, in these contexts. The results yielded by this approach are discussed in the concluding section.

2. EVOLUTION OF THE EARS ENVIRONMENT

2.1 The Plate Tectonic Setting

The tectonic process which gave rise to the EARS dates from a collision of a northeast drifting African plate with the Eurasian plate at about 45 Ma. The only significant far field extensional stress on the African plate since that time has been slab pull from the zone of plate convergence in the north and northeast. Otherwise, ridge-push from the Mid-Atlantic and West-Indian oceanic ridges has caused compression on this plate. Thus EARS development had been due to an in-field dilatational stress field attributed to asthenospheric upwelling and lateral flow. Following collision, the continent more slowly drifted over the African Superplume, the hypothetical large scale mantle temperature structure shown in Figure 1. Thermal uplift and softening by heating from underneath is believed to have caused stretching deformation and rifting in the lithosphere.

Other geophysical and geochemical data support the existence of this large scale mantle structure.

The regional Bouguer gravity field (Fairhead, 1979) in which negative anomalies map the continent's characteristic high plateau topography, the African Superswell (Fig. 2), is attributed to the isostatic rise of a thermally expanded, light African lithosphere and its being dynamically supported by an anomalously hot asthenosphere.

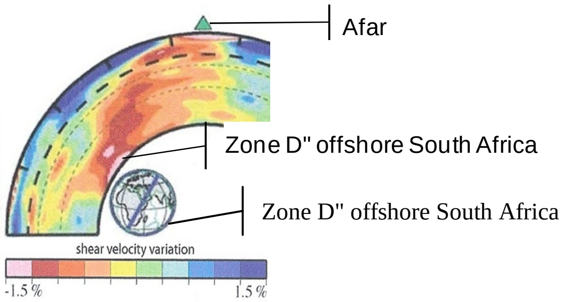

Figure 1: The disposition of the hypothesized "African Superplume" as reflected in the seismic shear wave velocity anomaly along a NNE-SSW profile (from Fig. 5 (A), Ritsema and Allen, 2003).

The inferred temperature anomaly is believed to have resulted from the perturbation of the temperature boundary conditions in a focal zone of the core-mantle boundary region (Lower Mantle Zone D") under the SE Atlantic Ocean offshore from South Africa (e.g. Bunge et al, 1998).

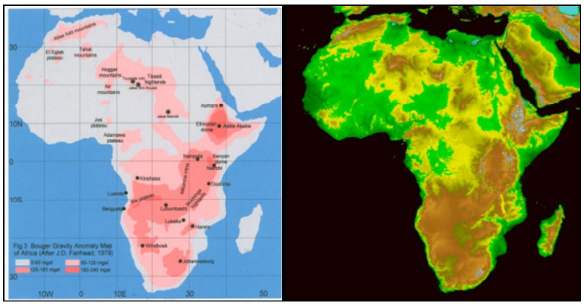

Figure 2: Left, Bouguer gravity anomaly pattern in Africa; values are >-60 mgal (grey), -120, -180 and dark red <-240 mgal (from Fairhead, 1979). The -180 mgal contour line approximates 150 km lithosphere thickness (Fairhead, 1977). Right, the African Superswell. Elevations range from <500m a.s.l. (green) through yellow and shades of brown to grey at >2,500m (DEM from USGS).

The Superplume and Superswell coincide with the region of the DUPAL anomaly (Fig. 3) mapped by Pb isotope variations in mid-oceanic ridge and ocean island type basalts. The Pb isotope anomaly is believed to map a region of anomalously hot and tumescent lower mantle, thought to be made up of ancient subducted oceanic lithosphere (White, 2005, p. 501, citing Duprat and Allegre, 1982).

Northward, the thermal structure rises into the upper mantle to reach its highest elevation under Afar, N.E. Ethiopia (Fig. 1). Zhao et al (1999) confirm that no significant seismic velocity reduction is discerned within the upper mantle beneath southern Africa.

Since the end of Gondwana supercontinent assembly at about 550Ma, the African lithosphere had been in an extensional stress field. The main tectonic event occurred during the Mesozoic when the supercontinent fragmented by rifting along Panafrican orogenic belts. This process engendered the African Plate (Fig. 3, right).

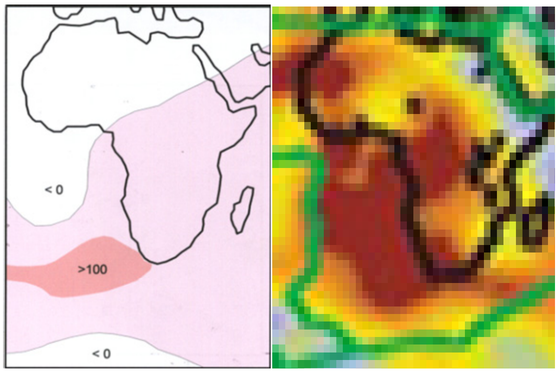

Figure 3: Left: Disposition of the DUPAL anomaly (from Fig. 9.27, Wilson, 2001). Numbers express Δ8/4 values: percent differences between the $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios in mid-oceanic ridge and ocean island type basalts; contour lines are approximate due to sparse data distribution; Right: shear wave tomographic slice at 2850km depth, just above the core-mantle boundary (from Fig. 2A, Ritsema et al, 1999); green lines mark the boundaries of the African plate: the Atlantic and Indian oceanic ridges in the west, south and east, the Red Sea median axis in the northeast and the zone of African-Eurasian plate convergence in the north. The Zagros fold belt is in the far northeast corner.

Many rifts of the Mesozoic tectonic phase became the aborted rift systems of the interior regions and the failed rift arms which punctuate the passive margins of the Indian and Atlantic coasts. The significance of this pre-EARS tectonic phase is that many of the structures were reactivated during the late Tertiary to form the southern part of the present Western rift and the southern EARS branches.

An important outcome of the deep mantle tumescence and consequent crust fracturing during the pre-EARS period had been the creation of the world's largest igneous activity since the Mesozoic. Considerable volumes of flood basalt flows and terminal silicics were erupted during the late Oligocene to early Miocene (Ethio-Yemen region) and the Miocene (Kenya). Varying degrees of melting in the DUPAL anomaly region fed this volcanism (Kieffer et al., 2004). Earlier, during the Eocene, basaltic volcanism had occurred in S. Kivu, on the DRC-Rwanda border, and commenced in Turkana, in the Ethio-Kenya border area, as independent magmatic episodes, but still related to repeated crust tectonic structuring.

2.2 The African Basement and Its Response to Rifting

The EARS developed in the Tertiary volcanic cover rocks in the north and east and in Precambrian basement in the west and south (Fig. 4). However, rifting was influenced by structures and rock fabrics in the Precambrian basement. The basement consists of Archean cratonic nuclei which were welded together by three successive Paleoproterozoic to early Paleozoic orogenic processes:

a. During the late Paleoproterozoic (2.05–1.8 Ga), new and reworked crust joined the Tanzanian and Congo cratons creating an ancestral continent which later broke up.

b. Late Mesoproterozoic orogenic belts were involved in assembling Rodinia supercontinent during 1.35–1.00 Ga which also broke up at the end of this period.

c. Gondwanaland supercontinent was assembled during the Neoproterozoic to early Paleozoic along several orogens collectively referred to as the Panafrican Orogenic belts.

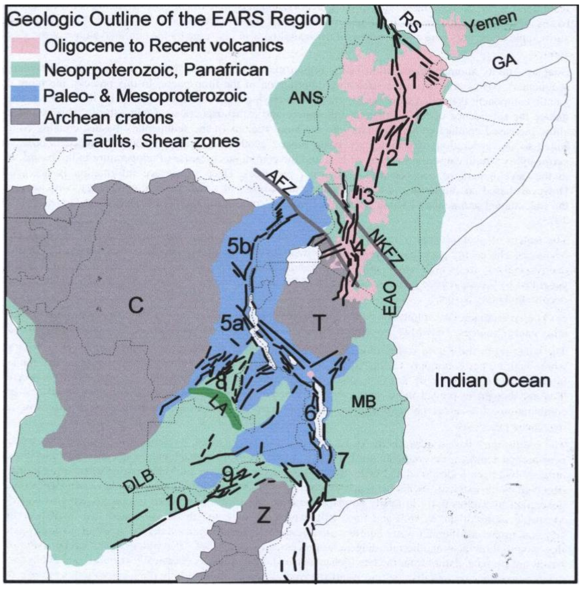

Figure 4: Outline tectonic makeup of the EARS region (based on the Geological Map of Africa, UNESCO-CGMW, 1985-90). Cratons: Congo (C), Tanzania (T) and Zimbabwe (Z, northern part of Kalahari craton). Orogenic belts: Paleo- and Mesoproterozoic (blue), Panafrican (green): Damara-Lufilian (DLB), Lufilian Arc (LA), East African (EAO) comprising the Mozambique Belt (MB) and the Arabian-Nubian Shield (ANS). EARS sectors: Afar (1), Main Ethiopian (2), Turkana (3), Main Kenyan (4), Western (5, a & b are respectively the SE and NE limbs), Malawi (6), Urema (7), SW branches (8) and Zambezi (9); 10 is the Ganzi-Chobe fault (Botswana), southern border fault of the incipient Okavango rift. RS: Red Sea, GA: Gulf of Aden, ASZ: Aswa Shear Zone, NKFZ: N'Doto-Karisa Fault Zone. Black lines are as shown in the map legend.

This architecture of Africa controlled EARS and mantle plume development:

a. The cratons consolidated during the Archean and are deep keeled, mechanically strong and isotropic. They characteristically behave as rheological barriers to rift propagation and mantle upwelling which they refract into their peri-cratonic orogenic belts.

b. The rock fabrics and structures of the Paleo- and Meso-Proterozoic greenstone belts were amenable to rifting of thick crust. This determined the development of the Western and southern EARS branches.

c. The distinction of the Panafrican Orogens is that they are the most mobile of all African basement terrains and have been the most preferred loci for tectonic breakup, mantle plume intrusion and magmatism. They hosted rifting and volcanic activities during the Permian, Jurassic, Cretaceous and the Tertiary to Quaternary. They facilitated Gondwana fragmentation during the Mesozoic.

3. EARS DEVELOPMENT

3.1 Seismicity

The dynamics of rifting in the EARS region is illustrated by the distribution of seismic epicenters (Fig. 5) magnitudes and focal depths.

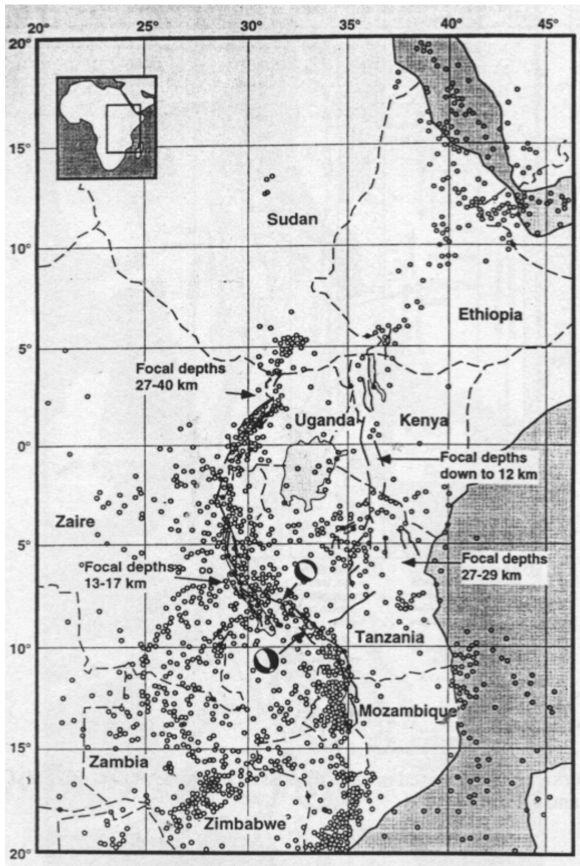

Figure 5: Epicenters of 20th Century earthquakes in Africa (from Morley, 1999 citing Nusbaum et al, 1995). Note: the 13-17 km focal depths are from sites close to 9.0^{O}S, 33.5^{O}E (Rungwe area), to the southeast of where they are shown.

Seismicity is less frequent, of lower magnitude and shallower in the northern and eastern EARS sectors reflecting the prevalence of thin ductile lithosphere in the region of the Panafrican age East African Orogenic belt (EAO). In the west and south, greater epicenter densities, earthquake magnitudes and focal depths reflect the thicker and more brittle nature of the Paleo- and Mesoproterozoic orogenic belts within which the Western Rift is developing.

3.2 EARS Structures

Structures and rock fabrics inherited from the Proterozoic orogenic processes have influenced rift opening and the subsequent onset of mantle-crust interactions. In the later, active rifting phase, mantle plume activities have contributed to enhancing the tectonic process to progressively advanced stages.

3.2.1 The Northern and Eastern EARS Sectors

With its generally longitudinally disposed structures favoring rifting under a broadly latitudinally oriented extensional stress field, the EAO hosts the NNW-SSE to NNE-SSW oriented northern and eastern members of the EARS consisting of the Afar, Main Ethiopian and Kenya rifts. The dispositions of individual rift sectors may vary reflecting longitudinally varying stress field orientation and faulting along zones of least mechanical resistance. The border faults and flexures developed at various times during the Miocene. Starting during the late Pliocene, tectonic activity concentrated along the present axial zones. The rift floors are occupied by thick layers of lava, pyroclastic products, volcano-sedimentary rocks and many volcanoes and calderas. Several small and mostly shallow lakes occupy local tectonic or volcanotectonic depressions. These lakes form the local hydrologic discharge areas and thermal springs often occur on their shores.

As shown in Fig.4, the northern EARS sectors (MER and Afar) developed in the Arabian-Nubian shield (ANS), the northern member of the EAO 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 southern member of the EAO. 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. This seems to have rendered the ANS more amenable to rift development than the MB. 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 (Wilson 1989, p.331, citing Shudovsky, 1985).

The initiation of rifting and volcanism in Turkana region (45 Ma) predated those in the above rift sectors and had been plume independent. These are discussed in 3.3 below. 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.

Two structural features influence the localization of magmatic and hydrothermal activities in these rift sectors:

3.2.1.1 Axial rift structures

These are the zones along which tectonic and magmatic activities concentrated since the late Pliocene and are viewed as the precursors of mid-oceanic ridge development.

In northern and central Afar, six zones of axial tectonic activity opened during 1.2 to 0.04 Ma. They trace the zones of incipient crust oceanization. Most are situated off-center, on opposite sides of the rift floor and terminate at transverse structures. This structural pattern defines microplates with boundaries that are the sites of the most recent volcanism. A chain of eight, discontinuous, right stepping en echelon, segments of the Wenji Fault Belt (WFB), the MER axial tectonic and magmatic zone, each host Quaternary fissure basalt fields and one or more silicic volcanoes. On the Kenya rift floor, the dispositions of the numerous volcanoes show that the zone of most recent tectonic and volcanic activity is continuous throughout its length.

3.2.1.2 Transverse structures

Numerous transverse faults cross the northern and eastern rift sectors. Most post-date rifting and are more common in the MER and Afar. They are considered to be analogous to transform faults at mid-oceanic ridges. These structures play key roles in the localization of high standing volcano constructions and caldera volcano formations along the rift axial and rift marginal zones.

Some structures, notably the Aswa Shear Zone, the Anza rift structures and the Lufilian Arc (Fig. 4) predated and influenced EARS development. These are discussed under 3.2.3 and 3.3 below.

3.2.2 The Western and Southern Rift Sectors

The Western Rift and the southern branches developed in the thick and fairly competent Paleo- and Mesoproterozoic terrains (Fig. 4) and are typically half graben structures with considerable vertical fault displacement (1,400 m in the L. Tanganyika rift zone). All, except the northern part of the Western Rift, are inherited structures from the Mesozoic when they were involved in Gondwana rifting and were later associated with Neo-Tethys Sea transgression. The Malawi and Urema (Mozambique) rift sectors are bounded by high border faults and are amagmatic. They exhibit weak hydrothermal activity. Rift hosted late Tertiary to Quaternary volcanism has taken place only in the Western Rift where crossing fault systems of various characteristics control the localization of igneous activity.

The Western Rift comprises two limbs: a NW-SE trending limb in the southeast, and a N-S to NE-SW oriented limb in the northeast (5a and b in Fig. 4). The two arms intersect in the area to the south of L. Kivu, the site of repeated basaltic volcanism since 70 Ma. The southeastern limb is made up of two left stepping en-echelon half grabens, the lakes Tanganyika and Rukwa rift zones which contain Mesozoic sediments, indicating them to be old structures reactivated during the later Miocene. The northeastern limb extends through Birunga volcanic field and terminates at Aswa Fault Zone in NW Uganda and is the younger member: Abeinomugisha and Mugisha (2004) give a late Oligocene to early Miocene age for the opening of the Albertine graben, the northern part of this rift arm.

3.2.3 The Southwestern EARS Branches

The seismically and hydro-thermally active members of this tectonic regime include the Upemba, Mweru and Bangweulu half grabens and the various minor structures of Eastern DRC. They are found in the southern and central parts of the extensive Mitumba Mountains, a thermally uplifted high plateau region situated between the Congo craton in the west and L. Tanganyika rift zone in the east (Fig. 4). The arcuate Zambezi rift zone lying between Zambia and Zimbabwe is the southernmost of these rift branches. It is an inherited structure from Mesozoic times. These rift zones are all amagmatic.

Rift propagation has been controlled by the dispositions of Precambrian structures. The NE-SW oriented sub-parallel Upemba, Mweru and Bangweulu half grabens of the DRC-Zambia border area developed within the Panafrican Damara-Lufilian belt but rifting became restricted to the foreland region of the Lufilian Arc in the northeast (Fig. 4). Its propagation further to the southwest was hampered by the cross-cutting Lufilian structures. However, the region exhibits intense seismicity, thermally uplifted crust and an active, NW-SE oriented extensional stress field (Fairhead, 1977). The locus of EARS propagation from the Western rift seems to have been redirected via the Malawi rift to the Zambezi rift zone. These zones are seismicity active and relay incipient rifting into the Okavango basin of Botswana to the southwest (Scholz et al, 1976, Atekwana et al, 2004).

3.3 Influence of Pre-EARS Structures

As mentioned above, EARS opening and magmatism in Turkana rift zone was influenced by the reactivation of the pre-existing NE-SW oriented grabens and the NW-SE striking N'Doto-Karisa Fault Zone which was earlier involved in forming the Cretaceous age Anza graben. EARS opening took place along the N-S oriented MB structural trend, across the older structures. This structural setting contributed to localizing volcanism, including that of Barrier volcano. The structures were also responsible for the migration of rifting and igneous activities eastward during 23-15 Ma. The present Turkana rift zone is about 200 km wide and has opened to 40km width (Morley, 1999), the widest in the EARS, next to in the Afar.

There are also two cases where inherited rift structures promoted EARS rifting and magmatism to more evolved stages than elsewhere in the Western rift. Rejuvenated rifting at the two ends of the southeastern arm of the Western rift appears to have become sufficiently advanced to promote the initiation of rift bound volcanism much earlier and to be more evolved than in the northeastern arm: Late Miocene in South Kivu and Rungwe in the southeast (Ebinger et al, 2003), and Pleistocene in the Toro-Ankole and Birunga volcanic fields in the northeast (Barifaijo, 2001). These are further discussed under 4.2.2.1 below:

3.4 Mantle Plume Development and Impact

Plume development was influenced by the architecture of the continent described under 2.2 above, preferentially taking place under regions occupied by the orogenic belts, especially under the more mobile Panafrican orogens. The number and location of discrete mantle plumes under continental Africa are open to debate (e.g. Burke, 1996). Passive seismic tomography and active seismic experiments coupled with other geophysical and geological work in the EARS region have however helped in better describing the probable actual situation.

Ritsema and Allen (2003) have shown that, among 37 hotspots worldwide, eight deep rooted mantle plumes were distinguishable by the seismic shear velocity images of their tails extending to the 670 km mantle discontinuity. In the EARS region, the Afar plume has been shown to have such a disposition.

Simiyu and Keller (1997), Nyblade (2000) and Weeraratne et al (2003) describe mutually coherent aspects of the mantle structure under East Africa. These may be synthesized to describe anomalously low seismic velocities beneath the Tanzanian craton, consistent with the spreading of a hot mantle plume head beneath the craton. Two arms of the plume rise to shallow depths under the Western and central Kenya rifts, rising to a higher level under the later.

The locations of the above three plume structures are accepted as determining the distribution and characteristics of igneous activities in the more active magmatic sectors of the EARS, except in Turkana as pointed out earlier.

4. VOLCANISM & HYDROTHERMAL ACTIVITY

The distribution and characteristics of the hydrothermal activities that are associated with EARS magmatism may best be viewed as reflecting anomalous situations that are overprinted on the large scale background geothermal regime peculiar to the region. Compared to other continental regions undergoing lithosphere extension, the background geothermal regime is characterized by high subsurface temperatures due to heating by the underlying high temperature mantle tumescence. Its distinction from the magmatism-induced anomaly is in that upward mantle heat transport is restricted to conduction and does not involve hot mass transport into the upper crust. Ground water movement would play an important role in setting up the more efficient convective heat transfer system in the upper crust in both cases.

The distinction between these mechanisms of upward heat transport is important for recognizing the significance and geothermal resource development potential associated with hydrothermal activities in the non-volcanic and low volcanicity EARS sectors, and to appreciate the contrast with those in the high volcanicity sectors.

4.1 The Background Geothermal Regime as Reflected in Hydrothermal Activity in Amagmatic EARS Zones.

The southwestern and southern rift branches lie outside the regions of influence of the East African mantle plume and are amagmatic. Rifting is believed to be due to stretching deformation over broad deep seated hot mantle (the early, Passive Rifting model in 4.2 below). The occurrence of thermal springs is attributable to meteoric water circulation through deep levels of hot faulted upper crust which is conductively heated by this tumescent mantle.

4.1.1 The Southern EARS Branches

In the southernmost (Malawi and Urema) EARS sectors, thermal springs discharge low volumes of dilute, low temperature waters in areas of crust that are cooler than to the immediate north and west. The thermal springs seem to preferentially occur on the western sides of the rift basins indicating that they may be outflows from the thermally uplifted blocks to the west. These rift sectors are at the stage of fairly advanced passive rifting in thick and old lithosphere. They however lie in cooler crust areas on the eastern flank of the African Superswell.

4.1.2 The Southwestern EARS Branches

The southwestern, Upemba and Mweru EARS sectors exhibit a greater occurrence of thermal springs, some at high temperature. In the Kariba area of Zambezi rift zone, some springs are reported to be at near-boiling temperatures and to deposit silicious sinter (Waring, 1965), indicating high subsurface temperatures. These rift branches formed in Panafrican terrain. High density and sometimes high energy thermal spring activity takes place also in the Mesoproterozoic Kibaran and coeval terranes of eastern DRC. These regions of high energy thermal spring activity are thermally uplifted over tumescent mantle and stand at and above 1,000 m. elevation. They are seismically active and broken up by faulting even outside the rifted zones.

The thermal springs in these regions thus owe their relatively high energy outputs to meteoric water circulation in the underlying fractured high temperature upper crust which is heated by the Superplume.

4.2 The Anomalous Geothermal Regime as Expressed in the Magmatic EARS Sectors

Various rifting-magmatism models describe the marking differences between the various magmatic EARS sectors. Wilson (2001, Chapter 11) summarizes three which will be referred to here integrally: a) the widely accepted conception of Active and Passive rifting, b) Barberi et al.'s (1982) distinction between High and Low volcanicity (HV and LV) rifts, and c) Bailey's (1983) two magma series involving differentiation from parent magmas with contrasting alkalinities. As the paradigm for these dichotomous visions, the EARS is commonly distinguished between the Eastern and Western branches. These models are best understood as providing two generalized temporal snap-shot views of rift development in a continuum. In its present state, the EARS has individual sectors which mark the different evolutionary stages in continental rifting from initial lithosphere fracturing to eventual transition to mid-oceanic ridge development. It is thus proposed that the magmatic and hydrothermal activities of the EARS can usefully be viewed in the context of its evolving though these successive stages.

The concept of Passive/ Active rifting is useful for distinguishing between rifting phases where mantle plume impact on the lithosphere is absent or present which has important implications regarding the LV or HV rift activities, the petrogenetic affinities of the volcanics, and, in consequence, regarding the nature of the hydrothermal activities and their indicated geothermal resources. It is possible to distinguish different stages of rifting depending on the relative influence that the deeper mantle tumescence may have regarding the absence or presence of magmatism during the passive rifting phase, and that of the shallower focused mantle plumes in promoting evolving volcanism in time and space during the active rifting phase. This scheme will be used here to summarize the tectonic and magmatic affiliations of the different areas of hydrothermal activity.

4.2.1 The Passively Rifting Magmatic Stages

In the interest of better understanding the processes involved in the heating of the hydrothermal fluids of the EARS magmatic areas, it is useful to view upward magma transport as having two components: the melt and volatile phases. The two phases make up a homogeneous mixture under the high pressures which prevail under normal asthenospheric conditions but separate into the two phases with reduced pressure, which is thought to happen when lithospheric structuring reduces the confining pressure in the underlying asthenosphere. The significance of this is that the component which rises through the lithosphere first following the initiation of rifting is the more mobile, volatile, component. With advancing passive rifting, the melt phase is erupted during a later evolutionary stage.

4.2.1.1 The volatile eruptive stage

Lithosphere fault structuring un-muffles mantle regions that would have long remained sealed under stable lithosphere and would be particularly enriched in volatile components. Under Africa, this would have been the situation since Gondwana amalgamation at 550 Ma. The volatile components accumulate in the uppermost asthenospheric mantle beneath the structured lithospheric mantle zone and escape upward along the faults. Heat transported by volatiles following lithosphere structuring is thus thought of as an important "magmatic" heat source for thermal springs which occur in the EARS sectors where there is no eruption of the melt component.

The northernmost part of the Western Rift may be considered as belonging to this early, "volatile eruptive" phase. At Buranga in Uganda, thermal springs discharge CO_2 rich waters at higher than $80^{O}C$ temperature. The nearby lower temperature thermal springs of Beni district in DRC appear to occur as outflows in this tectonic setting. At Kibiro further to the north, CO_2 rich high temperture thermal spring occurrence is associated with faulting on the eastern border and shoulder of the L. Albert Rift. CO_2, together with other volatiles (mainly H_2O and CH_4) are also discharged into the faulted bottom of L. Kivu, and reportedly that of L. Albert. Tassi et al (2009) provide geochemical data which show that these volatiles are of mantle origin. These areas are situated in the younger, northeastern arm of the Western rift, which appears to still be a major zone of mantle degassing. From the geothermal point of view, the large volume of volatile discharge can be viewed as marking the transition of deep seated upward heat flow from dominance by conduction to the more efficient convective mode. It also marks the initiation of mantle communication with the surface and predicts the transition of rifting to the melt eruption stage.

4.1.1.2 The hyper-alkaline melt eruptive stage

At a few locations in the more recently opened northeastern limb of the Western rift (5b in Fig. 4), accommodation faults have enhanced lithostatic pressure reduction in the mantle and promoted melt generation. The type of Quaternary magmatism which ensued from this stage of continental rift development is globally unique in its petrogenetic attributes and warrants review in the interest of discerning its geothermal resource implications.

Adiabatic magma generation by lithostatic pressure release is promoted in the heated lithospheric mantle where it is tapped by deep reaching faults. Where volatiles are injected into the lithospheric mantle, the solidus is lowered and metasomatic melting is induced. This process, entailing only small fraction partial melting, is accepted to explain the small scale eruption of alkaline basic and sometimes ultrabasic volcanic products which characterize the volcanic fields of the northeastern limb of the Western Rift. These alkaline rocks are silica-under-saturated, often highly potassic and are commonly associated with carbonatite eruptions. Mafic rocks make up more than 75% of the erupted products which is due to the paucity of silica in the parent magma and the absence of crustal contribution in magma generation. High concentrations of the incompatible elements in the erupted rocks are the key evidence for the lithospheric mantle being the primary magma source and for the small degree of its partial melting. The often characteristically highly potassic content is also attributed to this element's incompatibility in the solid phase which favors its early partitioning into the liquid phase during partial melting. This situation is illustrated in volcanic activity in the two northern volcanic fields of the Western rift: Toro-Ankole, Uganda (Barifaijo, 2001) and Birunga in the DRC-Rwanda border area (Rogers, 1998).

Metasomatism-generated melts have low viscosity and high buoyancy due to paucity in silica and their being highly volatile charged. They are mobile and thus tend to rise directly to the surface, seldom undergoing chemical or mineralogic modifications by interacting with the upper crust. High level magma generation and storage is thus the exception than the rule in these volcanic fields.

A shared characteristic among these volcanic fields is the large volume of mantle sourced CO_2 which is discharged at thermal springs. Similarly to the non-volcanic zones of the Western rift (discussed under 4.2.1.1 above), the large volume volatile discharge is here believed to be predominantly due to lithosphere structuring rather than to transport by the melt phase. The primary heating agent for such springs is thus believed to be mantle derived hot volatile mixing with ground water.

The extreme case of the type of magmatism is reflected in the explosive volcanism at Katwe in the Toro-Ankole volcanic province in Uganda. Rift bound volcanism took place on a rift accommodation structural setting, as is required for volcanism to occur in this part of the Western rift. The volcanic rocks are primarily pyroclastic and of basic and ultrabasic compositions. They are silica under-saturated and strongly alkaline (highly potassic where K_2O concentration may reach 12%). A large number of low lying phreatomagmatic explosion craters have produced a large quantity of mantle xenoliths of residual pyroxenite (Barifaijo, 2002). Carbonatite volcanism has also taken place in and around the area. Isotope data (^{13}C and ^{18}O in carbonatite) and xenolith abundance show that magma rise from the lithospheric mantle source was sufficiently rapid to preclude its chemical and mineralogic modification by interaction with the crust (Wilson, 1989, p367). The evidence is thus in favor of the volcanic rocks not being associated with magma storage below the surface.

Thermal springs discharge near neutral, 50-66^{O}C water on the shore of Kitagata crater-lake at Katwe. As is common with thermal springs in the Western rift, they are rich in CO_2 and deposit travertine. Cation geothermometers give up to 240^{O}C for subsurface temperatures (Armannsson, 1994), the higher range being uncharacteristic of CO_2 rich waters. From the nature of volcanism, there is no evidence for the heating of the thermal springs in crustal regions underlain by a shallow magma body. They are believed to owe their heating to large volume hot volatile mixing with the local ground water.

The Birunga volcanic field exhibits a more evolved form of alkaline volcanism than Katwe as some primary magma evolution is evident. Of the eight large volcanoes, six lie on the DRC-Rwanda border on the eastern rift shoulder and are extinct. These volcanoes young to the southwest towards the eastern rift margin, Karisimbi (240 Ka) and Bisoke (80 Ka) standing closest to it. The only two active volcanoes, Nyiramulagira and Nyiragongo, also the youngest at 20 Ka, are situated within the rift in DRC. All volcanoes lie along young, rift orthogonal structures of various orientations. None cross the whole rift basin, but in combination they seem to accommodate changes in border fault dispositions. Here too, they provide suitable structural conditions for metasomatic magma generation as in Toro-Ankole. The volcanic products are potassic and display strong enrichment in the light incompatible elements (e.g. Santo et al, 2003) indicating small scale melt derivation from the lithospheric mantle. However, Rogers et al (1998) have shown that volcanic rocks exhibit derivations from magma differentiation which mostly took place within the lithospheric mantle or in the lower continental crust. There is however no evidence of extended differentiation in shallow magma chambers in most cases.

The exception in the Birunga field is Karisimbi volcano where crustal contamination in its trachytic lavas is believed to be of upper-crustal origin and associated with crust assimilation and fractional crystallization (AFC) processes in a shallow magma chamber (Rogers et al, 1998). The volcano may thus have a shallow magma body which may serve as a geothermal heat source. However, the characteristically small scale of magma generation can be expected to be a limiting factor on the size of a possible geothermal field there.

Gisenyi thermal spring occurs in Rwanda on the N.E. shore of L. Kivu to the southwest of Karisimbi volcano. It discharges less than 5 l/s of sodium bicarbonate-chloride type water at up to 75^{O}C temperature (Newell et al, 2006). In contrast to other thermal springs in the Western rift, The thermal water has low CO_2 content and does not deposit travertine. The interpreted subsurface temperature is about 180^{O}C. The hydrological setting of the spring would determine whether hot water rises by buoyancy from depth along the adjacent rift border faults or whether it flows laterally toward the lake, the local hydrologic sink, from a higher standing upwelling area, perhaps situated under Karisimbi volcano.

A number of low temperature (<40^{O}C) springs occur on the northwestern shore of L. Kivu in DRC close to the active volcanoes. Kabuno bay, where they occur, is the zone of highest level of limnic volatile injection into the lake bottom.

The highest thermal spring temperatures recorded in the volcanic fields of the Western Rift are from Mayi ya Moto, DRC, and are more than 95^{O}C (Vikandy et al, 2008). They seem to be superheated for their elevation (c 1,100m a.s.l.). They issue sodium-bicarbonate-chloride-sulfate type waters with pH ranging from 8 to 9. Chemical analysis results are not complete but underground temperature is indicated to be in the range of 163-177^{O}C. The springs occur at the base of a within-rift horst, adjacent to Mayi ya Moto volcano and about 60 km to the north of Nyiramulagira volcano. Lava from Mayi ya Moto has extended southward and coalesced with the Birunga volcanic field. Information on the volcanic rocks was not available but the reported high energy of hydrothermal activity may indicate the existence of a shallow cooling magma heat source, as thought to possibly be the case at Karisimbi, and warrants follow-up.

Since the Pleistocene, volcanism in the northern Tanzania part of the Eastern Rift has been dominated by the eruption of carbonatite of mantle origin, a variation in the above described metasomatic theme. The L. Natron rift zone attained its present structural form since 1.2Ma. The typically explosive volcanism of the area has produced large volumes of pyroclastic materials from ten Pleistocene age volcanoes of which four were active until recntly. In addition to the commonly erupted nephelinites and phonolites, carbonatite lavas and pyroclastics were also produced. Oldoinyo Lengai, unique in the world for erupting sodium-carbonatite, is presently active. The petrologic character of Pleistocene to Holocene volcanism precludes its being supported by high level magma storage. Eruption is believed to be fed by magma which ascends rapidly to the surface. Thus the hydrothermal features are here thought to be heated by other agencies than by shallow magma bodies.

The numerous thermal springs of L. Natron rift issue at the rather low temperatures of 30^{O}C -50^{O}C, have very large total discharge with thermal energy output estimated at 100MWt (Hochstein et al, 2000). This heat is here believed to be due to the lateral flushing of the surrounding anomalously hot subsurface by ground water draining into the lake, the regional hydrologic discharge zone.

4.2.2 The Actively Rifting Magmatic Stages

In these stages, mantle plumes are actively involved in progressing rifting by interacting with the lithosphere. These interactions take place at progressively shallower levels as rifting advances, finally causing the breaching of the crust on the onset of its oceanization. The softening and erosion of the lithosphere is accepted to be more efficient in driving crustal attenuation and rifting than stretching deformation, and during this active phase the pace of rifting and magma production increase. With upward heat transport with hot mass transfer being more efficient than conductive heat flow, the increasing upward magma transport increases the heat that is available at the shallow depths that are reached by ground water. This increases the distribution and energy content of hydrothermal activities, reflecting the increase in the distribution of high enthalpy geothermal resources. AFC processes take place to varying degrees in the upper crust. The stages of this active rifting phase trace the evolution of magma generation from the initial stage during which plume action on the lithospheric mantle causes its thermal erosion (delamination) and/ or amalgamation (Kivu and Rungwe), through the intermediate stage when the plume head reaches and penetrates the Moho and similarly interacts with the crust (Main Ethiopian and Kenya rifts). The culmination of this progression is reached when plume action breaches and consumes the crust whereby asthenospheric mantle magma sources assume primacy (axial zones of the Afar rift).

4.2.2.1 The initial active rifting stage

According to Simiyu and Keller (1997), mantle plume rise has occurred under the Western Rift. This would have been determined primarily by the extent of plume buoyancy and rift opening. These appear to have sufficiently advanced to cause the rise of the plume arm and the heating and erosion of the base of the lithosphere in the more developed older southeastern limb of the Western rift.

Two zones, S. Kivu and Rungwe volcanic fields, are commonly considered as sharing the style of volcanism of the LV Western rift. However, petrochemical data indicate that they are at more advanced stages of magmatism than in the northeast (see 4.1.1.2 above). Mantle plume impact causes the production of more evolved volcanic rocks. This more advanced state of rift development than in the northeast is thought to have been due to the easier facilitation of EARS rifting by the reactivation of Cretaceous rifts. S. Kivu and Rungwe zones may thus be taken as belonging to the initial stages of active rifting.

The southern L. Kivu volcanic field occupies a small region straddling the DRC-Rwanda border area. Furman and Graham (1999) report geochemical evidence for the thermal erosion of the lithospheric mantle underneath this volcanic field. Another evidence for lithosphere attenuation is that the seismogenic layer thickness is only 10-20 km (Doser and Keller, 1999). As indicated under 3.2.2 above, it is a zone where the younger (late Miocene) NNE-SSW trending L. Kivu and older (Cretaceous) SE-NW trending L. Tanganyika rift sectors intersect. Volcanism was associated with the two generations of rifting: four episodes occurred within the Cretaceous tectonic regime between 70 and 18 Ma, and another three at 8-7, 1.9-1.6 and 0.01 Ma during the EARS tectonic phase. Lava dated 1.9-1.6 Ma was erupted from centers aligned on a western border fault of L. Kivu rift zone in Thibinda volcanic area, DRC. The 10 Ka old lava erupted in a nearby small area on Idjwi Island which has been the site of recurring volcanism also during 49 and 28Ma. Volcanism of all phases produced tholeiite or basanite lava. The small amount of trachytic lava appears to be a product of differentiation of parent basaltic magma.

Thermal springs of up to 72^{O}C occur at Kankule and environs in the fault zone on the southwestern shore of L. Kivu. They issue near neutral sodium-bicarbonate waters, which are much more dilute than those of the lower temperature springs on the north side of the lake. There is a large volatile input along faults into the bottom of the lake. Chemical analysis data are incomplete and do not allow reliable subsurface temperature estimation.

Lower temperature springs occur to the south, in the adjacent areas of Burundi, DRC, Rwanda and Tanzania which lie along the direction of hydrologic discharge from L. Kivu. They may be outflows from a heating zone in the area of the Kankule springs. The most notable are Mashyuza springs which occur in Rwanda about 15 kms to the south of L. Kivu. They discharge 50 l/s, CO_2 rich water at up to 66^{O}C. They deposit considerable travertine. The subsurface temperature is estimated to range up to 140 ^{O}C.

Rungwe volcanic field is situated at the triple junction of the Rukwa-Malawi-Ruaha rift branches. Seismic focal depths of 13-17km (Morley, 1999) indicate a thinned brittle crust under the area. The structural setting has favored more extensive volcanism than elsewhere in the Western rift: about 3,000 km^2 in area and extending over 90 kms in the NNW-SSE direction of Malawi rift faults. The latest volcanism occurred during the Quaternary. The last eruption was in about the year 1800. Igneous rocks are mostly silica under-saturated lavas and pyroclastics. (Harkin, 1960). They range from basalts to trachytes, trachy-andesites, phonolites and rare quartz trachyte. Furman and Graham (1994) recognized crust involvement in magma generation. Salic rocks make up about 50% of the erupted rocks which Harkin attributed to magma from the melting of older syenite intrusives. The presence of a magma body is thus indicated. Carbonate contamination of magma has been attributed to probable melt contact with pre-Cretaceous carbonatite intrusions. No carbonatite eruption is associated with volcanism at Rungwe.

No fumaroles are known to occur in the volcanic field, possibly due to the high rainfall quenching upward vapor rise. However, numerous thermal springs and fossil sites of past activity occur on low-lying ground in the three rift arms (Hochstein et al, 2000). They occur along faults. The most significant springs are at Kilambo and Songwe.

Kilambo thermal spring occurs at the base of Embaka fault about 15 kms to the SE of the Kiejo eruptive center. It issues 20-40 l/sec of sodium-bicarbonate water at 70^{O}C. Subsurface temperature is about 180^{O}C. Kilambo is CO_2 rich and deposits travertine, probably due to the hot water circulating in carbonatite contaminated volcanic rocks in the subsurface. Siliceous sinter occurs on Embaka fault to the north of Kilambo, deposited by a thermal spring which seems to have since ceased flowing due to the decline of the ground water table. Recent phreatic explosion craters occur on the up-thrown side of Embaka fault.

Songwe thermal springs, the hottest and most impressive in Tanzania, occur in Rukwa rift zone about 30 km west of Rungwe. They issue near neutral, CO_2 rich, sodium bicarbonate type waters at up to 86^{O}C and deposit considerable travertine, probably due to the same causes as at Kilambo. They occur along a NW-SE running fault system which extends from the Rungwe volcanic field. On hydrologic grounds, these thermal springs are thought to be heated under Rungwe and to outflow down the hydrologic gradient to where they presently occur.

In the southern terminal area of the Eastern rift, the plume arm which rises northward from under the Tanzanian craton is still deep seated under the volcanic fields of the Tanzania-Kenya border area. It appears that the volcanism and hydrothermal activity at L. Magadi, Kenya, represents a state of transition between that of L. Natron rift zone in the south and the central Kenya rift zone in the north. The thermal springs are high pH sodium-bicarbonate types with salinity in the range of 1.0 to 3.8%, which probably is not a feature of the deep parent fluid. Spring temperatures range up to 85^{O}C. The subsurface temperature is estimated at 140^{O}C (McNitt et al, 1989). The heating area is not obvious except that it would lie to the north, the direction toward which the spring temperatures verge to the highest values. In this area spring flow is more than 130 l/s. The area is made up of densely faulted alkaline basalt and trachyte lavas of Pleistocene age, indicating AFC processes in the upper crust. No fumarole activity is known on the young and relatively small eruptive centers in the immediate area.

4.2.2.2 The intermediate active rifting stage

The Kenya Rift and the MER may be thought of as being in the intermediate stages of active continental rifting: magmatism involves melt generation variously from lithospheric or asthenospheric mantle sources or from AFC in the upper crust. These melts erupt extrusives of various chemical characters.

These EARS sectors are the type cases for the HV rifting of Barberi et al (1982). The marking attributes are that rifting is relatively rapid compared to the Western Rift, it exhibits large scale igneous activity with lava and pyroclastic products occupying the rift floors to great depth. Mantle derived volcanic rocks evolve in time toward transitional to sub-alkaline basalt and derivative chemistries indicating increasingly larger fraction partial melting of the mantle source. Continuous spectra of mafic-to-silicic rock compositions arise from the differentiation of the basaltic parent magmas. Bimodal petrologic associations are attributed to secondary magma sourcing from the melting of low solidus upper crustal rocks.

This being the overall picture, Spatial and temporal variations are observed in the volcanism of these two rifts (refer to 3.2.1 above). These generally trace the loci of rift evolution which control the degrees of mantle-crust interactions involved in melt generation: decreasing alkalinity and increasingly silicic differentiates northward. On the other hand, the overall state of these interactions diminishes the significance of these differences from the gross geothermal perspective. In addition, the large number of geothermal prospects in these rift sectors will allow only a unified view of the modes of occurrence where comparable geologic associations exist. From the gross geothermal resources point of view, this intermediate stage can be considered to be the most important. As primary basaltic magma intrudes the upper crust, its cooling releases the latent heat of crystallization which goes into secondary magma generation by melting the lower temperature upper crustal rocks. These tend to be silica rich and viscous and may be largely destined to cool in the subsurface, creating longer lasting heat storage systems.

In these rift sectors, the initial fissure basalt eruptions of the Pleistocene have in time given way to the construction of central volcanoes. Accordingly, a large number of silicic volcanic edifices have been built up on the rift floors. They are commonly characterized by fumarolic and solfatara activities and less commonly by the occurrence of high temperature, near-neutral, chloride to bicarbonate type thermal springs in their adjacent areas of hydrologic discharge. Interpreted minimum reservoir temperatures are commonly in the region of $200^{O}C$ or more. Drilling has tapped reservoirs at much higher temperatures, more than $320^{O}C$ in both the Olkaria and Alutu geothermal fields of Kenya and Ethiopia respectively. On geochemical and geophysical evidence, the better known volcanic centers are believed to be fed from magma bodies situated at various shallow crustal levels. Others which are less investigated in the subsurface may be considered analogous to these based on shared geologic character, structural setting and hydrothermal activity. Where volcanic centers are built up of cumulates of young, periodically erupted differentiated products, they indicate magma bodies that are long-lived and that may support high enthalpy geothermal resources.

Volatiles release, although not in the large volumes discharged in parts of the Western rift, results in the formation of calderas by Krakatoan style explosive volcanism. As a result, the Kenya, Main Ethiopian and southern Afar rift floors are characterized by the production of large volumes of pyroclastic rocks and the formation of numerous calderas. Many calderas have large diameters, measures of the probable dimensions of the underlying plutons and/ or their relative proximity to the surface. The exsolution of volatiles under the reduced confining pressures at shallow depths increases magma viscosity and the likelihood of its storage in the shallow subsurface. Often, the magma bodies feed resurgent volcanism and also structure the caldera floors after collapse. The young calderas are associated with similar hydrothermal feature occurrences as the central volcanic edifices. The extra attraction of the caldera volcanoes as geothermal objectives is that they tend to be associated with the focusing of both magma rise and storage, as well as hydrothermal fluid convection within themselves. These offer relatively clear exploration targets and resource concentrations which enhance the economies of resource exploitation. The trachytic Menengai and the rhyolitic Corbetti calderas, respectively in Kenya and Ethiopia, are representative of the numerous similar volcanic structures. These have been partially explored and have yielded encouraging results.

4.2.2.3 The advanced active rifting stage

The rift axial zones in the northern and eastern parts of Afar Rift represent the terminal stage of continental rift development. Crust oceanization has been taking place in stages along seven axial zones since 1.2Ma (3.2.1.1 above). The sialic crust has been largely attenuated along these zones, diminishing and often precluding its participation in magma production. Volcanism is thus primarily due to mantle magma generation. The silicic end-products of magma differentiation typically make up only about 5% of the erupted rocks. The zones are occupied by basaltic volcanic fields which vary between early stage lava plateaus and late stage central volcanic ranges. They are characterized by various degrees of fumarolic activity. The general paucity of ground water in the Afar has caused most fumarolic activities occurring on the volcanic ranges to be rather weak and contaminated by atmospheric gases. It also accounts for the general lack of thermal springs in the immediate base areas of the volcanoes.

Most of the volcanic centers have not been considered in the present list of prospects due to possible risks of volcanic and magma induced seismic activities, remoteness and the availability of a large number of conventional targets. Of special interest is Fiale, in the axial zone of Asal rift in Djibouti. Its attraction is also due to the fact that it lies n a region that has been explored in the past. Fiale is a Kilauean style volcanotectonic collapse structure, with a thick solidified lava lake occupying its floor. From seismological data, a large body of mantle magma is discernible at 4.5 kms depth. Only weak steam leakage along one kjar is discernible. Sea water is thought to quench the shallow subsurface of the Asal rift floor. Geophysical survey data suggest that a vapor phase reservoir in the about 1,000 m depth range lies between a shallow condensate layer and an inferred deep brine source.

As variations of the above tectono-magmatic setting, the axial volcanic zones often exhibit dyke-propagated structural tip zones which are amagmatic. Hydrothermal activities show them to be high temperature subsurface zones. Other varieties are found in fractured rift floor basement areas with no association with surface volcanism. Some exhibit high temperature thermal spring activity with hydro-geochemical characteristics which indicate high subsurface temperatures (e.g. Teo and Danab in Central Afar). Others are marked by fumarolic activity, sometimes very sublime and not easily noticeable due to the hot and dry climate.

The Dubti geothermal field in Tendaho, Ethiopia, is situated on a structure which is considered to be a dike-driven fault zone situated along a SE trajectory of the young (0.04 Ma) Manda Hararu zone of crustal separation. Exploration drilling has yielded 250^{O}C hot water with high mass flow from a sedimentary reservoir at 500m depth. This shallow reservoir is believed to be underlain by a higher temperature primary reservoir situated in late Pliocene age basaltic rift floor basement heated by dike intrusions.

5. CONCLUSIONS

The distribution, relative density of occurrence and degree of dynamism of hydrothermal activities in the EARS region depends on the stage of rifting reached in its various sectors. This is fundamentally determined by the degree that the African Superplume plays in heating the crust, in the case of zones subjected to passive rifting by stretching deformation, and by the focused impact of the mantle plumes in driving active rifting and magmatism.

The geological settings of the hydrothermal features of the Western rift are dwelt on in somewhat more detail than those in the actively rifting High Volcanicity sectors. This is because there is a tendency to view the northern part of the Western and southern terminal part of Eastern rifts in the same light as the other magmatic EARS sectors respecting the nature of the heat sources of the hydrothermal features. This obscures the fact that the commonly idealized shallow magma body heat source may not always be invoked to account for their heating, nor is it necessary, as illustrated by the occurrence of high energy hydrothermal features in the clearly amagmatic EARS sectors. Conductive upward heat flow at deep crustal levels relayed to the surface by convective transport by ground water in the shallow crustal depths can account for the heating of features in such areas (e.g. the Zambezi basin). High temperature volatiles are proposed to be the principal mode of upward heat transport in EARS sectors that are amagmatic (e.g. Kibiro and Buranga in Uganda) or have primitive forms of magmatism (e.g. Katwe and most of the Birunga volcanic field), The considerable volatile discharges in these areas are of mantle origin.

The largest proportion of sites of high energy hydrothermal activity, and consequently those considered to have good geothermal energy development prospect, are situated in the main Ethiopian Rift (MER) and Central Kenya Rift (CKR). This is shown to be due to the intermediate stage of active rifting being characterized by large volume anatectic magma generation and storage in the upper crust.

Table 1 provides a summary of the findings of this study and shows the relationship between hydrothermal activities of the EARS region with mantle influence, the progression of rifting through its different evolutionary stages and that of magmatism from the eruption of primitive effusives to that of the most evolved volcanic products.

Based on the presently available information summarized in this paper, a large number of geothermal prospect areas that are associated with EARS magmatism of various forms are shown in Figure 6 and Table 2. All exhibit hydrothermal activity. Most are related to magmatism which is expressed in conventional volcanism. Some, situated in the northern part of the Western rift, are thought to be associated with what is here considered to be the most primitive form of volcanism: mantle derived volatile effusion, precursor to primitive hyper-alkaline volcanism. Still others, in Afar, show evidence of being heated by subsurface basaltic magma diking which is rarely reflected in recent surface volcanism. Most prospects in the list are judged to be suited to exploitation in conventional condensing geothermal power plants. The few others which show high non-condensable gas content or moderate subsurface temperatures may be exploited using binary cycle or backpressure generating plants.

These resources need to be developed for alleviating growing electricity supply problems. The countries in the region mostly lack other indigenous sources of electricity or have need for improving their power generation mixes.

Table 1: Summary tectonic setting of areas of hydrothermal activity in the EARS region. $T_{max.}$ indicates maximum hydrothermal feature temperatures that are lower or higher than 60^{O}C. Chem. indicates typical chemical character

Mantle Impact		Rifting		Volcanism	Hydrothermal Activity		
		Mode	Stage		T_{max}	Chem.	EARS branches
African Superplume	Marginal	Passive	Advanced	None	Low	Dilute	Malawi, Urema
	Central		Intermediate		High	HCO_3	East D.R. Congo
							SW EARS branches,
						SiO_2	L. Kariba area (Zambezi rift zone)
			Advanced	Volatile eruptive		CO_2 rich	Kibiro, Buranga
				Alkaline melt eruptive	Low		Katwe, Birunga
Afar and East African Plumes		Active	Early	Some AFC	High	HCO_3	S. Kivu, Rungwe, L. Magadi
			Intermediate	Extensive AFC		Cl^-, SiO_2	Several zones in MER and CKR
			Advanced	Basaltic		(Fumarolic)	Fiale, Afar
				None, Diking		Cl^-, SiO_2	Tendaho, Afar

Table 2: Geothermal prospects of the magmatic EARS sectors. *: drilled fields. Numbers are as in Fig 6.

No	Prospect/Field	No.	Prospect/Field
	Eritrea		**Ethiopia** (contd.)
1	Jalua	28	Alutu (Langano)*
2	Alid	29	Corbetti
3	Nabro	30	Duguna
4	Dubbi	31	Korke
5	Girale Dubbi		**Kenya**
	Djibouti	32	Barrier
6	Fiale	33	Namarunu
7	Gale Le Koma*	34	Emuruangogolak
8	Hanle-Gagadde	35	Sailali
	Ethiopia	36	Paka
9	Borawli (Northern)	37	Korosai
10	Ma'Alalta	38	Baringo (Korosai?)
11	Malahale	39	Bogoria (Arus)
12	Debahu	40	Menengai
13	Ayrobera	41	Eburru*
14	Dubti (Tendaho)*	42	Olkaria*
15	Allalobeda	43	Longonot
16	Borawli (Souhern)	44	Suswa
17	Teo	45	L. Magadi
18	Danab		**Uganda**
19	Gabilema	46	Kibiro
20	Yangudi	47	Buranga
21	Gewane		**Rwanda**
22	Amoissa	48	Gisenyi-Karisimbi
23	Dofen		**D. R. Congo**
24	Tedecha	49	Mai ya Moto
25	Boseti	50	Thibinda
26	Boku		**Tanzania**
27	Tulu Moye	51	Rungwe

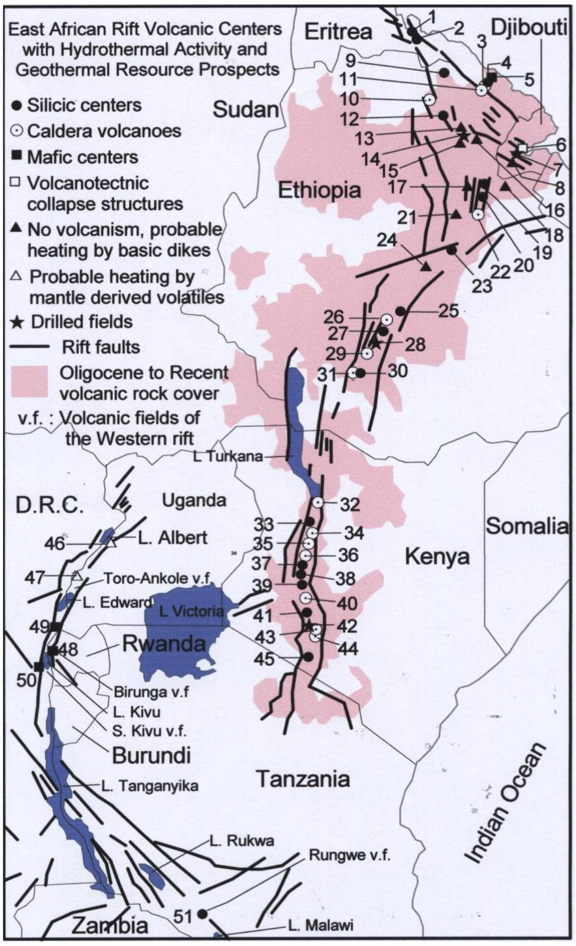

Figure 6. Locations of geothermal prospects in the magmatic EARS sectors. The prospects are listed in Table 2 with the same numbers.

ACKNOWLEDGMENT

The author gratefully acknowledges the constructive editorial work of the Technical Program Committee which has helped to improve the structure and content of the contribution. Any persisting shortcomings are however due to him.

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