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Significance of Tectono-volcanic Axes in Menengai Geothermal Field

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ABSTRACT

Tectono-volcanic structures involve both lavas and faulting unlike volcanoes which are just large piles of lava. They are good recharge and up flow structures for geothermal systems. Molo and Solai TVA (Tectono-Volcanic Axes) are the major structures in Menengai Geothermal Field and have so far proven to be very significant in resource exploitation. These prominent volcano-structural features are characterized by zones of faults and fractures along which volcanic eruptions have taken place. Numerous manifestations such as fumaroles and hot grounds are also present and manifest along these structures and their transfer zones, such as the Makalia fault transfer zone in the central caldera. Leat (1984) explains that most of the fumarolic activity seem to occur along the fractures that resulted from the Menengai collapse. The tectonic activity has resulted into a buildup of fracture systems that are important as aquifer zones and also contributes to fluid permeability.

Leat (1984) associates the Molo system with a NW-SE trending ridge where Pre-caldera rock units are seen, and therefore the Molo system should be older than the Solai system which cuts into the caldera on the NNE side. In Menengai, the first volcanic activity was marked by the growth of a low-angle trachyte lava shield, around 0.18 Ma (Leat, 1984). A Krakatau-type collapse followed to form the 77 km^2 caldera enclosed by a well preserved ring fault. According to Lagat et al, 2011, the ring structure has only been disrupted by the Solai graben faults on the NE and the Molo TVA on the NNE sides of the caldera. The Ol' rongai faults form part of the major Molo TVA and are oriented in the NW-SE direction, same orientation with the Menengai pre-caldera. On a regional scale, the Ol' rongai system extends northwards through Lomolo and past the Gotuimet volcanic center. The Solai TVA system is younger than the Menengai caldera. The Solai structural system has numerous faults that strike in the NE-SW and NNE-SSW direction and cuts Menengai on the Northern caldera wall. This axis appears to be an extension of the Makalia fault from the south with a transfer zone in the central caldera.

1. Introduction

Tectono-volcanic structures form by faulting over rising magmas. Unlike volcanoes, which are just large piles of lava, tectono-volcanic structures involve both lavas and faulting. Hence, both the tectonic and volcanic activities give rise to well buildup fracture systems that are important as aquifer zones and also contribute to fluid permeability. The high permeability in the tectono-volcanic zones is majorly demonstrated by the numerous manifestations such as fumaroles and hot grounds present along these structures and their transfer zones. Hence, tectono-volcanic axes are good recharge and up flow structures for geothermal systems and are thus very significant in the resource exploitation.

Menengai Geothermal Field is one of the major High- Temperature geothermal fields in Kenya. The field is characterized by a shield volcano with highest peak at an elevation of 2278 m.a.s.l. and comprises the Menengai caldera, the Ol'rongai in the northwest, and parts of the Solai graben to the NE. The geology of Menengai is divided into post-caldera, syn-caldera and pre-caldera stages while, tectonically, there are two systems: the Ol'rongai and the Solai fault systems. This research paper will focus on the two major tectonic structures which have been very significant in resource exploitation. Production drilling is underway in Menengai geothermal field and it has been discovered that wells within the tectonic zones have relatively higher yield than those outside the said zones.

Molo and Solai TVA (Tectono-Volcanic Axes) are the major structures that characterize the Menengai Geothermal Field. These prominent volcano-structural features are characterized by zones of faults and fractures along which volcanic eruptions have taken place. The Molo TVA is older than the Solai system which cuts into the Caldera. In Menengai, the first volcanic activity was marked by the growth of a low-angle trachyte lava shield, around 0.18 Ma (Leat, 1984). The Ol' rongai faults form part of the major Molo TVA and are oriented in the NW-SE direction, same orientation with the Menengai pre-caldera. On a regional scale, the Ol' rongai system extends northwards through Lomolo and past the Gotuimet volcanic center. The Solai TVA system is younger than the Menengai caldera. The Solai structural system has numerous faults that strike in the NE-SW and NNE-SSW direction and cuts Menengai on the Northern caldera wall. Leat (1984) further explains that there is an approximately N-S line of vents outside and to the S of the caldera, the line is parallel to the regional fault trend in this part of the Rift. The Solai TVA appears to be an extension of the Makalia fault from the south with a transfer zone in the central caldera.

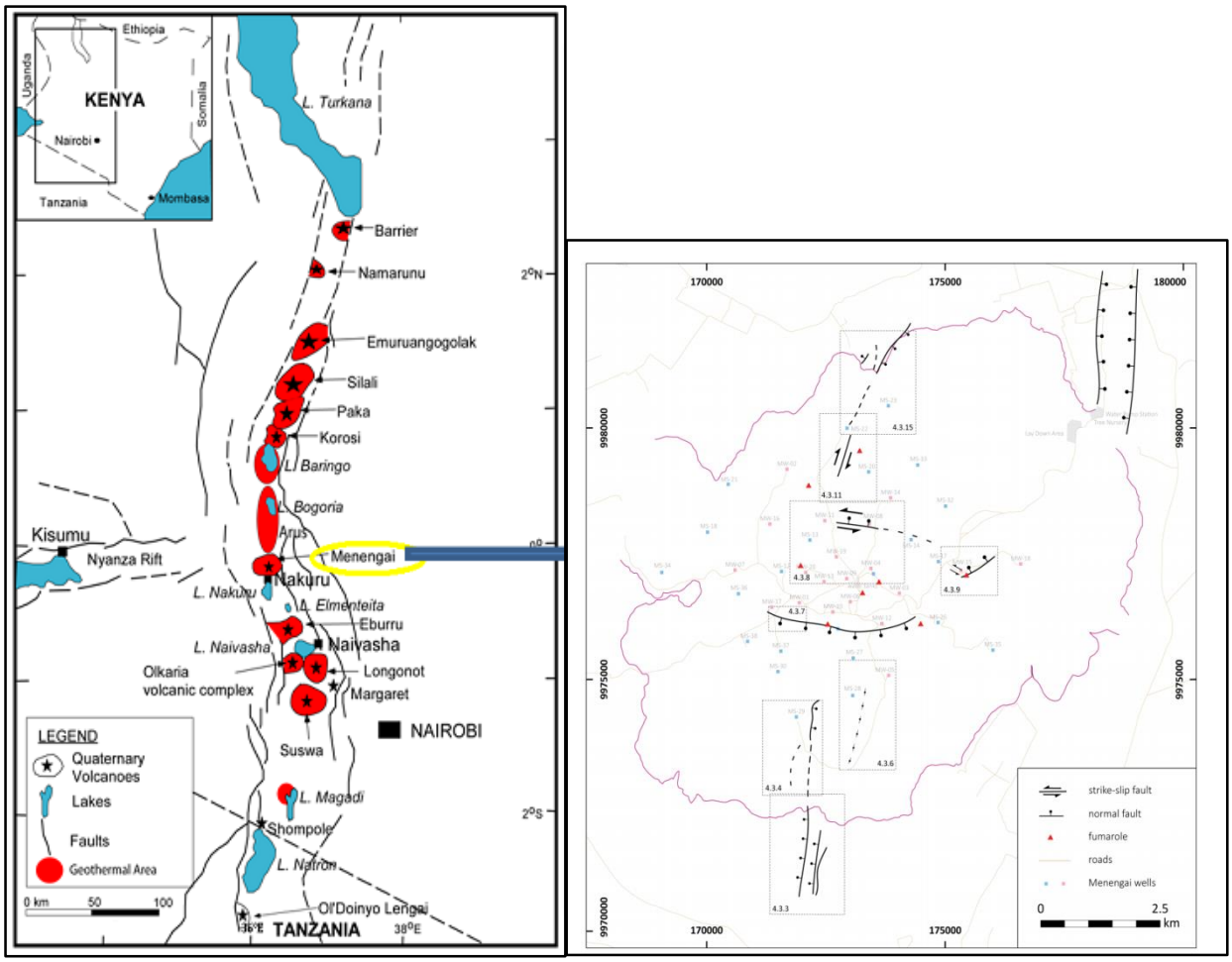

Figure 1(a) Location of Menengai Geothermal Field and Menengai Caldera. (b) Overview map of Menengai Caldera with principal structures (Modified from Strecker et al. 2013)

2. GEOLOGIC AND STRUCTURAL SETTING

Menengai geothermal field is in the Kenyan segment of the East African Rift system and extends from Lake Turkana in the north to the north of Tanzania near Lake Natron as shown in figure 1 above. In the central Kenya Rift, normal faults were partly reactivated as normal faults with a strong strike-slip component, leading to a higher degree of shearing and a left-stepping arrangement of Quaternary normal faults (Strecker et al. 1990; Zielkeet al. 2009). The Menengai caldera, north of Nakuru is located in the transition between the NW-SE oriented central, and the NNE-SSW oriented northern Kenya Rift valley (Strecker et al. 2013).Menengai is a trachytic central volcano underlain by a high level magma chamber. Geological activity started shortly before 0.18 Ma; with the growth of a low - angle trachyte lava shield having a volume of about 30 km³ (Leat 1984).The formation of the shield volcano began about 200,000 years ago and was followed by the eruption of two voluminous ash-flow tuffs, each preceded by major pumice falls. The first took place about 29,000 years ago and produced a large caldera. The Ol' rongai ignimbrite and the Athinai trachyte immediately north of Menengai are associated with the collapse of the Ol' rongai caldera, and are probably older than 0.3 Ma (Leat 1991). The second major eruption gave rise to Mid-Late Pleistocene volcanic rocks which took place probably around 1 Ma and is exposed in the ranges to the north at Kisanana and Solai, and the corresponding Mbaruk and West Lake Trachyte formations, which characterize the areas south of Menengai (Leat 1991). The youngest volcanic manifestations are a series of lava flows on the caldera floor that probably indicate the post-caldera collapse. Related volcanic deposits, particularly two ignimbrites, are exposed in the immediate vicinity of the caldera (Strecker et al. 2013).Post-caldera activity has largely been restricted to inside the second caldera and produced mainly lavas (at least 70 flows), sheet-forming fall pumice deposits and strombolian cinder cones (Macdonald, 2011). Geothermal manifestations in Menengai include such signatures but not limited to fumarolic activity inside the caldera and on the North Eastern flanks; young volcanic activity indicated by numerous recent eruptions; large caldera collapse and intense tectonics resulting to intense faulting.

3. MAJOR STRUCTURES IN MENENGAI GEOTHERMAL FIELD

Structures in Menengai Geothermal Field are majorly controlled by two tecto-volcanic systems namely Molo and Solai structural systems. Tectono-volcanism involves a mix of intense faulting and volcanism giving rise to major fracture systems that enhance highly permeable zones, suitable for geothermal resource exploration. Simiyu, 2009 explains that eruptive volcanoes, with caldera collapses and concentration of tectonic grid faulting (block and fissure faults) in northern Menengai are characteristic of extension faulting associated with spreading (rifting) at crustal boundaries. The Molo TVA is older than the Solai system which cuts into the Caldera. The floor of Menengai is covered by several post-caldera lava flows.

3.1. MoloTectono-volcanic Axis

This is the major TVA in the region and is referred to as the Molo System (Geotermica, Italiano 1987).This prominent structural feature is oriented in the NW-SE direction, same orientation with the Menengai pre-caldera. The Menengai volcanic activities that took place in the early Pleistocene epoch resulted to the Ol' rongai volcano through which the Molo TVA cuts forming the Ol' rongai faults. The NNE-SSW striking normal faults cut the Menengai caldera rim to the north and disappear below the pyroclastic cover and reappears on the SW corner of the caldera. If extrapolated, the northern and southern fault zones may coincide to form an extensional fault regime. Strecker et al. 2013 explains that this is best expressed at the southeastern caldera rim, where, in continuation with a fissure zone north of Ronda Hill, a system of young NNE-SSW striking normal faults and aligned craters (cave area to the north of Nakuru Prison) cuts the caldera rim and supports the notion of ongoing WNW-ESE oriented extension. The Molo TVA is associated with aligned fumaroles and silica-sinter coatings which may have formed during fumarole activity (Lynne et al. 2006).

3.2. Solai Tectono-volcanic Axis

The Solai TVA system is defined by the NNE-SSW oriented eastern margin of the Solai graben which is approximately a 200-m-wide intensely cataclasized. This fault system is younger than the Menengai caldera and cuts the wall approximately 24 km NNE of Menengai and 2.5 km E of Lake Solai. The fault system is not exposed within the floor of the caldera probably due to thick lava deposits. The Solai structural system has numerous faults that strike in the NE-SW and NNE-SSW direction and cuts Menengai on the Northern caldera wall. This axis appears to be an extension of the Makalia fault from the south with a transfer zone in the central caldera. Solai TVA seems to be linked to a major fault of the Aberdare detachment, which is sufficiently deep and close to the rift trough, and constitutes the fault system cutting the recent pyroclastic deposits north of Menengai caldera. The Solai TVA is part of the Solai graben. The Solai TVA is majorly characterized by faulted phonolites that are decomposed to a fault gouge, which consists of reddish clay with lithic clasts (Strecker et al. 2013).The fault zone continues over a total length of approximately 30 km along the eastern margin of the inner rift zone. Some of the Menengai eruption centers seem to align to the Solai TVA.

4. RESISTIVITY OF MENENGAI GEOTHERMAL FIELD

Measuring the electrical resistivity of the subsurface is the most powerful prospecting method in geothermal exploration (Gylfi and Knútur 2013) Resistivity is directly related to a number of parameters that characterize geothermal reservoirs. Such parameters include the following but not limited to: salinity, temperature, porosity, permeability, and alteration

4.1. Resistivity Cross-sections

Resistivity cross-sections plotted from 1D inversion data show a typical resistivity structure of a high-temperature field. There is a high-resistivity layer near the surface due to un-altered lava formations; underlying is a low-resistivity zone which is a result of low-temperature alteration minerals; this is further underlain by a high-resistivity core where chlorite and epidote usually dominate representing high-temperature hydrothermal alteration minerals. There is a noticeable observation from the cross sections: along the permeable zones where the tectono-volcanic axes are likely cutting through, there is a very low resistivity at depth. This might be associated with magma intrusion along these zones thus a possible increase of productivity along these zones (Gichira, 2011).

4.1.1. Cross-section NW_SE

High resistivity from about 100 Ωm covers almost the entire surface area to a very shallow depth of about 100 m which can be associated with unaltered surface lava formations. Below the high-resistivity top layer is a low-resistivity zone with resistivity values of less than 30 Ωm; an indication of low-temperature hydrothermal alteration minerals. This low-resistivity zone extends to a depth of 1500 m from the surface. Underlying the low-resistivity zone is a high-resistive zone which seems to be lying between two conductive anomalies; this zone extends to a depth of 2500 m below the surface. However, this zone is more conspicuous in the southeast part of the profile than in the northwest. In a typical high-temperature geothermal system, this zone would coincide with the high-resistivity core where high-temperature hydrothermal alteration is more pronounced. Deep below this high-resistivity core is a low-resistivity anomaly with resistivity of 5 Ωm; this zone starts at a depth of 3500 m to the southeast side of the profile and is likely the heat source for the Menengai field.

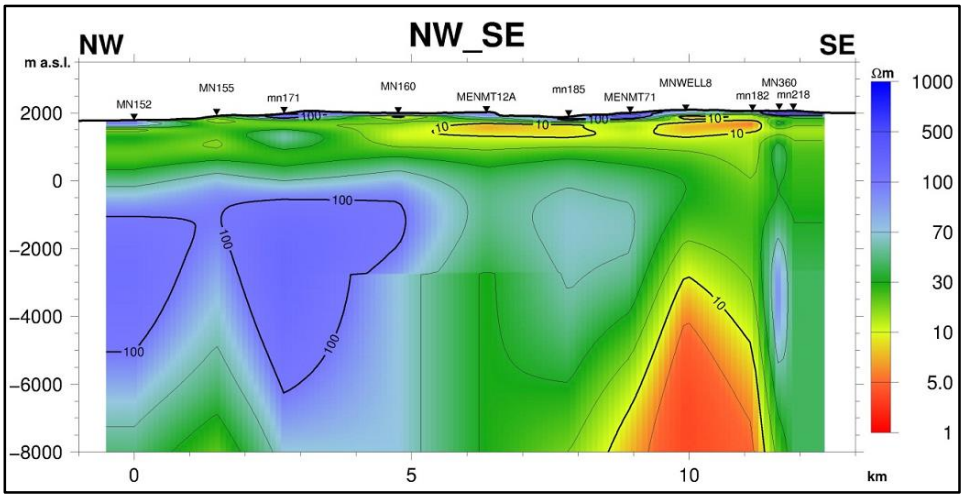

Figure 2. Resistivity cross-section NW-SE in Menengai Field based on the output from 1D joint inversion of MT and TEM data (after Gichira 2011)

4.1.2. Cross-section MW-05_MW-03

This section cuts the study area in a SW-NE direction. The profile covers only four soundings and the extreme southwest and northeast sections of the profile are very resistive from the surface to the bottom. However, the middle part of the profile looks promising with a low-resistivity anomaly from the surface to about 150m below the surface. Below this anomaly is a high-resistivity core which extends to a depth of about 4000 m below the surface followed by a conductive body which starts from a depth of about 5000 m below the surface and extends to the bottom of the profile.

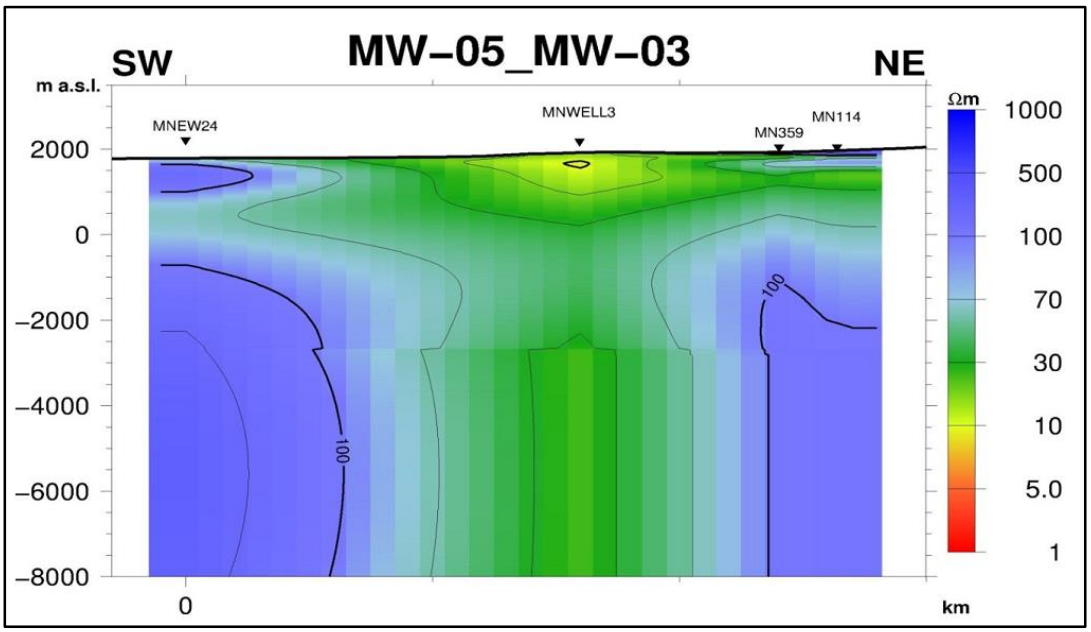

Figure 3. Resistivity cross-section MW-05_MW-03 in Menengai Field based on the output from 1D joint inversion of MT and TEM data (after Gichira 2011)

4.1.3. Cross-section MW-06_MW-09

This profile runs from MW-06_MW-09 from northwest to southeast. The surface has high resistivity which is characteristic of most unaltered rock formations. The central part of the profile has high resistivity extending from the surface to the bottom while the northwest and the southeast parts exhibit the typical resistivity structure of a high-temperature geothermal formation. This is to say that, an unaltered formation covers the surface. Thus, the resistivity is high and below this is a conductive anomaly which overlies a high-resistivity core and below is a conductive body which has been interpreted as a possible heat source for the geothermal field.

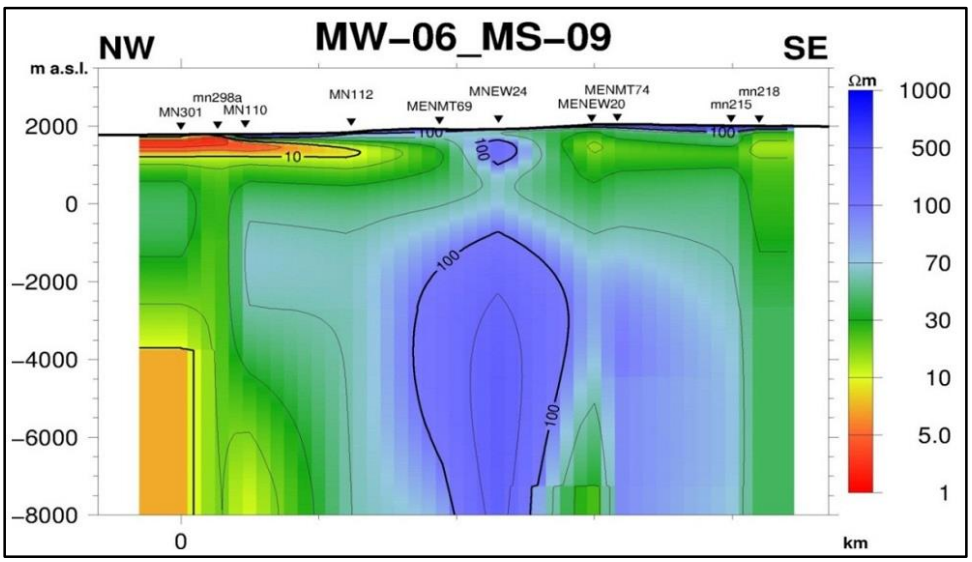

Figure 4. Resistivity cross-section MW-06_MW-09 in Menengai Field based on the output from 1D joint inversion of MT and TEM data (after Gichira 2011)

4.2. Resistivity Variations with Depth

According to Gichira, 2011, at 1000 m b.s.l. resistivity shows at a depth of about 3000 m below the surface and the resistivity structure of the study area at this point resembles the resistivity structure at sea level. This gives a possibility of the high-resistivity core extending to this depth; thus, the thick resistivity core would be an indication of a good reservoir for a high-temperature system. At 2000 m b.s.l resistivity decreases further in the southern part of the study area to lows of 5 Ωm, giving an indication of a possible heat source probably to the possible reservoir zone at a depth of between 400 m b.s.l. and 1000 m b.s.l. At 3000 m b.s.l. decreasing

resistivity further confirms the possibility of a heat source beneath the Menengai caldera.The resistivity within the caldera at this point is less than 5 Ωm. Measurements and modeling of magnetotelluric data (Wamalwa 2011; 2013) record a low-resistivity zone at 4 to 6 km depth, which has been associated with a magma chamber. From the iso-resistivity map ((Fig 5), it is clearly demonstrated that resistivity along the tectono-volcanic zones is lower in comparison to adjacent areas.

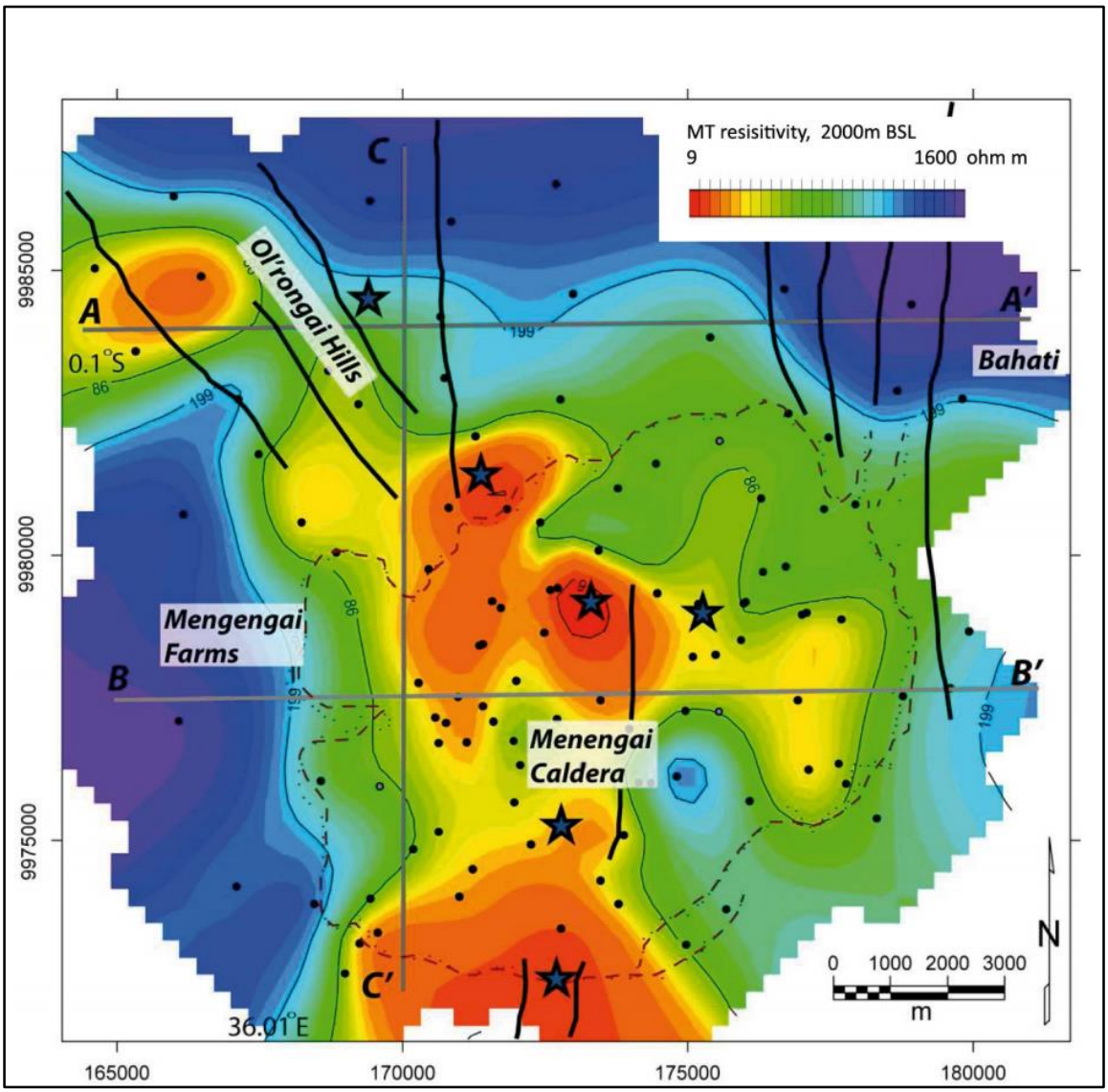

Figure 5. Resistivity map of Menengai caldera for a sector of 2000 m below sea level, which translates to approximately 4000 m depth. Red color highlights low resistivity zones. Data based on inversion models of magnetotelluric data by Wamalwa (2011).

5. SEISMIC EVENT DISTRIBUTION AND MAGNITUDE VARIATION

Menengai is a relatively seismically active area located in the region where the failed Kavirondo rift branch joins the main Kenyan rift (Mariita, 2007). Events are more concentrated within the Menengai caldera. This is the area around the central to the southern part of the caldera and on the NE caldera wall (Simiyu, 2010). Another area with a large cluster of events is within the Olbanita area to the central NW of the Menengai caldera where the events are also shallow. Events are also observed to occur along two specific trends: along the rift axis in a NNW-SSE trend that starts from Majani Mingi through Olbanita, Menengai and dies out at Lake Nakuru in the South East; and a trend parallel to the Nyanza rift axis in NE-SW direction along the major axis of the caldera with clusters from Bahati on the Aberdare ranges, through the caldera, Nakuru town and Rongai. The Menengai caldera appears to be at an intersection of these two trends and thus at a triple junction. This shows that these fault zones along the rift axis and Nyanza Rift are still active and their point of intersection is therefore likely zones of magma injection and thermal fluid up-flow.

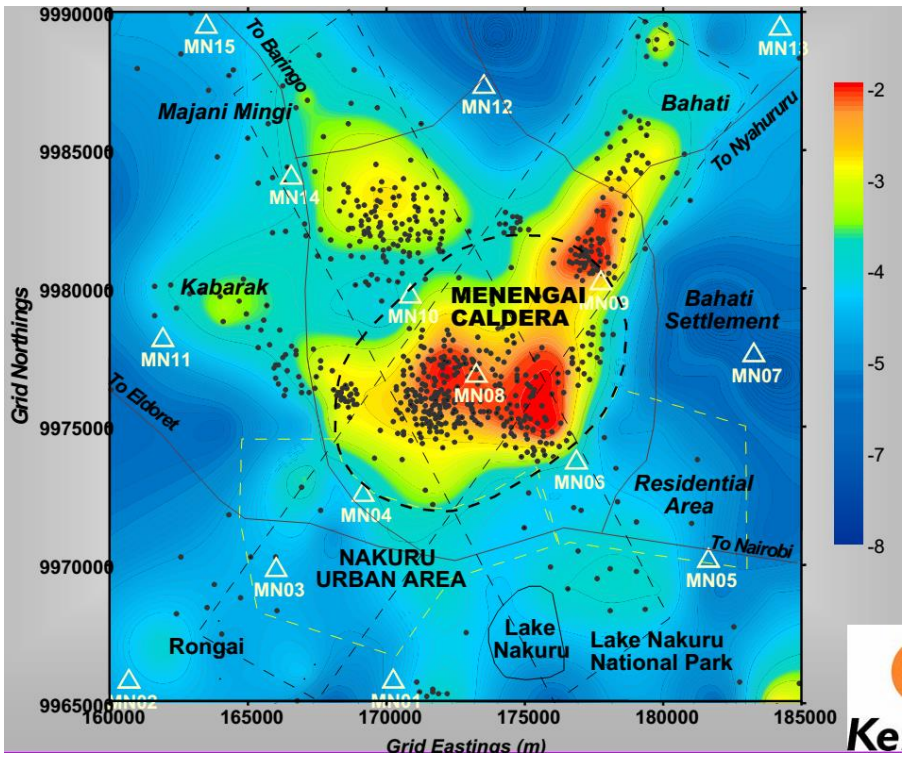

Figure 6. The distribution of seismic events located within the Menengai prospect (Simiyu 2010).

Ray paths from deep events through the centre of the Menengai field show that there is a deep attenuating body directly beneath the central part of the caldera structure and taking on geometry with a NE-SW major axis that is consistent with the structure (Simiyu, 2010). At shallow depth, the location of individual bodies occur along NNW-SSE and NE-SW trends that could be controlled by the Nyanza rift and Kenya rift axial fault structures along which there has been magma injection.

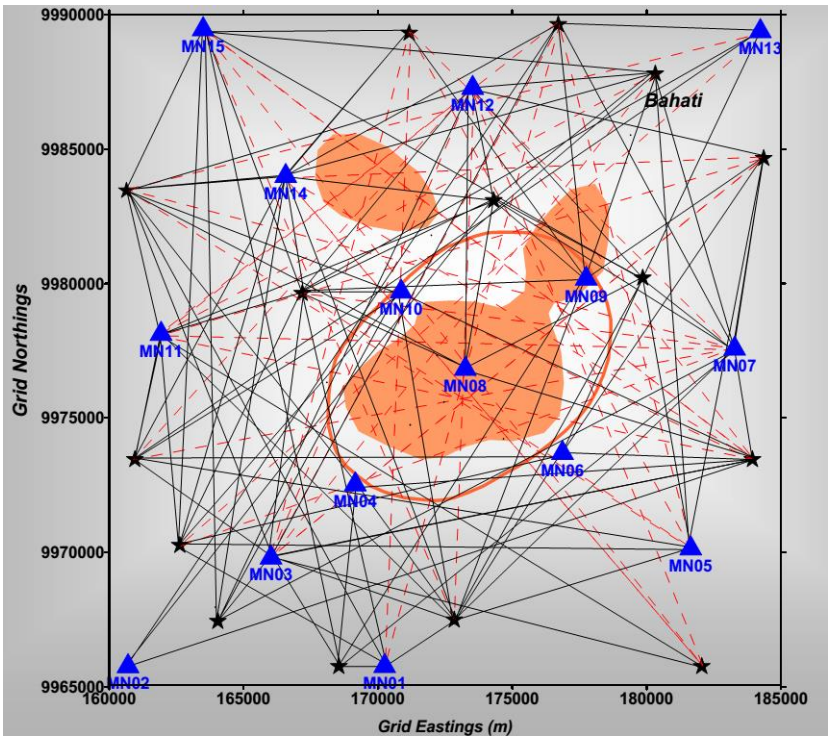

Figure 7. Seismic Ray paths across Menengai Caldera (Simiyu 2010)

6. HYDROTHERMAL ALTERATION

Hydrothermal alteration is mainly caused by changes in temperature, pressure, or chemical conditions in rock formations over the prevailing conditions, (Mibei 2012).The hydrothermal alteration of specific wells sited within the tectono-volcanic zones is studied in comparison to that of wells outside the said zones. Menengai wells MW-06, MW-09 and MW-13 show high-temperature minerals at depth,such as epidote, actinolite and wollastonite. The other common alteration minerals include: chalcedony, pyrite, illite,

pyrrhotite, albite, and quartz (Figure 8). All these wells are drilled within the major Menengai faults thus good fluid permeability. As a result, the three wells have relatively high yields compared to the rest.

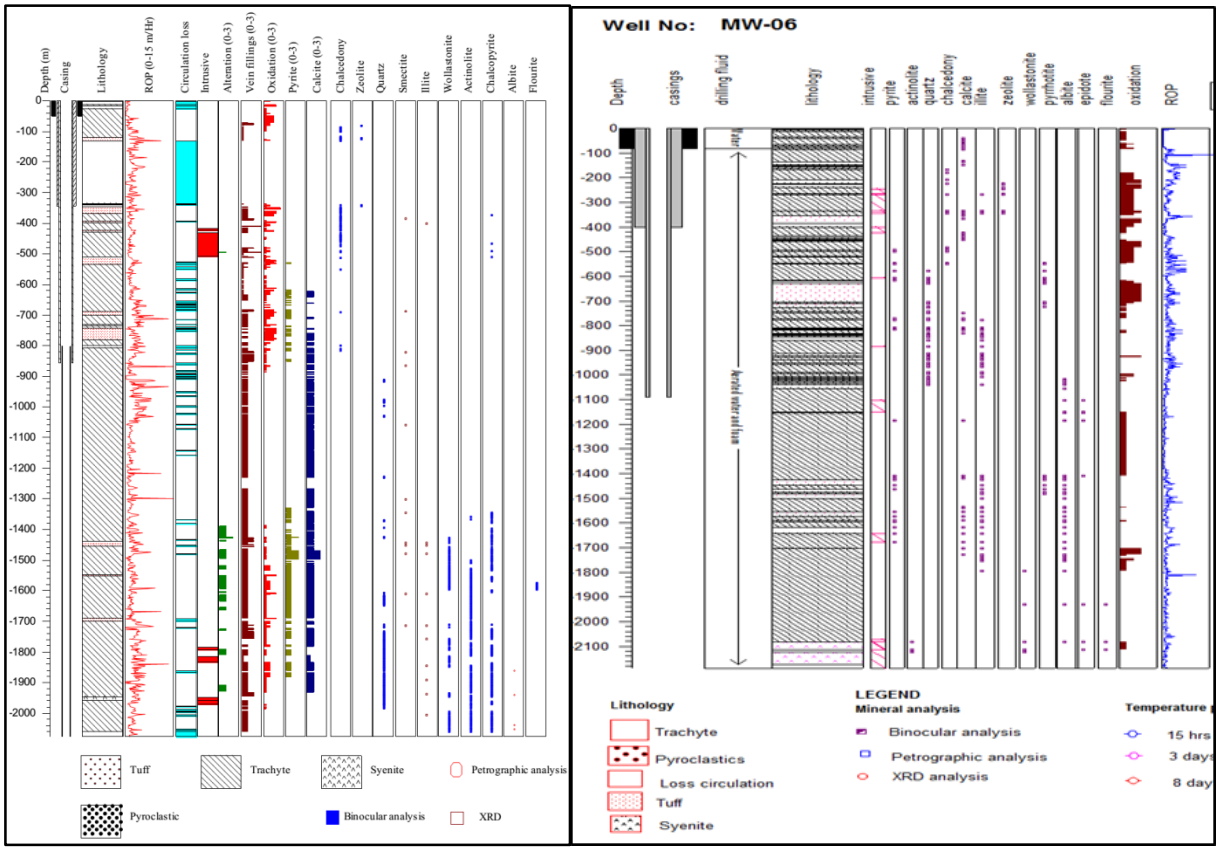

Figure 8. Hydrothermal alteration mineral distribution of wells (a) MW-09 and MW-06

On the other hand, wells MW-05 and MW-07 seem sited off the tectono-volcanic axes. These wells show relatively lower temperature minerals even at great depths (Figure 9) and have very low yields in comparison to others. The only hydrothermal minerals encountered in these wells are oxides (probably hematite and magnetite), zeolite, quartz, calcite, clays, and pyrite.

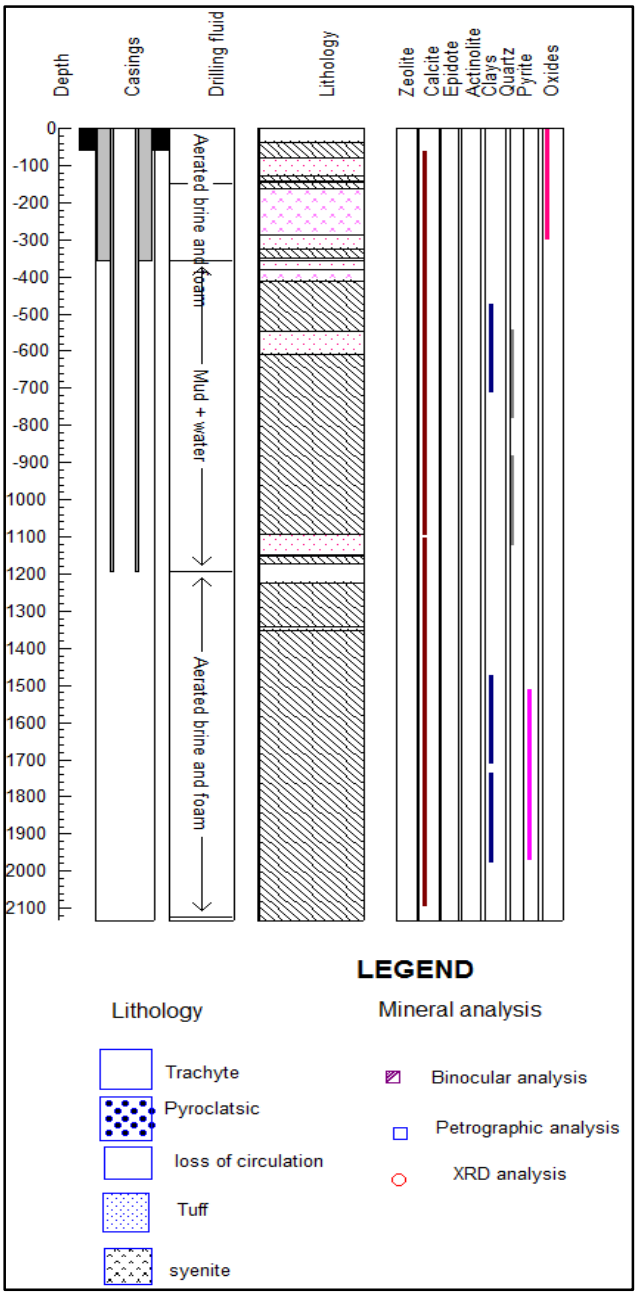

Figure 9. Hydrothermal alteration mineral distribution of well MW-07

7. TECTONO-VOLCANIC STRUCTURES IN OTHER COUNTRIES/ PLATES

These structures are also present in other countries and have been found or at least with more studies might be of great significance in geothermal exploitation. These include for instance,

The Reykjanes Peninsula Oblique Rift- Iceland (Pall, 2008).

The Main Ethiopia Rift –Ethiopia (Solomon, 2012)

The Island of São Jorge - Numbian plate (Mendes et al. 2012)

7.1. The Reykjanes Peninsula Oblique Rift

Located in SW Iceland, it is a structural continuation of the Reykjanes Ridge. The whole ridge north of 56◦N is oblique to the spreading direction and resembles faster spreading ridges, both with regard to topography and seismicity. The tectonic structure on the Reykjanes Peninsula is characterized by volcanic systems that are arranged en echelon along the plate boundary. The fissure swarms of the volcanic systems are oblique to the boundary. Less conspicuous, but probably equally important, are strike-slip faults that cut across the plate boundary at a high angle. They are expressed as N-S trending arrays of left-stepping, en-echelon fissures with push-up hillocks between them. Seismicity and magmatic activity within the Reykjanes Peninsula is high and appears to be episodic (Pall, 2008).

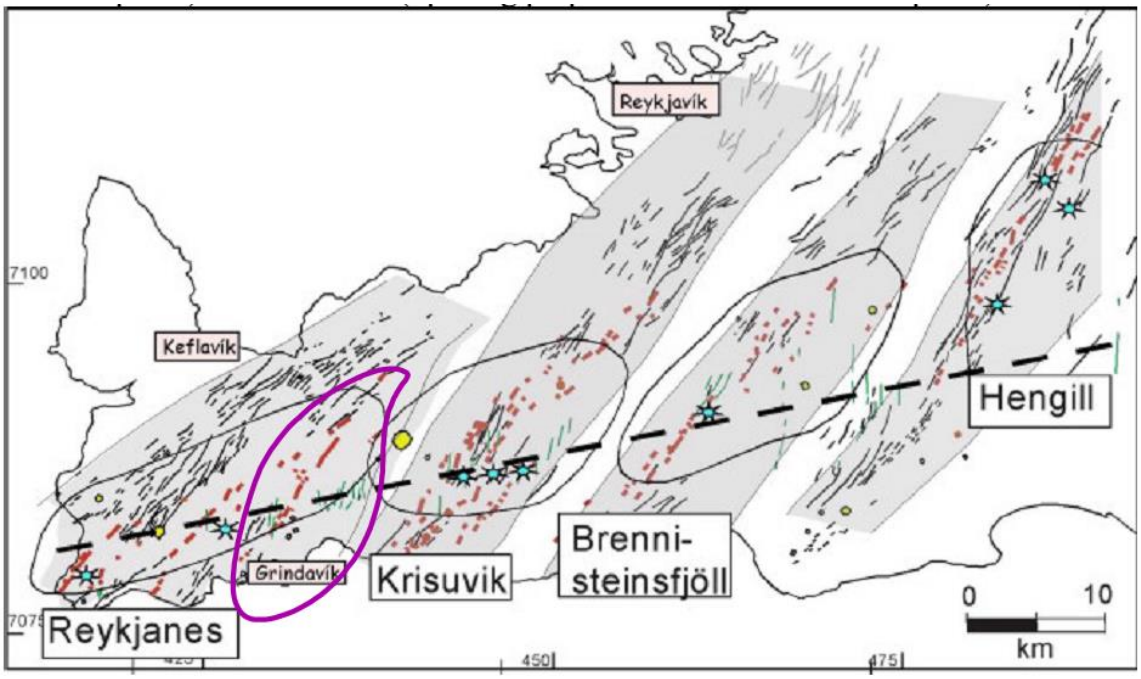

Figure 10. Tectonic map of Reykajanes Penisula showing fissure swarms (black lines), eruptive fissures (red lines), strike slip faults (green lines), and the approximate location of the plate boundary (dashed line), and geothermal centers (blue stars), four volcanic systems shown in grey shading and black ellipses. Purple ellipse shows a possible 5th system, the Grindavik system, proposed by Jakobson, (1978). (data from Arnason et al., 1986; Einarson, 1991; Eyolfsson, 1998; Hreinsdottir et al, 2001; Sigurdsson, 1985; Saemundsson and Einarsson, 1980; Jakobsson, 1978).

8. DISCUSSION AND CONCLUSIONS

Tectono-volcanic structures involve both faulting and volcanic activities thus resulting into enhanced high fluid permeability, good recharge and up-flow zones. The volcanic activity may give rise to magmatic intrusions at shallower depths thus increased thermal activity while cracking and faulting increase the openings to the magmatic heat source. As a result, tectono-volcanic structures are very significant in geothermal resource exploration and exploitation.

Molo and SolaiTectono-Volcanic Axes are the major structures in Menengai Geothermal Field and have so far proven to be very significant in resource exploitation. They are characterized by zones of faults and fractures along which volcanic eruptions have taken place. Numerous manifestations such as fumaroles and hot grounds are also present and manifest along these structures and their transfer zones. The tectonic activity has resulted into a buildup of fracture systems that are important as aquifer zones and also contributes to fluid permeability. The prominent tectono-volcanic structures are majorly used to site wells in Menengai Geothermal Field. Wells within these zones have proven to yield a higher productivity than wells outside. Other areas where tectono-volcanic structures are significant in geothermal exploitation include Iceland, Ethiopia, etc.

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