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Geological, volcanological, petrological and structural studies to evaluate geothermal occurrence within an axial rift segment of the central Kenya Rift Valley

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ABSTRACT

The Eastern Branch of the East-African Rift System (EARS) is characterized, both in Kenya and Ethiopia, by a succession of central volcanoes alternating with lava fields emitted from dikes along the rift floor axis with an average spacing of 50 Km between the volcanoes. Central volcanoes – commonly with calderas – have been considered as major targets for geothermal energy development whereas the fissural type of volcanic activity are up to now disregarded or considered to have low potential. We focused on a segment of the central part of the Kenya Rift, north of Eburru volcano and south of Lake Elmenteita (between 0°27' and 0°38'S) where a "text-book", well developed rift-in-rift structure is observed. Open fissures emitted recent lava fields and domes along the 30 Km long N-S axis of a graben characterized by symmetrical normal faults facing the active axis, 5 Km wide basin, with ages of the volcanic products increasing on both sides away from the axis.

Petrological investigations (with more than 100 rock samples studied under the polarizing microscope) show a large variety of magma, ranging from alkali olivine basalts to mugearites, trachytes and pantelleritic obsidians, with a relative abundance of the last. Geochemical analysis carried on a selection of 21 fresh aphyric rock samples provide a rather complete view of the various kind of liquids emitted during the last million year along this active segment of the rift.

As a whole, the conceptual model of the volcanic system characterizing this segment of the rift implies successive phases of volcano-tectonic events characterized by:

1. A tectonic event implying the opening of axial fissures with normal faulting reactivation on both sides;
2. The partial melting of initial basaltic magmas from a shallow (20 Km deep) anomalous mantle;
3. The development of successive magma chambers elongated along the rift axis at shallower (a few Km) depth, allowing for the differentiation of the magmas up to pantelleritic liquids by crystal fractionation.

With a spreading rate registered at 2.5 mm per year in this segment of the rift, a 2.5 Km opening was accommodated during the last My that fit well with the observed width of this active rift axis. Of course, the process is not continuous. Every 100 ky, violent volcano-tectonic events of 250 m opening allowed for renewed normal faulting and the injection of new batch of basaltic magma which then differentiated during each other consecutive quiescence periods in the elongated magma chamber formed during the previous event along the rift axis.

Such a volcano-tectonic context appears quite favorable for the development of a geothermal system, and in fact, we observe that all open fissure and faults in this 150Km^2 wide area are emitting steam, showing the wide extension of a shallow geothermal reservoir covering the whole surface of the rift floor axis. If the area appears to be representative of other portions of the EARV, this conceptual model open new perspectives for the development of geothermal energy in the region, not limited to central volcanic systems only.

1. Introduction: a striking volcano-tectonic feature of geothermal interest

Until now, geothermal exploration and development in the Eastern Branch of the East-African Rift System (EARS) concentrated in areas where magma chambers were thought – or even proved - to have developed thanks to the central volcanoes, i.e. stratovolcanoes with calderas and/or recurrent magmatic emissions of differentiated products (like trachytes, rhyolites, or phonolites). However, it is known that this rift is characterized, both in Kenya and Ethiopia, by a succession of central volcanoes alternating with lava fields emitted from dikes along the rift floor axis. The volcanoes occur at an average spacing of 50 Km between the volcanoes.

The research engaged on this site concerns two major issues:

i. The first is geological and fundamental: understanding of the volcano-tectonic process acting along the rift segments in contrast with the (generally better known) central volcanoes (subject of the thesis by Nyawir, one of the authors).

ii. The second concerns the geothermal characteristics and production potential of these areas, which are more extensive along the EARV than central volcanic systems presently targeted (e.g. Olkaria, Menengai, Suswa, etc). This is therefore a subject of major interest in the African region, besides the site itself!

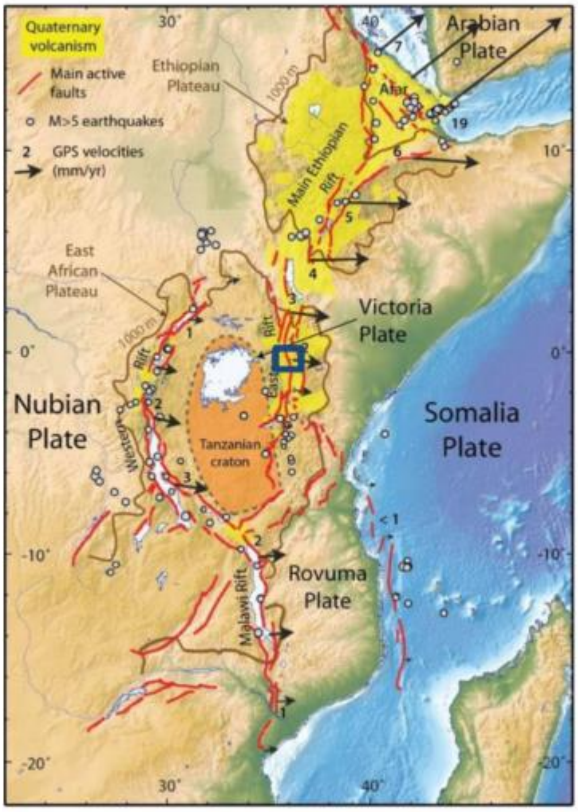
Up to now, this fissural type of volcanic activity was disregarded as a geothermal target, either purely neglected or considered to have low priority. Of course, such type of volcanism made of fissures spread along the rift floor fed by undifferentiated basaltic lava produced by partial melting of the upper mantle with only limited differentiation, was not considered as appropriate for a geothermal development. But when the emissive system develops along a unique axis, as observed in the oceanic spreading segments, with earlier lavas emitted on the sides and youngest concentrated along the axis, a linear heat source will develop along the active rift axis. And if, in addition, significant amount of differentiated magmatic products are found, we have an even more convincing indication of the presence of a magma chamber.

Searching for sites suitable for geological field studies applied to geothermal research and development in the Kenya Rift valley (KRV), our attention focused on the area located between the Olkaria and the Menengai geothermal sites, north of Eburru volcano and south of Lake Elmenteita (between 0°27’ and 0°38’S) where a “text-book”, well developed rift-in-rift volcano-tectonic segment is observed.

Compared with surrounding central volcanoes, volcanological observations show that lava flows and domes dominate, with limited pyroclastic products, except for the part of the activity which developed in the wet climatic event when a 300m deep lake occupied this basin circa 100ky ago, determining the development of hyaloclastite cones and ash falls.

2. Structural context of the KRV portion located between Olkaria and Menengai

South of Ethiopia, the EARV is divided into two branches, the western and eastern ones, with KRV characterizing the eastern branch. Despite sharing almost equally the spreading rate between the two Somalia and Nubian plate (Fig.1) at the level of Lake Victoria, the eastern branch is characterized by higher volcanicity, with thinner lithosphere and uprising anomalous mantle (Wendlandt & Morgan, 1982; Windley, 1984; Fairhead, 1986, Khan et al., 1988) allowing for the development of a succession of central volcanoes considered as geothermal targets of interest (Fig.2).



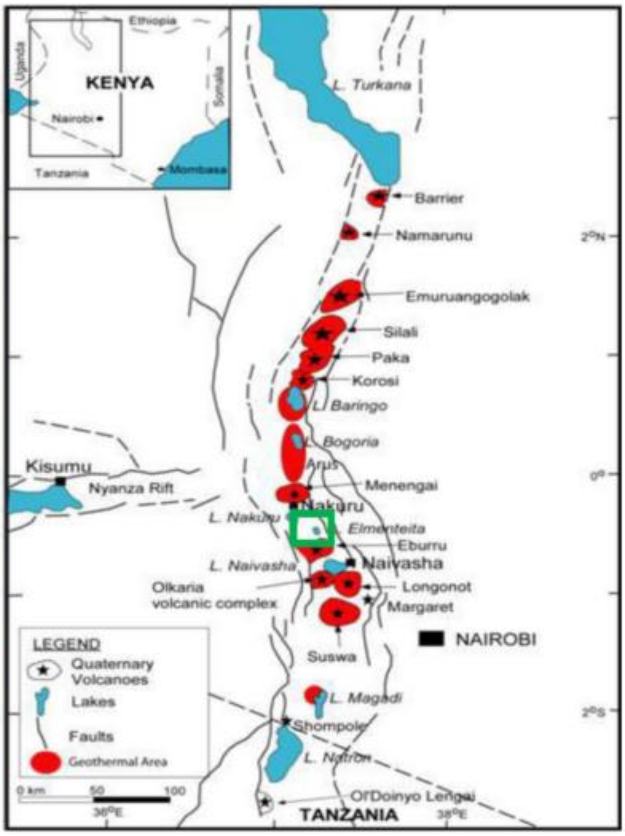


Figure 1 (Left) : The East African Rift system, with major fault systems (in red), large magnitude earthquake location (white dots for M> 5), manifestations of Quaternary volcanism (in yellow) and plate-motion vectors with GPS velocities (black arrows, with numbers in mm/y). Observe the progressive decrease of the spreading rate from South to North along the EARV, including in the RV where GPS velocities vary from 3mm/y at Lake Turkana to 1mm/y at Lake Magadi. Otutu site is pictured in blue rectangle on base map from Calais (2016).

Fig. 2 (Right) : Location of the Otutu site (green rectangle) in the Kenya Rift Valley (KRV). Base map by GDC showing the identified geothermal sites (in red) located mostly at the level of central volcanoes.

The project is located in the area where the rift floor is the highest (almost 2000m asl compared with Turkana (300m asl) and Magadi (600m asl), between two of these major central volcanic systems, which also happen to be the two main geothermal sites presently explored and developed in Kenya, Olkaria to the south and Menengai to the north. This is also considered as the area of the KRV where the mantle activity is the highest (Allan et al., 1989; Clarke et al., 1990). In this central part of the KRV, the rift shifts from a NNW-SSE to a NNE-SSW direction[1] at the place where it crosses the E-W trending Nyanza Rift (Fig.3). A more detailed observation shows that the recent and present-day activity concentrates north of Olkaria along a N-S segment that extends north up to lake Elmenteita, where the activity is shifted west at the level of lake Nakuru where another active segment contributes to the Menengai volcano and caldera also shaped by the influence of the transverse Nyanza Rift (Fig. 3 and 4).

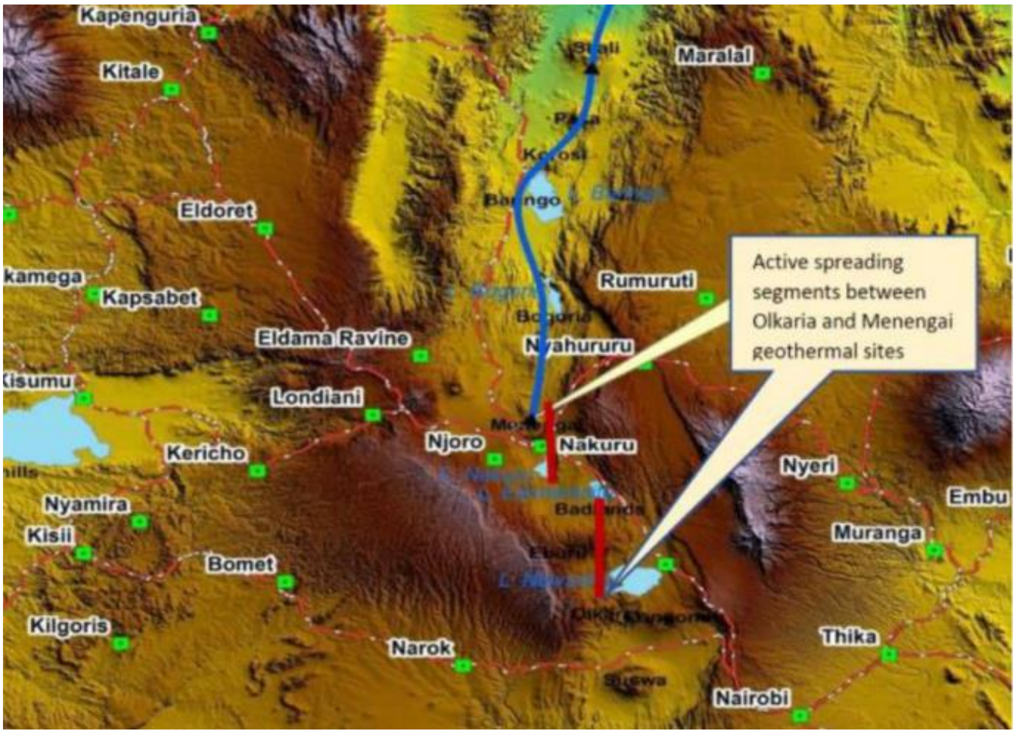


Figure 3: Change in direction of the Kenya Rift border faults from NNW-SSE in the area located between Olkaria (south) and Menengai (north) to NNE-SSW in the rest of the KRV. The present active rift axis (in red) is however trending N-S. A single axis is active between Olkaria (west of Lake Naivasha) and Elmenteita including Eburru.

As a result, the presently active rift is oblique with respect to the inner and outer rift major faults, touching the eastern margin to the north at the level of Lake Elmenteita and the western margin to the south at the level of Olkaria. This variation in the faulting direction reflects changes in the stress directions that affected the Kenya Rift Valley from Miocene to present. According to Bosworth and Strecker (1997), the least horizontal stress direction from 12 to 6 Ma was oriented NE-SW to ENE-WSW, whereas about 2.6 Ma, faulting occurred in response to E-W extension (as at present). But in the Late Pleistocene, after circa 0.6 Ma, the central Kenyan rift experienced further clockwise rotation into NW-SE orientation and finally rotated counter-clockwise into the present N-S direction, implying some strike slip components in the fault system. The segment located between Eburru and Elmenteita is characterized by a well-defined graben, with symmetrical normal faulting facing each other on both sides of the active axis (Fig. 5).

[1] It may be worth noting that the NNE-SSW direction characterize the Main Ethiopian (continental) Rift when the NNW-SSE direction characterize the Red Sea and Afar (oceanic) rifts. The same direction is also observed in the central Turkana rift.

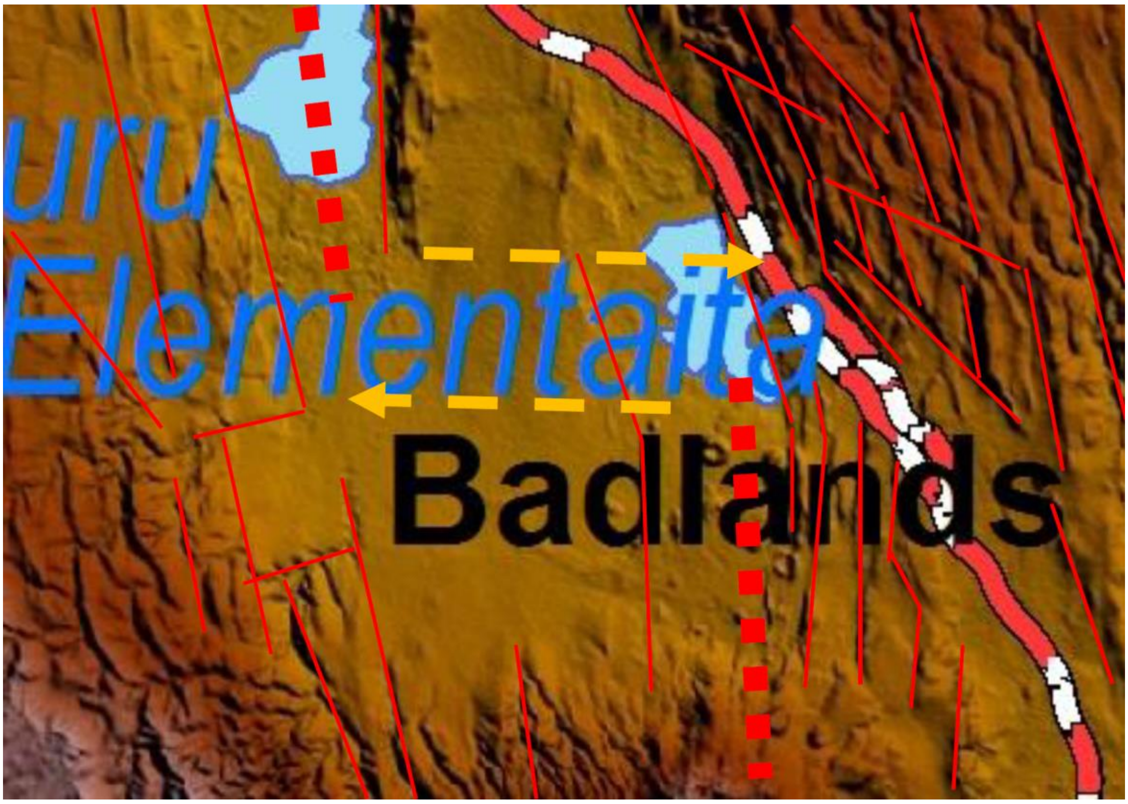


Figure 4: detailed view of Otutu (here called Badlands) showing, at the level of Elmenteita, that the active axis is shifted along the eastern side of Lake Nakuru meaning that the area acts as a transform fault zone (yellow arrows)

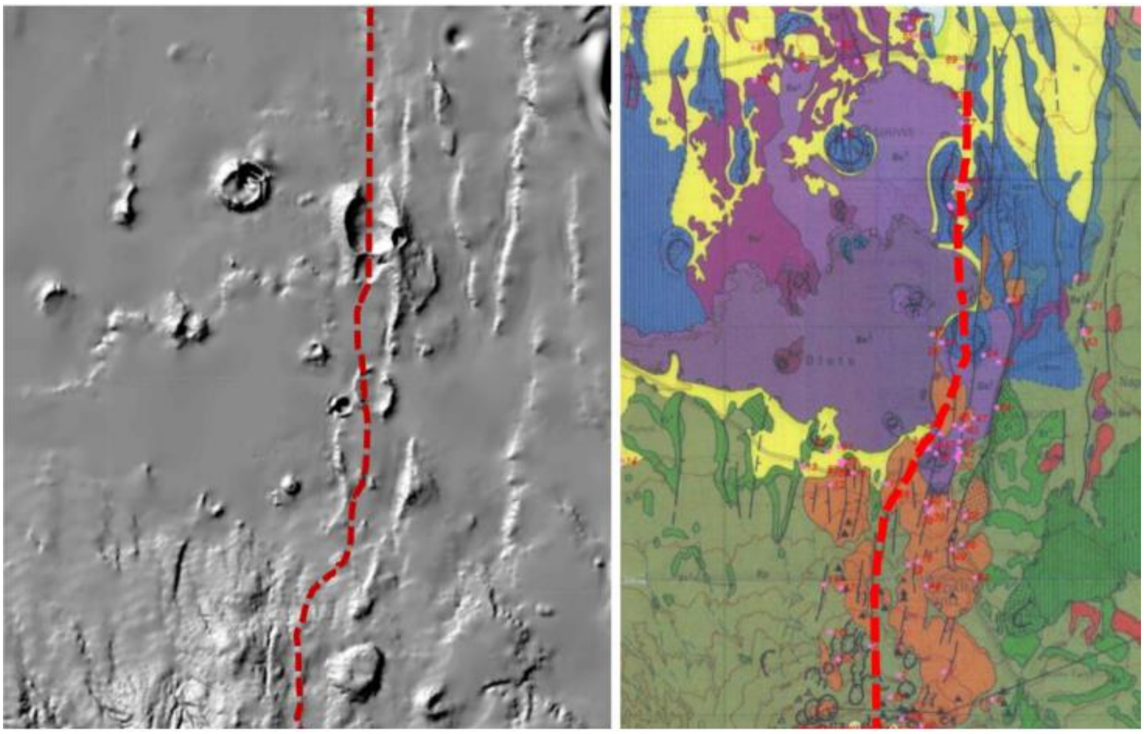


Figure 5: DEM model (left) and geological map (right) of the Otutu rift. DEM showing better the symmetrical normal faulting on both side of the active axis (underlined in dotted red). Basalts in blue and violet (most recent) while rhyolitic obsidian is in orange.

It also appears that the volcanic products are progressively getting younger from the margins towards the axis, a picture which is characteristic for an active rift segment (Fig.6). The northern part of the area is covered by recent (sub-historic) Aa basaltic flow that partly blanket the western half of the rift. This area, known as "Badland", was called "Otutu" by the indigenous Maasai population. A name that we considered, worth using for the area described in this paper. Having identified this Otutu rift segment, that ends at the level of Lake Elmenteita, the area located west of the lake towards Lake Nakuru where another N-S active emissive axis is observed, hence appear as a transform fault zone, explaining the weakening of the northern extremity of the spreading rift axis (Fig. 3) and the sinking of the rift floor covered by thick sediments.

Fig. 6: Schematic geological section across the Otutu rift. The axis of the rift is characterized by the most recent volcanic units emitted from open fissures that are also leaking steam. The age of the volcanic units is increasing symmetrically from the axis to the margins, with normal faults facing each other on both sides.

3. Otutu rift: a remarkable volcano-tectonic evolution

The Otutu rift developed on the floor of the rift valley during the last million years. Whereas the volcano-tectonic regime that formed the KRV started 25-30 My ago, the graben was formed only 4 My ago. From about 1.7 My the inner narrow trough developed within which the well reserved and still active volcanoes are located (Clarke et al. 1990, Strecker et al., 1990). Open fissures emitted recent lava fields and domes along the 30 Km long N-S axis of a graben characterized by symmetrical normal faults facing the active axis, 5 Km wide basin (Fig.5). As in spreading rift segments, the age of the volcanic units, as well as of the tectonics appear to decrease from the main rift eastern and western margins toward the rift axis where the hydrothermal activity presently develops, in a nearly symmetrical pattern. We have seen however that the site is located in a portion of the KRV where the direction of the main rift faults shift around the Tanzania/Nyanza craton, from the dominant NNW direction, taking a NNE trend (see Fig.3). As a result, the rift floor widens on the western side, and this affects the rift axis symmetry. This is well expressed along the western margin of the main rift escarpment where a shift of 15 km is observed along an E-W discontinuity at the latitude of the site.

a. The pre-rift axis trachyte event

On both sides of the lava fields emitted in this recent period, the rift floor is covered by trachyte flows well exposed in the so-called Waterloo ridge, dated 1.2 My (Baker et al., 1988). This ridge is faulted on its eastern side by an older east-facing fault up to 160 m high that limit the Ilkek plain (an earlier sedimentary rift part of the Naivasha basin). On its western side, it was affected by the normal faulting of the rift. This trachyte is lightly porphyritic displaying alkali feldspar (anorthoclase) and pleochroic green amphibole phenocrysts; the groundmass is microcrystalline and frequently altered. The flow is continuous over several kilometres[2], with a thickness that may exceed 40 metres (Fig.7).

On the western side of the rift axis, the normal faulting is less visible, as the whole area sunk, but open faults are still frequent, and attentive observations show that the tectonics was also quite violent there. Several hyaloclatite and scoria cone cut by E-W normal faults with dip west are left with only the western rim, the central and eastern side having been down faulted, amputed and covered by more recent lava flows emitted along the rift axis (Fig. 8).

Figure 7: Photograph (from W to E) of the normal faults (trending N-S with downthrows W) affecting trachyte flow limiting the Otutu rift on the eastern side. Note that basaltic hyaloclastites and pumice emitted from Otutu rift axis accumulated at the foot of these faults (photo J. Varet).

Figure 8: satellite view (left) and field photograph (J. Varet, 2016) of a succession of "half cones" toping half-shields on the western side of the Badlands area, that have been dissected by N-S normal faults, the eastern part of them being now buried under more recent lava flows emitted along the rift axis.

b. The early rift sub-lacustrine events

One of the characteristics of the site, which has a determinant influence on its geology (sedimentation as well as volcanology) is the fact that – located at the bottom of the rift valley – it is deeply affected by fluctuating climatic conditions. Elmenteita, now reduced to a

[2] as well observed in the main eastern fault scarps

brackish feature of limited extension, used to be part of a much larger lake (including lakes Nakuru and Naivasha, Fig.9) in the humid periods that prevailed – with several fluctuations – during the Plio-Pleistocene. Called Gambian Lake by Thompson and Dodson (1958), 3 levels have been identified where beaches and terraces were formed, the highest reaching +220 metres compared with the present lake surface. The earliest period dates back to about 1Ma and lasted 400 y, with a later period between about 150 and 60 ka BP and a late Pleistocene to Holocene period between 15.000 and 5.650 y BP, when it finally evaporated allowing for the separation of the 3 present lakes 3.000 y BP (Richardson, 1966; Butzer et al., 1972; Bergner et al., 2009).

The result of these successive humid periods is the development of lacustrine sediments in the basin, frequently interbedded with volcanic ash layers. In particular, the formation of diatomite deposits was favoured and Lake Elmenteita is surrounded, in its southern and western sides, with wide diatomite layers that predate and also cover the basaltic flows of the early Otutu fissural emissive period. As a result, the volcanic activity affecting the rift floor developed under sub-aqueous conditions, with strong magma-water interactions having a huge impact on the volcanic processes, with resulting hyaloclastite rings and deposits. These rings are much larger in diameter than their subaerial equivalents (scoria cones), the lava being squeezed and fragmented in thin glassy chards and expelled at higher latitude and finally spread at larger distance from the emission centre. This allow for hyaloclastite basaltic ash layers to be eventually intercalated with silicic ash in the surroundings, including the lacustrine sediments, and to accumulate at the foot of the faults along the eastern rift margin as observed east of the hyaloclastite rings.

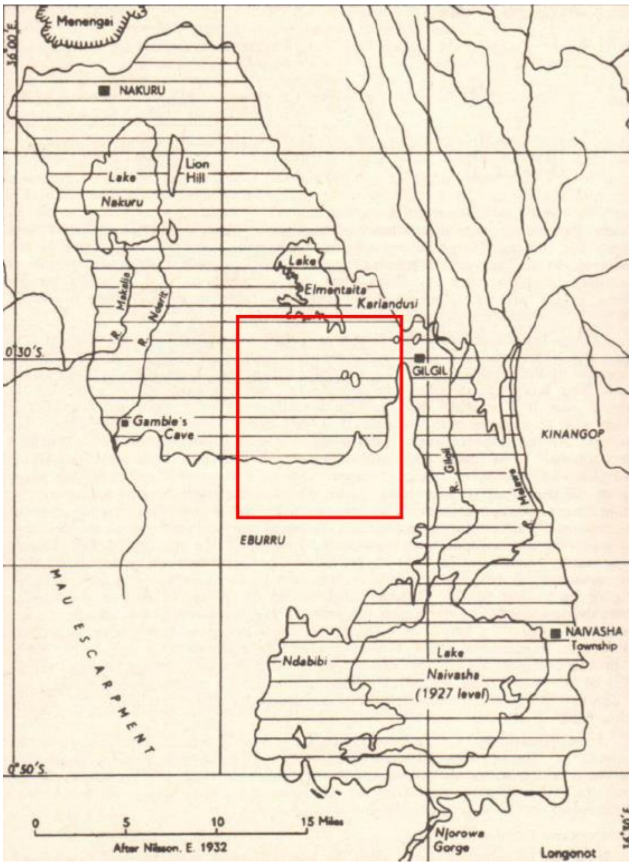


Figure 9: Map showing the maximum extent of the Gambian Lake (map from Thompson and Dodson, 1958) later dated 9.200 y. BP (Butzer et al., 1972) with location of the studied area (red rectangle) almost totally immersed.

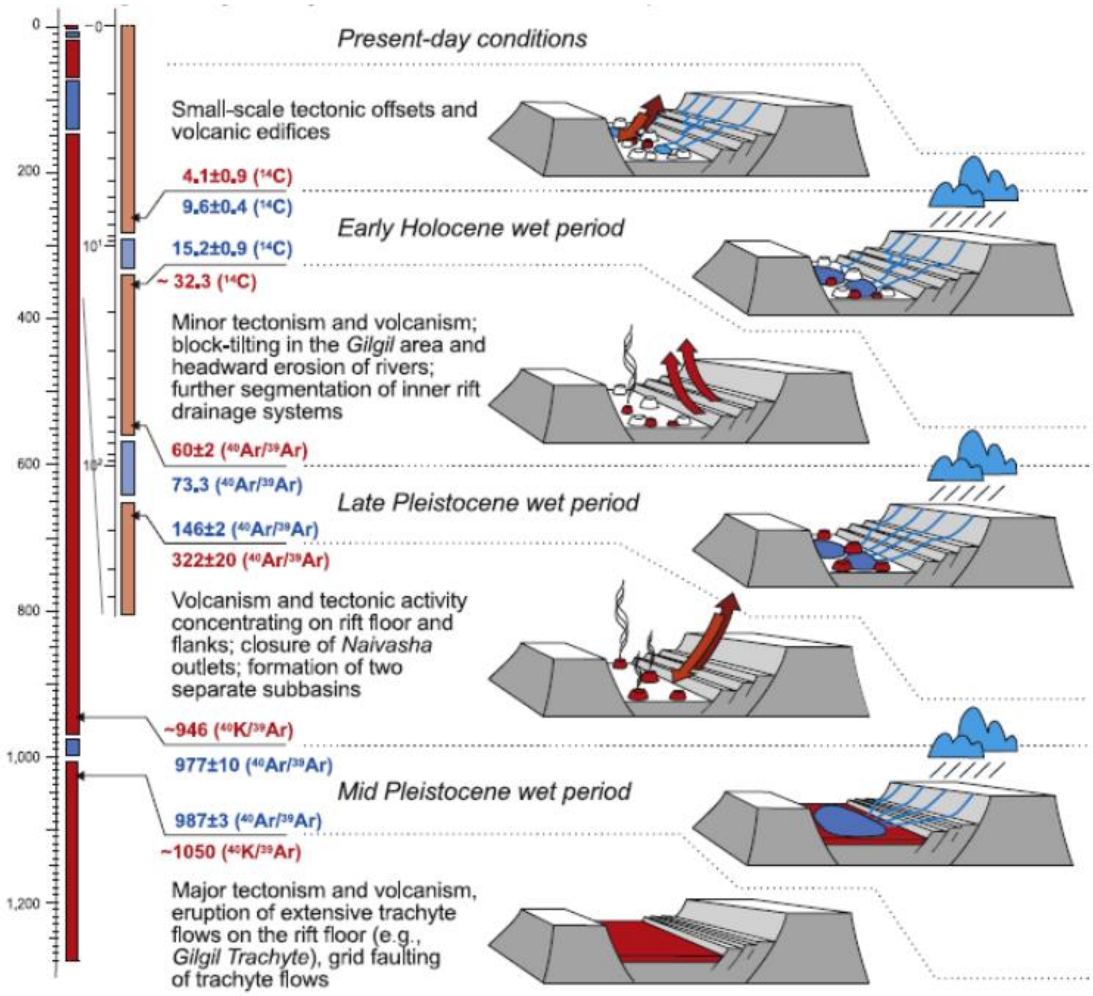


Figure 10: Successive climatic; tectonic and volcanic episodes affecting the central part of the Kenya Rift Valley in the Plio-Pleistocene between 1,2Ma and present (From Bergner et al., 2009).

The hyaloclastite rings display spectacular effects of open and normal faulting, as these discontinuities have been amplified by the erosion affecting these fragile tuffs. One of them, called Losiwire, with a diameter of 1.4 km and a maximum height of 120m (typical proportions for hyaloclastite rings) is affected by a small graben along its N-S axis, with normal faults looking towards the axis on both sides. Another, called Karterit (formed by 2 coalescent ash rings 2.6 km long and 2 Km wide) display a succession of hyaloclastites and subaerial scoria emitted from the same dike along the rift axis (Fig. 11). Another earlier ash ring also shows transverse NE-SW faulting. These observations show that the early Otutu axial rift volcanic activity (between 1000 and 400 Ky) was simultaneously tectonic and magmatic, with basalt emissions resulting from open faulting and diking.

3.1. Otutu inner rift

All along the floor of the rift, detailed observations – in particular immediately south of the Otutu basaltic flow - confirm the very distinct nature of this tectonics. Numerous, very recent, open fissures are visible cutting through rather recent lava flows, that frequently leak steam, creating linear wet zones that favour the development of the vegetation (with bushes and trees in inaccessible positions). These fissures are best seen when affecting lava flows but are also marked in pyroclastic surfaces by the rectilinear orientation of galleys. They are dominantly N-S with a slight (10°) NNE-SSW tendency (Fig.12).

Figure 11: Satellite views (up) and land photographs (below) showing 3 hyaloclastite rings. Left is Losiwire affected by open fault along its axis and symetrical normal faults are also visible on both sides. The two coalescent rings of Karterit, aligned along the N-S axial rift fissure (central image) are affected by N-S faulting along their axis and on the eastern flank. A contemporaneous NE-SW extension event that contributed to its edification also affects the NE edge of the southern ring. This may explain the apparent displacement towards north of the eastern rim of the main ring. A subaerial lava lake occupied the floor of the northern ring showing a continuous magmatic activity along the rift axis predating and postdating the Gambian lacustrine event (i.e. before and after 3.000y BP). On the right, older rings (1.000 to 400 Ky) observed on the sides are affected by intense faulting of N-S and NE-SW directions (Photos J. Varet, 2017).

Towards the active rift axis, normal faulting also affects very recent volcanic centres, such as a doubled rimmed scoria cone or an obsidian domes further south (Fig. 13). These faults also control the hydrothermal activity (see orange clay zone near the SW corner of Fig. 13). All emissive centres (marked to the north by hyaloclastite cones, and further south by scoria cones and domes) are clearly produced from the same fissures of N-S direction that mark the rift axis. Volcanological observations show that – in the successive events that marked the development of this rift - volcanic emissions and faulting were contemporaneous, meaning that successive dramatic telluric events succeeded to form the present shape of the Otutu rift (Fig.14).

This implies active diking in the same direction along this axis, which most probably only partly reached the surface. 5 to 10 such events can be identified, meaning that, over the last My, these paroxysmal events occurred with a circa 100.000 years interval. With a spreading rate of 2.5mm/y, this means that each event could accommodate for up to 250 m extension through diking and normal faulting. Considering that the events were apparently more frequent in the recent period (the last known eruption, at Cedar Hill, was dated 3.000 y BP (Clarke et al. 1990), this means that an important heat source is available along the Otutu rift axis.

In several places, besides these faults of N-S dominant direction, other subsidiary faults are also detected after accurate study, both from air or satellite images and from direct observations in the field. The most striking are sub-E-W trending normal faults and open fissures that are observed even in the most recently faulted area along the rift axis. These sub-E-W faults are generally short and affect the individual N-S faulted panels (as observed on Fig.14).

Figure 12: Open fissures affecting the Otutu rift floor axis. Numerous such fissures are crossed by the road (the red oval area is detailed right), marked by more vegetation due to the water leakage (steam) along these faults. They extend further south where they affect recent rhyolitic flows, marked by deep canyons trending in the same direction (orange). Several galleys are also following such faults (yellow). Satellite images (up) and field views of the same (photos by J. Varet, 2017).

Figure 13: Left: Satellite image of N-S trending normal faults observed along the rift axis, the highest to the east affecting a former shield volcano elongated in the same direction. In the central part of the image, near to the rift axis, a double-rimmed scoria cone, clearly cut by later N-S trending open fissures and faults, display a NE-SW trending feeding direction. Right: recent obsidian dome along the eastern side of the rift axis cut by open and normal faults (Photo J. Varet, 2017).

Figure 14: Two obsidian domes on the inner Otutu rift margins, west (up) and east (down). Observe the apparently transverse feeding direction and the normal (looking towards rift axis) and open faults – partly synchronized - affecting the dome-flows. Towards rift axis, the flows are cut by successive faulting with more recent flows covering the rift floor.

At the crossing with N-S faults, they are frequently the site of hydrothermal activity. Therefore, as a whole, if the area is characterized by a well-defined N-S trending rift, it appears that the structure is more complex and equally affected by transverse faulting that is equally extensive and "leaky" for both magmatic and hydrothermal fluids. This is of importance in view of geothermal development as it should influence the permeability of the reservoir.

3.2. The recent "Aa" basaltic flow

One should also note that the recent "Aa" basaltic flow having given the English name to the area also appears to extend mainly in a transverse, E-W direction. The SW limit of the flow is rectilinear and strikingly trending E-W. But this is apparently not the direction of the feeding dikes responsible for this wide basaltic effusion, and rather results from the pre-existing topography, itself determined by an important earlier E-W fault with dip north that is not directly visible at the surface. Although no visible feeding fissure or dike could be identified, the examination of the shape of the recent scoria cones feeding the Badlands Aa basalt flows indicate a possible NE-SW direction oblique to the rift axis (see Fig. 15). An orientation also visible in the SE side of the active rift floor in a fairly recent double-rimmed scoria cone (seen in Fig.13) as well as in the earlier southern part of the hyaloclastite cone (seen in Fig. 11). The later emissive centres (3.000 y BP to Present) will all be sub-aerial, characterized by typical scoria cones with a height and width of similar size order. At least 5 can be numbered, the latest 60 m high, with a 150 m wide crater.

Figure 15: View of the sub-aerial basaltic scoria cones having fed the recent Aa flows (Photo J. Varet, 2017) and below) satellite image of two of these scoria cones, which seems to result from NE-SW trending fissures.

4. Petrological field sampling and analysis

If not influenced by the shallow water, this whole volcanic activity in the area is essentially characterized by lava flows and domes, without marked pyroclastic eruptions. However, in terms of petrology, a large variety of products is found ranging from alkali basalts to trachytes and peralkaline rhyolites. It could appear strange that such a wide variety of differentiated products could be developed at a fissural stage. However, observations also show that shield structures tended to form, built on initial basaltic flows and intermediate terms (hawaiites, mugearites and trachyte flows).

About 130 samples were collected in the Otutu rift, geo-localized by GPS, and described in the field and using polarising microscope (for further details, see Varet, internal reports and Nyawir- to be published). This complements the earlier studies, petrographic and mineralogical, by Sutherland (1974) and Ren et al., (2006) centred on the Eburru volcanic complex allowing for a thermobarometric study showing emplacements at 668-708°C for the pantellerites and 709-793 for the trachytes. Radiometric age datings were published by Baker and Mitchell (1976, 1988). Unfortunately, we could not engage new age determinations yet.

5. Geochemical analysis and modelling

Major and trace element data on bulk rocks were first obtained by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) at IUEM, Plouzané (Brest University, France). The samples were finely powdered in an agate grinder. International standards were used for calibration tests (ACE, BEN, JB-2, PM-S and WS-E). Rb was measured by flame emission spectroscopy. Relative standard deviations are ±1% for SiO2, and ±2% for other major elements except P2O5 and MnO (absolute precision±0.01%), and ca. 5% for trace elements. Concentrations of additional trace elements were measured by Inductively Coupled Plasma Mass Spectrometry (ICPMS) at IUEM, using a Thermo Element 2 spectrometer following procedures adapted from Barrat et al. (1996, 2000). Based on standard measurements and sample duplicates, trace element concentration reproducibility is generally better than 5% (Barrat et al., 2007), and are in good agreement with the ICP-AES results.

Resulting data were plotted using classical major elements plots (Alkali/Silica, Fig. 16, and AMF, Fig. 17) showing rather regular trends for all samples, typical for transitional series found elsewhere in the EARV including Afar (Barberi et al, 1974). The regular calcium and aluminium oxide decrease show the role played by plagioclase fractionation (Fig. 18). The absence of iron enrichment in the intermediate show a clear alkaline affinity.

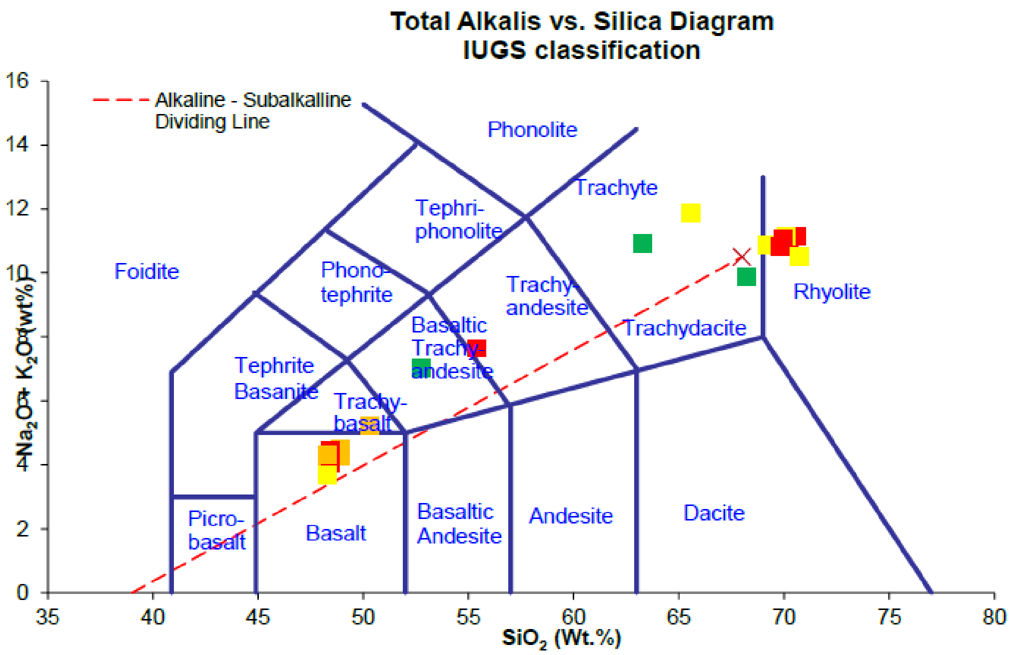


Figure 16: Alkali/silica diagram for Otutu lava samples. Colours vary according to location along and across the rift.

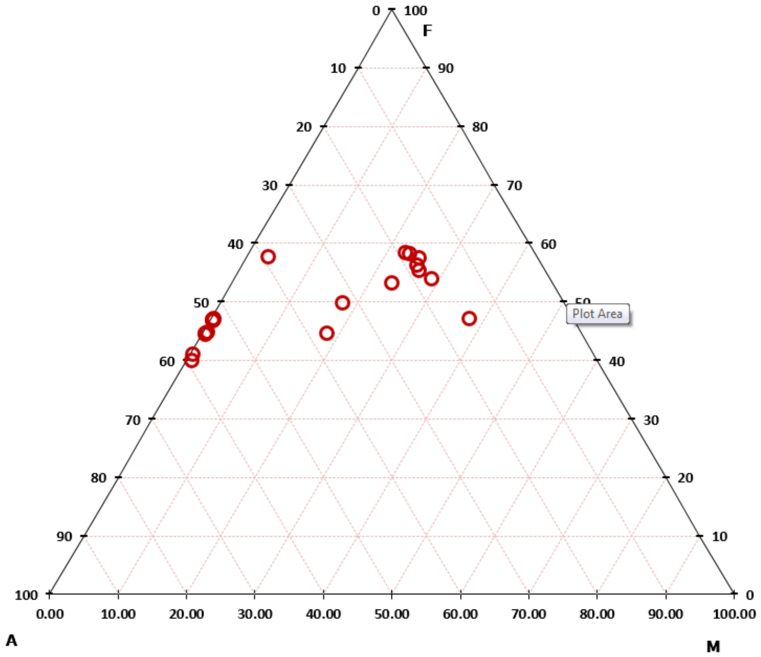


Figure 17: AFM diagram for Otutu lava samples: the sequence with limited iron enrichment clearly falls in the alkali-basaltic trend.

Coupled hygromagmatophiles (Fig. 18) display regular linear trends characterizing crystal fractionation patterns (Treuil & Varet, 1973). This is also confirmed by the REE behaviour. However, two samples display anomalous Europium contents. These correspond to the pre-rift trachytes of Gilgil area (so called Waterloo ridge), which also depart from the regular trends in other variation diagrams. However, with this exception which emphasise the pre-rift nature of this unit, all samples fall along the same line whatever their position along or across in the rift, as shown in Fig. 17.

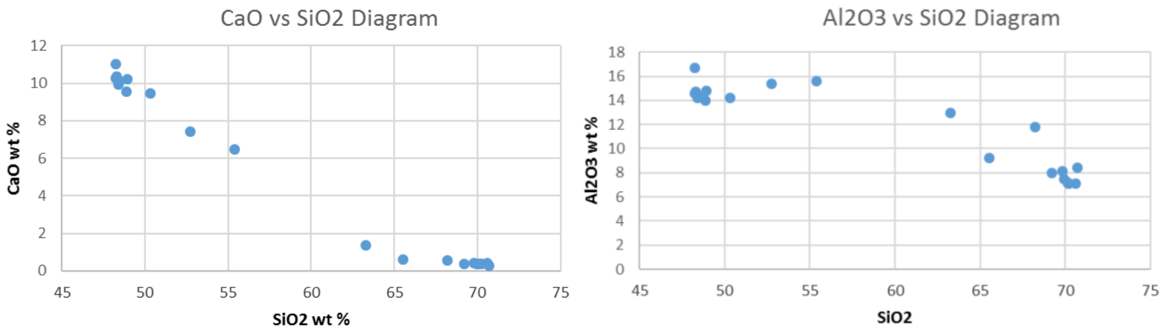


Figure 18: Major elements plots for the volcanic samples of Otutu rift/ Total alkalis, alumina and CaO versus silica.

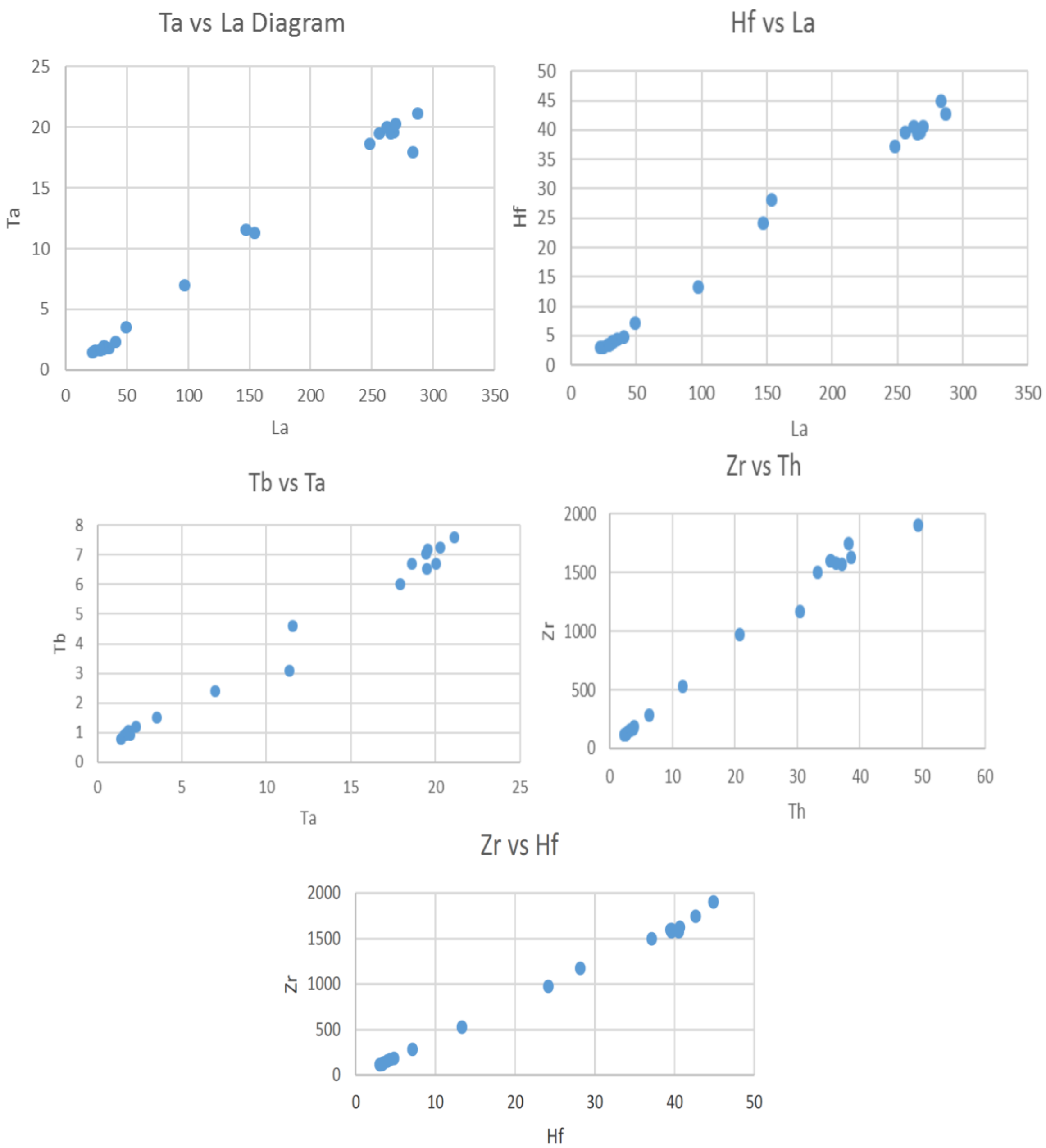


Figure 19: Diagram showing geochemical evolution by crystal fractionation as seen from linear plots of the hygromagmatophiles elements

6. Magmatology

The question of the evolution of the magmas found in these rift segments is a key problem that needs to be addressed. The Otutu area, selected for this research, offers good observation facilities, with a variety of volcanic types located along the rift axis: basaltic flows, obsidian domes and a variety of intermediate products (trachytes, mugearites, etc). In addition to the volcanological argument (all are issued from fissure eruptions, meaning that they are fed by dykes at depth along the rift axis), petrological and geochemical studies, analysis and modeling, show a regular evolution that can be explained by crystal fractionation from a single magmatic source. This is a fundamental result as it shows that long lasting magma chambers allowing for this magmatic differentiation do exist in single rift structures and not only in central volcanic units (where such structures at depth are expressed at the surface by calderas). However the question is raised to know if the magma is fractionated along the dykes feeding the Otutu rift axis or injected laterally from the Eburru central volcano. To this respect, the volcanology in the field, e.g. the length of the rift along which the variety of magmatic products including peralkaline rhyolites, and the lack of gradient with the distance to Eburru support the concept of fractionation in a specific magma chambers elongated all along the rift segment axis.

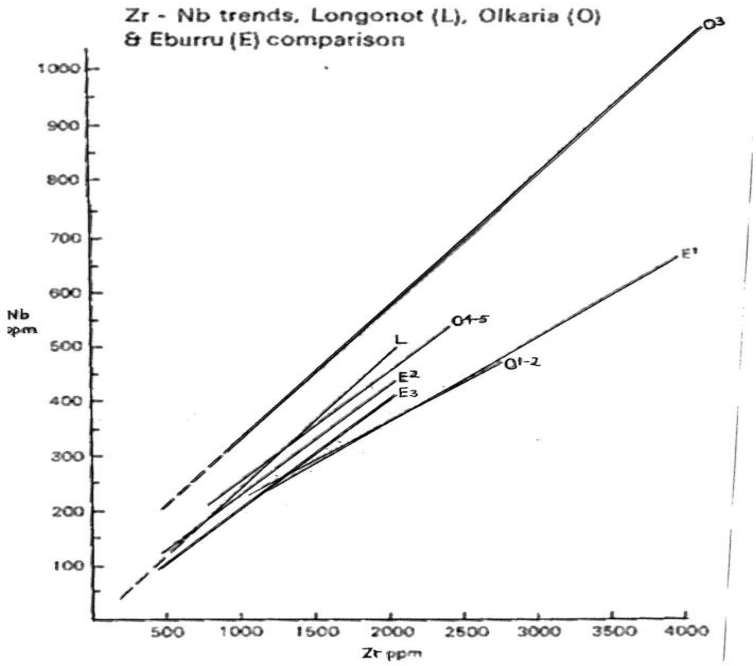


Figure 20: Diagram showing the Zr-Nb trends for Longonot, Olkaria, Eburru (with 2 trends, E1 and E2) and the Otutu Rift (modified from Allen, et al, 1989). E3 is the trend for the Otutu Rift.

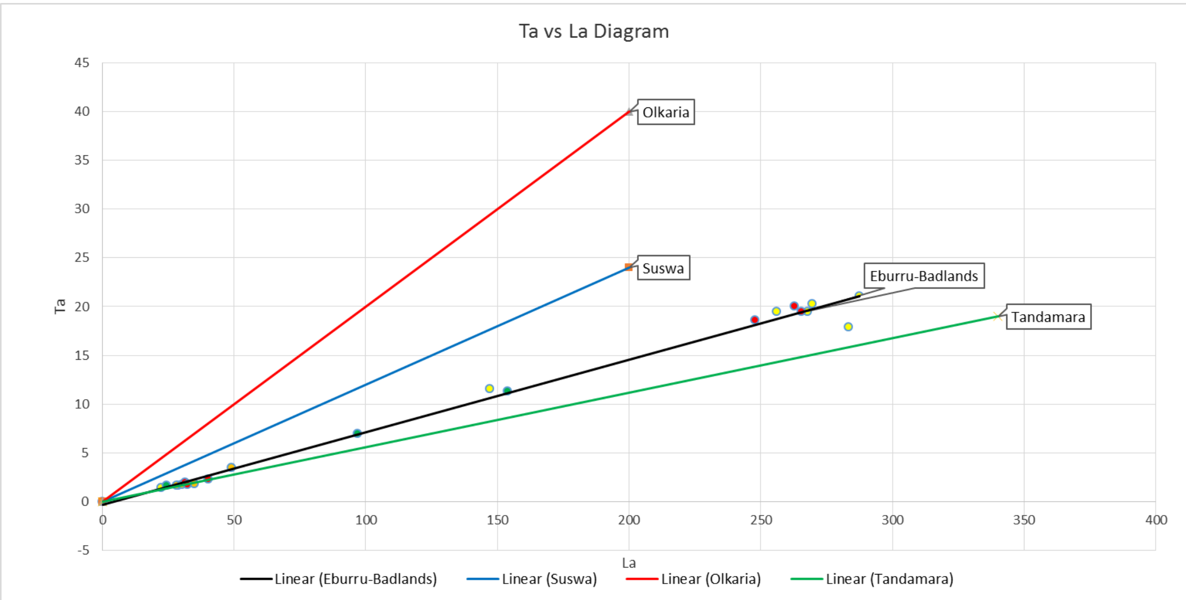


Figure 21: Diagram showing distinct origin of the samples in the Otutu rift-Eburru/Badlands (modified from Omenda 1997). Each unit display the same variation from basalts to rhyolites with no distinct geochemical evolution.

The petrology however show rather similar trends between Eburru central volcano and Otutu rift axis, although lava characterize the rift segments when pyroclatite eruptions dominate the volcanic centre. Geochemistry (Fig 20 & 21) do not allow to clearly separate the trends on all indices, but some more accurate plots show a distinct trend between Otutu rift and the ones of Eburru volcano (Nb/Zr, Fig. 20).

Spacing with time of the magmato-tectonics events show - by simple calculation - that the time and space required are adequate for differentiation to occur. With a measured spreading rate of 2.5 mm/y (as shown by GPS measurements, Calais, 2016, see Fig. 1) and an interval of 100 ky between events (no more than 10 events observed over the last My year), dykes as large as 250m and more than 10 km long will develop and should allow with time for magma fractionation to occur from basalts up to peralkaline rhyolites terms.

7. Geophysics

Several geophysical surveys were carried in the area by KenGen (Kandie et al., 2017) including gravimetry, TEM and MT, and also ground magnetic. We will not focus in this paper on these data, discussed elsewhere (KenGen, 2017), but simply report on the linear anomalies resulting from the processing of magnetic data, as shown in Fig. 22. This clearly indicate the presence along the Otutu rift segment of alternating magnetic anomalies set along the axis of the rift, in a quite similar pattern with what is observed in oceanic spreading segments.

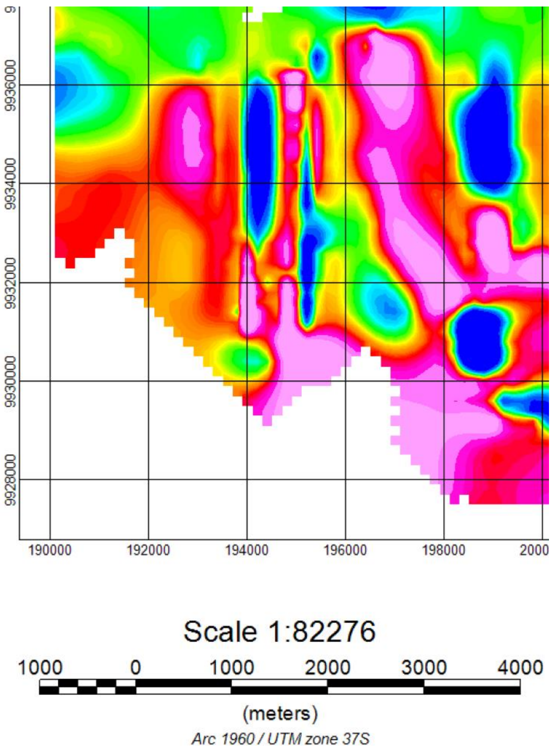


Figure 22: Map of the magnetic anomalies (upward continuation 1Km) in the Otutu area, showing alternating figures along both sides of the rift axis.

Of course, this interpretation, which support our hypothesis that Otutu is behaving as an active rift segment with successive fresh magma injection (and consecutive differentiation) along its spreading axis would require further in-depth - and more detailed - geophysical studies of the area.

8. Geothermal energy

The debate among geothermal developers concerned by the characteristics of the resource is to know whether Otutu is just a near-surface lateral leakage from the Eburru reservoir (a simple outflow) or a single geothermal system with its own heat source (elongated magma chamber) and geothermal reservoir (hosted in the fractured system observed and largely leaking at the surface) heated by its own magmatic source.

One of the authors (JV) sustain this second hypothesis, which fits with most available data including surface heat flow and gas emissions measurements and magnetic surveys (as shown in Fig. 22). However, it is not confirmed by the MT survey presently available. No deep conductive anomaly is observed along the rift axis from available data.

But it can be observed that the above calculation shows that the width of the magma chamber do not exceed 250m. Therefore, when the grid used for the MT survey is 1 Km, then that kind of measurement can't capture such details. In addition, the data processing (1D interpretations plots in 2D surfaces - maps of sections -) do not favour the identification of such a vertical structure. The authors therefore maintain the interpretation of a single, specific, geothermal system along the axis of Otutu Rift and recommend the undertaking of appropriate geophysical complementary surveys (circa 100m spacing of stations across the rift axis coupling TEM/MT with gravimetry and magnetic surveys) and joint inversion of the data (Hautot and Tarits, 2009).

It is one of the author's opinion (JV) that the observations developed in Otutu Rift should allow to reconsider the geothermal potential of the EARV in also considering single rift segments - and not the central volcanoes only (see Fig. 2) as potential geothermal targets.

9. Conclusion: Geological interpretation and geothermal implication

From our field observation, sampling, analysis and modelling, it appears that, after the widespread trachyte emission that predates the Otutu rift, a variety of volcanic products was emitted during each of the successive steps of the Otutu rift development, ranging from alkali-olivine basalts to pantellerites, with a few intermediate terms. This evolution can be simply explained by a process of crystal fractionation occurring in the faulted crust that is a few kilometres deep. It therefore appears that the volcano-tectonic context allowed for the development of successive elongated magma chambers along the rift axis during the last few hundred thousand years. This explains the important heat release along this axis, characterized by steam vents observed along all open fissure and faults that affect the whole rift floor and inner margins.

Some geophysical data presently available do not confirm this interpretation, in particular MT data. However, magnetic data modelling show alternating N/S linear anomalies displaying similarities with what is observed in oceanic spreading segments. Further detailed geophysical surveys with closer pacing and geochronological data are needed along and across this spreading axis in order to properly model the vertical dimension of the Otutu rift segment and better quantify its tectono-magmatic history. This would allow to confirm the hypothesis presented in this paper concerning the development of the heat source of this geothermal field. And in turn, this new vision of the rift magmatism along single rift segment found all along the Eastern Branch of the EARV between the central volcanoes now retained as geothermal targets would also appear as cases of interest for envisaging larger geothermal developments.

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