GEOTHERMAL EXPLORATION OF THE MENENGAI GEOTHERMAL FIELD

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ABSTRACT

In geothermal resource assessment a multidisciplinary approach is adopted. The aim is to ascertain and map the size of the reservoir, determine reservoir temperature and chemical composition of the reservoir fluids. An initial conceptual model guides on primary exploration well sites and is updated as and when new data is available. This paper describes findings and current status of Menengai geothermal exploration and resource assessment respectively. Deep drilling program in Menengai field has so far resulted in 31 geothermal wells within the Menengai Caldera. Geoscientific data acquired is continually reviewed and integrated to bring out an updated geothermal model of the field. Current assessment from the surface geology indicates that Menengai caldera has been volcanically active in recent geological time as evidenced by widespread eruption of lavas and pyroclastic. Regional structures are oriented in N-S, NNW-SSE and NNE-SSW. The N-S and NNW-SSE are older regional structures while the NNE-SSW are younger structures and has huge influence on reservoir fluid flow based on measured temperature contours. Borehole geology data infers a syn-caldera tuff marker horizon between 300-400 m CT is present in all almost all wells. High temperature alteration minerals like actinolite are present in wells drilled within the summit area indicating zones of contact metamorphism related to system of hot dike intrusions. In addition syenitic intrusive have been encountered in the wells within the caldera summit area during drilling. Gravity data collected so far presents an anomaly at the centre of the caldera, this is related to the magmatic body forming the dike intrusion. Furthermore, the aforementioned summit area exhibits shallow seismic movements confirming shallow magmatic activity. Measured temperature contours shows a marked NNE-SSW anomaly pattern inferring fluid flow pattern in the reservoir. The reservoir geometry is inferred from resistivity indicating that the reservoir is marked zone of resistivity values between 30-70 ohm-m. Reservoir fluids are of Na-HCO3 type with a high pH and moderately high chloride concentrations (> 400 mg/kg). A marked variation in fluids is evident whereby some wells discharge one phase (i.e. steam) while the others discharge two phase.

1.0 INTRODUCTION

The Menengai geothermal field is located in Nakuru within the central Kenyan Rift Valley and comprises the Menengai caldera, The Ol'rongai in the northwest and parts of the Solai graben to the northeast.

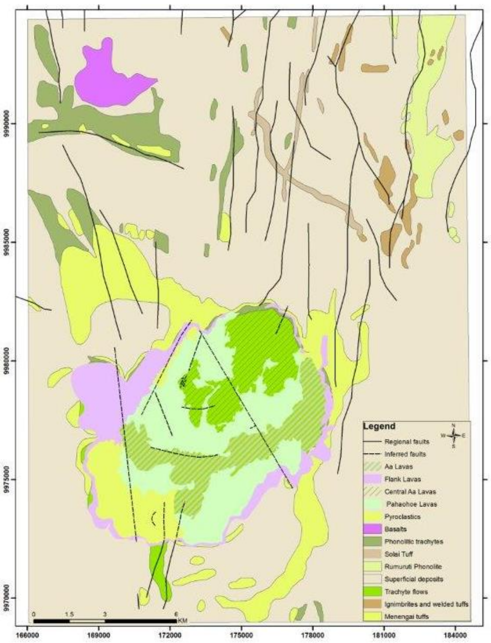


Figure 1: Geological map of Menengai geothermal prospect (modified from Robinson, 2015)

2.1 SURFACE GEOLOGY

The surface geology of the Menengai caldera is dominated by trachyte lavas (which exhibit variation in texture and flow), pyroclastics, ignimbrites and basalts. The youngest eruption lava flows are located at the centre of the caldera with a smaller flow to the south. The source of the youngest lava flows is traced to the fissures inferring recent fault activity. Preponderance of the pyroclastics are deposited to the west probably due to a prevailing easterly winds at the time of the eruption. The most productive wells are within the central caldera, an area. Areas to be considered for further exploration and expansion could be to the south and northeast where both young faults and eruptive activity are palpable (Figure 1).

Regional structures

The general trend of many structures within Menengai area prospect is N-S, NNE-SSW and NNW-SSE in western zone (Figure 2). The NNE-SSW normal fault forms the Solai half graben, These structures are younger than the caldera and cut through the caldera rim in the northeast. The N-S and NNW-SSE are older than the NNE-SSW faults and constitute the Molo graben to the north of caldera and it is within this narrow graben that the fault controlled Arus steam jets and fumaroles occur. The NNW-SSE structures also cuts through the Ol' rongai ridge, where geothermal manifestations in form of hot altered ground and travertine depositions occur. The boreholes immediately to the north and northwest of the Menengai caldera show lake water contamination indicating interconnection with Lake Nakuru system (Geotermica Italiana Srl, 1987) inferring possible permeability and interconnection between lake Nakuru in the south and the northern region of Menengai caldera made possible by these older N-S and NNW-SSE faults.

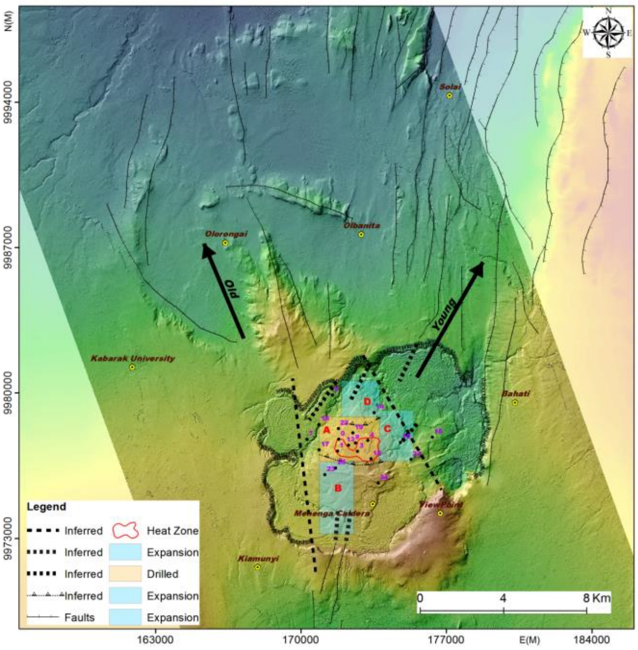


Figure 2: Regional structural setting

Local structures

In a local scale Menengai caldera (Figure 3) appears to have cut through a pre-existing NNW-SSE "ridge structure" associated with the primitive shield caldera. Geothermal manifestations occur within the central part of the caldera, northwest and north. Other important features of geothermal significance are found in the south where very young structures manifest including young eruptive events of a lava flow from the outer southern part of the caldera into the inner caldera region. From a geological perspective, this region is very interesting and could potentially be a resource area.

2.2 BOREHOLE GEOLOGY

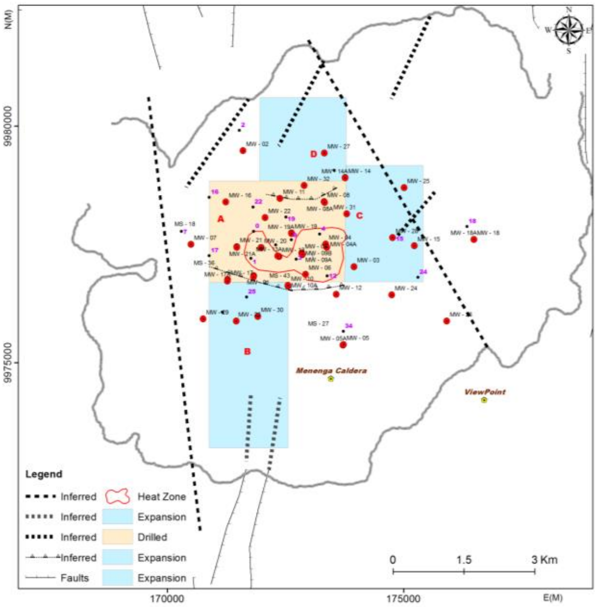


Figure 3: Menengai caldera local structures

Lithostratigraphy

The stratigraphy of Menengai (Figure 4) is complex however what is clear is that at least one marker horizons is present at 300-400 m CT (Mibei 2012). Based on current borehole geology data the top of the shield volcano is obvious i.e. the boundary of pre-caldera and the post caldera volcanics. Magma has been encountered slightly below 2 km within summit area where most of recent eruptions are evident.

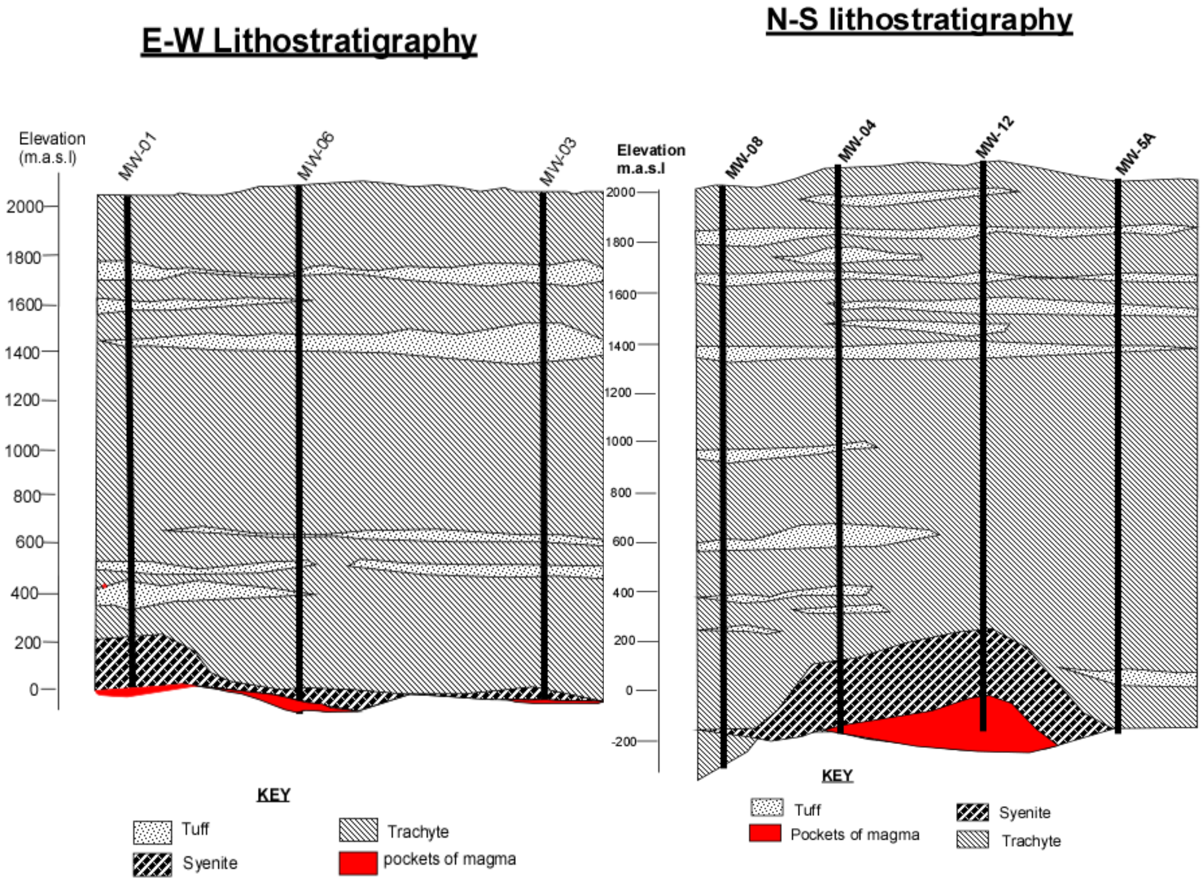


Figure 4: Lithological cross-section

Hydrothermal alteration minerals

The main hydrothermal alteration minerals are zeolites, pyrite, epidote, clays, calcite, Wollastonite, quartz, actinolite. The alteration model can be summarised into four zonation namely unaltered zone, zeolite zone, transition and quartz-illite zone (Figure 5). The quartz- illite zone demarcates the reservoir.

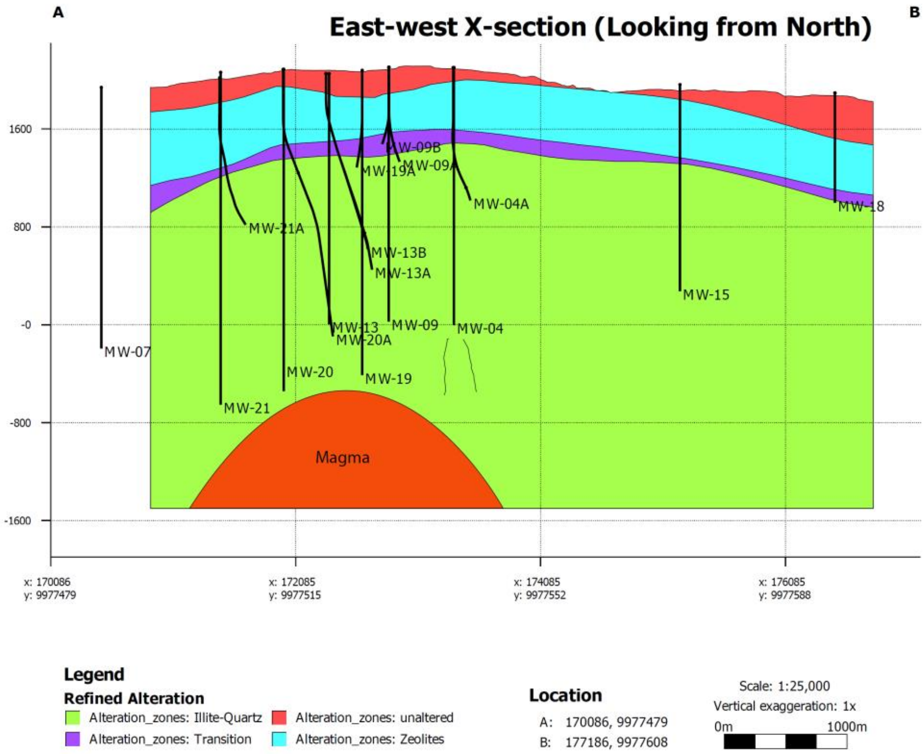


Figure 5: Hydrothermal alteration cross-section

Stratigraphic model

Figure 6 below shows a stratigraphic model generated from borehole geology data. It shows that Menengai is predominantly trachytic with intercalation of tuff lenses. The contacts between different lava flows and within tuff intercalations are the major permeability zones where feed zones are encountered. Magma is very shallow in Menengai especially at the caldera summit where magma is encountered at approximately 2 km, above this hot magma is a thick zone of syenite forming the roof of magma body.

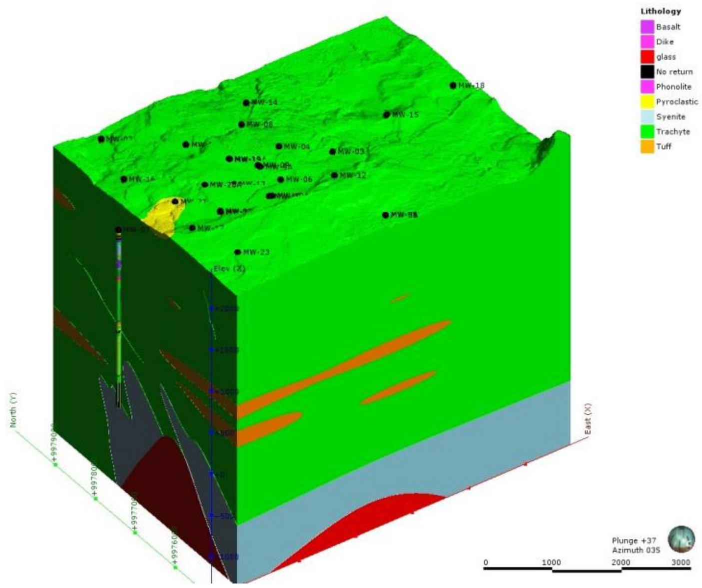


Figure 6:3D Stratigraphic model for Menengai

Alteration model

The alteration model is as highlighted in figure 7.The shallower depths is the unaltered zone , at slightly deeper depth is a somewhat thicker zeolite zone .The reservoir regions are within the illite -quartz zone which is separated by thin transition zone from the zeolite zone. The illite-quartz zone is bigger and horsts the reservoir and the magma zone. Alteration model shows slight doming within the caldera summit area indicating shallower reservoir depths within the centre of the caldera where shallow magma body is encountered.

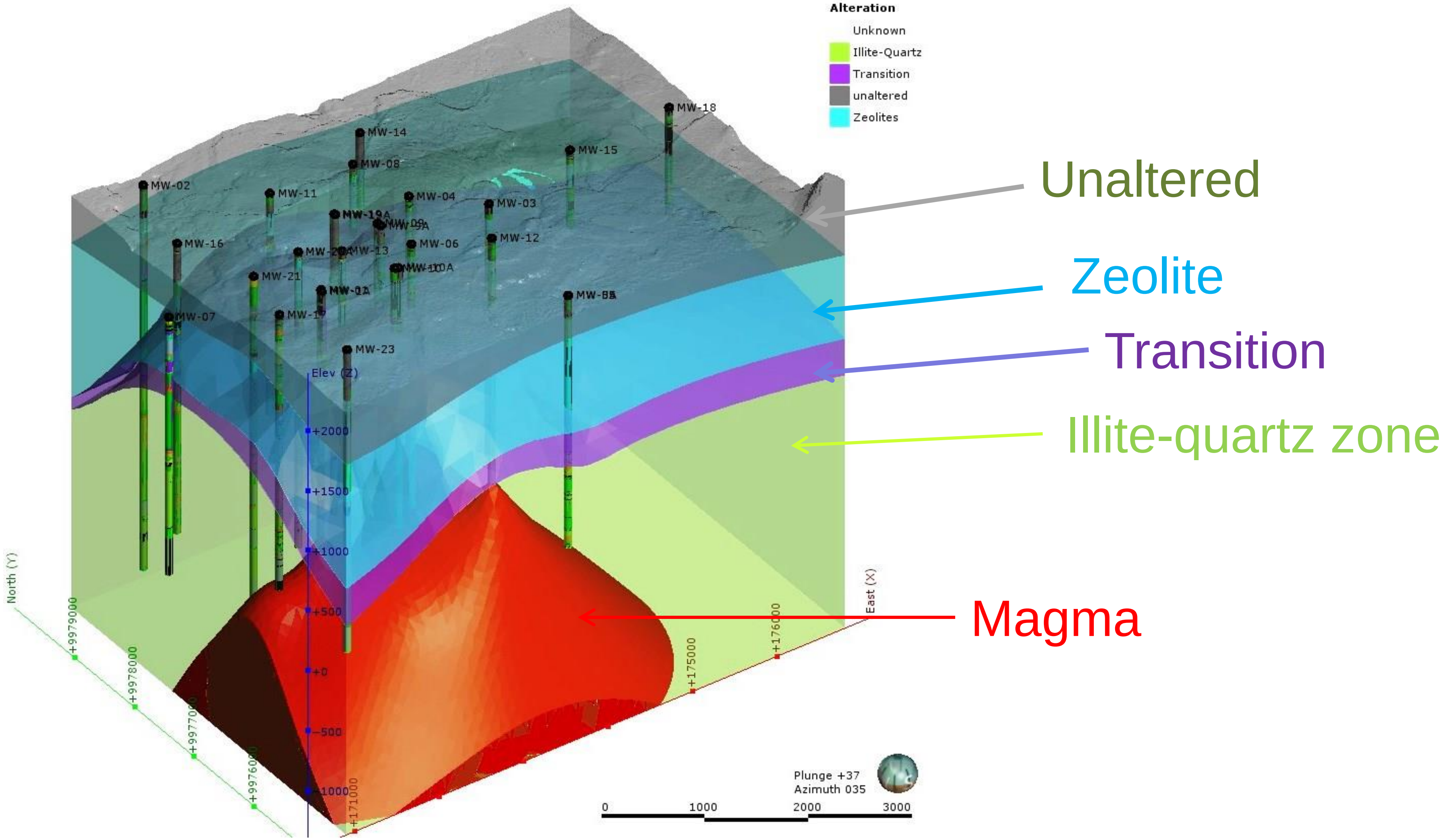


Figure 7:3D alteration model for Menengai

3.0 MEASURED TEMPERATURES

Contours developed from the measured temperatures and sliced at 400 m, 1200 and 2000 m using voxler software as demonstrated in (Figures 8), shows that the minimum temperature is 27°C in well MW-02 while the maximum temperature was in excess of 390° C measured at the bottom of wells MW-06, MW-04, MW-12 and MW-21.What could be of significance is that as you move deeper a particular high temperature zone oriented in NNE direction emerges. This can be interpreted effect of conductive temperatures from fluid flow pattern enhanced by the young structures of the Solai TVA. The 3D temperature model resulting from this is as highlighted in figure 9, indicating that within the central area of the caldera high temperatures are experience at shallower depth probably due to upwelling of steam and is therefore the upflow zone.

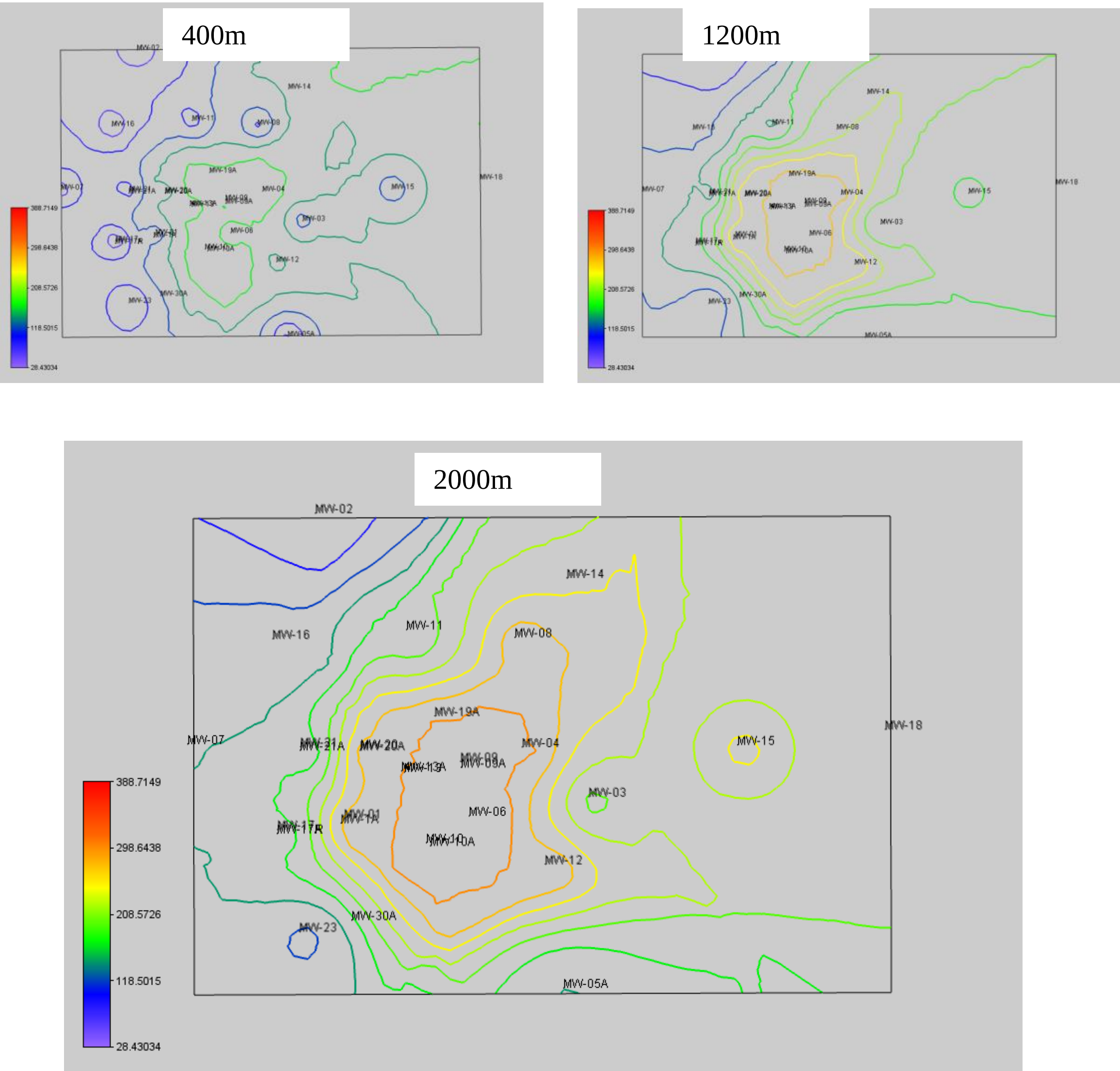


Figure 8: Measured temperature contours at 400m, 1200 m and 2000m

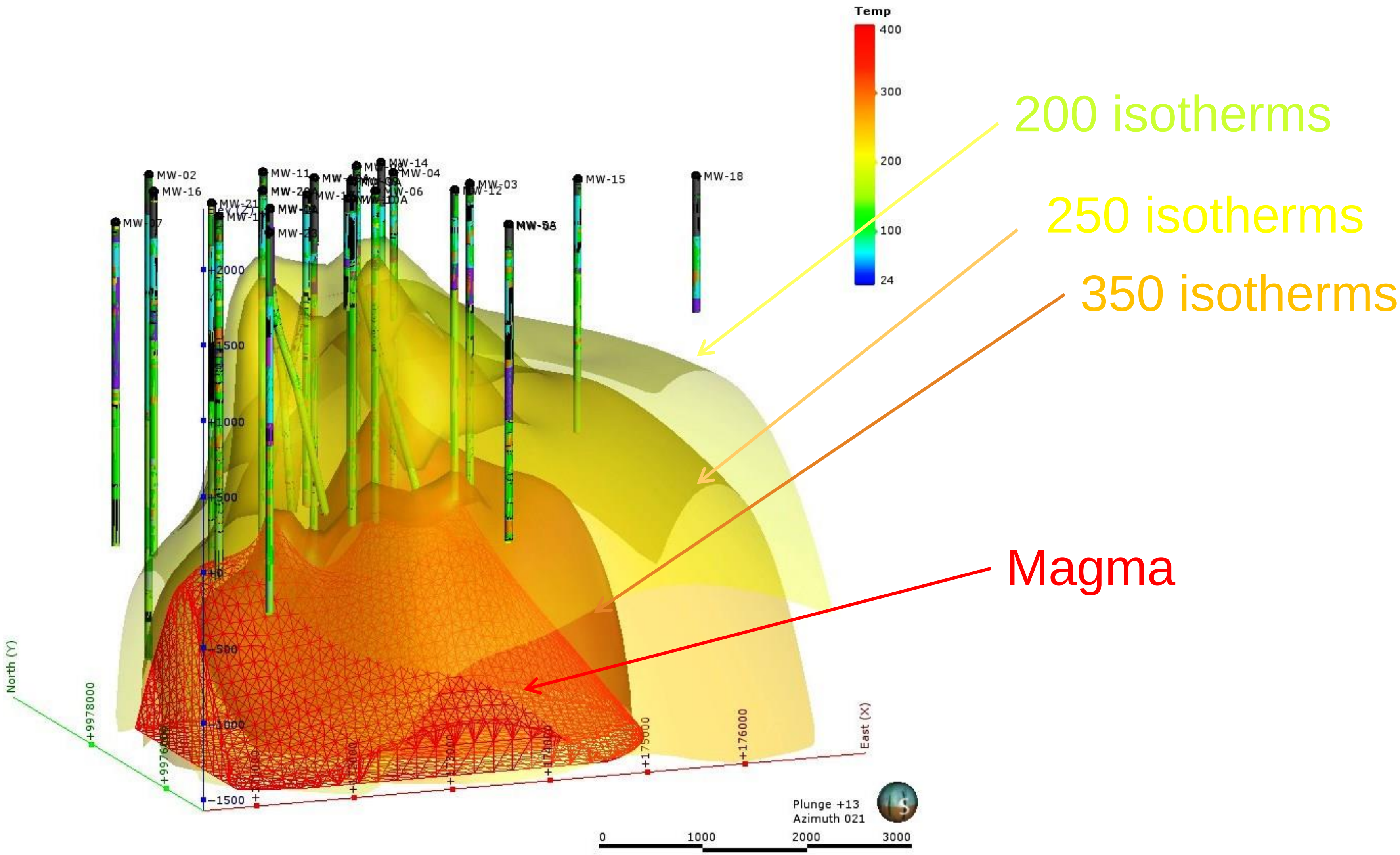


Figure 9: 3D temperature model for Menengai

4.0 GEOCHEMISTRY

Soil gas Survey

The proportions of non-condensable gases emitted from geothermal manifestations generally resemble those in underlying reservoirs, and for volcanic systems, CO_2 is highly emitted as compared with other gases (Goff & Janik, 2000). Carbon dioxide gas is thus used in geothermal exploration in different parts of the world (Chiodini et al., 1998; Magaña et al., 2004; Fridriksson et al., 2006, Voltattorni et al, 2010). CO_2 is known as one of the volatiles emanating from magmatic processes. In Menengai high carbon dioxide concentration in the soil gas (Figure 10) was observed around north east of the caldera and in the north west (Ol' rongai) areas. Other areas with high concentration are west of the caldera as well as north, east and south close to the caldera rim. The areas with high concentration of Rn-222 are indicative of areas of high permeability and high heat flow as shown by contemporaneous occurrences with the manifestations in the central, north and northeast parts out of the caldera (Figure 10).

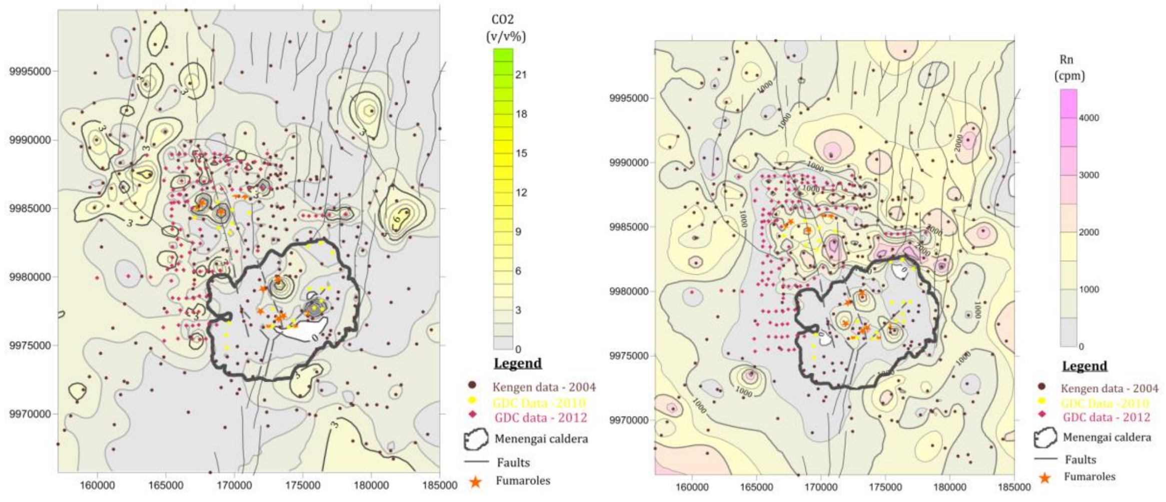
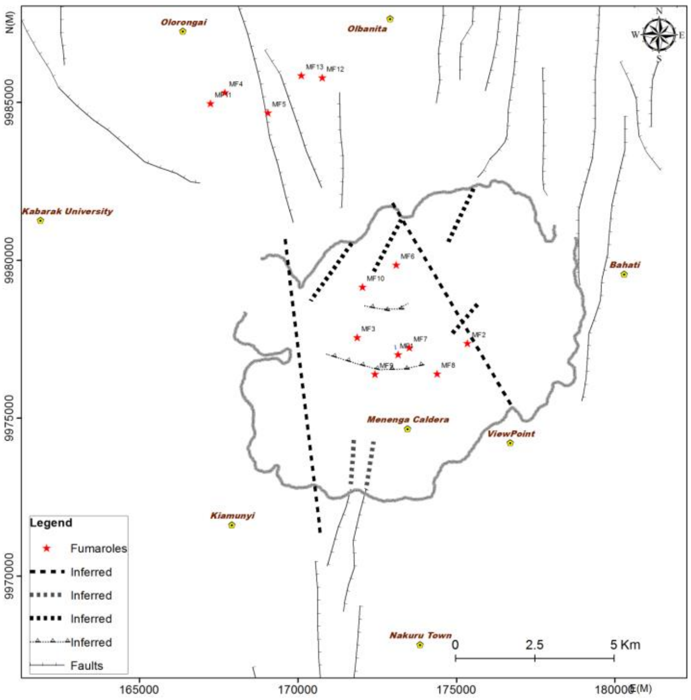


Figure 10: CO_2 and Radon (222 Rn) and distribution

Fumarole chemistry

Hydrothermal activity is manifested in the Menengai volcanic area by the occurrence of fumaroles and altered rock/grounds. Fumaroles (Figure 11) are located mainly inside the caldera floor. Three groups of active fumaroles found in the caldera have an aerial extent ranging from a few m^2 to less than a km^2. The first two groups in the central and western portion of the caldera floor are located within fresh lava flow and close to eruption centres. The third group of fumaroles is located in the central eastern part of the caldera floor is found at the young lava/pumice contact and has extensively altered the pumice formation. Geothermometry results are as highlighted in table 1, the reservoir temperature range from 276-352° C ,this agrees with measured temperatures from drilled wells in Menengai.



Fumarole No.	Geothermometry* (^{o}C)	
	T_{H2S}	$T_{H2S-CO2}$
MF-01	281	276
MF-02	293	304
MF-03	262	247
MF-06	296	302
MF-07	327	352
MF-08	295	299
MF-09	279	274

Figure 11:location and geothermometry results of fumarole data before drilling

Geothermal well chemistry

NCG content in steam and Scaling potential

Reservoir fluids in Menengai show relatively high non-condensable gas contributed almost entirely by CO2. This is envisage to bring some challenges but can be surmounted. The fluids have plotted above saturation line with calcite under natural reservoir conditions. It is inferred therefore that calcite scale deposition is real as indicated by results of saturation indices (Figure 12)

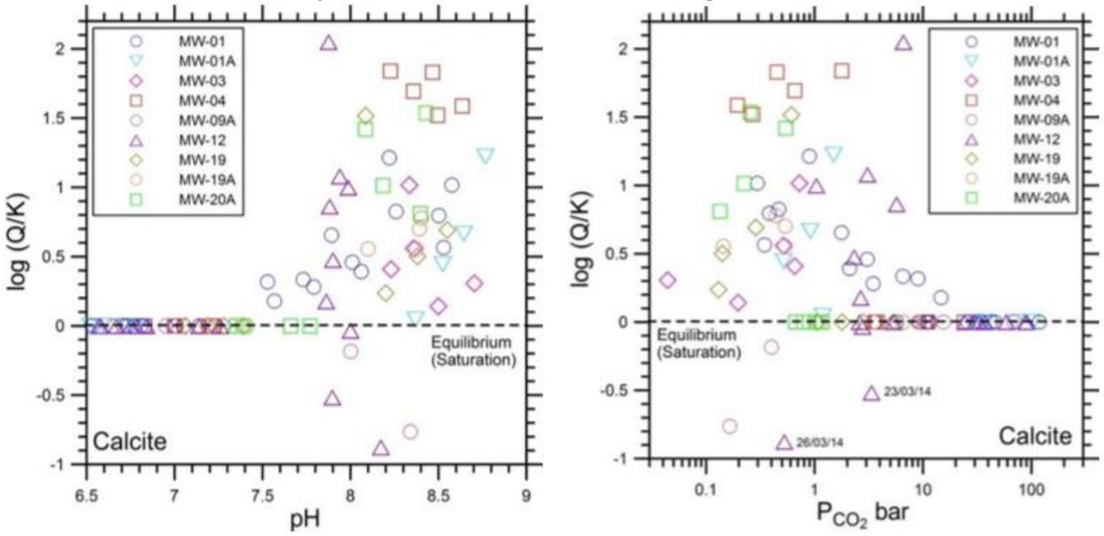


Figure 12: Saturation index with calcite vs. pH (left) and CO2 partial pressure (right) for the geothermal liquids met by the Menengai wells

5.0 GEOPYHSICS

Resistivity

Resistivity Cross section through the centre of Menengai caldera shows a thin high resistivity (> 100 ohm-m) which is the top layer of the fresh fractured lavas. It is underlain by a thick low resistivity (30 -70 ohm-m) layer defining as the reservoir zone. Resistivity of (< 10 ohm-m) to the west is poorly defined (poorly defined cap). At about 2000 masl the reservoir zone (30-70 ohm-m) is intruded by a high resistive vertically elongation (>100 ohm-m) feature interpreted as an intrusive, interpretations for this is still not conclusive (Figure 13)

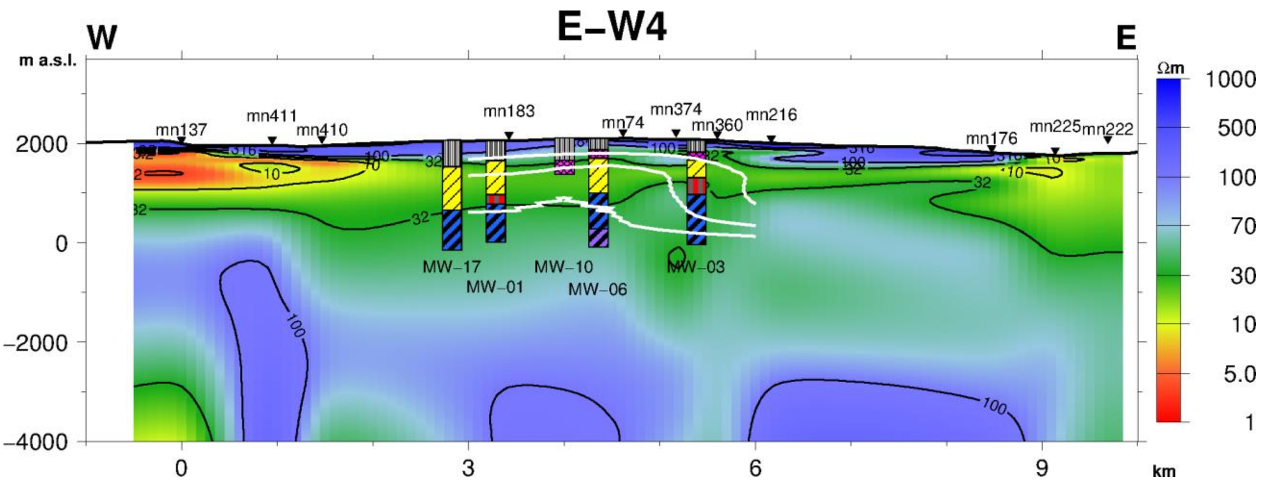


Figure 13. 1-D E-W4 MT resistivity cross-section

Gravity

Upto 60 data sets of gravity were used to develop a Bouguer anomaly map of Menengai caldera. The map shows gravity high at the centre of the caldera confined by gravity lows to the north, east and south. The anomaly infer the magma intrusion the central zone

Seismic data

(Simiyu 2009) defined a shallow magma body at the centre of the caldera evidence by the spread of intense, smaller and shallower micro-seismic activity, this is vice versa towards the caldera walls. Shallower events also occur around Ol'rongai area (Figure 14). In an effort to characterize the Menengai reservoir Simiyu 2009 applied the Vp/Vs ratio. A Vp/Vs ratio results showed a low ratio at the centre of the caldera and according to Simiyu (2009) this is consistent with a steam dominated reservoir zone at the central area of the caldera.

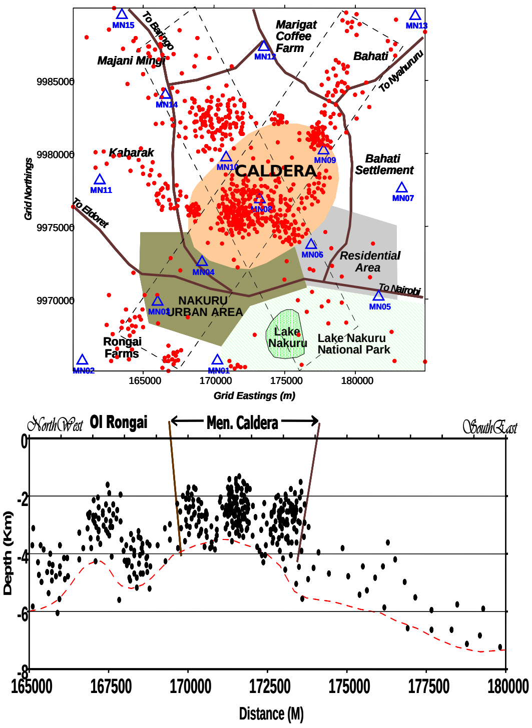


Figure 14: Seismic events at the within the caldera (Simiyu 2009)

6.0 CONCLUSION

Surface geology suggests that Menengai has had a recent volcanic activity marked by the recent lava flow. The south of the caldera has also been active in recent past based structures and evidence of volcanism in this area namely eruption cones, young lava flowing into the caldera from the outer rim. Therefore the central and south of the caldera are interesting areas for further geothermal exploration. Important structures for fluid flow are the young NNE structures , the older structures associated with Molo graben may be significant in controlling magma plumbing system below the caldera. From borehole geology there is a shallow magma at the centre of the caldera and is heat source driving the geothermal system with at least one up flow at the centre of the caldera based on current data. Poorly defined cap is present in Menengai as suggested by resistivity data. Measured temperature indicates that an outflow could be to the NNE or SSW from the pattern emerging form contoured data with depth. Possible areas for further exploration drilling are the south and NNE and possibly east. Calcite scaling is possible challenge in Menengai based on fluid chemistry.

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