

# Characterization of the Menengai High Temperature Geothermal Reservoir Using Gas Chemistry

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## Keywords

*Menengai, geothermal wells, triangular diagrams, chemical characteristics, mineral-gas equilibria, FHQ buffer, redox conditions*

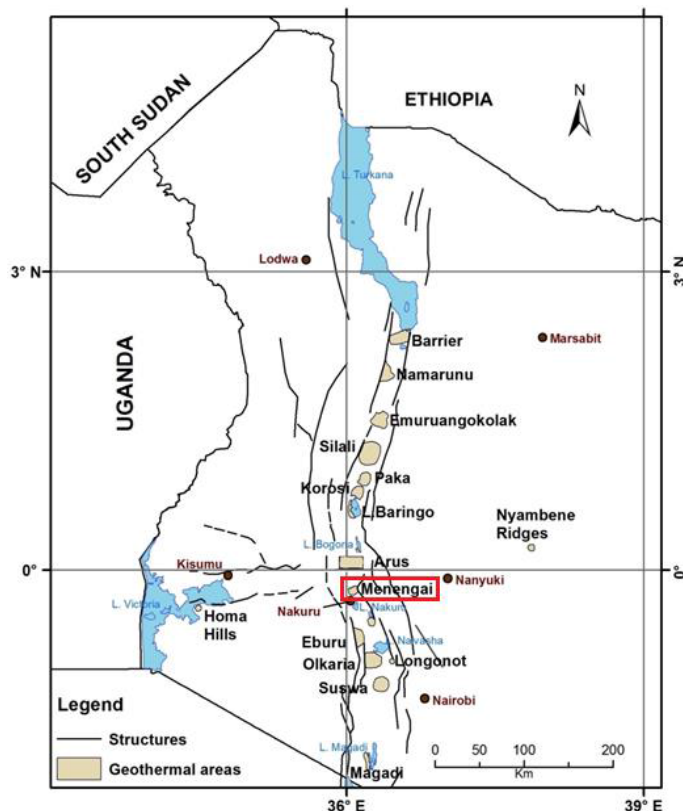
## ABSTRACT

Successful drilling of geothermal wells has been undertaken in the Menengai Geothermal Field and development of the field is currently underway, with generation of the first 100 MW of electricity scheduled to come online by 2015. This paper presents the characteristics of the Menengai geothermal reservoir from well discharge vapors. Two major chemical constituents,  $H_2O$  and  $CO_2$ , have been considered together with other gas species  $H_2S$ ,  $H_2$ ,  $CH_4$  and  $N_2$  to compare the chemical characteristics of vapors discharged by the Menengai geothermal wells by means of triangular diagrams. The Menengai geothermal reservoir fluids show variable  $H_2O/CO_2$  ratios. The results further indicate that low  $H_2O/CO_2$  ratios appear to reflect high temperatures from the deeper permeable horizons while higher ratios are characteristic of the relatively lower temperature upper feed zones in the wellbores. It is further noted that wells producing steam are richer in  $H_2S$  than wells discharging two-phase fluids. Investigation into mineral-gas equilibria reveal that the Fayalite-Hematite-Quartz (FHQ) buffer approximates the redox conditions supposedly present in the zones where gases attain chemical equilibrium in the Menengai geothermal reservoir. This inference is further affirmed by the lithological units encountered in the wells. Moreover, the vapors discharged by Menengai geothermal wells record equilibrium temperatures from  $280^\circ C$  to over  $340^\circ C$  and attainment of equilibrium in either a single phase or at a vapor/(vapor + liquid) mass ratio of varying values. These equilibrium temperatures are comparable to measured temperatures in the deepest sections of the wells.

## 1. Introduction

The Menengai Geothermal Field is hosted in the Menengai volcano situated in the central sector of the Kenya Rift Valley (Fig-

ure 1). Deep drilling of geothermal wells in this geothermal field started in February, 2011 and proved the existence of exploitable steam (see Figure 2 for the location of the wells). Presently, plans are underway to have the first 100 MW of electricity connected to the national grid by 2015 with production drilling ongoing. Out of nine wells discussed in this paper, six discharge a two-phase mixture while three discharge single phase fluids (vapor dominated). It is however important to note that well MW-20, though two-phase, has discharged over 90% vapor as it attained



**Figure 1.** Map showing location of Menengai volcano (highlighted) and other geothermal areas in Kenya (GDC, 2012).

thermal stability and exhibits high enthalpy close to that of a single vapor phase. Well MW-01 has had three major discharge regimes distinguished by rig work overs that subsequently led to improved productivity of the well.

A considerable effort has been made towards understanding the magmatic-hydrothermal system of Menengai from fluids discharged by the geothermal wells (e.g. Kipng'ok, 2011; Sekento, 2012; Malimo, 2013). The main contribution of this paper is to characterize the Menengai geothermal reservoir from the chemistry of vapors discharged by the wells as well as provide some insight into mineral-gas equilibria in the reservoir.

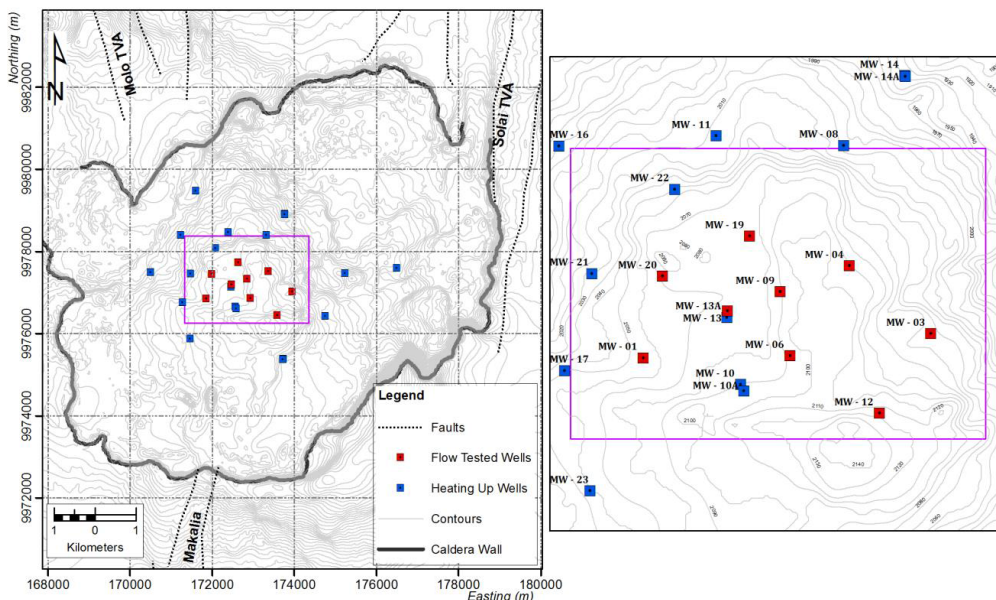


Figure 2. Map showing the Menengai caldera and the location of geothermal wells (GDC, 2014).

## 2. Geological Setting

Much has been published on the geology of Menengai with several researchers having carried out investigations for varying reasons ranging from academic to geothermal resource surveys (McCall, 1967; MacDonald et al., 1970; Griffith, 1977; Jones & Lippard, 1979; Jones, 1985; Griffith, 1980; Griffith and Gibson, 1980; Leat, 1983, 1984; Williams et al., 1984; Geotermica Italiana Srl, 1987; MacDonald et al., 1994; Mungania et al., 2004; Lagat et al., 2010). These studies, particularly those directed towards geothermal energy exploration, indicated the presence of a geothermal system whose heat source was presumed to correspond to the magmatic chamber responsible for the eruption of a huge volume of pyroclastic flows that resulted to the collapse of the Menengai caldera. The rocks, from these studies, and those encountered in the wells (Omondi, 2011; Mibei, 2012) are peralkaline trachytes with minor/subordinate pyroclastic intercalations.

The main structures within the Menengai geothermal area are; the Ol'Rongai and Solai structural systems and the Menengai caldera ring faults (Mungania et al., 2004; Lagat et al., 2010). The Ol'Rongai structural system is represented by a concentration of faults oriented NW-SE. These faults form part of the larger Molo tectono-volcanic axis (TVA), Geotermica Italiana Srl (1987). The Menengai caldera has the same NW-SE orientation and was prob-

ably influenced by these faults (Leat, 1984). The Solai structural system comprises structures that extend NE-SW from the Solai area towards Lake Nakuru, south of the caldera. It includes numerous faults and/or fractures that strike in a NE-SW and NNE-SSW direction and form part of the Solai TVA (Figure 2).

## 2. Sampling and Analysis

Steam samples were collected, together with water samples (for the two-phase wells), with the aid of a Webre separator connected to the horizontal fluid flow pipe between the wellhead and the atmospheric silencer. The well discharge vapors were collected in 325-340 ml evacuated gas sampling flasks containing 50 ml of 40% w/v NaOH solution. The gas sampling bulbs were weighed before and after sampling to determine the amount of steam condensate collected. The acidic gases, CO<sub>2</sub> and H<sub>2</sub>S, were analyzed by titration using 0.1M HCl and 0.001M mercuric acetate while the other non-condensable gases (CH<sub>4</sub>, H<sub>2</sub>, N<sub>2</sub> and O<sub>2</sub>) were analyzed by gas chromatograph. The results are discussed in subsequent sections of this paper.

## 3. Gas Chemistry

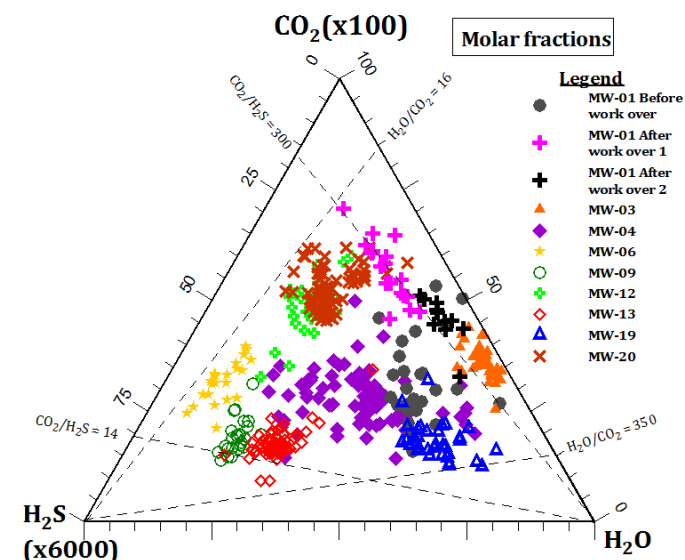
The relative abundance of gases in geothermal fluids will depend both on the fluid type (dilute/saline) and temperature (Arnórsson, 1986; Nicholson, 1993). These gases can originate in the crust, mantle and atmosphere. In

magmatic systems, the source of the reactive components (i.e. CO<sub>2</sub>, H<sub>2</sub>S, and H<sub>2</sub>) are believed to be solidifying magma bodies, while the main source of nitrogen is the recharging meteoric waters that have equilibrated with the atmosphere (Scott et al., 2011). The proportions of these gases may differ from system to system or even in different parts of the same system. In the present contribution, the chemical characteristics of Menengai well discharge vapors have been compared by means of triangular diagrams, where, the two major chemical components, H<sub>2</sub>O and CO<sub>2</sub>, are considered together with other gas species i.e. H<sub>2</sub>S (Figure 3), N<sub>2</sub> (Figure 4), H<sub>2</sub> (Figure 5), and CH<sub>4</sub> (Figure 6).

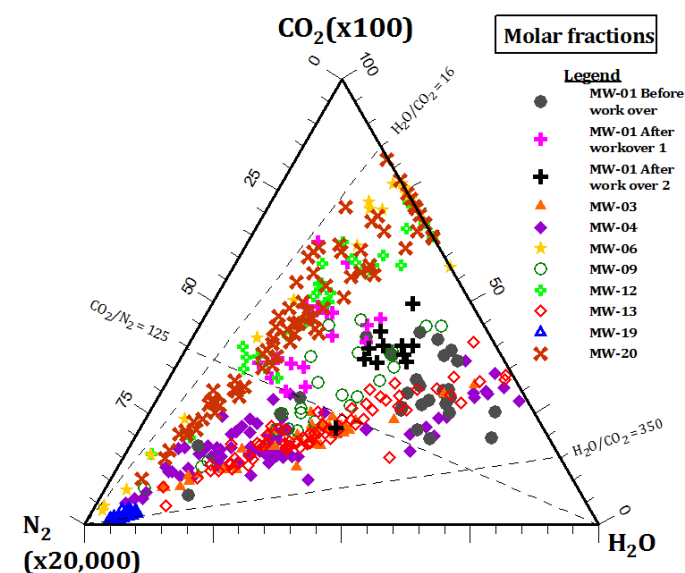
In the ternary plots presented in Figures 3 to 6, Menengai reservoir fluids show variable H<sub>2</sub>O/CO<sub>2</sub> ratios, ranging from 16 to about 350. Fluids from wells MW-19, MW-03 and some samples from well MW-04 and MW-01 (before work over) show comparatively high H<sub>2</sub>O/CO<sub>2</sub> ratios. Fluids from wells MW-20, MW-01 (after work over 1), MW-12, and MW-06 have relatively low H<sub>2</sub>O/CO<sub>2</sub> ratios, while samples from well MW-09, MW-13, MW-01 (after work over 2) occupy an intermediate position. Although the CO<sub>2</sub> content, which varies between wells, significantly influences this ratio, it is noted that high H<sub>2</sub>O/CO<sub>2</sub> ratios appear to reflect relatively lower temperature fluids entering in at the shallower aquifers (for the two-phase wells). This inference

is made taking into account the different solute geothermometer temperatures (particularly silica temperatures) of wells discharging a two-phase mixture (Malimo, 2013). Moreover, Kipng'ok (2011) and Suwai (2011) noted the existence of multiple feed zones of varying temperatures in well MW-01 (i.e. highest temperature in the deepest feeders and relatively lower in the upper/shallower producing aquifers), and which appears to be characteristic of Menengai two-phase wells.

The ternary plot of H<sub>2</sub>O-CO<sub>2</sub>-H<sub>2</sub>S (Figure 4) indicates that wells MW-06, MW-09 and MW-13 that produce a single steam phase are richer in H<sub>2</sub>S relative to wells discharging two-phase fluids. Well MW-01 (after work over I and II) and well MW-03 are characterized by the highest CO<sub>2</sub>/H<sub>2</sub>S ratios (>300), which may be due to low contributions of deep steam to the well discharge.



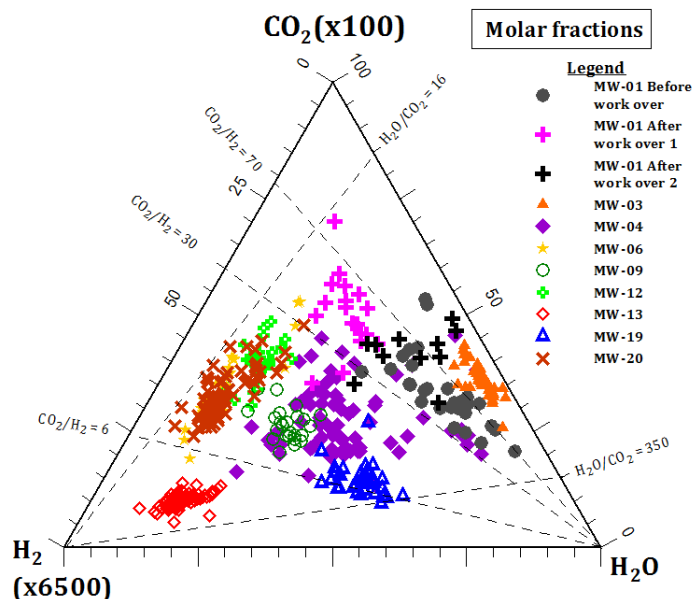
**Figure 3.** Ternary plot of H<sub>2</sub>O-CO<sub>2</sub>-H<sub>2</sub>S showing the reservoir fluids feeding wells MW-01, MW-03, MW-04, MW-06, MW-09, MW-12, MW-13, MW-19 and MW-20 in the Menengai Geothermal Field.



**Figure 4.** Ternary plot of H<sub>2</sub>O-CO<sub>2</sub>-N<sub>2</sub> showing the reservoir fluids feeding wells MW-01, MW-03, MW-04, MW-06, MW-09, MW-12, MW-13, MW-19 and MW-20 in the Menengai Geothermal Field.

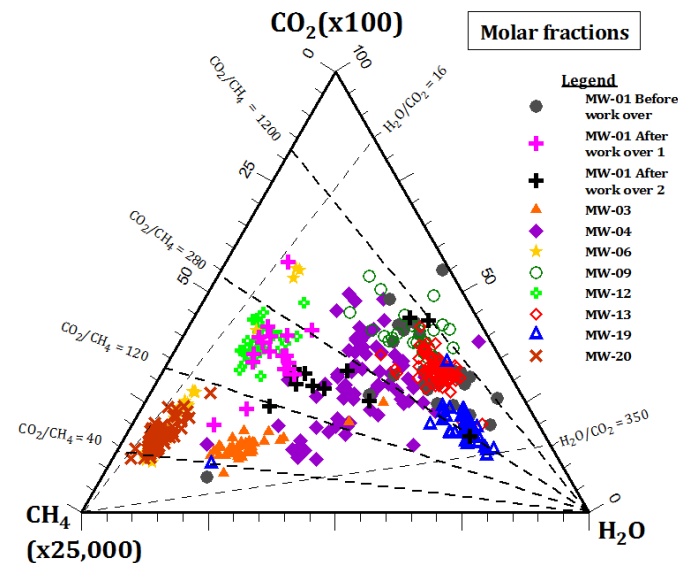
This is further confirmed by the middle graph (H<sub>2</sub>S) in Figure 8, at least in the case of well MW-01, which does not indicate higher discharge enthalpy after work over I and II despite a significant improvement in output.

In the ternary plot of H<sub>2</sub>O-CO<sub>2</sub>-N<sub>2</sub> (Figure 4), most samples from wells MW-01, MW-12, MW-06, MW-09 and to some extent MW-20 appear to be N<sub>2</sub>-depleted relative to most samples from wells MW-03, MW-04, MW-13, and MW-19. Differences in the N<sub>2</sub> content could be attributed to preferential nitrogen loss upon boiling, particularly in wells MW-01, MW-12, MW-06 and possibly MW-09. It is also possible that air contamination could have occurred during sampling and/or the presence of aerated drilling fluids in the reservoir given that the results are for wells that were being tested not long after completion of drilling. There are however other sources of N<sub>2</sub> in geothermal fluids. Norman et al. (2001) observed from examination of well discharges that wells have N<sub>2</sub> and Ar concentrations of up to ten times greater than that of air saturated water (ASW) and concentrations as low as one tenth that of ASW. Furthermore, studies in Iceland have shown that N<sub>2</sub> may also have its origin in magmatic gas or decaying organic matter (Giroud, 2008).

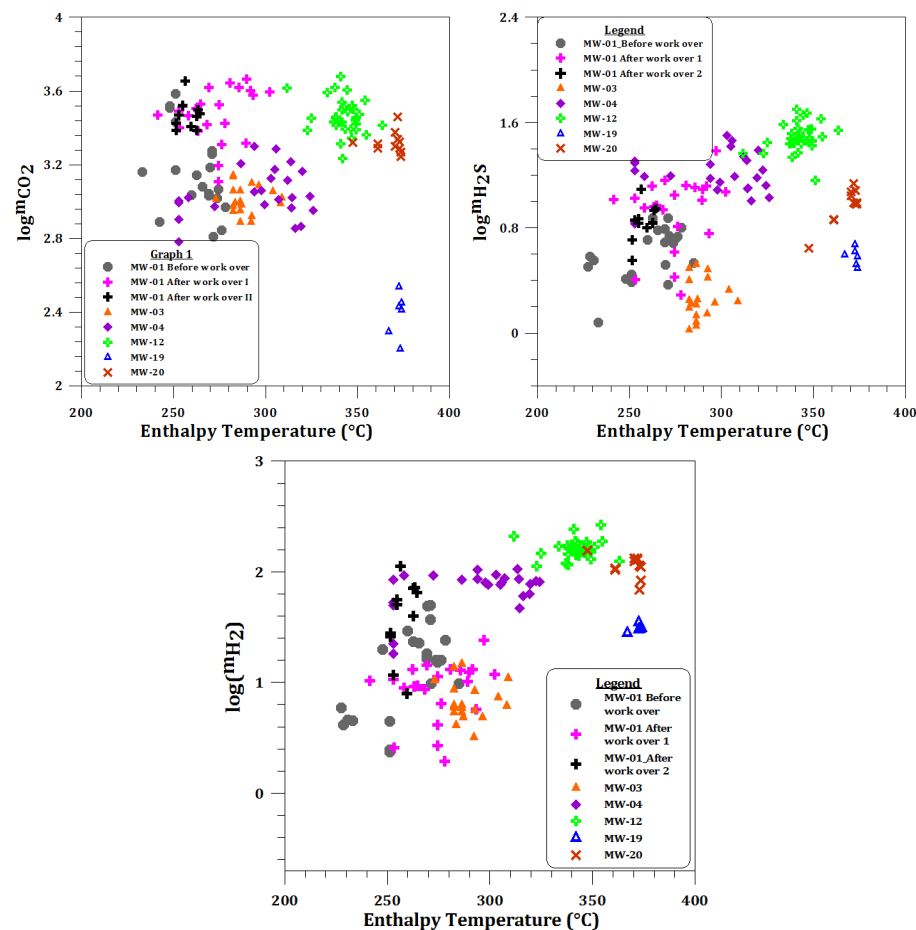


**Figure 5.** Triangular plot of H<sub>2</sub>O-CO<sub>2</sub>-H<sub>2</sub> showing the reservoir fluids feeding wells MW-01, MW-03, MW-04, MW-06, MW-09, MW-12, MW-13, MW-19 and MW-20 in the Menengai geothermal field.

The ternary plot of H<sub>2</sub>O-CO<sub>2</sub>-H<sub>2</sub> (Figure 5) illustrates varying H<sub>2</sub> content in the Menengai wells with MW-13 being the richest in H<sub>2</sub>, having CO<sub>2</sub>/H<sub>2</sub> ratios lower than 6, while fluids from wells MW-03 and MW-01 are the poorest in this gas, with CO<sub>2</sub>/H<sub>2</sub> ratios higher than 30 and 70, respectively. Fluids of wells MW-04, MW-06, MW-09, MW-12, MW-20 and to some extent, MW-19 have intermediate characteristics, with 6 < CO<sub>2</sub>/H<sub>2</sub> < 30. High H<sub>2</sub> is usually taken to indicate the presence of vapor fraction in the initial reservoir fluid, which raises the concentrations of the weakly water soluble H<sub>2</sub> in the aquifer liquid but not so much the concentrations of the more soluble CO<sub>2</sub> and H<sub>2</sub>S (Giroud, 2008; Arnórsson et al., 2010). This view is also supported by the recorded high ('excess') enthalpy as measured in these wells (>1800 kJ/kg) except for well MW-04 (~1400 kJ/kg) and MW-12 (~1650 kJ/kg).



**Figure 6.** Triangular plot of H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub> showing the reservoir fluids feeding wells MW-01, MW-03, MW-04, MW-06, MW-09, MW-12, MW-13, MW-19 and MW-20 in the Menengai geothermal field.



**Figure 7.** Plot of CO<sub>2</sub> (top, left), H<sub>2</sub>S (top, right) and H<sub>2</sub> (bottom) against temperature of discharge enthalpy as measured, assuming the existence of a single liquid phase in the reservoir for the two-phase wells (majority of samples from wells MW-19 and MW-20 have high discharge enthalpy reflecting temperatures above the critical point of water, are not included). *m* denotes component concentrations in mmol/kg.

On the other hand, the ternary plot of H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub> (Figure 6) shows the CO<sub>2</sub>/CH<sub>4</sub> ratios of wells MW-03, MW-06 and MW-20 fluids are comparatively low (40 to 120) while CO<sub>2</sub>/CH<sub>4</sub> ratios of fluids from wells MW-01 (before work over), MW-09 and MW-13 are relatively high (280 to 1200). The CO<sub>2</sub>/CH<sub>4</sub> ratios of fluids from wells MW-01 (after work over I and II) and MW-12 are intermediate (120 to 280), whereas those of fluids from well MW-4 and MW-19 largely occupy the intermediate and high CO<sub>2</sub>/CH<sub>4</sub> ratio segments.

Variations from well to well in the contents of H<sub>2</sub> and CH<sub>4</sub> might be related to the existence of different redox conditions, temperature, pressure, and vapor/(vapor + liquid) mass ratio (referred to as *y* value) in the zones where gas equilibration is attained. Since H<sub>2</sub> and CH<sub>4</sub> are minor components, they are expected to be affected by chemical reactions, particularly hydrogen, which is highly reactive, rather than methane, which reacts slowly, especially at relatively low temperatures.

A correlation between gas concentrations (CO<sub>2</sub>, H<sub>2</sub>S and H<sub>2</sub>) and fluid temperatures derived from enthalpy of total discharge (as measured) is presented in Figure 7. As already noted, discharge enthalpy values are often higher (i.e. 'excess') than those expected for a liquid phase (Muturia et al. (2014). This indicates the occurrence

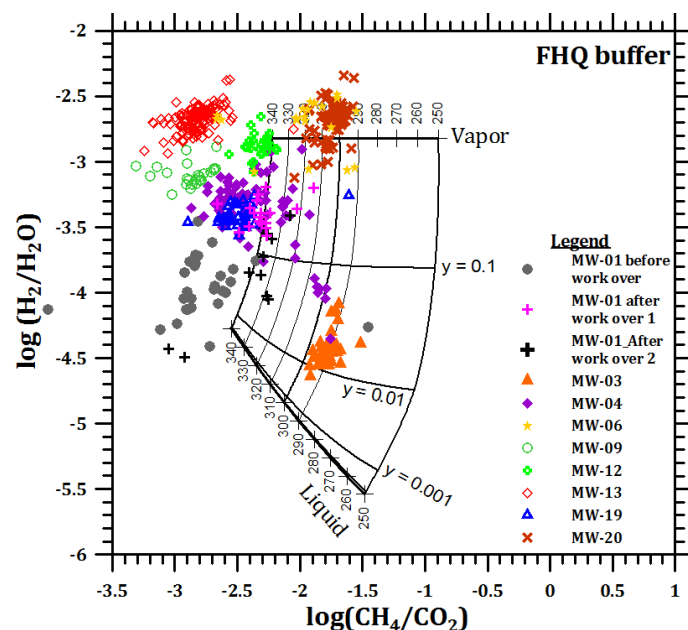
of boiling in the geothermal reservoir and/or the inflow of separated steam into the boreholes under dynamic conditions. The H<sub>2</sub>S and H<sub>2</sub> graphs in Figure 7 show a somewhat strong correlation with temperature indicating that the high gas content (particularly H<sub>2</sub>S) is reflective of high source aquifer temperature. Further evidence on the occurrence of boiling in the reservoir is inferred from the high H<sub>2</sub> content (i.e. suggestive of the presence of vapor fraction in the initial aquifer fluid). The graph of CO<sub>2</sub> versus temperature however paints a rather slightly different picture (except for well MW-19) in that most samples, especially from MW-01 after work over I and II, appear unrelated to the fluid temperature. It is also important to note that the relative abundance of CO<sub>2</sub> has been found to be high at temperatures below about 250°C but decreases with increasing temperature until at about 300°C, when it starts to increase again (Arnórsson, 1986). Considering this view, it's possible that the bulk of the CO<sub>2</sub> (i.e. higher values to a relatively lower enthalpy temperature), observed in well MW-01, particularly after work over, may be coming from the shallower feed zones of temperatures less than 250°C. The measured enthalpy is therefore higher than would be for these upper feeders, as a result of the contribution from the deeper and hotter producing aquifers.

#### 4. Gas Equilibria and Geothermometry

The concentrations of reactive gases in the aquifer fluids are greatly affected by physical properties such as boiling and recharge, but

are generally believed to be in close equilibrium with specific hydrothermal mineral assemblages (e.g. Karingithi et al., 2010; Arnórsson et al., 2010; Scott et al., 2011). In this paper, the Fayalite-Hematite-Quartz (FHQ) redox buffer given by Giggenbach (1987) has been employed in investigating the Menengai reservoir vapors. Giggenbach (1987) showed that the FHQ redox buffer appears to provide a good approximation for many geothermal systems although Chiodini and Marini (1998) found that differences may exist in distinct geothermal systems or even in different parts of the same system. The diagram of  $\log(\text{CH}_4/\text{CO}_2)$  vs.  $\log(\text{H}_2/\text{H}_2\text{O})$  in Figure 8 shows that the FHQ buffer appears to reproduce to approximate the redox conditions presumably present in the zones where gases attain chemical equilibrium in the Menengai geothermal reservoir.

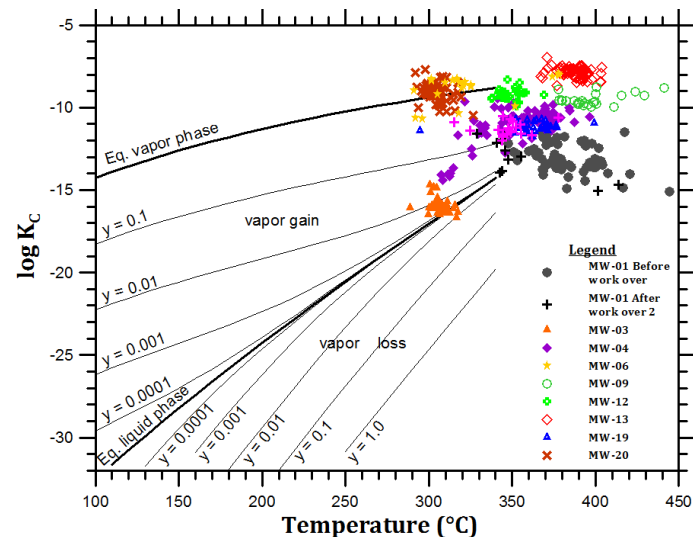
Well lithological units show the presence of olivine grains logged in wells MW-01, MW-04 and MW-06 indicating the presence of fayalite in Menengai (Mibei, 2012; Mbia, 2012). It was further observed that at deeper zones (>500 m depth), oxidation is related to contact zones while secondary quartz has generally been logged in Menengai wells. This provides further evidence favoring FHQ as the buffer that controls the redox conditions in the Menengai geothermal reservoir.



**Figure 8.** Graph depicting the reservoir fluids tapped by Menengai wells compared with the theoretical compositions expected for gas equilibration in a single vapor phase, in a single liquid phase (i.e. pure water), and in two-phase systems with different values of  $y$  = mass ratio of vapor/(vapor + liquid), under redox conditions controlled by the FHQ redox buffer.

The equilibrium temperatures depicted by Figure 8 are chiefly constrained by the  $\text{CH}_4/\text{CO}_2$  ratio while the  $\text{H}_2/\text{H}_2\text{O}$  ratio indicates the mass ratios ( $y$  values). The vapors discharged by wells MW-06, MW-13 and MW-20 record equilibrium temperatures from 280 to >340°C and attainment of equilibrium in a single vapor phase. Fluids discharged by wells MW-12, MW-09 and MW-01 (after work over II) appear to have achieved chemical equilibrium at temperatures  $\geq 340^\circ\text{C}$  and  $y$  values close to 1 or at  $y > 0.5$ , approximately. Most fluids from wells MW01 (after work over I) and

MW-04 record equilibrium temperatures from 320 to >340°C and gas equilibration at  $y$  of 0.1 to 0.5 approximately, while fluids from well MW-03 memorize equilibrium temperatures of 280-300°C and attainment of equilibrium in a two-phase system with  $y$  values of 0.01 to 0.03. It is evident that the gaseous concentrations of geothermal systems are directly correlated with the temperatures of the systems (Arnórsson and Gunnlaugsson, 1985).



**Figure 9.** Graph of  $\log K_C$  as a function of temperature and  $y$ , the fraction of steam showing the effects of vapor gain or loss with respect to the composition expected for the discharge of a pure equilibrium liquid phase (from Giggenbach, 1980). Also shown are the reservoir fluids discharged by Menengai wells.

The plot in Figure 9 shows the logarithm of the equilibrium constant (equation 2) of the reaction (equation 1) given by Giggenbach (1980).



$$K_C = \frac{X_{\text{H}_2}^4 \cdot X_{\text{CO}_2}}{X_{\text{H}_2\text{O}}^4 \cdot X_{\text{CH}_4}} \quad (2)$$

which is reported as a function of both temperature and  $y$ .

The inferences made in Figure 8 are fully consistent with those obtained from the plot in Figure 9. It is further observed that the estimated temperatures are generally consistent with those measured in the deepest portions of Menengai wells (Maturia et al., 2014). Some of the measured temperatures at depth are: >390°C in well MW-01 (under static conditions) and MW-04 (under flowing conditions); ~330 in well MW-03 under static conditions; ~325°C in MW-06 (under static conditions) and MW-12 (under flowing conditions), and ~320°C in MW-09 under static conditions (Maturia et al., 2014).

## 5. Conclusions

- Low  $\text{H}_2\text{O}/\text{CO}_2$  ratios, particularly for the two-phase wells, seem to reflect the hotter fluids produced by the deeper feed zones in Menengai while high  $\text{H}_2\text{O}/\text{CO}_2$  ratios are

characteristic of the relatively lower temperature fluids entering in at the shallower feeders. It is further noted that wells that produce single steam phase are richer in H<sub>2</sub>S relative to those discharging two-phase fluids.

- The Menengai geothermal reservoir exhibits redox conditions that are very close to those governed by the FHQ redox buffer indicating that hydrothermal circulation in the Menengai reservoir buffers the inflow of magmatic gases entering from below.
- The well lithological units indicate oxidation in Menengai wells at depths below 500 m while olivine grains and secondary quartz have generally been logged in the wells. This further affirms that redox conditions in the Menengai reservoir are controlled by the FHQ buffer.
- Gas equilibrium temperatures of Menengai fluids range from 280°C to >340°C. These equilibrium temperatures are comparable to those measured in the deepest portions of the wells, suggesting that the gases are chiefly contributed by the high-temperature environments intersected at these deepest sections.
- The fraction of steam (y) varies from well to well. Gas equilibrium is attained in vapor-dominated environments not only for the vapor-discharging wells MW-06, MW-09, and MW-13, but also for well MW-12 and MW-20, which discharges a two-phase mixture (although MW-20 appears to be dominated by steam). Gas equilibrium is established in liquid-dominated zones for well MW-01 before the work over and well MW-03. Gas equilibrium is achieved under intermediate y values (i.e. 0.1 < y < 0.5 approx.) for wells MW-04 and MW-01 after work over I.
- It is deduced that there seems to be an increase in the fraction of steam moving not only towards the central zone in Menengai (where the vapor-dominated wells MW-06, MW-09 and MW-13 are positioned), but also at greater depths in the wells.

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