

CONCEPTUAL MODEL OF THE MENENGAI GEOTHERMAL FIELD

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ABSTRACT

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 the N-S, NNW-SSE and NNE-SSW. The N-S and NNW-SSE are older regional structures. The NNE-SSW structures are younger structures and have huge influence on reservoir fluid flow jointly with the N-S structures as inferred from the measured temperature contours. Borehole geology data infers a syn-caldera tuff marker horizon between 300-400 m CT which is present in 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 intrusions have also been encountered in the wells within the caldera summit area and form the crown of a hotter body below. Gravity data collected so far presents an anomaly at the centre of the caldera; this is related to a magmatic body developing the dike intrusion. Furthermore, the aforementioned summit area exhibits shallow seismic movements confirming shallow magmatic activity. Measured temperature contours show a marked N-S to NNE-SSW anomaly pattern inferring fluid flow pattern and the probable geometry of the reservoir. The reservoir is marked by 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 the fluids is evident whereby some wells discharge one phase (i.e. steam) while the others discharge two phase. Calcite scale deposition is real as indicated by results of saturation indices.

1.0 INTRODUCTION

The Menengai geothermal field is located in Nakuru County within the central Kenya Rift Valley and comprises the Menengai caldera, the Ol'rongai volcanic area in the northwest and parts of the Solai graben in the North East. Drilling program inside the caldera region commenced in 2011. Various Challenges have been experienced ranging from formation collapses, permeability and sharp reservoir boundaries etc.

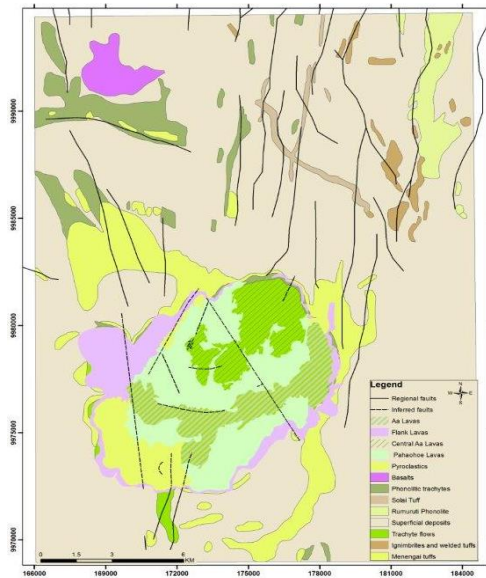


Figure 1:Menengai Geological map
(modified from Robinson, 2015

NNW-SSE structures are older than the NNE-SSW faults and constitute the Molo graben to the north of caldera. It is within this narrow graben that the fault controlled Arus steam jets and fumaroles occur further north of the Menengai caldera. The NNW-SSE structures also cuts through the Ol' rongai ridge, where geothermal manifestations in form of hot altered ground and travertine depositions occur. Extensions of these structures are evident south of the caldera within lake Nakuru area. As if to indicate the connectivity and transitivity nature of the NNW-SSW and N-S structures, Shallow water boreholes immediately to the north and northwest of the Menengai caldera show mixed hydrology of meteoric and lake Nakuru water components, (Geotermica Italiana Srl, 1987).

2.1 SURFACE GEOLOGY

The surface geology of the Menengai caldera is dominated by trachyte lavas (which exhibit variation in texture and flow), pyroclastic, ignimbrites and basalts. The youngest eruption is located at the centre of the caldera. The source of the youngest lava flows is traced to the fissures within the dome area inferring recent volcanic tectonic activity. Preponderance of the pyroclastic are deposited to the west probably due to prevailing easterly winds at the time of the eruption. The most productive wells are within the central caldera area (Figure 1).

Regional structures

The general trend of many structures within Menengai field is N-S, NNE-SSW and NNW-SSE (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

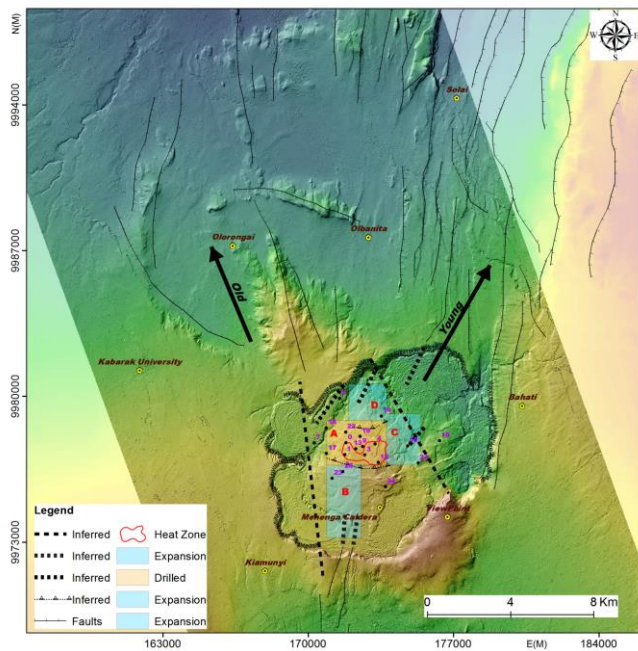


Figure 2: Regional structural setting

Local scale structures

In a local scale, the Menengai caldera appears to have cut through a pre-existing NNW-SSE “ridge structure” associated with the primitive shield volcano.

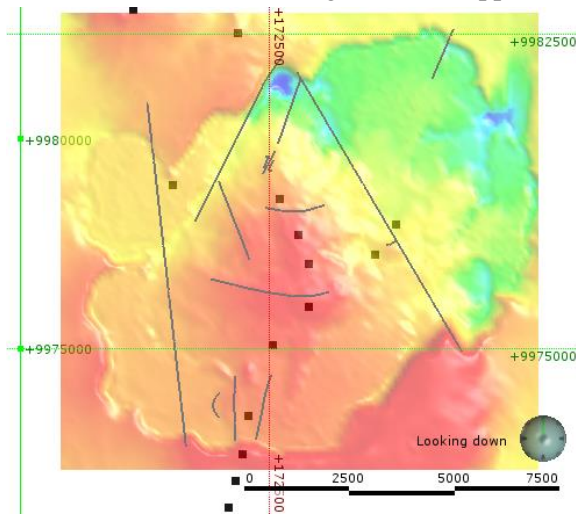


Figure 3: Menengai caldera local structures and eruption centres.

The margins of this primitive shield volcano. The margins of this primitive shield are marked by the sharp topographical changes in the east of the caldera and mild changes in the west. These margins are further elucidated in figure 3 by two almost parallel lines cutting through the caldera from the Northwest to the southern part of the caldera rim. Geothermal manifestations occur within the “ridge zone” of the caldera where buried NNW and N-S structures occur. Other important features of geothermal significance are found in the south where very young structures manifest including young eruptive events (dark squares) and a young lava flow from the outer southern part of the caldera into the inner caldera area.

2.2 BOREHOLE GEOLOGY

Stratigraphy

The stratigraphy of Menengai caldera (Figure 4) is complex. The rocks are mainly; trachytes with variation in chemistry, flow and texture (Mbia, 2014), occasional thin lenses of tuff and pyroclastic, a deeper syenite intrusion at 2000 m and below which a magma body is present. Geology logs have shown a persistent tuff formation in many wells at 300-400 m depth range which has been identified as marker horizon (Mibei, 2012). The 300-400 m tuff formation could be associated with syn-caldera activity and is found in almost all wells however some wells encountered loss of circulation in the said depth range. This has presented some challenges in conclusively characterising the inferred marker horizon. Based on the current data we can conclude that the volume of rocks above 300 m denote post caldera episodes while below 400 m are pre-caldera rock units. Permeability in Menengai field is mainly secondary in nature and is associated with lava flow contacts and fault fractures. Within the syenite intrusive permeability drastically reduces and our geological perspective has been that wells should not be drilled beyond 2100 m due to this reduced permeability associated with the syenite intrusion.

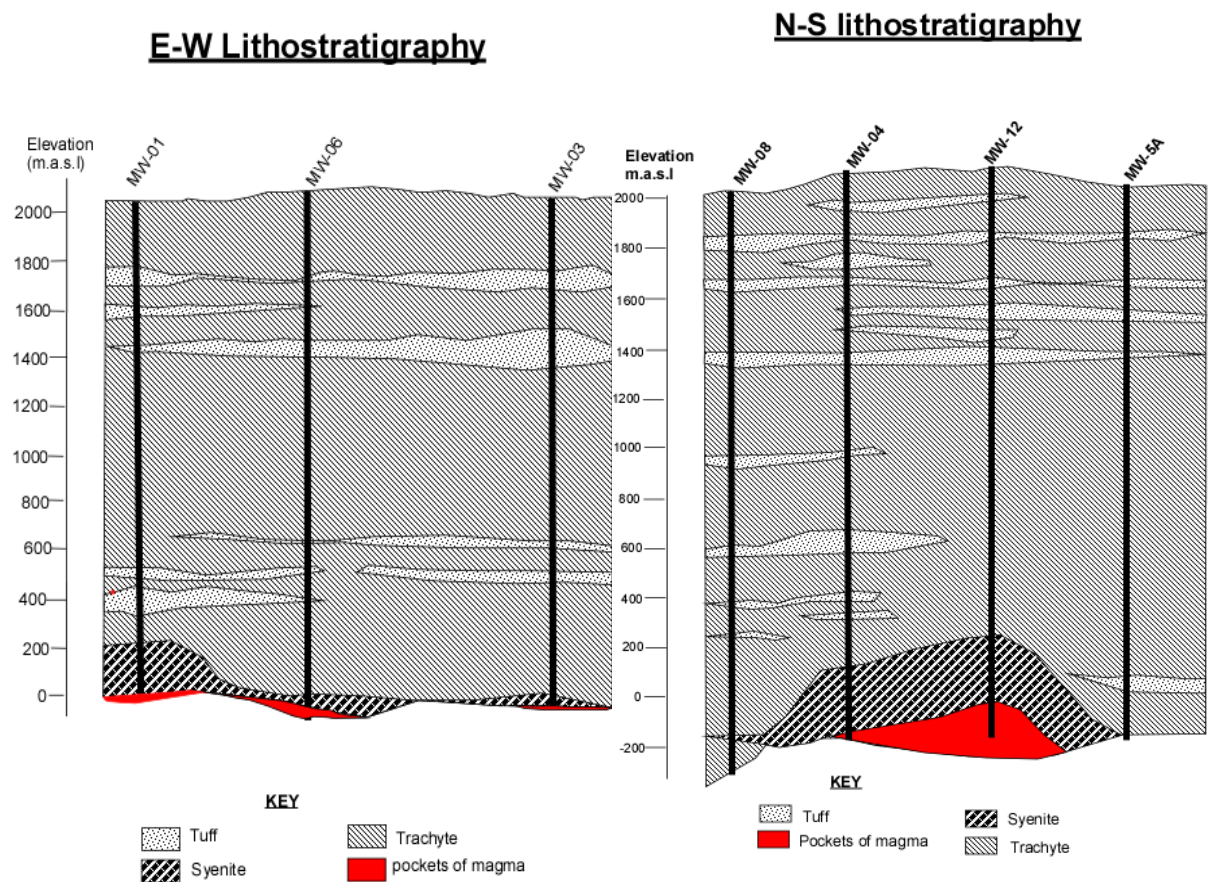


Figure 4: A Lithological cross-section

Stratigraphic model derived using Leapfrog geothermal

Figure 6 below shows a stratigraphic model generated from borehole geology data using leapfrog geothermal software. It shows that Menengai is predominantly trachytic with intercalation of tuff lenses. The contacts between different lava flows and 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 an approximate depth of 2.2 km. Above this hot magma is a thick zone of syenite forming the crown of magma body. The model is largely representative however, challenges of very thin rock strata, circulation losses etc. makes it very hard to constrain the stratigraphic model further curtailing the achievement of representation of realistic subsurface strata below Menengai.

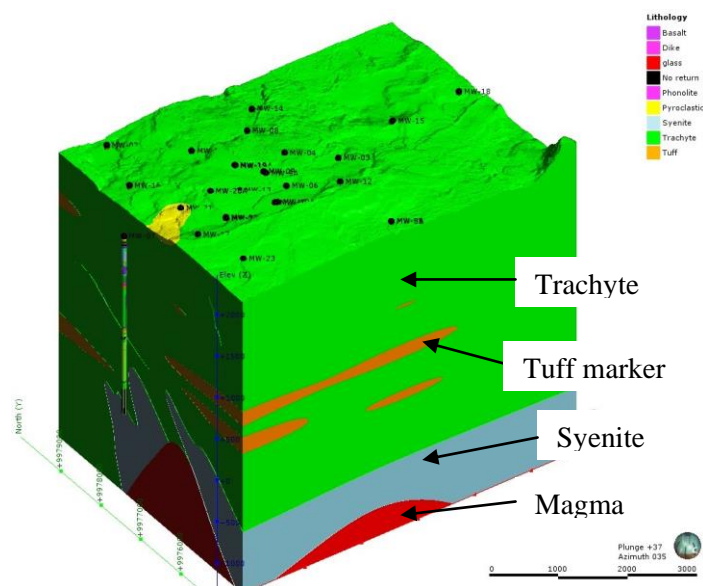


Figure 6: 3D Stratigraphic model for Menengai

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 zonations namely unaltered zone, zeolite zone, transition and quartz-illite zone (Figure 5). The quartz-illite zone demarcates the reservoir.

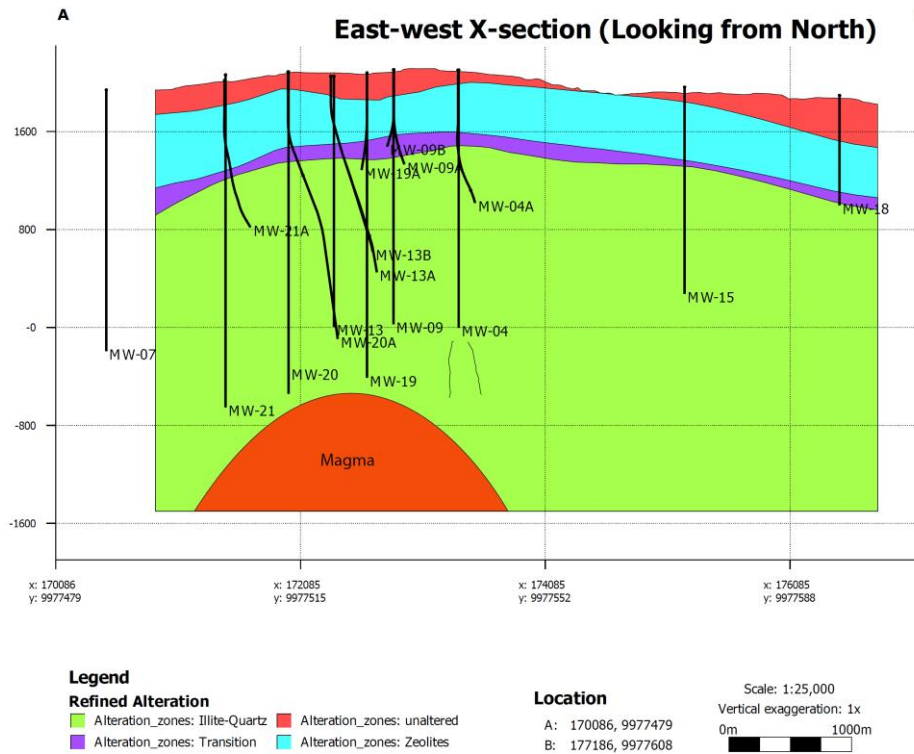


Figure 5: Hydrothermal alteration cross-section

Alteration model derived using leapfrog geothermal

A 3 D alteration model is highlighted in figure 6. The shallower depth is the unaltered zones (Grey), this zone is followed by zeolite zone (Blue) and a thin transition zone (Purple). The reservoir region is within the illite-quartz zone. In the illite-quartz zone other high temperature minerals like actinolite, chlorite and Wollastonite are found but they are not widespread and that is why illite and quartz were chosen as the index minerals for this zone. The illite-quartz zone is bigger and hosts the reservoir and the magma zone. Alteration model shows a slight doming within the caldera summit area indicating shallower reservoir depths within the centre of the caldera where shallow magma body is encountered and most of the wells here show shallow high temperature convective profiles.

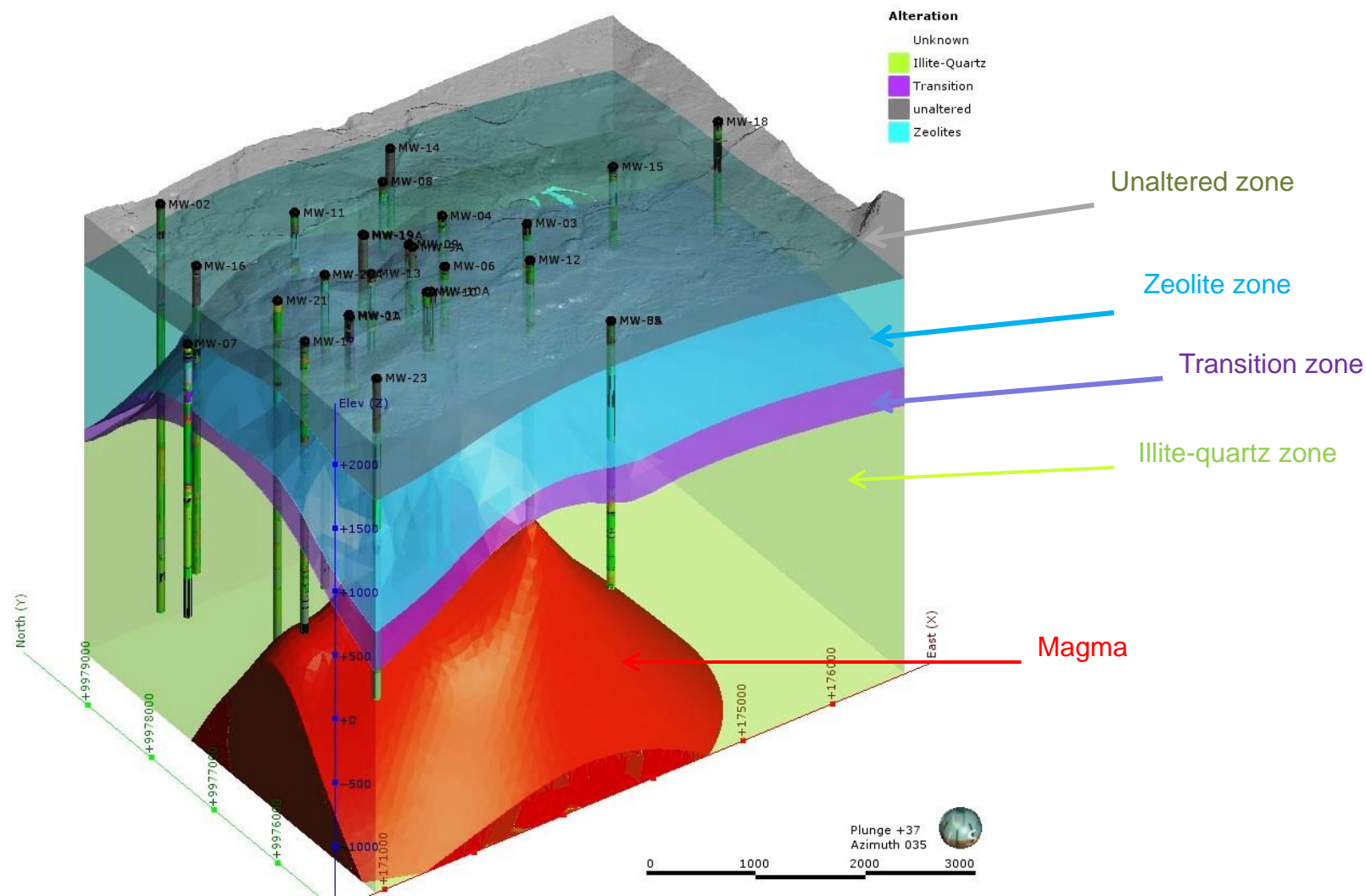


Figure 6:3D alteration model for Menengai

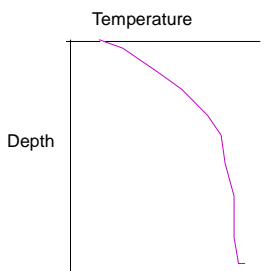
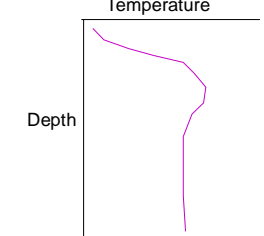
3.0 RESERVOIR DATA

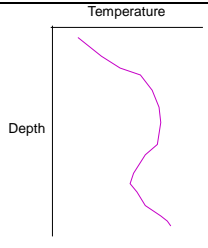
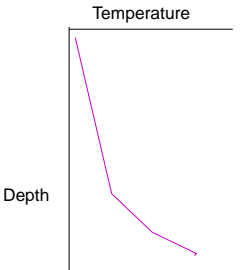
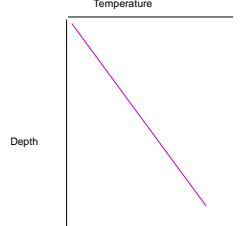
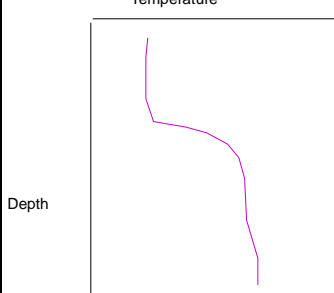
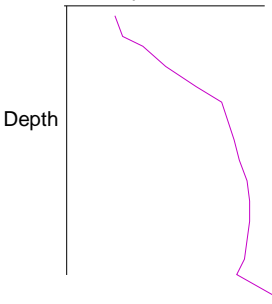
The approach used to interpret and model temperature data is described by Stimac and Mandeno (2016), where profiles are classified (Table 1) according to their shapes as follows;

- Outflow wells with a shallow temperature maximum, followed by a reversal;
- Upflow wells with high convective profiles resembling a two-phase gradient;
- Infield wells with high convective profiles with no reversals.
- Outfield wells with relatively low conductive gradients;
- Edge wells with high, nearly conductive gradients;

Most wells the wells in category A and G (Table 1) are in the Upflow or the infield areas, they are characterized by high temperature convective profiles usually with no reversal at depth. However a reversal at depth was present for those in category G inferring low permeability at depths. A few wells highlighted in category D are wells at the edge of the system characterized by profiles where a shallow convection followed by a down flow exists. The principle concept in temperature data modeling is that temperature distribution is related mainly to convective circulation and indicates flow paths and sources, as well as system edges and boundaries. The hottest areas are likely to be regions of Upflow zones whereas anomalously low temperatures may indicate down flow of cooler fluids. Overturns of temperature as in indicated by category C group typically indicate tabular outflow sheets where intermittent permeability is encountered. Conductive temperature profiles as in category D indicate insufficient permeability for hydrothermal fluid circulation.

Table 1: well profile classification

Category	Description	Wells
A) Upflow	 <p>They were drilled within the summit Area; they are mostly dry well with almost 100% steam. Well MW-23 however is low temperature but has the up flow pattern of profile.</p>	MW-10A, MW-12, MW-13, MW-06, MW-09, MW-13A, MW-23
B) Outflow	 <p>They are drilled away from the summit, MW-05A is the furthest from the summit area</p>	MW-05A, MW-17, MW-20A, MW-17A, MW-30A, MW-10

C) Overturn		They are close to the summit Area; some are slightly displaced from the central area. They indicate turbulent flows sheets, the permeability are therefore contacts zones separated by impermeable saddles.	MW-04, MW-19, MW-20, MW-22, MW-21A, MW-19A
D) Edge of the field		The indicate high bottom hole temperatures but lacks permeability.	MW-03, MW-11, MW-15, MW-16, MW-21, MW-24, MW-04A
E) Edge of the system		There not such profiled from Menengai and could be good news because we have not yet drilled to the edge of the system	No well
F) Cold water on top of system		Many of this wells had difficulty in discharging due to the cold top part of the wells	MW-01, MW-08, MW-18A, MW-1A
G) Up flow/ Steam zone on top of impermeable zone		They are dry steam well mainly within the up flow zone at the summit area. The bottom of this well high temperature but low permeability is experienced	MW-06, MW-09, MW-09A, MW-22, MW-13, MW-18A, MW-01A, MW-09B

Measured temperature model

Measured temperature data modelled by leapfrog geothermal and displayed by several iso-maps, indicates a persistent N-S high temperature anomaly zone with depth. This means high permeability in such orientation facilitating temperature transfer by convection is present. Most of the well profiles within this N-S anomaly fall under category A and G (Table 1). Consequently looking at the cross-section in figure 8, the wells on the left side (MW-13, and

MW-09) fall under this zone, they are characterised by shallow high temperature convection. To right side of cross-section (MW-15 and MW-18A) the high temperature values are much deeper, this could mean reduced permeability in such an area hence temperature transfer to shallow depths is hindered. The high permeability present within the N-S is enhanced by buried N-S structures.

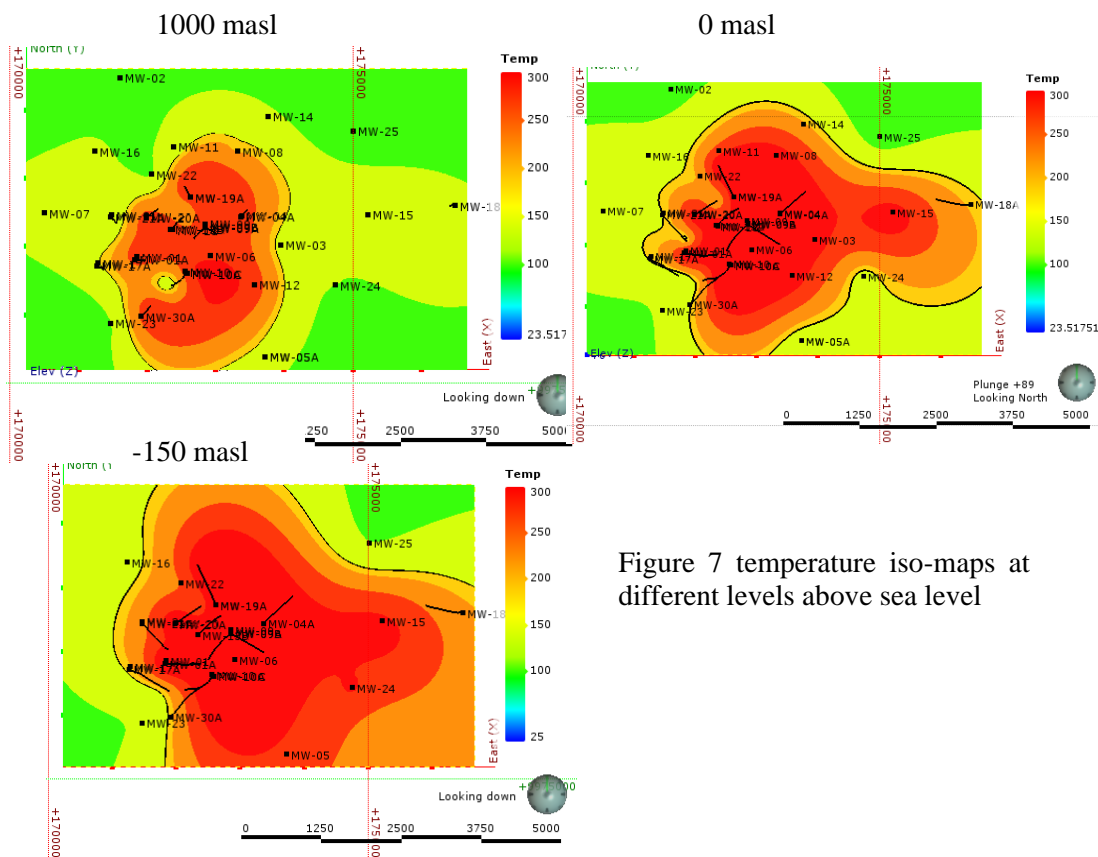


Figure 7 temperature iso-maps at different levels above sea level

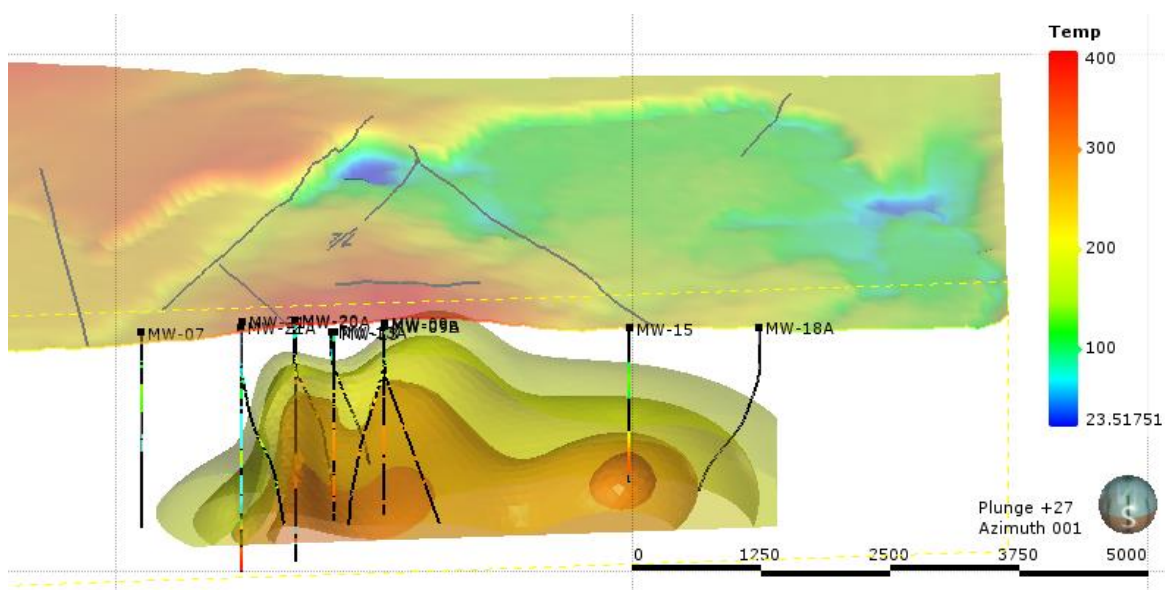


Figure 8: W-E temperature cross-section for Menengai

4.0 GEOCHEMISTRY

Not much geochemistry data has been input into leapfrog so far, therefore for this section we will discuss briefly the Characteristics of reservoir fluids and scaling potential for Menengai wells.

Characteristics of reservoir fluids

Most wells in Menengai discharge two phase (liquid + vapour) fluids, a few wells however, discharge vapour dominated to dry steam fluids. The wells at summit area are characterised by steam dominated to dry steam fluids this include; MW-06, MW-13 and MW-12. The vapour phase tends to reduce generally as you move away from summit area so that well further away from summit area e.g. well MW-07 are liquid dominated.

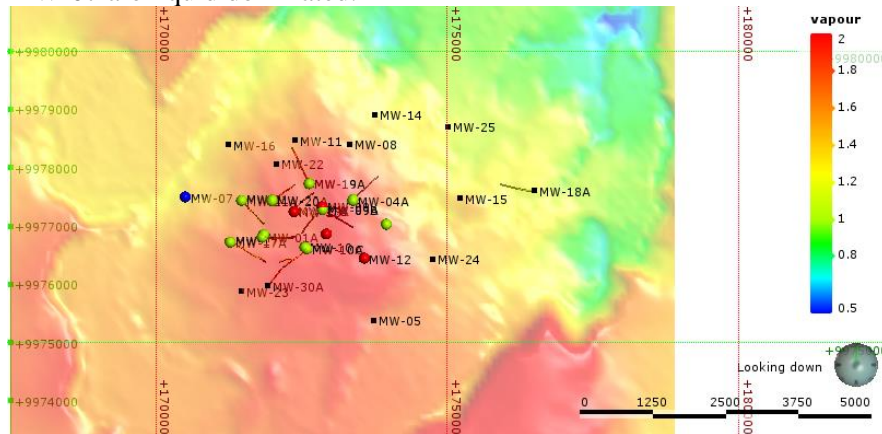


Figure 9: Reservoir fluid variation; *Dry steam to vapour dominated wells (Red)*, *two phase wells (Green)*, *liquid dominated well (Blue)*.

NCG content in steam and Scaling potential

Reservoir fluids in Menengai show relatively high non-condensable gas contributed almost entirely by CO₂. This is envisaged 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 10)

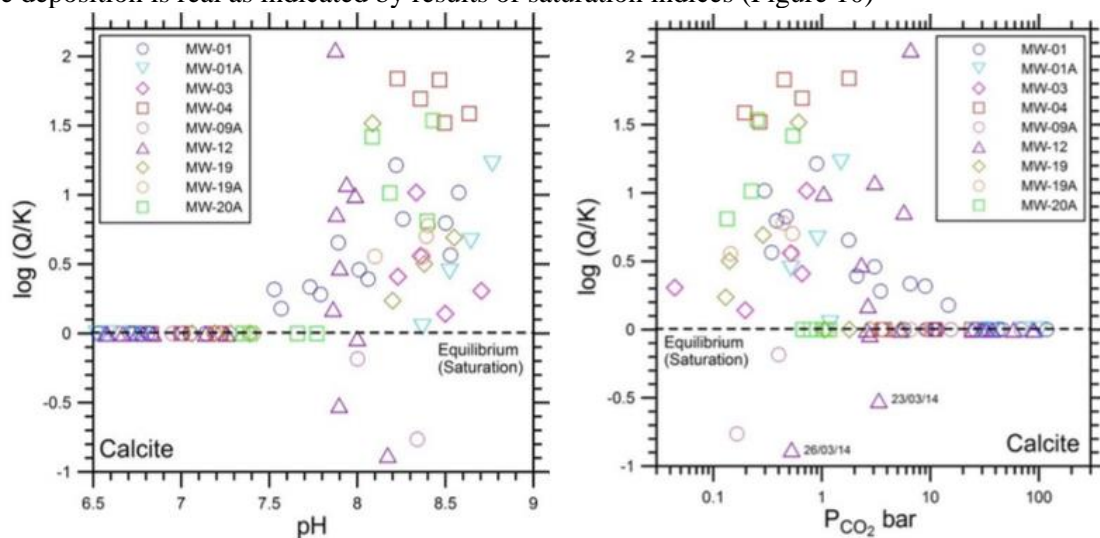


Figure 10: Saturation index with calcite vs. pH (left) and CO₂ partial pressure (right) for the geothermal liquids met by the Menengai wells (GDC 2016)

5.0 GEOPHYSICS

Resistivity

Resistivity data is the main geophysical data set that has been input into leapfrog software and will be described in this section. The data set are points from 3D joint inversions of MT and TEM. The Menengai resistivity structure can be characterised into three zones.

The below 20 ohm resistivity zone

The below 20 ohm zone consists of a shallow horizontal layer of varying thickness ranging from 150 m – 800 m and a vertical block/body at the caldera summit area penetrating deep beyond 3 km (Figure 11). The horizontal layer is thicker towards the edges of the caldera both to the west and east, it is however thinner at the summit/centre of the caldera. The horizontal layer can be interpreted as the cap of the Menengai geothermal system therefore at the summit area of the caldera the cap is thin or

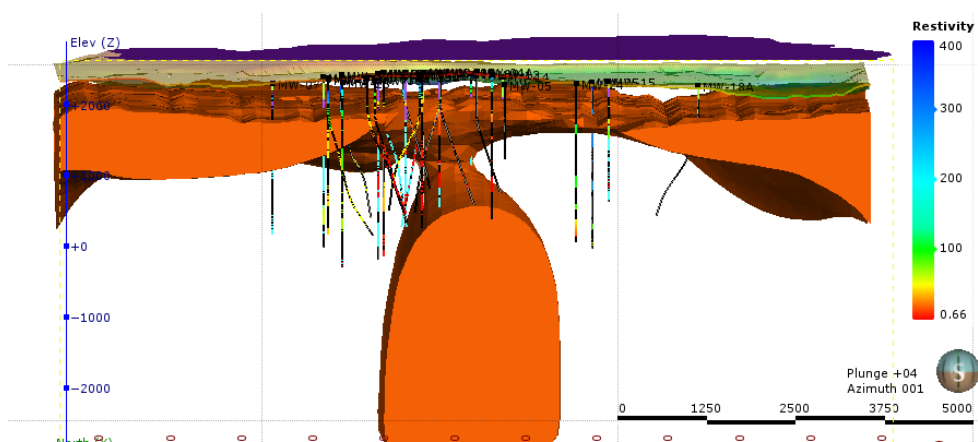


Figure 11: A resistivity zone of <20 ohm

area hence a thick deposition there. The hydrothermal alterations at this zone are mostly low temperature hydrothermal alteration mainly zeolites zone and low temperature clays as highlighted earlier in our hydrothermal alteration model. The vertical body is thinner towards the surface and thicker at depths beyond 1.5 km. The vertical block is a magmatic body at depths below 2 km. Above 2 km and towards the surface the body is transitioning into an up flow zone forming a Chimney of steam dominated permeable zone.

The 20-90 ohm resistivity zone

The zone is shown as light green (Figure 12) consisting of a shallower zone (from surface to 300 m

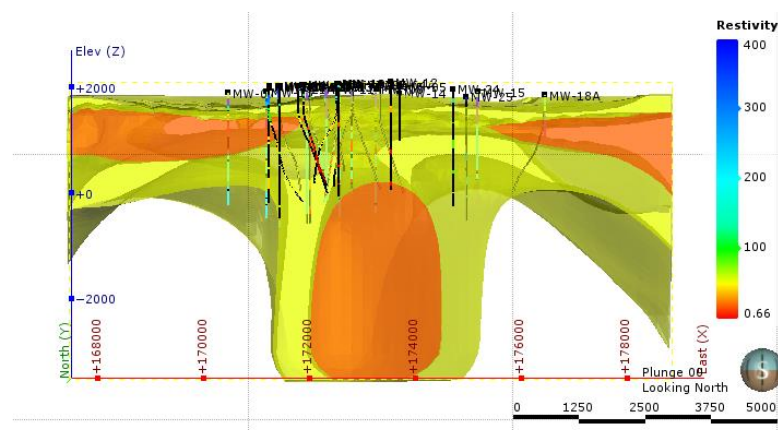


Figure 12: The 20-90 ohm resistivity zone

lacking in some sectors. The most likely geology units at these depths are tuff and pyroclastic intercalating the trachyte deposit so that most of the volcanic ash/pyroclastics deposit pounded the edges of the caldera summit

deep) of trachyte rocks with relative resistivity and a deeper zone (reservoir zone) below 1 km from depth to 2 km. At the summit area however, the zone mimics the vertical magmatic body of <20 ohm forming an outer coating to it. The Menengai

reservoir is therefore the deep 20-90 ohm zone.

The 90 to >100 ohm resistivity zone

This zone is very shallow consisting of fresh resistive trachyte rock at the surface and a deeper zone beyond 2 km (Figure 13). The interpretation for the deeper zone could be;

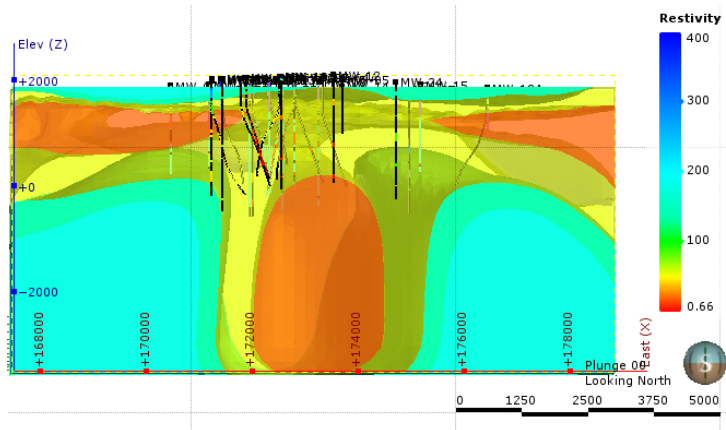


Figure 13: The 90 to >100 ohm resistivity zone

- Intrusion/impermeable zone
- A liquid dominated zone
- low permeable zone with a liquid reservoir

A more plausible interpretation could be a low permeable area with a liquid reservoir as evidenced from wells drilled at edges of the summit area e.g. MW-16 where low permeability was encountered and MW-07 where the discharge chemistry infers a liquid reservoir.

6.0 CONCLUSION

- Surface geology suggests that Menengai has had a recent volcanic activity marked by the recent lava flow.
- The important structures for fluid flow are NNE-SSW and N-S structures
- The up flow of the Menengai system is at the caldera summit with clear outflow at area around well MW-05A, MW-07, There are sharp boundaries for the reservoir around well MW-16 area

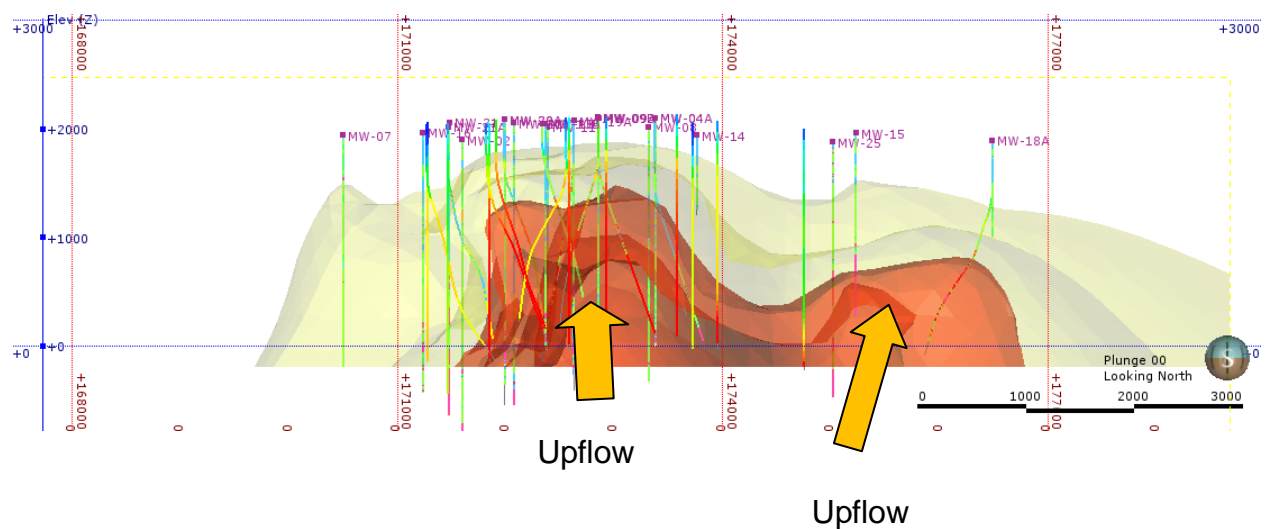


Figure 14: Menengai temperature model

- There is second Upflow around well MW-18A, the recharge is Solai graben and outflow is to the south

- The discharge chemistry varies indicating variation in reservoir fluids ranging from dry steam to vapour dominated zone at the summit area to liquid reservoir away from the summit area

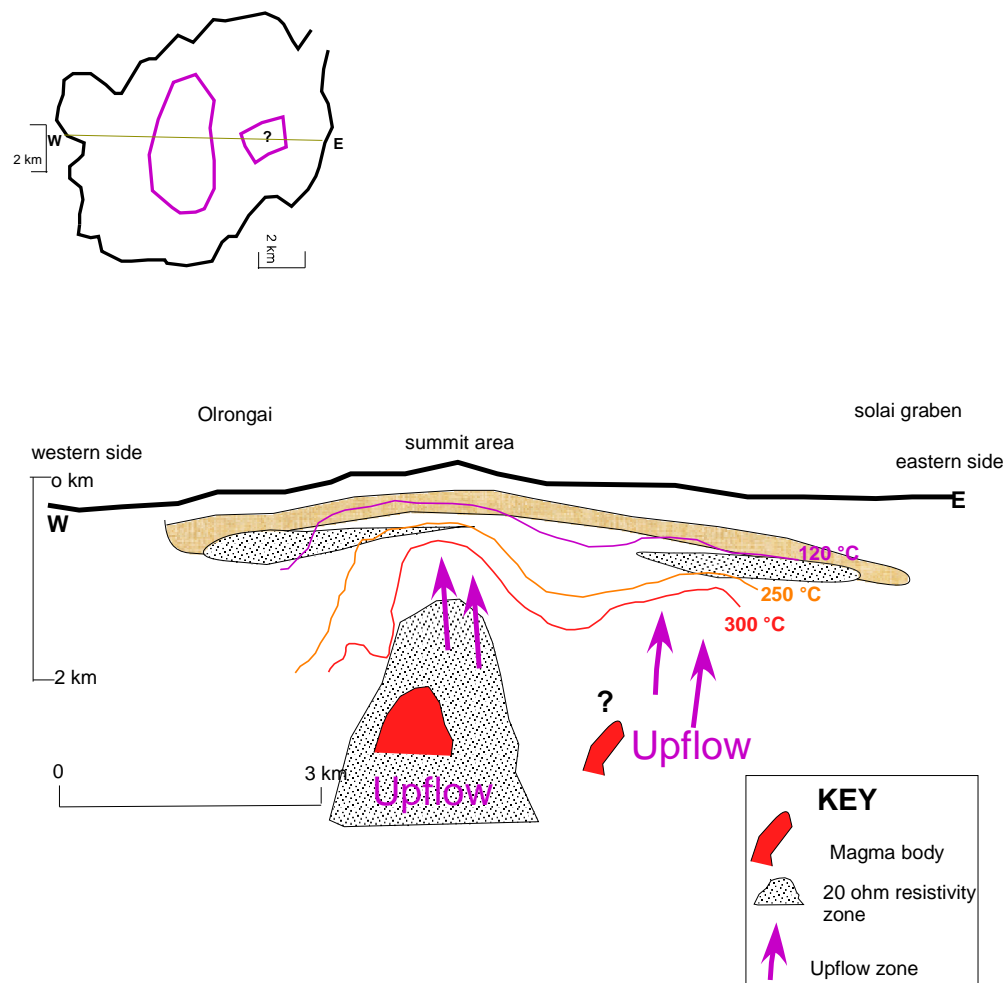


Figure 15: Menengai conceptual model

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