Proceedings, 7th African Rift Geothermal Conference
Kigali, Rwanda 31st October – 2nd November 2018

Menengai Geothermal Field - Eastern Upflow

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Keywords

Menengai, upflow, geothermal system

ABSTRACT

In Menengai, increased production drilling and subsequent modeling has greatly improved the understanding of the geothermal system. Menengai hosts a structurally controlled geothermal system and the focal drilling targets are thus structures of proven permeability and high temperature to yield productive wells. Some studies and improvement of ideas have been on-going as more data becomes available, and various misconceptions have been rectified. Remarkably, the area to the east of the caldera was never a high priority for exploratory drilling based on two assumptions; (1) that the area lacked permeability due to absence of obvious surface structures and (2) there was the possibility of a cooling effect by cold meteoric water channeled by the Solai structure, both of which are now obsolete. Subsurface data show that the major reservoir begins at the quartz-illite-epidote zone; this zone exhibits two distinct doming features suggesting 2 upflow zones. One is in the vicinity of MW-15 and the other within the central caldera area. This zone indicates alteration temperatures of over 230°C. Accordingly, gas chemistry of fumarole MF-2 situated to the immediate north of MW-15 yields the highest equilibrium temperature estimate for the reservoir and low CO_2/H_2S ratio suggesting that it could be positioned within or near an upflow area in Menengai. Well MW-18A fluid discharge chemistry results appears to be benign and shows relatively low concentrations of carbonates compared to the other wells in Menengai.

1. Introduction and Background Information

In Menengai increased production drilling and subsequent modeling has greatly improved the understanding of the geothermal system. Menengai wells have so far enabled the proving of steam for the 105 MW geothermal power plants for Menengai phase one. The second phase of the Menengai project is to explore for, and provide steam for the envisioned 60 MW power plant within the caldera. However, Menengai field has not been short of lessons, the most important being precise well siting and design for wells based on proper integration and interpretation of surface and sub-surface data best achieved through integrated models and consultative discussions by all stakeholders.

Menengai hosts a structurally controlled geothermal system and the focal drilling targets are thus structures of proven permeability and high temperature to yield productive wells. Mapping of surface structures has so far been comprehensively done despite hindrances of rugged surface lava while temperature conditions have been inferred from fumaroles, resistivity, seismicity and subsurface data directly through wells. The permeability structure of the Menengai geothermal system is quite complex and may be attributed to the young nature of the caldera volcano.

The Menengai central caldera area has so far been optimally and successfully explored and drilled thus necessitating step out wells. MW-18A drilled east of the central caldera has opened up an opportunity to conduct further exploration drilling in the eastern sector. Surface surveys indicate that the area is within an intersection of the Solai and central caldera arcuate structure. Data from MW-15 confirm the existence of sufficient heat in excess of 300° C, based on the alteration mineralogy and temperature profiles. Permeability would be achieved by drilling directional wells as the circulation of fluids is controlled by faults and fault intersections. Temperature within the locality has been proven by MW-18A and MW-15.

2. Previous work

In the case of Menengai geothermal field, the understanding of the nature of the geothermal system started with the extensive study by Geotermica Italiana Srl in 1986/87 who carried out work with promising results on the occurrence of geothermal potential particularly within the caldera. The Menengai volcano encompasses the caldera, Ol'Rongai and Ol'Banita plains and parts of the Solai graben to the northeast. Despite the caldera being seen as the most promising area, the researchers discarded it for drilling due to: (1) the rugged lava which would have made infrastructure works difficult (2) the area posed a volcanic hazard which was seen as high in case an eruption. Four drill locations were therefore sited Ol Rongai –Ol Banita area and within the Solai zone. Work done by KenGen and the Ministry of Energy in 2004 (Mungania, J., and Lagat J., 2004) indicated the existence of a hot, ductile, and dense body centered under Menengai caldera with a geothermal upflow at the central caldera.

GDC took up this the aforementioned model and conducted further work in 2010 and so far thirty-seven (37) geothermal wells have been drilled within the caldera proving a viable geothermal system. In Menengai, it is obvious that geothermal resources are abundant and easily accessible, a breakthrough in the understanding of the nature of geothermal system is being achieved with each drilled well whether productive or not.

In 2015, GDC hired a consultant firm, Electroconsult S.p.A (ELC) to carry out a feasibility study to quantify the geothermal resource potential based on the subsurface information available at that time. The resource area, based on available data was bound within the central caldera by the NW-SE major structures. It is for this reason the resource estimate of 150 MWe was obtained from the Monte Carlo Simulation. ELC thereafter reviewed the resource potential in February 2016 and based on additional available information from the additional drilled wells and the steam potential was revised down to about 100 MWe. The cumulative steam from tested wells has so far surpassed 130 MWe with more being realized as drilling continues.

What is notable however, is that the area east of the caldera was never a high priority for exploratory drilling based on two assumptions: (1) that the area lacked permeability due to absence of obvious surface structures and (2) there was the possibility of a cooling effect by cold meteoric water channeled by the Solai structure, both of which are now obsolete. Although the previous models created were not incorrect, they lacked sufficient information to confidently propose exploration wells in the area. It is only with the ongoing development of Menengai field that it was deemed necessary to step out to the east after drilling MW-15 and proving the presence of high temperatures therein.

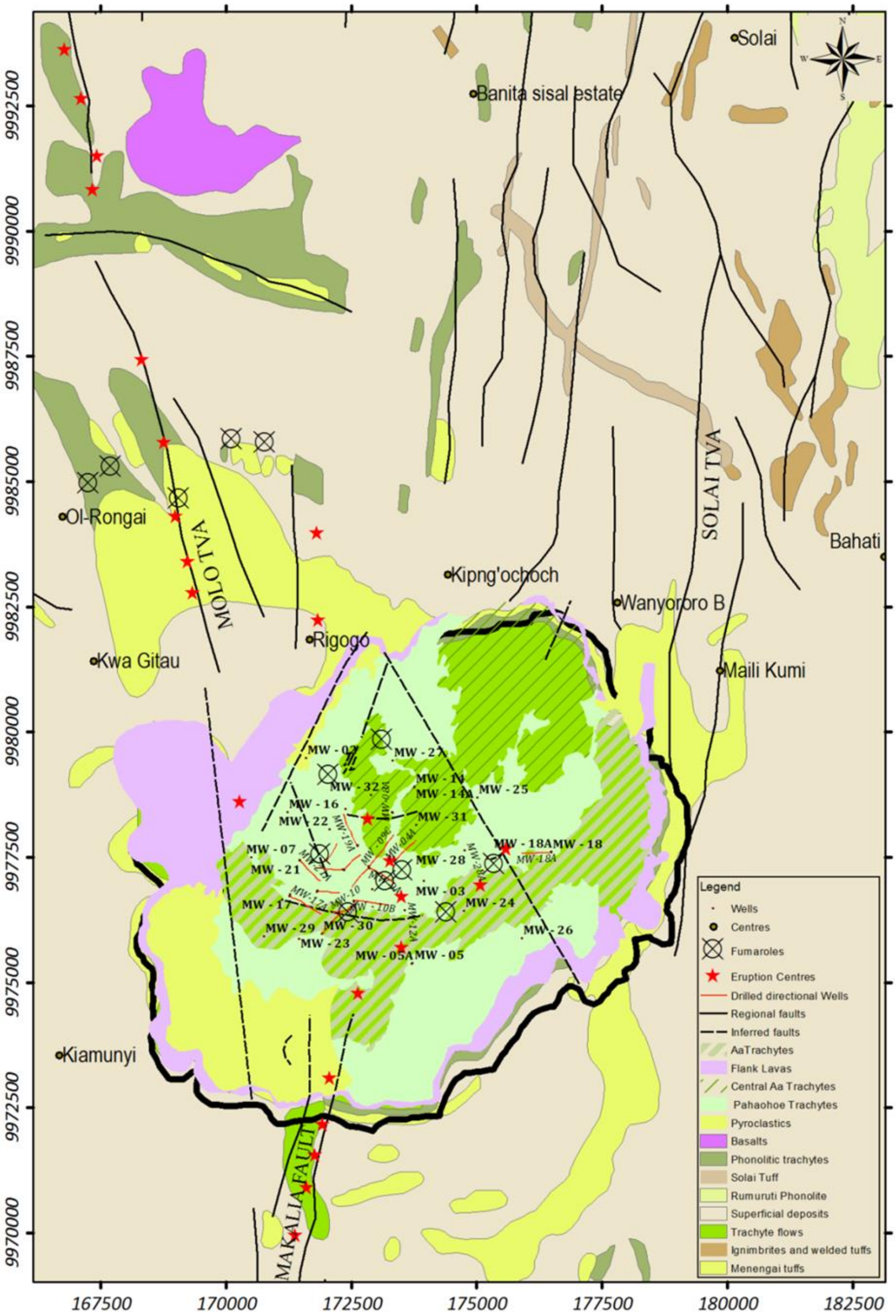

Figure 1: Menengai geothermal field with drilled wells within the caldera.

3. Evidence of an upflow system

3.1 Solai structure zone

The Menengai caldera floor is primarily overlain by young trachytic lava which obscures many surface features, prompting the inference of faults from alignment of eruption centres and fumaroles, geophysical data and ultimately correlation from wells. Some studies and improvement of ideas have of course been on-going during preceding studies, and various misconceptions have been rectified. The mappable surface structures include the Makalia fault and its extension, south of the caldera, the arcuate fault associated with the doming at the central area, and the Solai fault which cuts into the caldera and presumably intersects the arcuate fault. The NE-SW fault located along the northern caldera wall does not align with other structures in the Menengai area; explicably piecemeal caldera collapse often causes complex tectonic outcomes.

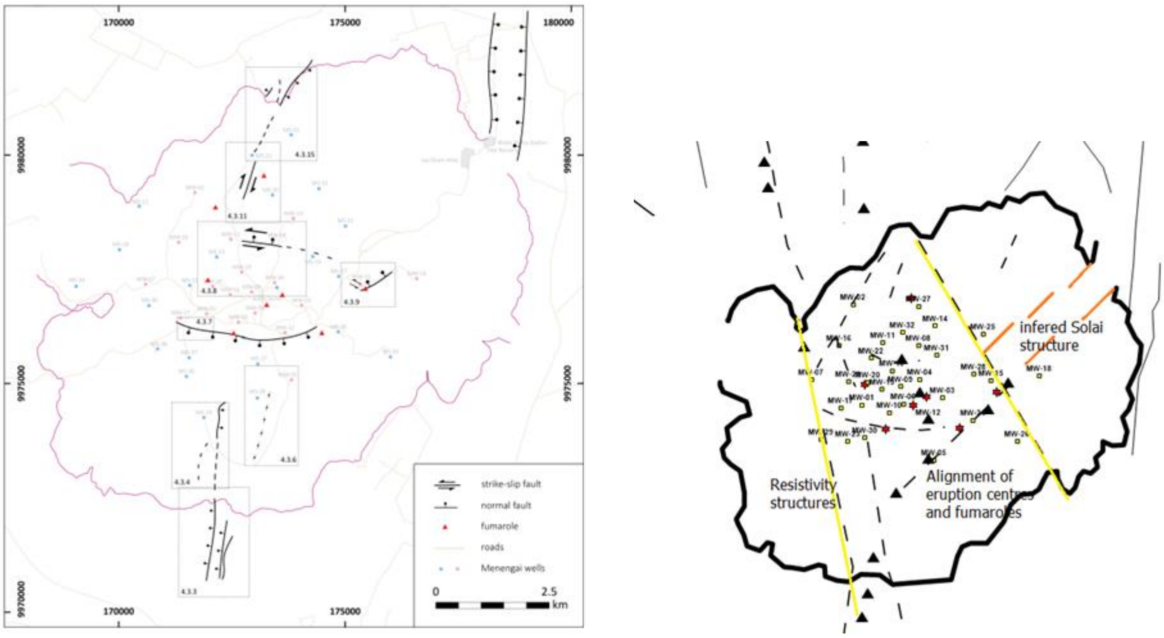

Figure 2: Surface faults and inferred structures.

The Solai Tectonovolvanic axis (TVA) appears to be linked to a major fault of the Aberdare detachment which is quite deep and close to the rift trough and constitutes the fault system cutting the pyroclastic deposits north of the Menengai caldera (Strecker et al 2013). Furthermore, its associated fault cuts through the caldera wall, construing an age relatively younger than the collapse activity. The presence of a fumarole (MF-2) along its confluence with the central caldera arcuate fault indicates that permeability is enhanced and that it is unlikely the Solai fault causes a cooling effect in the system. An assumption here is that it channels cooler fluids at shallower depths and hot geothermal fluids at great depths. Additionally, it is probable that the lava flow on the surface obscures more geothermal features related to the structure.

3.2 Menengai Fumarole (MF-2)

The fumarole is located at Eastings 175353 Northings 9977375 and discharges at approximately 92°C, its location is along the Solai fault zone, south of MW-15 and east of MW-18A. Menengai fumaroles generally discharge at low pressures with outlet temperatures spanning between 56ºC to 92ºC. The chemistry of the fumaroles display varying degrees of atmospheric contamination affected by steam condensation. The resulting gases are affected to a considerable extent by chemical changes induced by both steam condensation and mixing with air. It is noted that fumarole MF-2 appears to experience relatively low air addition.

During the GDC field studies in 2010, measured TDS values for fumarole MF-2 gave the highest values suggesting possibly high temperature deep circulating fluids or long residence time of the waters in the reservoir, an indication that the fumarole is tapping from a deep magmatic source. The fumarole coincides with the area, which recorded some of the highest values for Rn-222, CO_2 and Rn-222/CO_2 a clear indication of a potentially permeable zone. (GDC, 2010).

By assuming a geothermal origin of both Rn-222 and CO_2 in the fumarole steam, the ratio Rn-222/CO_2 would be a good indicator of fumaroles associated with potential geothermal reservoirs and zones of good permeability, where both gases flow relatively fast. Among the sampled fumaroles, fumarole MF-6 located inside the caldera within the north western part, recorded the highest ratio of 517 followed by fumarole MF-2 at 476, located in the eastern part of the caldera.

Accordingly, fumarole MF-2 shows relatively minimal contamination (Figure 3), and consequently yields the highest equilibrium temperature estimate for the reservoir and lower CO_2/H_2S ratio suggesting that it could be positioned within or near an upflow area in Menengai. Also, the CO_2/N_2 ratio supports MF-2 as the least contaminated and therefore the fumarole closest to the upflow zone as conceptualized in Figure 4.

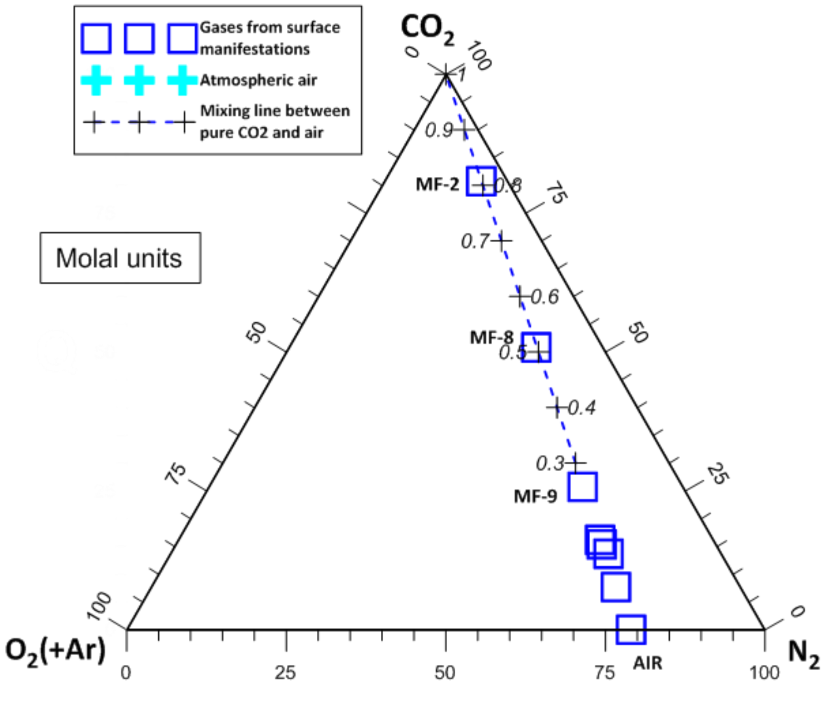

Figure 3: Triangular plots of CO_2-N_2-O_2 for the thermal manifestations of interest, also showing the mixing line between pure CO_2 and atmospheric air.

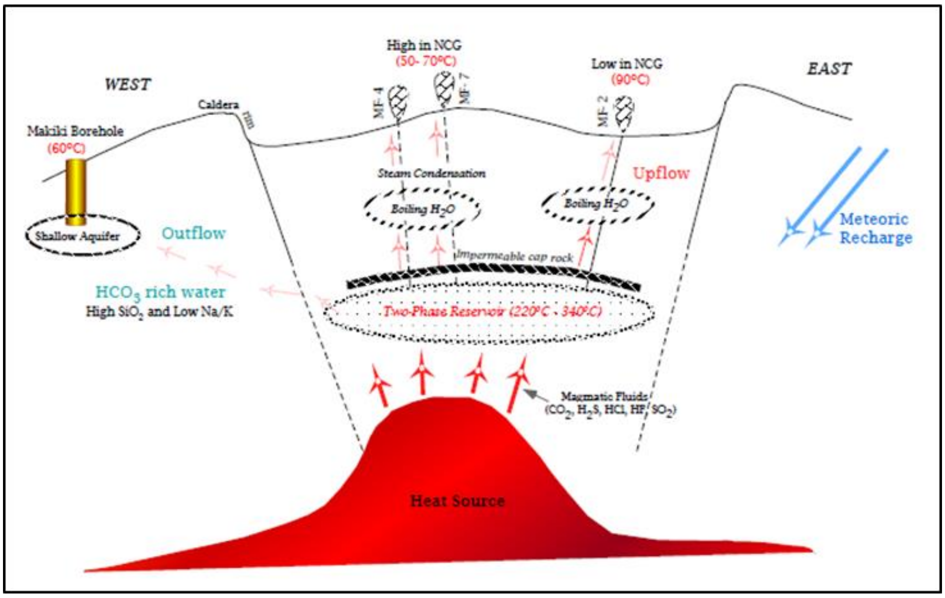

Figure 4: Geochemical model of Menengai based on surface data.

3.3 Doming of hydrothermal alteration zones

One method of identifying upflow zones is to correlate hydrothermal alteration zones within a field and identify zonal distribution consistent with the present thermal structure of the field. Due to higher temperatures in upflow zones, hydrothermal alteration minerals tend to plot in a dome-like pattern when correlated with adjacent wells because the high temperature minerals tend to appear shallower in upflow areas and deeper away from the upflow.

In the Menengai field, five hydrothermal zones are recognized: the unaltered zone, the smectite-zeolite zone, the transition zone, the quartz-illite-epidote zone and the wollastonite-actinolite zone. The shallower depth (0-100 m) is the unaltered zone which consists mainly of pyroclastics and trachytes showing a high level of oxidation. At slightly deeper depth i.e. 100-400 m, is a somewhat thicker zeolite zone marked by the presence of circulation losses in many wells, this section of the well makes it difficult to determine the exact boundaries of this zone (Mutua, 2015). The zone is nonetheless marked by the presence of chalcedony, calcite, smectite and zeolites and the temperature range is less than 200°C. A thin transition zone approximately 100 m thick is observed below the smectite-zeolite zone.

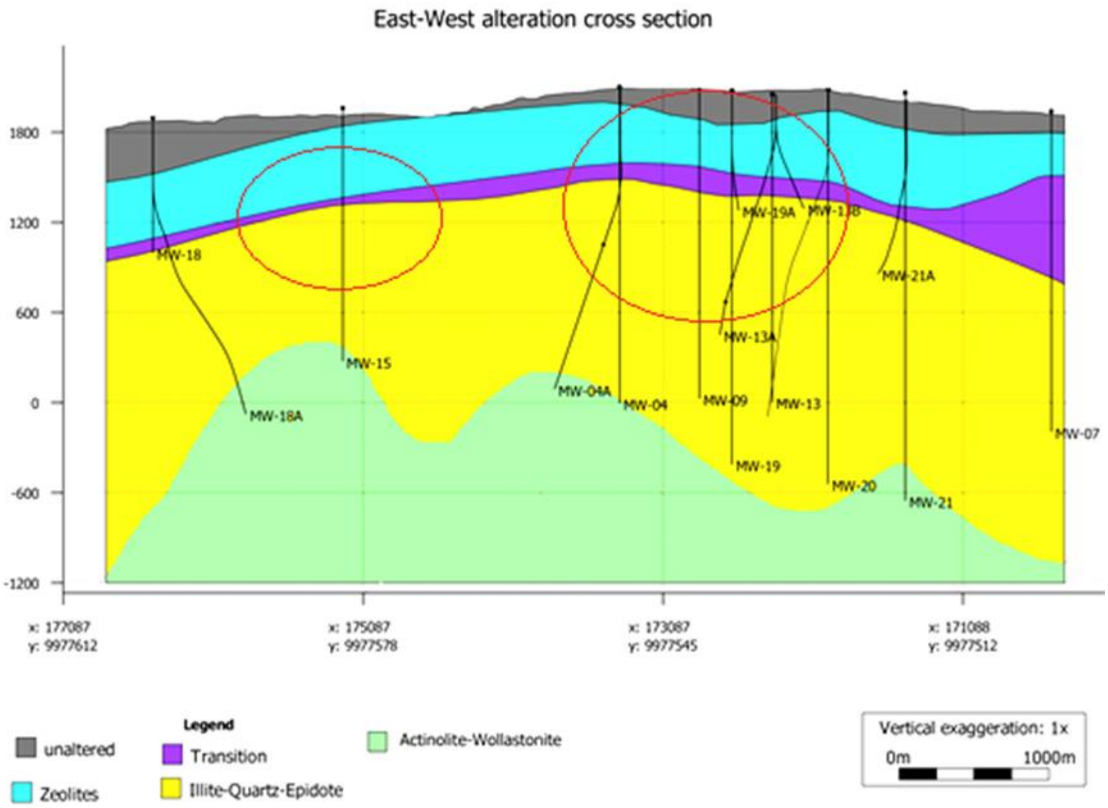

Figure 5: Alteration mineralogy east to west.

The major reservoir begins at the quartz-illite-epidote zone; this zone exhibits two distinct dome like structures suggesting 2 upflow zones (Figure 5). One is in the vicinity of MW-15 and the other within the central caldera area. This zone indicates alteration temperatures of over 230°C. The doming implies shallower reservoir depths within the two localities where both shallow intrusives and magma bodies have been encountered. The deepest zone is the wollastonite-actinolite zone; defined by the appearance of wollastonite and actinolite although quartz, illite and epidote sometimes appear. This zone ranges from 1300 m, and persists to the bottom of the well. The appearance of actinolite at this zone reveals formation temperatures of above 300°C and shallow intrusive dikes.

Founded on experience of drilled wells within Menengai, the actinolite-wollastonite zone usually indicates proximity to the hot syenitic intrusive bodies which frequently result in fairly impermeable wells particularly at depths exceeding 2000 m. The hydrothermal alteration patterns give clear indications that it would be advisable to only drill directional wells where the actinolite wollastonite minerals indicate a shallow domed pattern. In so doing, the wells would have a larger column within the more permeable and productive quartz-illite-epidote zone and a shorter high temperature column with limited permeability at target depth.

3.4 Discharge results of MW-18A

The results below present well MW-18A chemical and gas results for samples collected between mid-January 2017 and April 2017. The well was drilled to a depth of 2108 m CT with the production casing shoe set at 1194 m depth.

3.4.1 Liquid phase components

Well MW-18A results show relatively low concentrations of carbonates in the fluid discharge compared to other wells in Menengai. Both the carbonates, silica, chloride, fluoride and sulphate contents appear to be relatively steady, averaging about 2500 mg/kg, 1020 mg/kg and 1280 mg/kg, 200 mg/g and 230 mg/kg respectively (Figure 6). The relatively high chloride and silica suggests intense boiling and water-rock interaction. Fluoride is relatively high as well suggesting the possibility of uptake of calcium in calcite formation or addition of volcanic gases (hydrogen fluoride). Sulphate content is also notably high indicating either a possibility of mixing of high temperature steam with lower temperature fluids or the influence of surface water pumped during drilling and completion tests, although this may be unlikely considering the low N_2 content in the vapor phase. The high sulphate content could be the result of oxidation of hydrogen sulphide and thus explaining the low H_2S values in the gas. The major feed zone is located towards the bottom of the well (pressure profiles pivot at a depth of 1900 m), with minor permeable horizons above of slightly lower enthalpies.

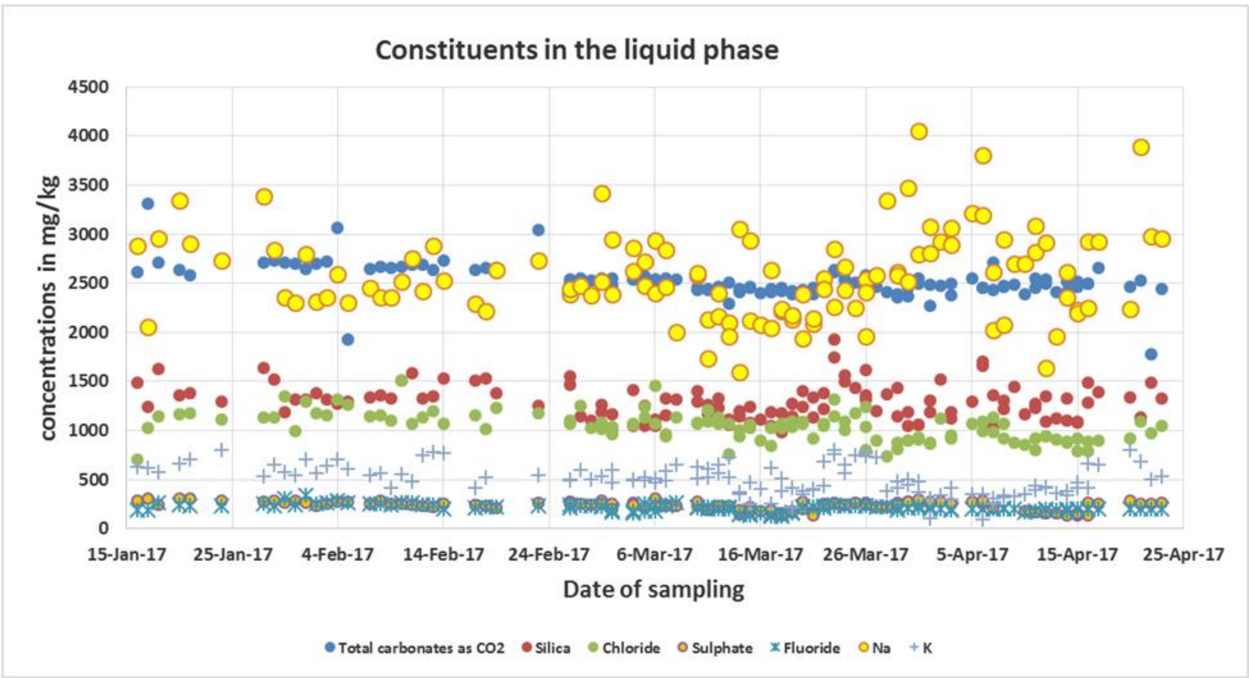

Figure 6: Well MW-18A liquid phase constituents.

3.4.2 Gas Chemistry

Volatiles in the vapor phase appear to be low relative to other wells in Menengai, particularly CO_2 which is the predominant solute in the steam and commonly poses numerous challenges if present in significant amounts (Figures 7 and 8). N_2 is present in low concentrations implying that the reservoir has minimal water rich in atmospheric components e.g. drilling water. This may also infer that the well has heated up sufficiently. No specific trend is seen in H_2, H_2S and CH_4 contents with progressive flow tests although the results are still few to make clear deductions.

Generally, as depicted by Figures 7 and 8 the average CO_2 content is about 360 mmol/kg and the total gas content is estimated at 1.6 w/w%. This is relatively low and ranks among the wells that have the lowest NCG in Menengai.

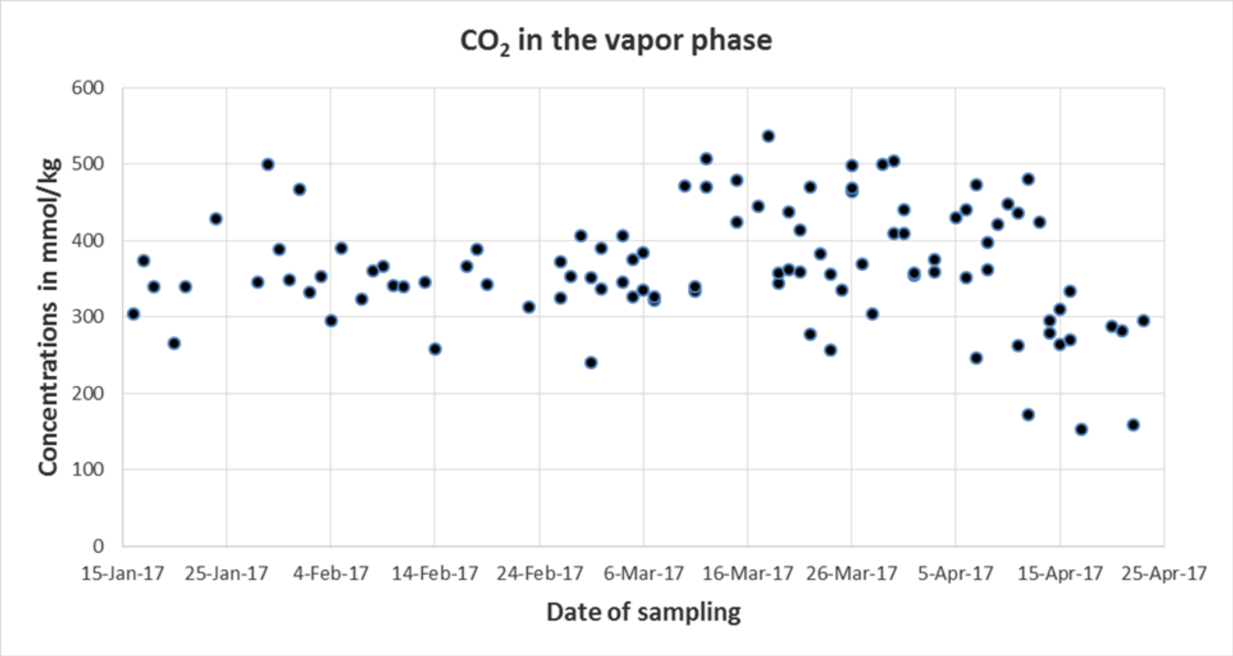

Figure 7: CO2 in the vapor phase.

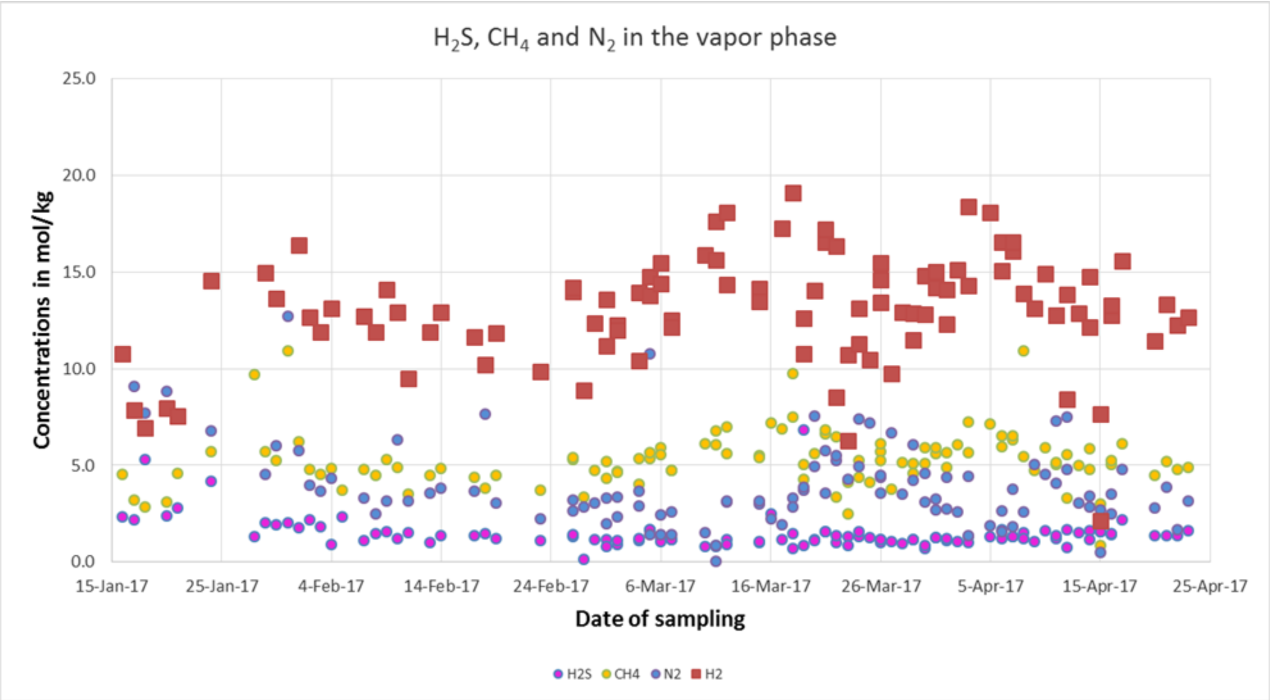

Figure 8: Other volatiles in the vapor phase.

3.4.3 Solute and Gas Equilibrium temperatures

As depicted by Figure 9, both solute (quartz and Na/K) and gas equilibrium temperatures estimate the reservoir fluid to be between 280 and 320°C and show a relatively good correlation both between the different geothermometers and the dynamic temperature measurements downhole. However, due to the low H_2S, the H_2S geothermometer function yielded low values suggesting a possibility that H_2S content may not be reflecting equilibrium conditions which could be due to mixing of fluids of different enthalpies. Generally, the good correlation confirms the dominance of the deepest aquifer despite the possible minimal mixing of fluids of different enthalpies as also inferred from the correlation of silica-enthalpy (Figure 12) and CO_2/H_2s ratio (Figure 13).

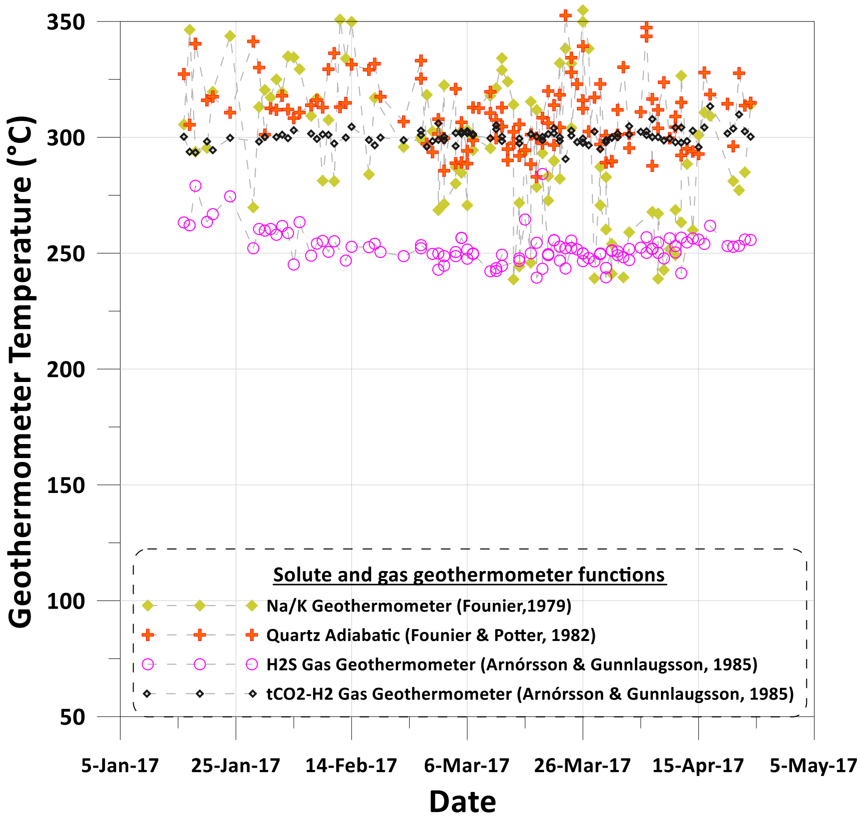

Figure 9: Solute (quartz and Na/K) and gas (H_2S, CO_2/H_2) equilibrium temperatures.

3.4.3 Saturation state

The graphs in Figure 10 depict oversaturation of well MW-18A reservoir water with respect to calcite despite the relatively low CO_2 (averaging 360 mmol/kg) and total gas content of about 1.6% by weight (third lowest in Menengai). Going by the graph, it is inferred that calcite precipitation is likely in this well, although other factors may come into play e.g. kinetics and mixing.

On the other hand, the well waters appear to be under-saturated with respect to amorphous silica even with the silica content being the highest recorded in Menengai, averaging 1,300 mg/kg, and as high as >1900 mg/kg. Amorphous silica deposition is unlikely even at lower temperatures below 100°C as observed in the graphs in Figure 10 (right).

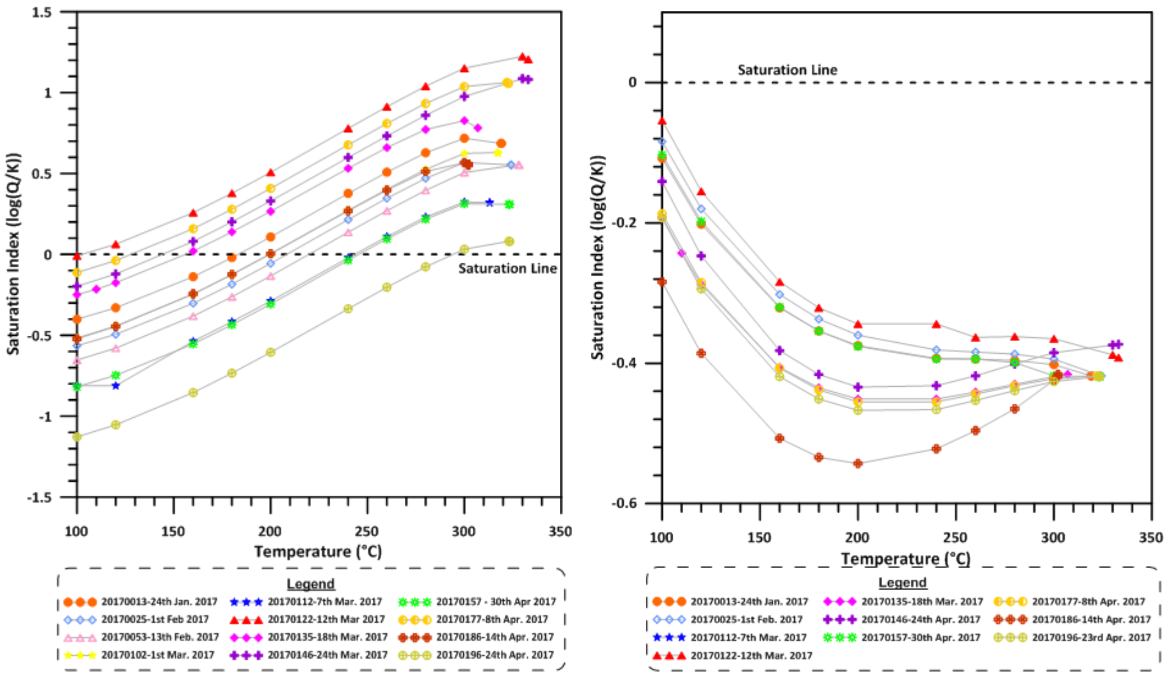

Figure 10: Saturation state of well MW-18A reservoir water with respect to calcite (left) and amorphous silica (right) assuming single step adiabatic boiling at quartz equilibrium temperature (with the aid of Watch of Arnórsson et al., 1982, version 2.4 (Bjanarson, 2010)).

3.4.4 Steam Quality

The quality of steam discharged by MW-18A with regard to its gas content appears to be generally good compared to other wells in Menengai. The well is relatively low in non-condensable gases (NCG) with gas results indicating a total of 1.6% by weight (Figure 11). CO_2 is the main constituent contributing over 90% of the NCG.

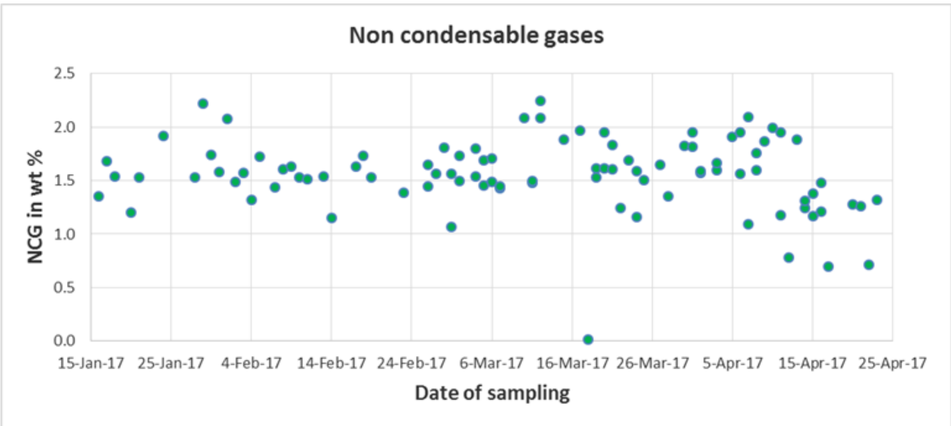

Figure 11: Well MW-18A NCG in wt. %.

3.4.5 Comparison of MW-18A with other wells in Menengai

Well MW-18A chemical constituents in relation to those of other wells in Menengai are depicted by the graphs in Figures 12 - 14. The well discharge generally appears to display equilibrated reservoir fluid that has sufficiently interacted with the host rock and encountered minimal mixing during its ascent to the surface. Generally, well MW-18A fluid appears to be benign and exhibits characteristics of an upflow zone fluids except for the relatively low H_2S in the gas which is attributed to mixing of lower and high temperature fluids, the latter being dominant.

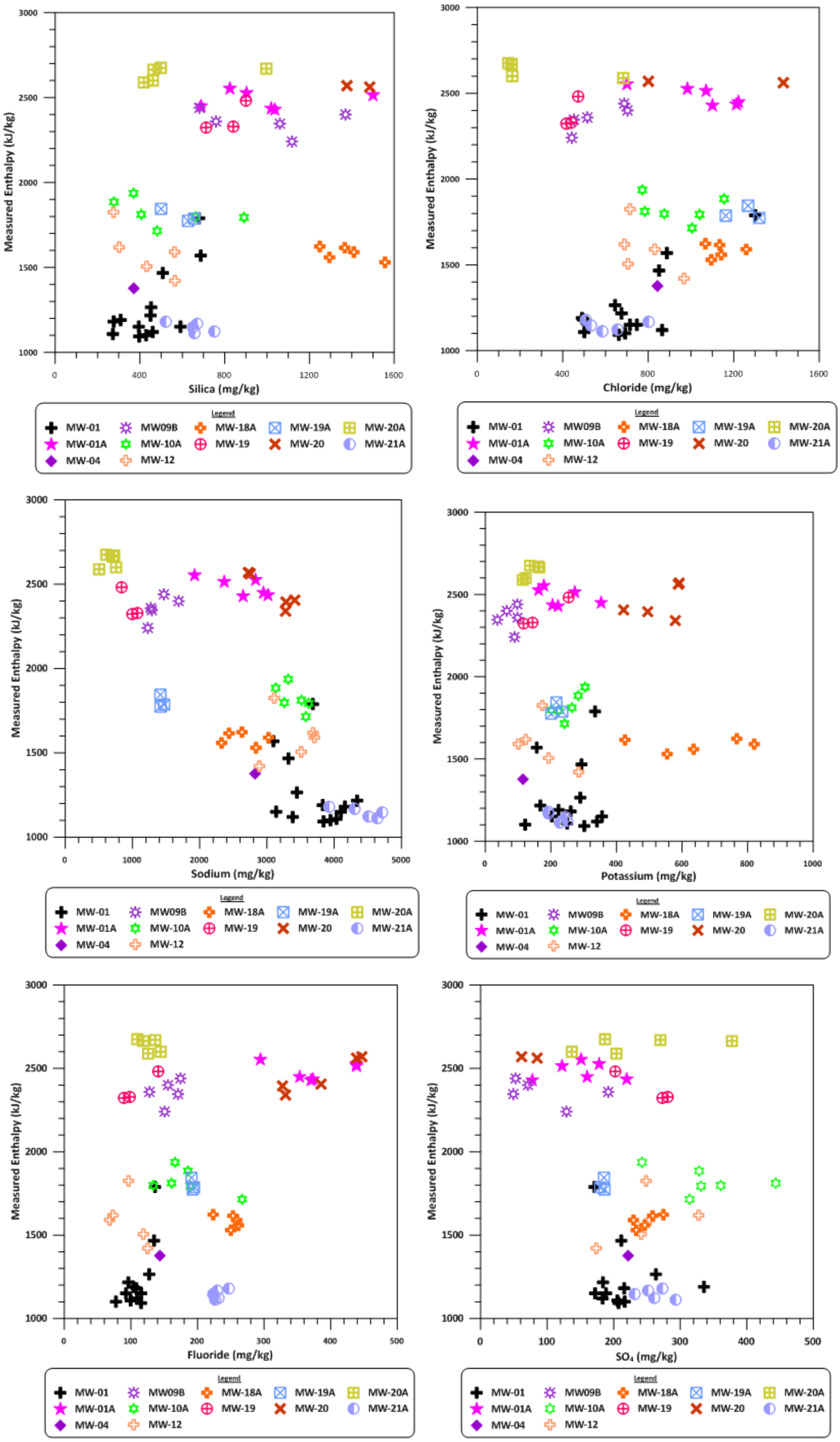

Figure 12: Correlation of chemical constituents in the liquid phase with measured enthalpy.

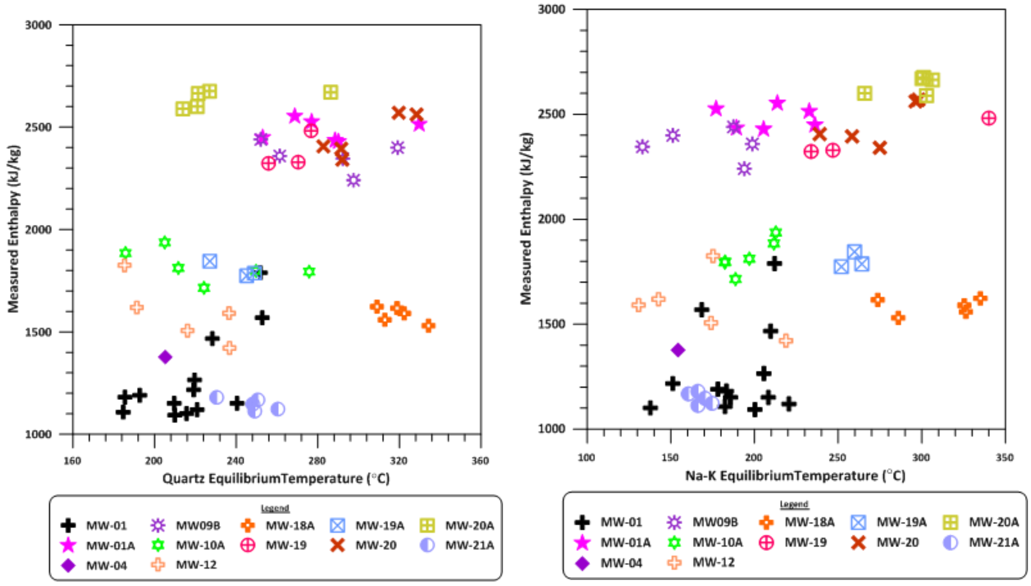

Figure 13: Correlation of solute geothermometers with measured enthalpy.

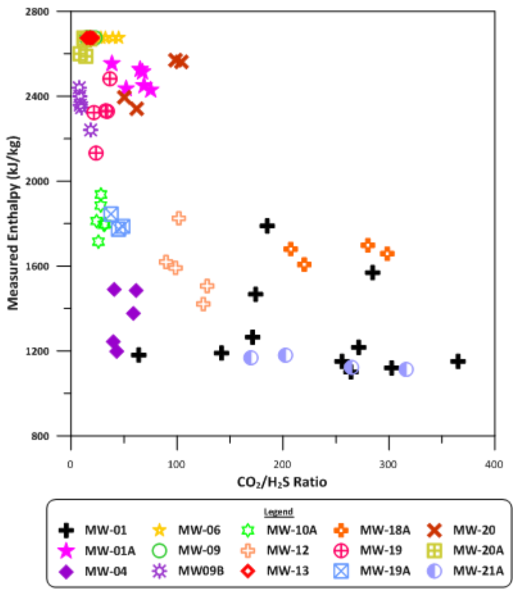

Figure 14: Correlation of CO_2/H_2S ratio with measured enthalpy.

4. Conclusion and recommendation

This paper discusses the possibility of an east caldera upflow for geothermal development of the Menengai phase II 60 MWe power plant. Results from surface and sub-surface data favour a model where an obvious heat source and permeability is proven. The chemistry of fumarole MF-2 concurs with the geophysical model (Figure 15) and the measured temperature model (Figure 16). Highly productive wells will best be achieved by drilling directional wells so as to intersect the fault intersection and sub-vertical faults. The principal benefits (environmental and economic) of directional drilling, compared to vertical drilling, are that fewer drill-pads and less surface piping are needed (Axelsson and Franzson, 2012). Directional drilling also enables reaching drilling targets that are not easily accessible by vertical wells.

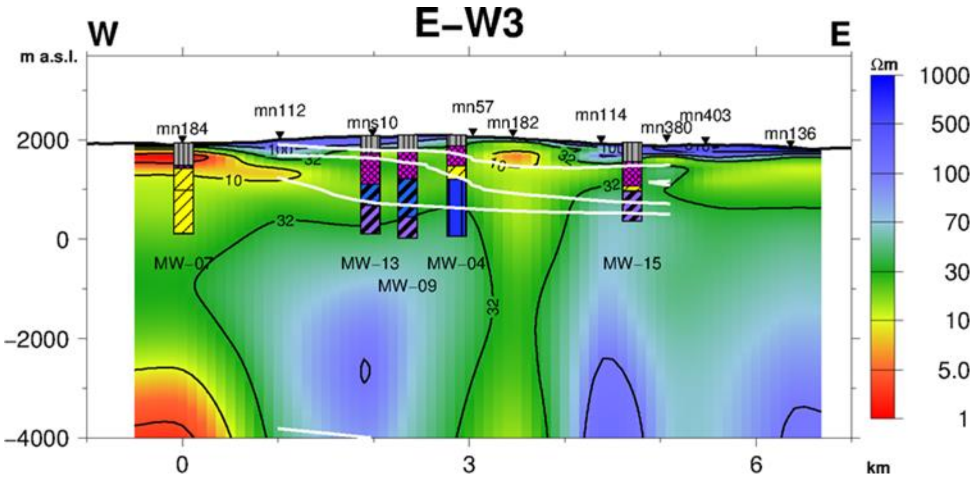

Figure 15: Resistivity model West to east across the caldera.

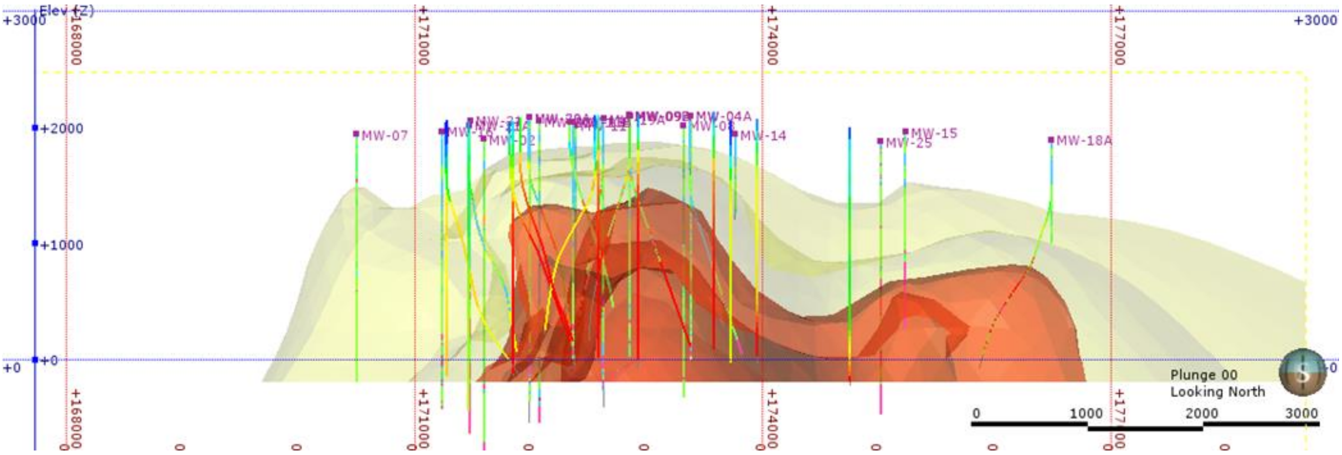

Figure 16: Measured temperature model of Menengai wells.

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