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Provenance of Phase Segregation and Conductive Heat Transfer Processes in the Menengai Geothermal System

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ABSTRACT

Menengai geothermal field wells displays heterogeneous physico-chemical properties. For instance, the enthalpy of individual wells ranges from water enthalpy of less than 1000 kJ/kg to dry stream enthalpy of about 2700 kJ/kg. Whereas, individual wells' chemistry of volatiles and non-volatiles components vary spatially. This may be ascribed to various physico-chemical processes in the geothermal system. This paper therefore, presents the qualitative evaluation of the provenance of phase segregation and conductive heat addition in Menengai geothermal system with the view of providing insights into the possible cause of excess enthalpy (i.e. the enthalpy of the discharged fluids is higher than that of the enthalpy of steam saturated liquid at the aquifer temperature; hd,t > hf,l). The trends displayed by the non-volatile Cl concentration in the total well discharge and in the liquid phase as a function of discharge enthalpy suggests that Menengai has a heterogeneous reservoir, with excess enthalpy dominantly caused by phase separation and conductive heat transfer from hot rock to the circulating fluids. Moreover, SiO_2 vs. enthalpy was used to evaluate the mixing scenarios between the shallow end-member feed zone and a deep end-member steam dominated feed zone and ultimately identify the aquifers of provenance of the geothermal liquids feeding the selected wells.

1. INTRODUCTION

1.1 Background of the study

Menengai is an elliptical caldera oriented in an NE-SW strike direction located on the floor of the Kenya rift valley with abundant high-temperature geothermal activity. It is one of seven late Quaternary caldera volcanoes in the inner trough of the Kenya Rift Valley, which are associated with a high thermal gradient as a result of shallow intrusions (Figure 1). It is dominated by silica-saturated peralkaline trachyte (erupted in recent times within the caldera), pyroclastic, ignimbrites and basalts. Multiple studies have been undertaken skewed towards deciphering the geochemistry of the discharged fluids from the Menengai geothermal reservoir (e.g. Kipng'ok, 2011; Sekento, 2012; Malimo, 2013; Kipngok, 2014, Auko, 2014). This present study seeks to assess the provenance of physico-chemical processes such as phase segregation and conductive heat transfer and their potential influence in the chemistry of the fluids and the physical reservoir conditions. Multiple studies of the Menengai geothermal system have demonstrated that the wells drilled in Menengai display heterogeneity in physico-chemical properties. For instance, the enthalpy of individual discharged wells ranges from water enthalpy of less than 1000 kJ/kg to dry stream enthalpy of about 2700 kJ/kg. On the other hand, permeability varies spatially as well as the chemistry of volatile and non-volatile components.

1.2 Geological background

Menengai is an elliptical 'piecemeal' caldera of the Krakatau-style formed through different episodes of collapse that are associated with two major eruptions thus leading to the partly superposed lava flows of different ages. The lava flows cover virtually the entire caldera floor. The rocks conform to the pre, syn-and post caldera volcanic activities that started about 0.18 Ma (UP and GDC, 2013; Leat, 1984). The surface and subsurface geology of Menengai geothermal field is predominantly trachytic with intercalations of tuff and pyroclastics. Pulses of trachyphonolite and basalt are also reported to be present in Menengai. Studies of drill cuttings from various wells have also revealed syenitic intrusions. The varying texture of trachyte and the intermittent tuff intercepted reflect different eruption episodes. In addition, the highly altered basalt penetrated by some wells at greater depths is presumed to be older than the caldera and could correspond to the pre-caldera volcanics that dates about mid to late Pleistocene. Geothermal activity manifests at the surface in the form of weak fumaroles, steaming grounds and steam vents, most of which are structurally controlled (Mibei and Lagat, 2011; Omondi, 2011; Kipchumba, 2013; Lopeyok, 2013; UP and GDC, 2013; Mbia, 2014).

The majority of the subsidiary structures inside the caldera floor have different orientations and could demonstrate the possible result of an interference pattern between the regional stress field and a local stress-field perturbance. It is therefore postulated that central-caldera structures are incompatible with the remainder of the structural inventory and thus are interpreted to reflect a local, magmatically driven stress-field perturbation.

1.3 Subsurface geology

According to binocular analysis and petrographic microscope observations, the lithological units encountered in most drilled wells are dominated by trachyte, tuff and pyroclastics and a syenitic intrusion intercepted at depth with varying degree of alteration. Hydrothermal minerals in Menengai occur as replacement of primary minerals or as vein and vesicle fillings. The Menengai alteration mineralogy model is defined by the four zones; unaltered, zeolite, transition and illite and quartz. A syenitic intrusion was intercepted intermittently in a number of wells hence yielding different orders of magnitude of permeability although marked by high temperature minerals such as wollastonite and actinolite, which are invariably seen forming in vugs as discussed by Kipchumba (2013).

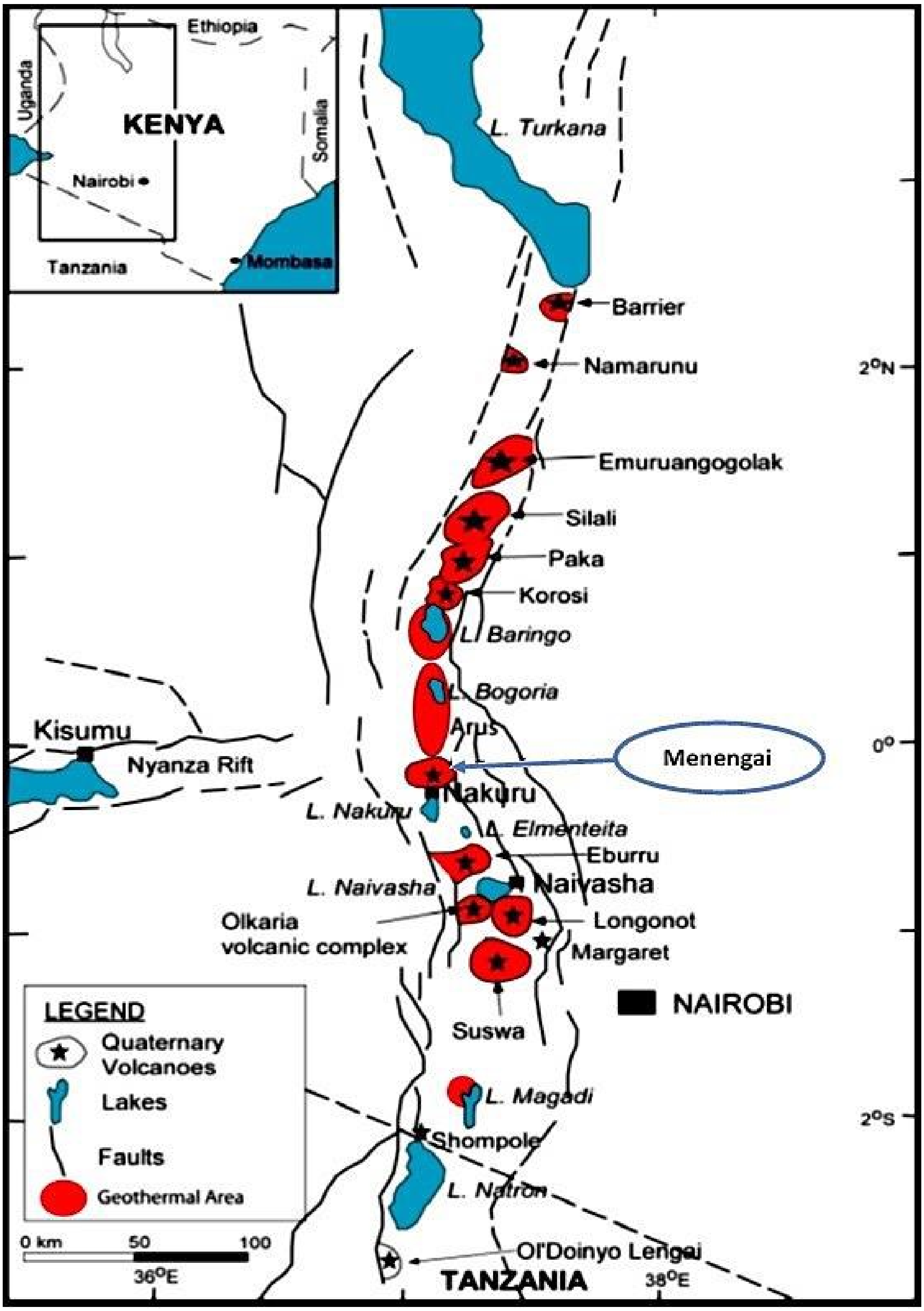

Figure 1: The location of the Menengai geothermal field in Kenya.

2. GENERAL CHEMISTRY OF THE DISCHARGED FLUIDS

2.1 Water chemistry

The chemistry of discharge fluids in the Menengai wells exhibits widely varying chemical properties from well to well. This observed variability is ascribed to the heterogeneity of the reservoirs feeding Menengai wells. The fluid discharge belong to the $NaHCO_3$ facies with significant chloride concentrations. The gas content in the steam varies greatly in weight %**,** and of which is over 90% CO_2.

Calculation of chemical composition of reservoir liquids is usually affected by boiling and potential causes for observed discharge enthalpy. Figure 2 (left) shows the relationship between total discharge enthalpy as measured and aquifer temperature. The aquifer temperatures were obtained from analysis of temperature logs (under flowing and static conditions) and fluid geothermometry. It is noted in Figure 2, left that most wells in Menengai are characterized by excess enthalpy, in some cases very pronounced, owing to reservoir boiling and preferential steam inflow into the well yielding varying in-hole steam fractions ranging from 0.1 to over 0.9. The corresponding percentages of deep steam computed through analysis of the silica enthalpy plot of Figure 6 are within the same range. In some wells, dilution and conductive cooling is inferred. In this regard, several assumptions must be made in order to translate chemical compositions of the well discharge fluids of excess enthalpy wells into geothermal reservoir fluid compositions.

Reservoir pH values computed with the aid of WATCH computer code (Arnórsson et al. 1982, version 2.4 of Bjarnason 2010) range from 7.5 to 8.8. Notably, the WATCH program may slightly overestimate reservoir values given that pH values calculated by WATCH are controlled by partitioning of gases (chiefly CO_2) between coexisting vapor and liquid phases. The relative concentrations of major anions (HCO_3+CO_3, SO_4, and Cl) adapted from Giggenbach (1988) show that Menengai reservoir liquids belong to the Na-HCO_3 facies (Figure 2, right). A few of the wells though (MW-19, -19A, 19B and 20A may be classified as Na-HCO_3-Cl waters. It is worth noting that the Giggenbach (1988) trilinear diagram was plotted under the premise of the existence of mature Na-Cl waters in an andesitic volcano. However, studies in Menengai, Ol'karia and Aluto Langano situated along a continental-rift zone have displayed existence of mature Na-HCO_3 type of waters. In this respect, the trilinear diagram may be modified. Moreover, available data for volcanic gases, though comparatively limited in number, indicate that subduction-zones volcanic gases are enriched in Cl relative to hotspot and divergent-plate volcanic gases (Symonds et al., 1994; Sawyer et al., 2008). Notably, sulphate content in the reservoir liquids is relatively high (50 to about 300 mg/kg) suggesting varying degrees of mixing of high and low enthalpy fluids.

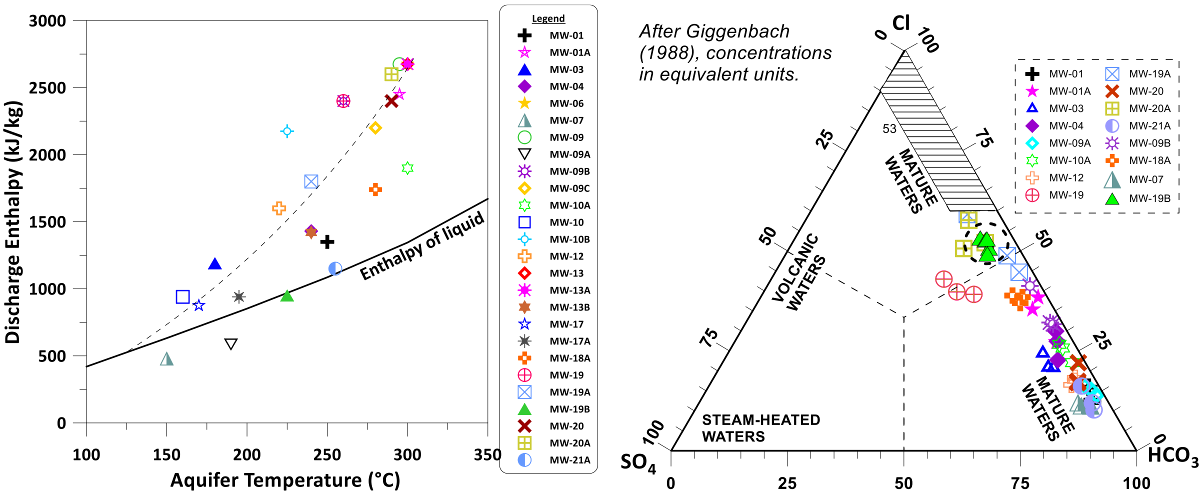

Figure 2: Correlation of measured enthalpy and aquifer fluid temperature (left) and Cl-HCO_3-SO_4 ternary (right)

Sodium is the dominant cation in the reservoir liquids and inversely correlates with discharge enthalpy (Figure 3, left). In principle, these differences may be ascribed to the different temperatures present in the zones of provenance of these liquids. It is evident that the concentration of an aqueous solute in the total discharge will decrease as discharge enthalpy increases if excess enthalpy is caused by phase segregation, which seems to be mostly the case in Menengai. The concentrations of K also appear to generally have an inverse correlation with temperature except for wells MW-20, MW-18A and MW-01 (Figure 3, right). Accordingly, the Na/K ratios appear to mostly decrease with increasing enthalpy (Figure 4, left), consistent with what is expected.

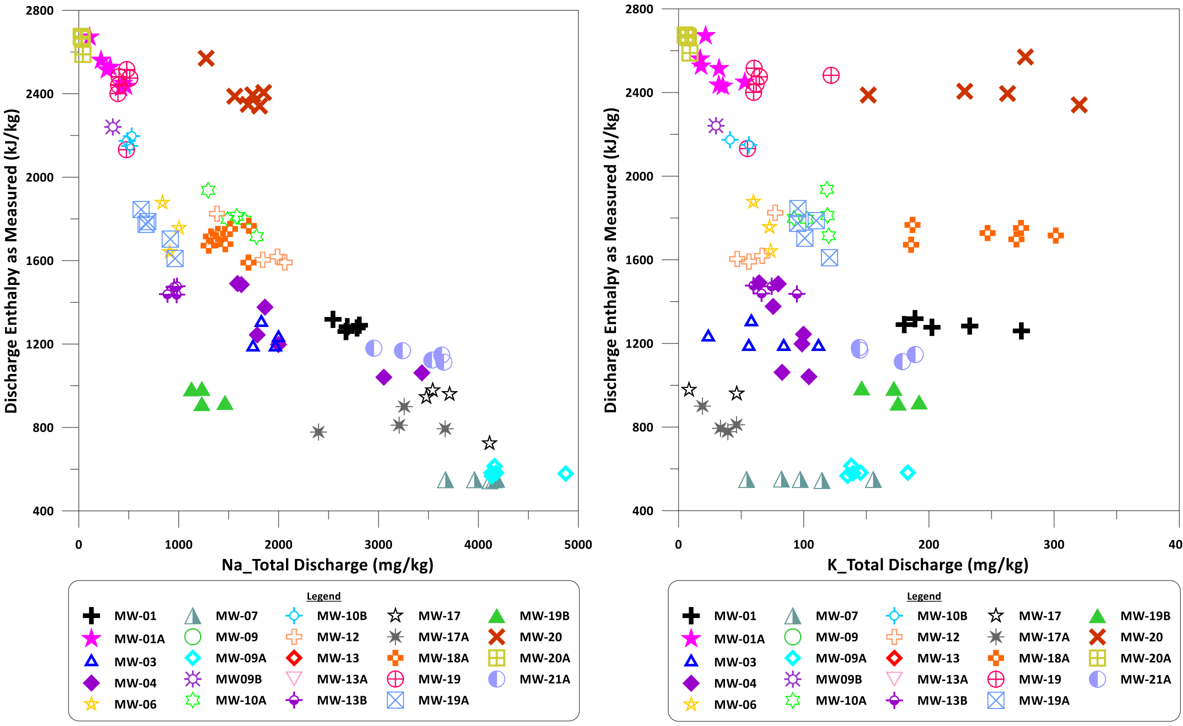

Figure 3: Correlation plots of enthalpy and Na (left) and enthalpy and K (right)

Low calcium is observed in the samples analysed, with no clear relationship to enthalpy. The low concentrations could be the consequence of uptake of Ca from the fluid as a result of formation of $CaCO_3$ upon flashing of the geothermal water. On the other hand, fluoride concentrations are notably high in the well discharges and could largely be due to two possibilities; removal of calcium as calcite deposits leading to excess fluoride or the addition of fluoride to the fluid by condensation of volcanic gases (HF).

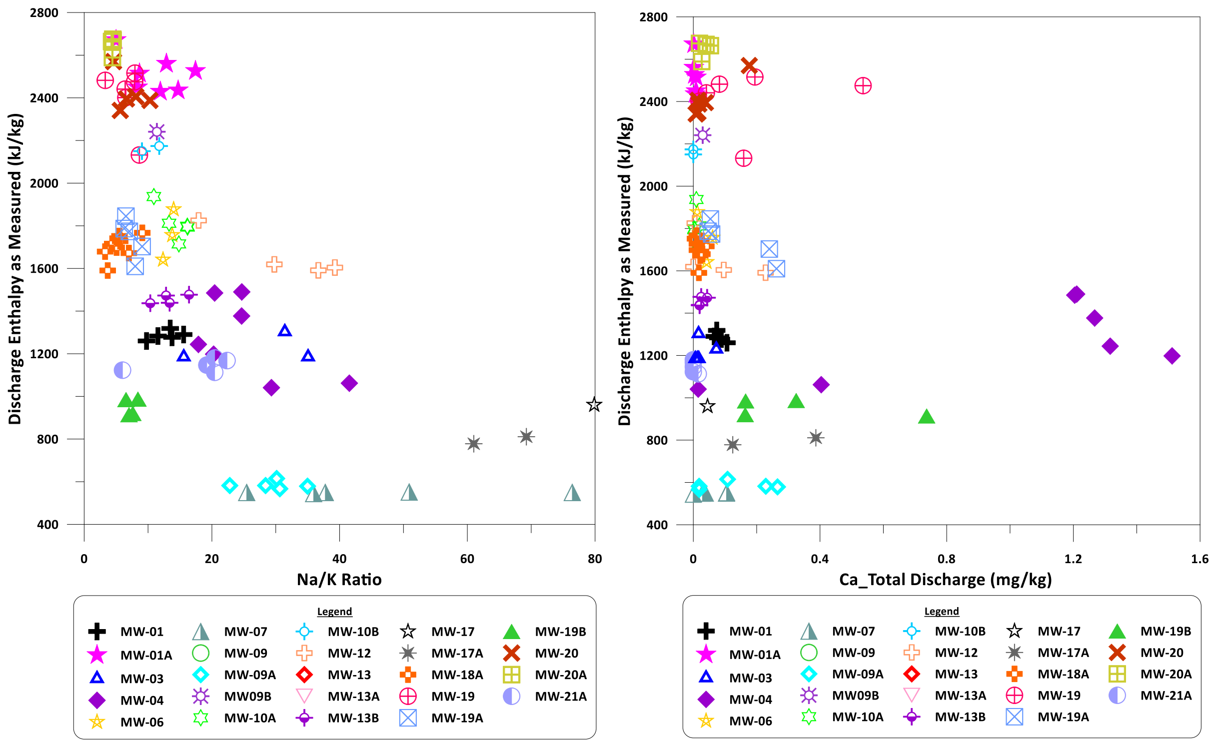

Figure 4: Correlation plots of enthalpy and Na/K ratio (left) and enthalpy and Ca (right)

2.2 Gas chemistry

Before considering gas equilibria, it is instructive to contrast the concentration of gas species with discharge enthalpy (Figures 7 and 8) to investigate the gas chemistry of reservoir vapors and reservoir liquids. The enthalpy has been preferred as a reference variable to the fraction of reservoir steam, because the enthalpy data are available for all the gas samples whereas the fraction of reservoir steam is not. CO_2 is the dominant gas in the Menengai geothermal reservoir accounting for over 90 percent of the gases present. It is observed that there is an inverse correlation of CO_2 content with discharge enthalpy as measured. This could be attributed to boiling in the reservoir and subsequent gas loss. H_2S concentrations are largely controlled by reservoir temperature although other processes like mixing of higher enthalpy with lower enthalpy fluids may also be responsible.

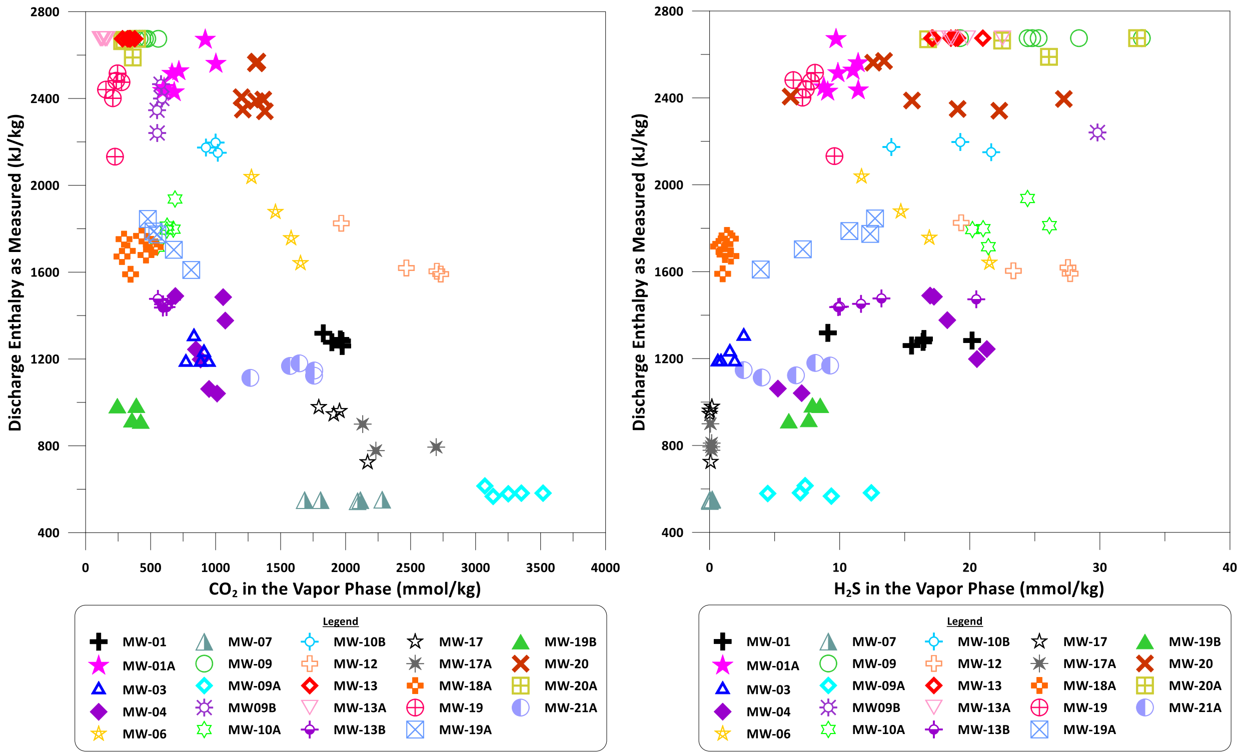

Figure 5: Correlation of enthalpy with CO_2 (left) and with H_2S (right) in the vapor phase

The concentration of H_2 is also dependent on temperature and suggests varying steam vapor fractions in the reservoir(s) tapped by Menengai wells. Methane appears to vary depending on well location, although is notably present in relative abundance in lower enthalpy wells. This suggests that the main source of CH_4 in the Menengai wells discharge fluid is not the high temperature reservoir at depth, despite the possible existence of equilibrium between CO_2 and methane inferred from the redox conditions approximated by the Fayalite-Hematite-Quartz (FHQ) buffer (Kipngok et al., 2014).

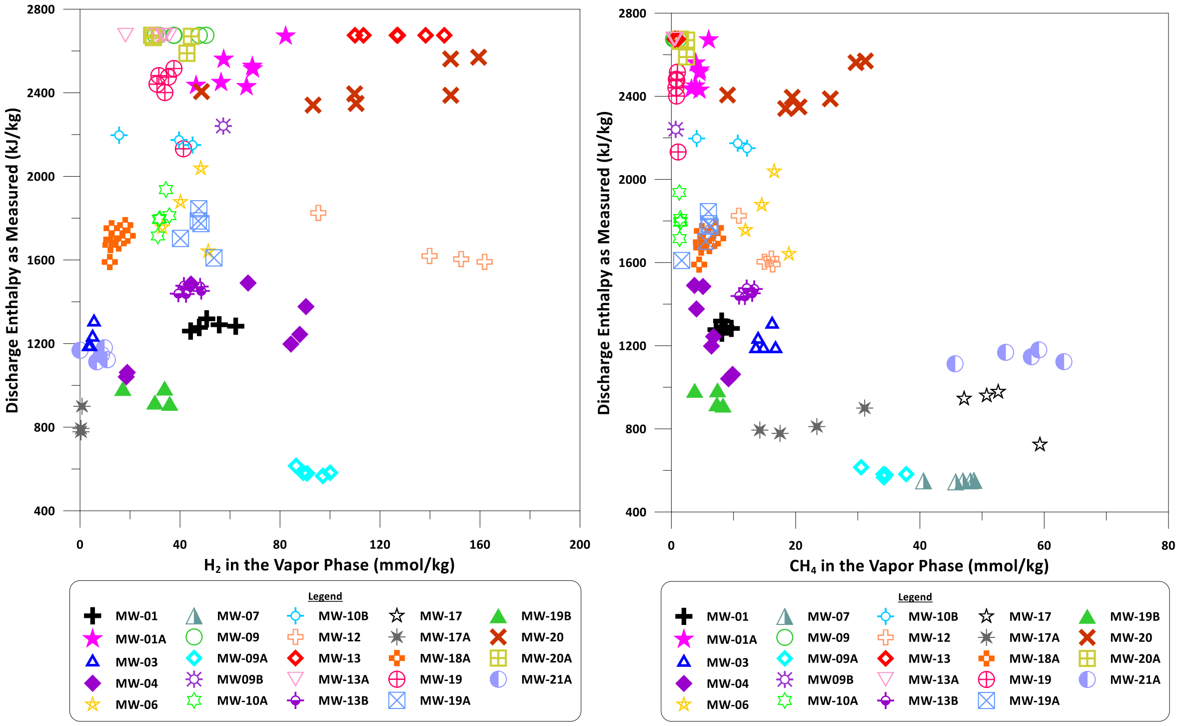

Figure 6: Correlation of enthalpy with H_2 (left) and with CH_4 (right) in the vapor phase

3. PHYSICOCHEMICAL PROCESSES THAT CONTROL FLUID CHEMISTRY

Physico-chemical processes that control the fluid chemistry and physical conditions of the wells have been evaluated. The cause of calculated excess reservoir gas concentration and excess discharge enthalpy may result from the same processes (Auko, 2014). Various Menengai wells display excess discharge enthalpy (i.e. the enthalpy of the discharged fluids is higher than that of the enthalpy of saturated liquid at the aquifer temperature; $h^{dt} > h^{f,l}$). The inferred processes modifying the chemistry of the fluids in Menengai system is described below.

3.1 Cl in the liquid phase and total two-phase discharge as a function of discharge enthalpy h^{dt}

The chemistry of well discharges can be used to distinguish between the excess discharge enthalpy caused by phase segregation and by conductive heating. Therefore, the relative contribution of the two processes can be qualitatively evaluated by plotting the liquid phase and total discharge concentrations of a conservative aqueous solute against discharge enthalpy (Glover et al. 1981; Arnórsson et al., 2007; Scott et al., 2011). Arnórsson and Stefánsson (2005 a, b) extensively described the methodology and equations for calculating liquid phase and total discharge concentrations.

The concentrations of Cl in the liquid phase and total two-phase discharge as a function of discharge enthalpy of selected wells are presented in Figure 7. The figure indicates systematically-decreasing concentrations of Cl in the total well discharge as fluid enthalpy increases, suggesting that the dominant cause of elevated discharge enthalpies is liquid–vapor phase segregation, i.e. the retention of liquid in the aquifer rock due to its adhesion onto mineral surfaces. However, closer inspection of the figure also some possible increases in Cl concentration in the liquid phase with an increase in enthalpy, which fits the model of heat addition via conductive heat transfer from the intercepted intrusions to the circulating fluids to induce boiling, thus contributing to the excess enthalpy and even forming superheated steam. Thus, the concentration of Cl in the liquid phase as a function of discharge enthalpy yields a mixed pattern, which suggests that the excess discharge enthalpy has contributions from both phase separation and conductive heat transfer.

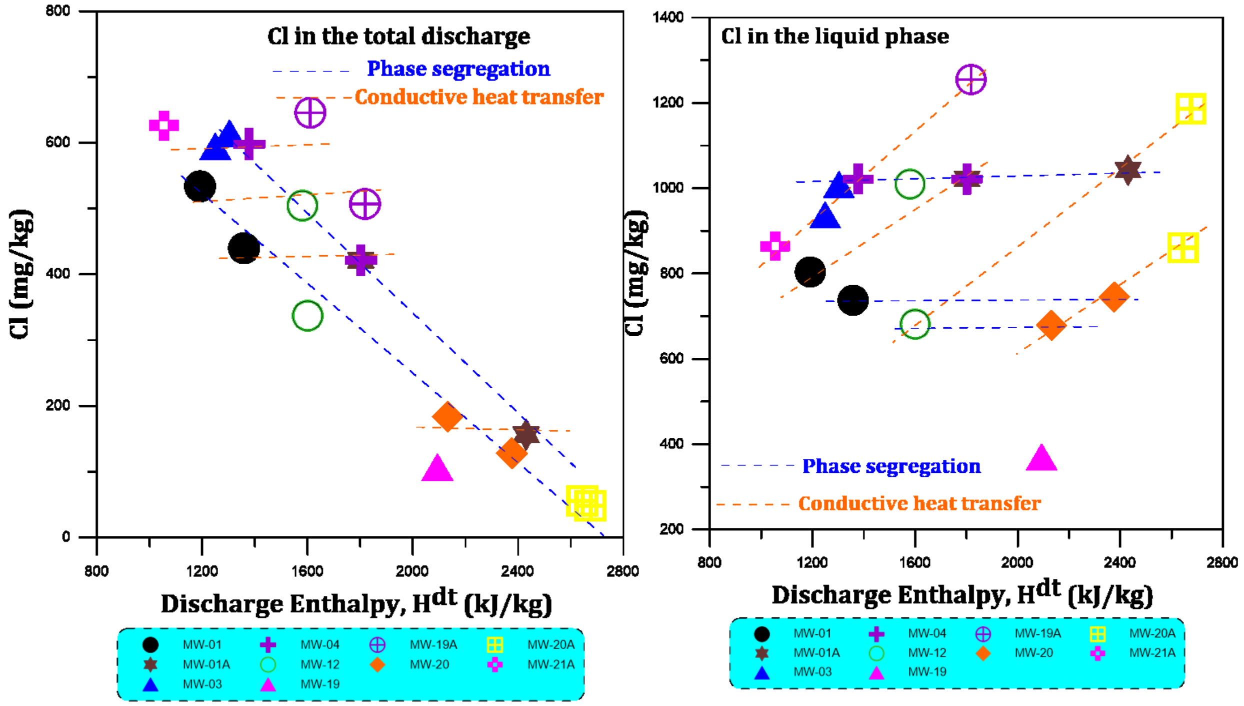

Figure 7: The concentrations of Cl in the liquid phase and total two-phase discharge as a function of discharge enthalpy (Hd,t)

3.2 SiO_2 vs enthalpy cross plot

A correlation plot of total discharge concentration of SiO_2 vs. enthalpy was generated to evaluate the processes that modified the chemistry and physical properties of the well discharge (Figure 8). The plot was used to evaluate the mixing scenario between the shallow end-member feed zone and a deep end-member steam dominated feed zone. The plot was also used to obtain the apparent silica equilibrium temperature of the geothermal liquids entering the wells. Features, procedures and equations of the bell-shaped curve is exhaustively described by Marini (2004). Also shown, in the diagram are the lines connecting the average steam and the average liquid entering the well (red dashed lines) and the inferred silica equilibrium temperature of the average liquid.

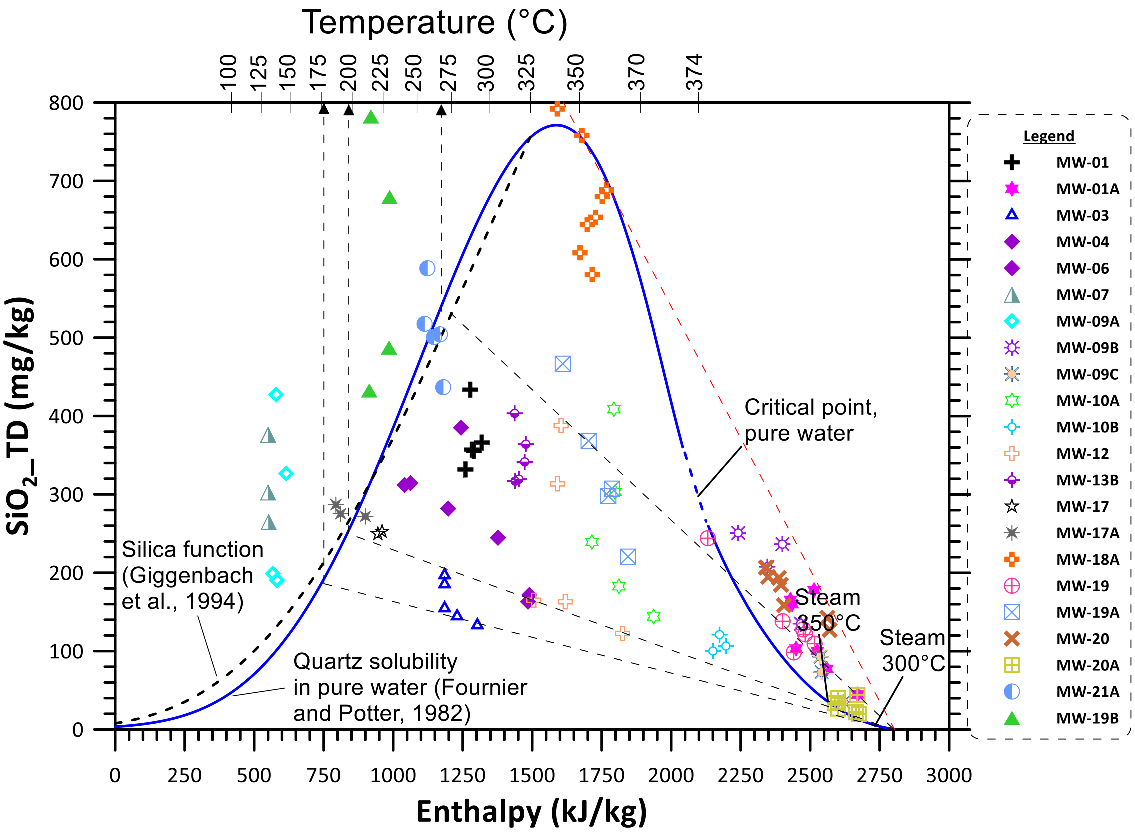

Figure 8: Correlation plot of total discharge concentration of SiO2 vs. enthalpy for the reservoir fluids tapped by Menengai wells, also showing quartz solubility in pure water (Fournier and Potter, 1982) and solubility of quartz/chalcedony (Giggenbach et al., 1994).

From the plot SiO_2 vs. enthalpy of the Menengai wells (Figure 8), the following deductions can be drawn from the relative positioning of the samples:

Three categories of reservoir fluids are inferred: (i) fluids with a relatively high vapor fraction (MW-20A, -01A, -09C, -19, -09B, -10B, 1-0A, -19A), (ii) liquid dominated fluids (MW-01, -21A, -18A, -04, -13B, -12, -17A, -03,) and (iii) fluids that have undergone conductive cooling and/or mixing with lower enthalpy equilibrated fluids (MW-19B), and significant mixing with lower enthalpy fluids (MW07 and MW-09A). The relative positioning of the samples outside to the left the bell shaped curve is an indication that fluids entering the wells had initially boiled in the reservoir and subsequently undergone conductive cooling.

3.3 Cl vs enthalpy cross plot

The Cl-enthalpy plot of Figure 9 depicts the different characteristics of Menengai wells and the possible processes that are responsible for the observed variations in the chemistry of wells discharge fluid. It is inferred that the main upflow is located in the central part of the caldera in the vicinity of well MW-13. In the eastern sector, it is possible that another upflow exists around well MW-18A (Njue and Kipngok, 2018). Several processes influence the fluid composition leading to the observed variations in the fluid chemistry, which include; boiling and phase segregation (the dominant process), mixing/dilution and conductive cooling. Addition of magmatic fluids is another possible factor.

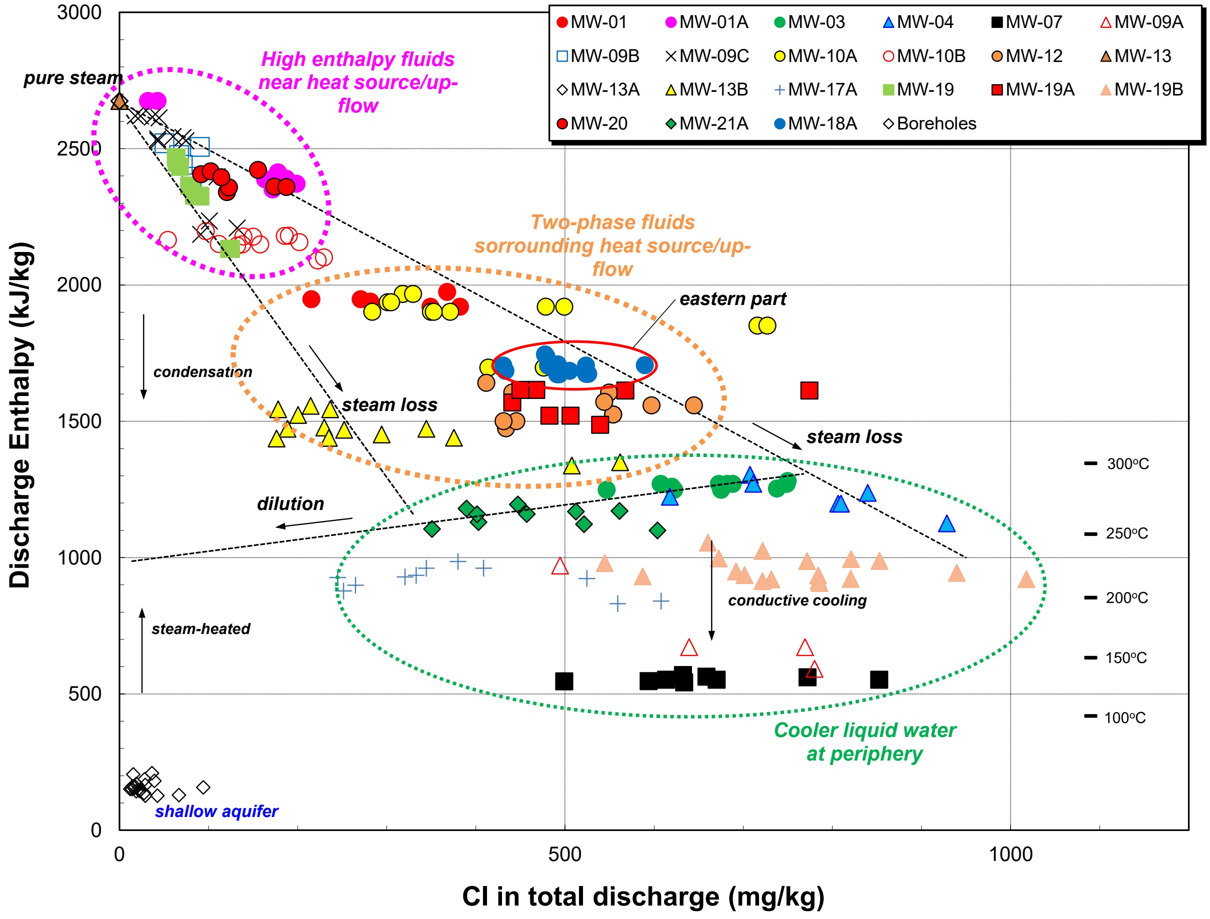

Figure 9: Cl-enthalpy plot of Menengai wells fluids

3.4 Volatile mineral buffers of CO_2, H_2S and H_2

The procedure adopted to assess fluid-mineral equilibrium is that described by Scott et al. (2014) and Auko (2014). As observed, the main cause of elevated discharge enthalpies in Menengai is liquid-vapor phase segregation i.e. the retention of liquid in the aquifer rock due to its adhesion onto mineral surfaces. Selected wells that represent the characteristics of different parts of the Menengai geothermal reservoir were used to assess equilibria between gases and the mineral assemblages that control these gases. Three of the models described by Arnórsson et al. (2007) and thermodynamic data presented in Arnórsson et al. (2010) were used to evaluate gas-mineral equilibria in these wells. Model 1 represents an isolated system while model 2 and 3 correspond to a closed system and an open system respectively. The equilibrium curves of mineral assemblages that could potentially control the activities of the main reactive gases CO_2, H_2S, H_2 are compared with that of the calculated dissolved gas concentrations assuming unit activity. The results for the models are shown in Figure 10 and 11.

Depending on the model used (i.e. model 2 and 3), CO_2 appears to be superficially controlled by hydrothermal mineral assemblages except for well MW-21A which may be have a source controlled contribution. H_2S is also in equilibrium with hydrothermal mineral assemblages with the exception of well MW-18A. It therefore follows that, the relatively low H_2S in well MW-18A and MW-03 and other related wells is still a subject of investigation.

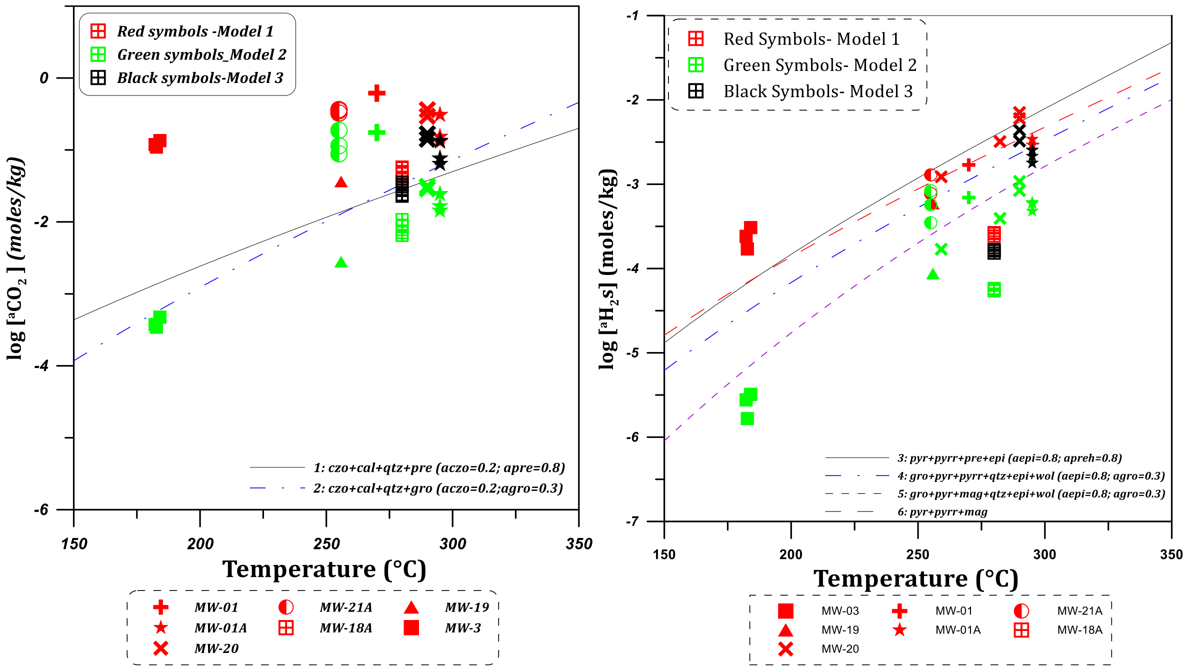

Figure 10: State of equilibrium between calculated concentrations of CO_2 and H_2S in the aquifer water in selected wells using models 1, 2 and 3.

It can be deduced that H_2 concentrations are higher than would be in equilibrium with respective mineral assemblages in all wells selected. This agrees with earlier observations of significant vapor fraction(s) in the reservoir(s) in Menengai, at least at depth for most wells. The graphs further show the most appropriate models that can be used for the different wells based on their enthalpies.

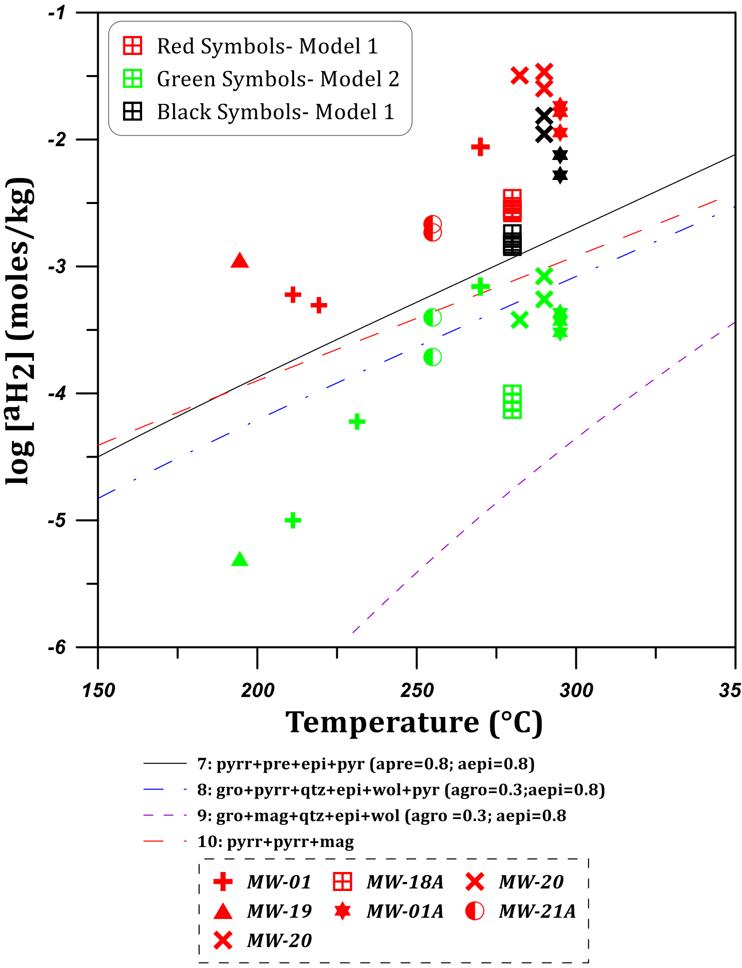

Figure 11: State of equilibrium between calculated concentrations of H_2 in the aquifer water in selected wells using models 1, 2 and 3.

4. CONCLUSIONS

Menengai reservoir water belongs to the Na-HCO_3 facies although wells located in the northern sector of the central part may be classified as Na-HCO_3-Cl type.

The widely varying chemical properties from well to well indicate heterogeneity of the reservoirs feeding the wells at Menengai.

The predominant processes occurring in the Menengai reservoir are boiling and partial or full phase segregation for wells with high vapour fraction, with significant contributions from heat transfer from hot rock or magma compounding to form superheated steam in certain wells. Moreover, mixing and conductive heat transfer/cooling play a role.

Three categories of reservoir fluids feed the wells: (i) fluids with a relatively high vapor fraction (MW-20A, -01A, -09C, -19, -09B, -10B, 1-0A, -19A), (ii) liquid dominated fluids (MW-01, -21A, -18A, -04, -13B, -12, -17A, -03,) and (iii) fluids that have undergone conductive cooling and/or mixing with lower enthalpy equilibrated fluids (MW-19B), and significant mixing with lower enthalpy fluids (MW07 and MW-09A).

The cause of calculated excess reservoir gas concentration and excess discharge enthalpy may be ascribed to result from the same processes.

H_2S in the reservoir(s) in Menengai is largely controlled by hydrothermal minerals but H_2 is higher, suggesting the presence of significant vapor fraction in the reservoir, albeit in varying proportions/degrees. On the other hand, CO_2 demonstrates minimal hydrothermal mineral buffering and could be source-controlled from the mantle.

The inferred upflow location is within or in the locality of well MW-13 in the central part of the Menengai geothermal field although existence of another upflow is possible in the eastern sector of the field, in the vicinity of well MW-18A.

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