

Comparative Overview of Gases Discharged from Menengai and Olkaria High Temperature Geothermal Fields, Kenya

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ABSTRACT

An analogy of representative gas compositions from wells drilled into the Menengai and Olkaria volcanic geothermal systems is presented in this paper with a view of drawing parallels as well as identifying variances in the characteristics of the reservoirs tapped by the wells. This contribution seeks to provide an insight into the possible processes that govern the composition of well discharge vapors as well as characterize the Menengai and Olkaria geothermal reservoirs. To achieve this, triangular diagrams comprising two major chemical constituents, H₂O and CO₂, together with other gas species H₂S, H₂, CH₄ and N₂ were employed to compare the chemical characteristics of vapors discharged from these two systems. It is found that the Olkaria reservoir fluids generally exhibit high H₂O/CO₂ ratios relative to the Menengai fluids. This is attributed to variations in CO₂ gas content. High H₂S content seems to characterize Menengai wells, particularly those that discharge from the vapor dominated zones. This inference is indicative of either a higher flux of magmatic gas or enhanced boiling in the reservoir as a consequence of a higher heat flux. The latter is found to be common in the wells as this inference is also complemented by the significantly high H₂ content reported. Additionally, examination of mineral-gas equilibria indicates that fayalite-Hematite-quartz (FHQ) buffer approximates the redox conditions putatively present in the zones where gases attain chemical equilibrium in the Menengai geothermal reservoir but not in the Olkaria geothermal system. This is further affirmed by the lithological units intercepted by Menengai wells. It is possible that gases in the Olkaria geothermal reservoir are largely buffered by hydrothermal minerals and mineral assemblages as noted by previous researchers.

1. INTRODUCTION

The chemistry of volcanic and hydrothermal gases provides crucial insights on the physical and chemical conditions of the subsurface environments inaccessible to direct measurements. Geothermal gases have been classified as either tracers or indicators (Giggenbach, 1991). The less reactive tracer group (N₂, Ar and He) provide useful information on the possible origin of the geothermal fluids while the reactive gases (CO₂, H₂S, H₂ and in some systems, CH₄) have been used to characterize the physical nature of hydrothermal systems (Gudmundsson and Arnorsson, 2002). This paper utilizes new chemical data obtained from geothermal wellbores in the Menengai Geothermal Field where development started recently, together with the largely published chemical data from the Olkaria Geothermal Field to characterize the reservoirs intersected and tapped by the wells. Exploration drilling began in the Menengai Geothermal Field in the year 2011 and the results were quite promising, and subsequently led to appraisal drilling. Currently, production drilling is ongoing with the first 100 MWe scheduled to come online by 2015. In the volcanic geothermal system of Olkaria however, extensive drilling has been undertaken and the field has been under exploitation for over three decades now. A total of 261 MWe is presently being generated from the greater Olkaria geothermal area and an additional 280 MWe is expected before the end of the year, 2014 (MoEP, 2014).

The majority of wells in the Menengai Geothermal Field discharge two-phase fluids but some produce single steam. The wells that produce single steam phase are located within the central part of the caldera and points to an existence of a vapor dominated zone within the well-field (see Figure 2 for location of wells). The well discharge data further indicates the presence of multiple feeds in the wellbores with steam chiefly contributed by the deeper portions of the wells (Kipng'ok, 2011; Muturia, 2013). The Olkaria geothermal system is characterized by a liquid dominated reservoir though a single phase exists to the north of the Olkaria fault zone (Karingithi et al., 2010). However, a two-phase reservoir overlain by a vapor-dominated (steam) cap existed above the liquid reservoir in the Olkaria East sector when the first deep wells were sunk in the area (Ambusso and Ouma, 1991).

Generally, the reservoir fluids discharged by Menengai wells belong to the Na-HCO₃ facies (Malimo, 2013; Sekento, 2012; Kipng'ok, 2011) while the flashed water discharged by Olkaria wells is of both the Na-Cl or Na-HCO₃ types (Karingithi et al.,

2010; Malimo, 2009; Opondo, 2008, Wambugu, 1996). The greater Olkaria geothermal field has been subdivided into seven sectors for development purposes (Figure 3).

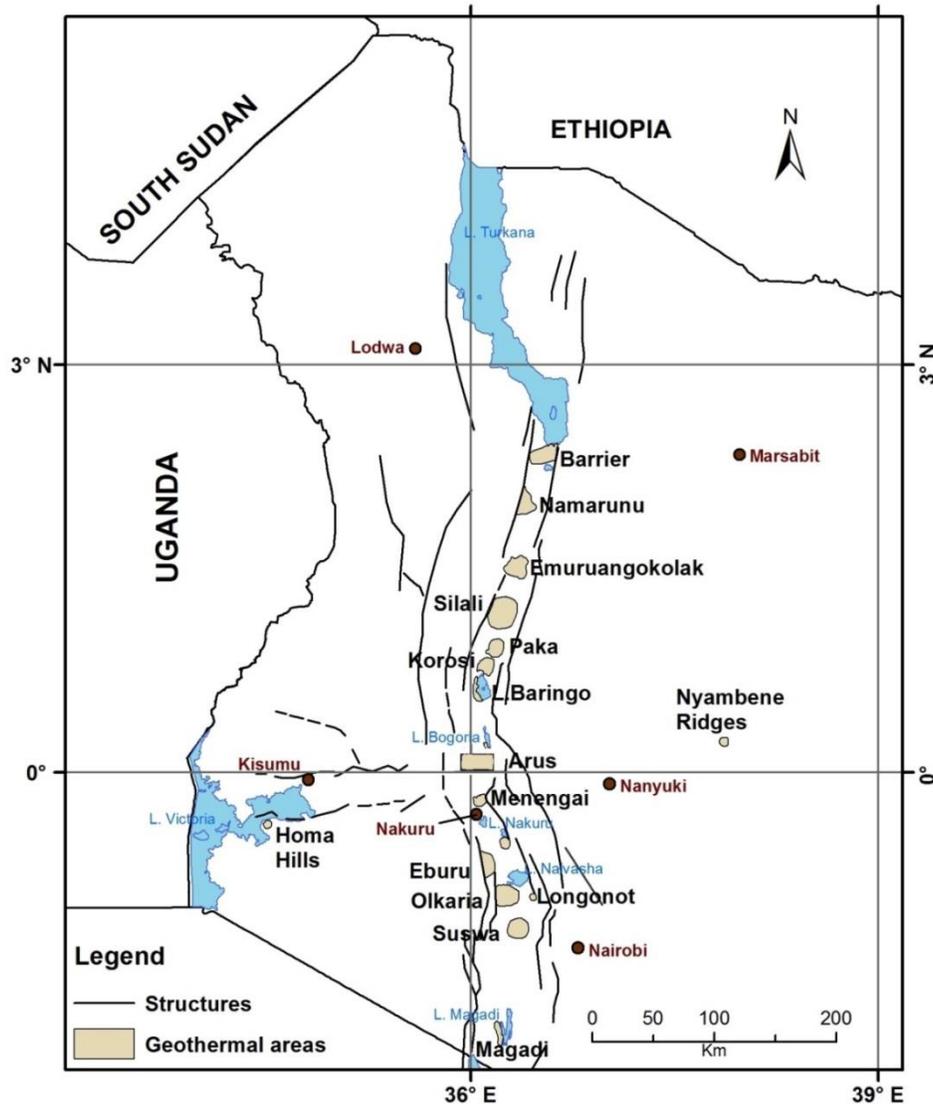


Figure 1: Map showing the location of Menengai and Olkaria volcanoes, and other geothermal areas in Kenya (GDC, 2012)

2. GEOLOGICAL BACKGROUND

Menengai and Olkaria are two of the major high temperature volcanic centers situated on the floor of the Kenya Rift, located in the central and southern segments, respectively (Figure 1). The Menengai shield volcano is located about 70 km to the north of Olkaria volcanic complex (Figure 1). The Kenyan Rift is part of the Eastern Africa Rift System that runs from a triple junction at the Gulf of Aden in the north to Mozambique in the south. The development of the rift valley within Kenya started during the late Oligocene 3 Million years ago (Baker *et al.*, 1971, 1972; Kampunzu and Mohr 1991; Smith 1994) and extends from Lake Turkana in the north to Lake Natron in the south (see Figure 1).

2.1 Menengai

The geology of Menengai has been described by several authors for reasons varying from academic to geothermal investigations (McCall, 1967; MacDonald et al., 1970; Griffith, 1977; Jones & Lippard, 1979, Jones, 1985, Griffith, 1980; Griffith and Gibson, 1980; Leat, 1983, 1984; Geotermica Italiana Srl, 1987; MacDonald et al., 1994; Mungania et al., 2004; Lagat et al., 2010).

Overall, the formations outcropping within the caldera and those intersected by the wells (Muturia, 2013) are of peralkaline trachytic composition with minor pyroclastic intercalations.

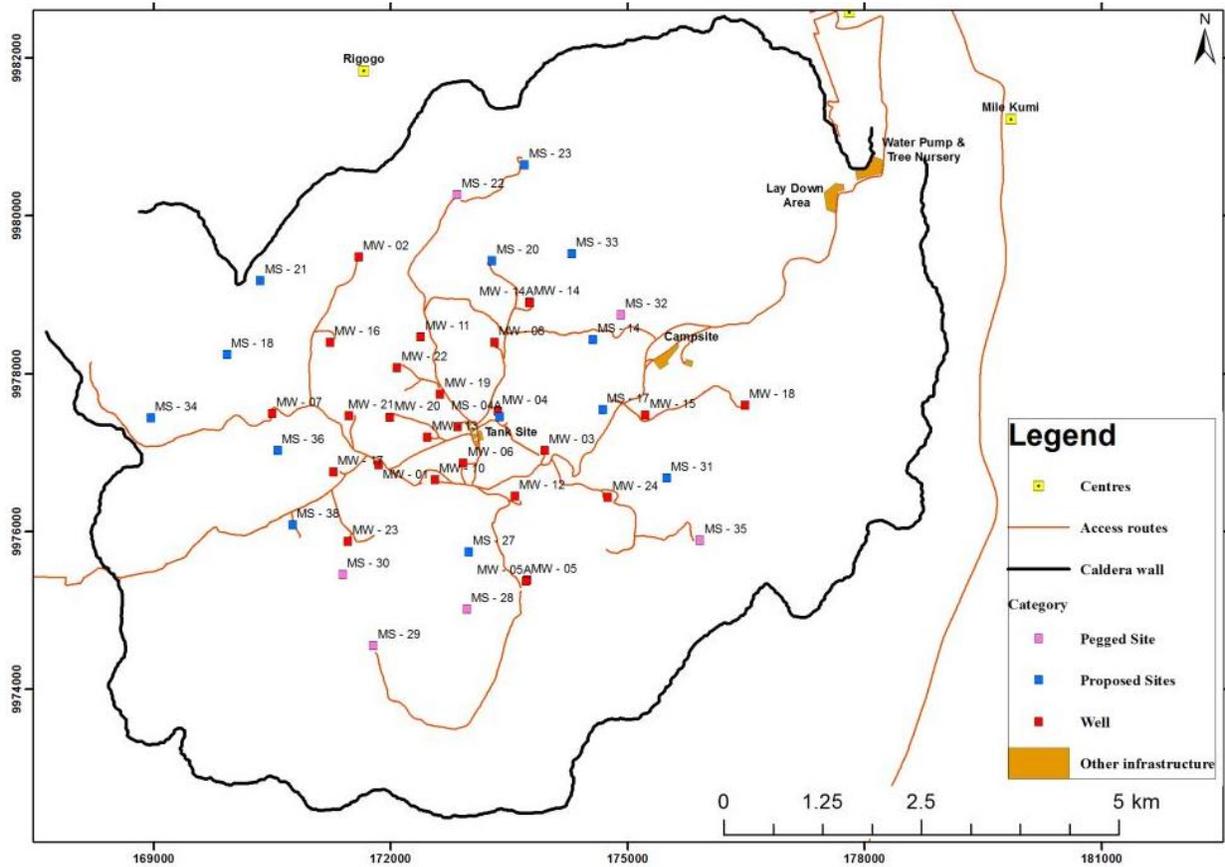


Figure 2: Map showing location of Menengai wells inside the Menengai caldera (GDC, 2014)

Structurally, the Menengai Geothermal Field is located within an area characterized by a complex tectonic activity associated with the rift triple junction; the latter being a zone at which the failed rift arm of the Nyanza rift joins the main Kenya rift. Two rift floor tectono-volcanic axes (TVA) that are important in controlling the geothermal system in Menengai include the Molo and the Solai TVA. The structures associated with Ol’rongai system (Molo TVA) are oriented to the NW-SE and are related to the NW-SE Menengai pre-caldera shield orientation (Leat, 1984). On the other hand, faults associated with the Solai system have a NE-SW orientation also assumed by the Menengai caldera. It is highly probable that the upflow of geothermal liquids from the reservoir towards the surface and their lateral migration, if any, is chiefly controlled by N-S- and NW-SE-trending faults and fractures.

2.2 Olkaria

The geology of the greater Olkaria volcanic complex has also been discussed by various researchers (e.g. Macdonald et al., 1987; Omenda 2000; Mungania, 1992; Clarke et al., 1990; Omenda 1998). Generally, the surface outcrops in Olkaria are mainly comendite lavas and their pyroclastic equivalents, ashes from Suswa and Longonot volcanoes with minor trachytes and basalts. Well lithological logs indicate the presence of a basalt (Olkaria basalt) underling the Upper Olkaria volcanics in the area to the east of Olkaria Hill. Generally, preceding authors (Muchemi, 1999; Omenda, 1998) disovered the subsurface geology of the Olkaria Geothermal Field into six broad lithostratigraphic groups based on age, tectono-stratigraphy, and lithology. The formations in chrono-stratigraphy order from the oldest to the youngest include the Proterozoic “basement” formations, pre-Mau volcanics, Mau Tuffs, Plateau Trachytes, Olkaria Basalts and Upper Olkaria Volcanics.

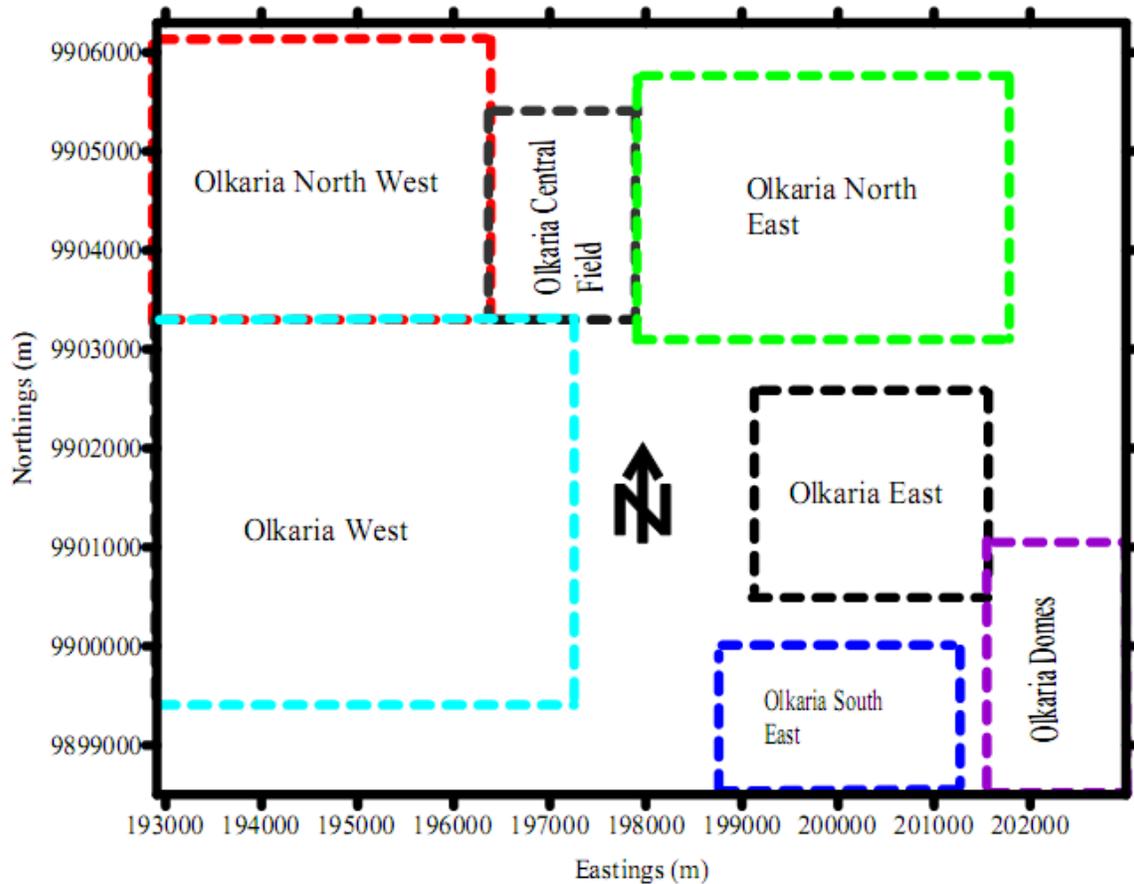


Figure 3: Map of the Greater Olkaria Geothermal Area (GOGA) showing the subdivision into different sectors (Opondo, 2008)

Structures present in the Greater Olkaria volcanic complex include; the Olkaria fault, Gorge Farm faults, Suswa lineament, and the Ol’Njorowa Gorge. The faults are prominent in the Olkaria Central and Olkaria West fields but are scarce in the Olkaria Domes area, possibly due to the thick pyroclastic cover (Ndombi 1981, Omenda 1998). The NW-SE and WNW-ESE faults are thought to be the oldest and are associated with the development of the main Rift Valley.

3. SAMPLING AND ANALYSIS

Collection and analysis of samples from Olkaria Geothermal Field that resulted in the data utilized in this paper was carried out as described by Karingithi et al. (2010). For the Menengai data set, gas samples were collected, together with the 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 to 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, CO₂ and H₂S, were analyzed titrimetrically using 0.1M HCl and 0.001M mercuric acetate while the other non-condensable gases (CH₄, H₂, N₂ and O₂) were analyzed by gas chromatograph. Sample collection and analysis was done as described by Ármannsson and Ólafsson, 2006.

4. GAS CHEMISTRY

Available gas chemistry data includes concentrations of gas constituents like CO₂, H₂S, H₂, CH₄, N₂ and O₂. Some important parameters like Ar and He are however unavailable due to analytical limitations hence somewhat limiting the information derived. This is because it would have been instructive to determine the extent of air entrainment (a potential process affecting the redox state of the gases), which is best evaluated by use of constituents representing either air or the magmatic phase as pointed out by Giggenbach (1987). In this section, triangular diagrams in which the two major chemical components, H₂O and

CO₂, are considered together with other gas species have been used to compare the chemical characteristics of Menengai and Olkaria well discharge vapors.

Menengai reservoir fluids show variable H₂O/CO₂ ratios, ranging from 16 to about 300 (Figures 4 and 5) with well MW-19 having the highest water content (higher H₂O/CO₂ ratio). Olkaria reservoir fluids indicate the highest H₂O/CO₂ ratio except samples from Olkaria West that appear to spread along the H₂O-CO₂ axis. The likely explanation for this observation is the CO₂ content in the wells. In Menengai however, it is noted that high H₂O/CO₂ ratios appear to reflect relatively lower temperature fluids tapped from the shallower aquifers in the wells. This inference is made taking into account the different solute geothermometer temperatures (particularly silica temperatures) of most of the wells discharging two-phase fluids (Malimo, 2013). Moreover, Kipngok (2011) and Suwai (2011) noted the existence of multiple feeds of varying temperatures in well MW-01 (i.e. highest in the deepest feeders and relatively lower in the upper/shallower producing aquifers), and which appears to be reminiscent of Menengai two-phase wells.

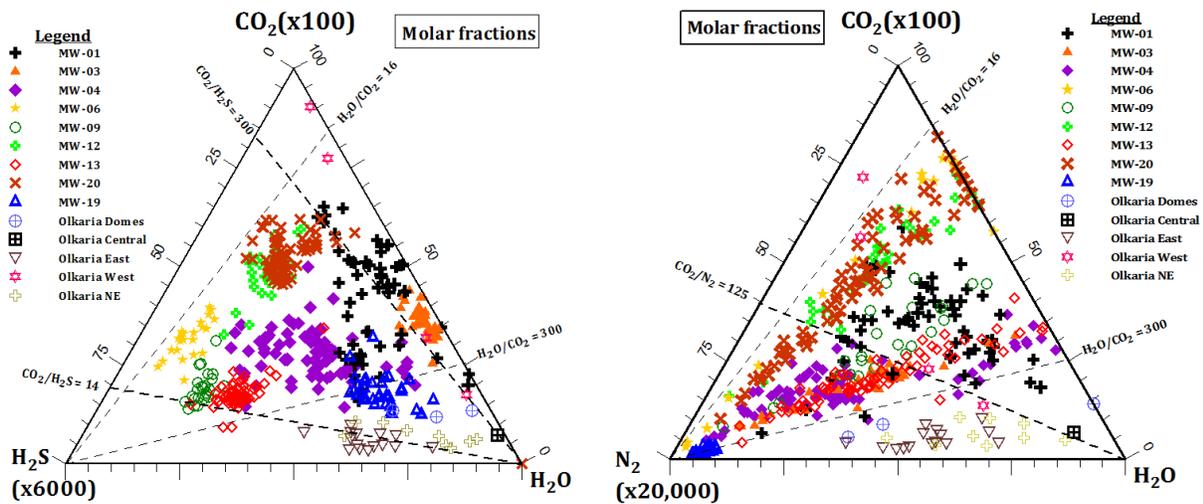


Figure 4: Ternary plots of H₂O-CO₂-H₂S (left) and H₂O-CO₂-N₂ (right) showing the reservoir fluids feeding Menengai and Olkaria geothermal wells.

The ternary plot of H₂O-CO₂-H₂S illustrates the fact that Menengai wells that produce single steam phase (i.e. MW-06, MW-09 and MW-13) together with samples from Olkaria East and north east are richer in H₂S relative to the other well fluids. These wells are characterized by lowest CO₂/H₂S ratios (<14), and is a good indicator that they could be located on or close to possible upflow areas within the geothermal field, particularly for Menengai.

In the ternary plot of H₂O-CO₂-N₂ (Figure 4, right), most samples from wells MW-01, MW-12, MW-06, MW-09 and to some extent MW-20 appear to be N₂-depleted relative to most samples from wells MW-03, MW-04, MW-13. Olkaria samples also appear to be slightly enriched in N₂ content. Differences in the N₂ content could be attributed to preferential nitrogen loss upon boiling, particularly in wells with high heat flow/content. It is also possible that air contamination could have occurred during sampling and/or due to the presence of drilling fluids in the reservoir and could be responsible for the N₂-rich samples, particularly for the Menengai wells most of which have been undergoing discharge testing until the present time. There are however other sources of N₂ in geothermal fluids. Norman et al. (2001) observed from examination of well discharges that wells have N₂ 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 from N₂/Ar ratios that N₂ has another source than air-saturated water, potentially entrapped air bubbles, magmatic gas or decaying organic matter (Giroud, 2008).

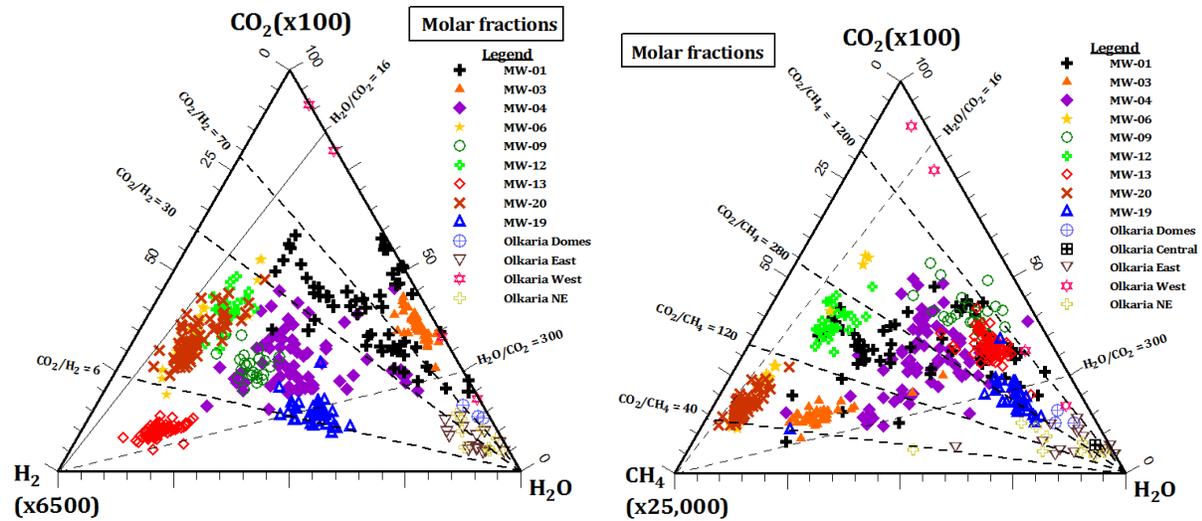


Figure 5: Triangular plots of H₂O-CO₂-H₂ (left) and H₂O-CO₂-CH₄ (right) showing the reservoir fluids tapped by Menengai and Olkaria wells.

The ternary plot of H₂O-CO₂-H₂ (Figure 5, left) generally illustrates that Menengai fluids are significantly richer in H₂ albeit in varying proportions. Olkaria wells on the other hand appear to be depleted in H₂ relative to Menengai. Menengai well MW-13 is the richest in H₂, having CO₂/H₂ ratios lower than 6, while fluids of wells MW-03 and MW-01 are the poorest in H₂, with CO₂/H₂ ratios higher than 30 and 70, respectively. Most fluids of Olkaria wells and fluids of wells MW-04, MW-06, MW-09, MW-19, MW-12 and MW-20 have intermediate characteristics, with $6 < \text{CO}_2/\text{H}_2 < 30$. High H₂ is usually taken to indicate the presence of vapor fraction in the initial reservoir fluid, which raises much the sparingly water soluble H₂ concentrations in the aquifer liquid but not so much the concentrations of the more soluble CO₂ and H₂S (Arnórsson et al., 2010). It is hence concluded that a high vapor fraction exists in the Menengai relative to the Olkaria reservoir.

Figure 5 (right) shows that CH₄ contents are distributed with most samples falling between CO₂/CH₄ ratios of 40 to 1200 units. Variations from field to field as well as from well to well in the contents of H₂ and CH₄ 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 H₂ and CH₄ are minor components, they are expected to be affected by chemical reactions, particularly hydrogen, which is highly reactive, rather than methane, which is considered a “slow” species, especially at relatively low temperatures.

5. GAS EQUILIBRIA

Giggenbach (1987) discussed the various processes presumably governing the redox in geothermal reservoirs. Karingithi et al. (2010) demonstrated that the concentrations of reactive gases H₂S and H₂ in the Olkaria reservoir fluids are generally kept in local equilibrium with pyrite-pyrrhotite-magnetite mineral assemblage. Furthermore, Karingithi et al. (2010) noted that CO₂ is controlled by close approach to local equilibrium with Epidote-prehnite-calcite-quartz mineral assemblage in most parts of the GOGA except in Domes and Olkaria West where its concentration is controlled by its flux from the magma heat source. Karingithi et al. (2010) further observed that the mineral assemblage pyrite-pyrrhotite-magnetite controls aquifer water H₂S and H₂ concentrations. In this paper however, the Fayalite-Hematite-Quartz (FHQ) redox buffer given by Giggenbach (1987) has been employed to investigate both the Menengai and Olkaria reservoir vapors. Giggenbach (1987) showed that the FHQ redox buffer appears to represent a good approximation for several geothermal systems although different redox buffers, rather than the FHQ only, are present in distinct geothermal systems or even in different parts of the same system as discussed by Chiodini and Marini (1998). The diagram of log (CH₄/CO₂) vs. log (H₂/H₂O) of Figure 6 shows that the FHQ buffer appears to sufficiently approximate the redox conditions presumably present in the zones where gases attain chemical equilibrium in the Menengai geothermal reservoir but not for the Olkaria reservoir. Only a few samples from Olkaria Domes plot close to the theoretical compositions expected for gas equilibration. This implies that different redox buffers, other than the FHQ control the redox conditions in the Olkaria geothermal reservoir.

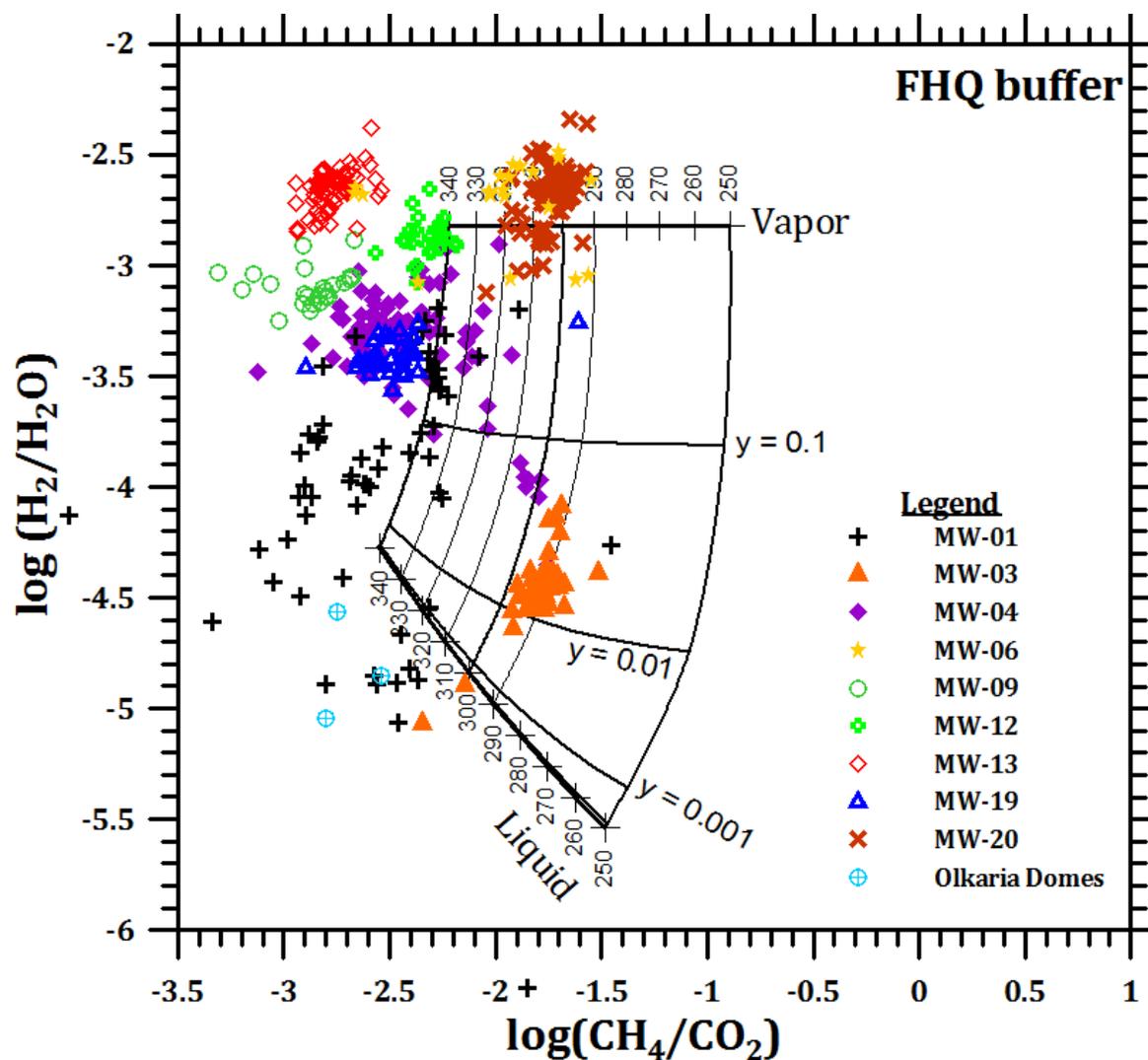


Figure 6: Graph depicting the reservoir fluids tapped by Menengai and Olkaria wells compared with the theoretical compositions expected for gas equilibration in a single vapor phase, in a single liquid phase (i.e. pure water), and in two-phase systems with different values of y = mass ratio of vapor/(vapor + liquid), under redox conditions controlled by the FHQ redox buffer.

Moreover, well lithological units show the presence of olivine grains logged in wells MW-01, MW-04 and MW-06 indicating that fayalite is present 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 wellbores. It is therefore concluded that the presence of olivine grains and abundant oxides as encountered in Menengai wellbores favors the FHQ redox buffer to control redox conditions in the Menengai hydrothermal system.

The equilibrium temperatures for Menengai depicted by Figure 6 are chiefly constrained by CH_4/CO_2 ratio while the $\text{H}_2/\text{H}_2\text{O}$ ratio indicates the mass ratios (y values). The vapors discharged from the wells record equilibrium temperatures ranging from 280 to >340°C and attainment of equilibrium in either a single vapor phase or in at different y values.

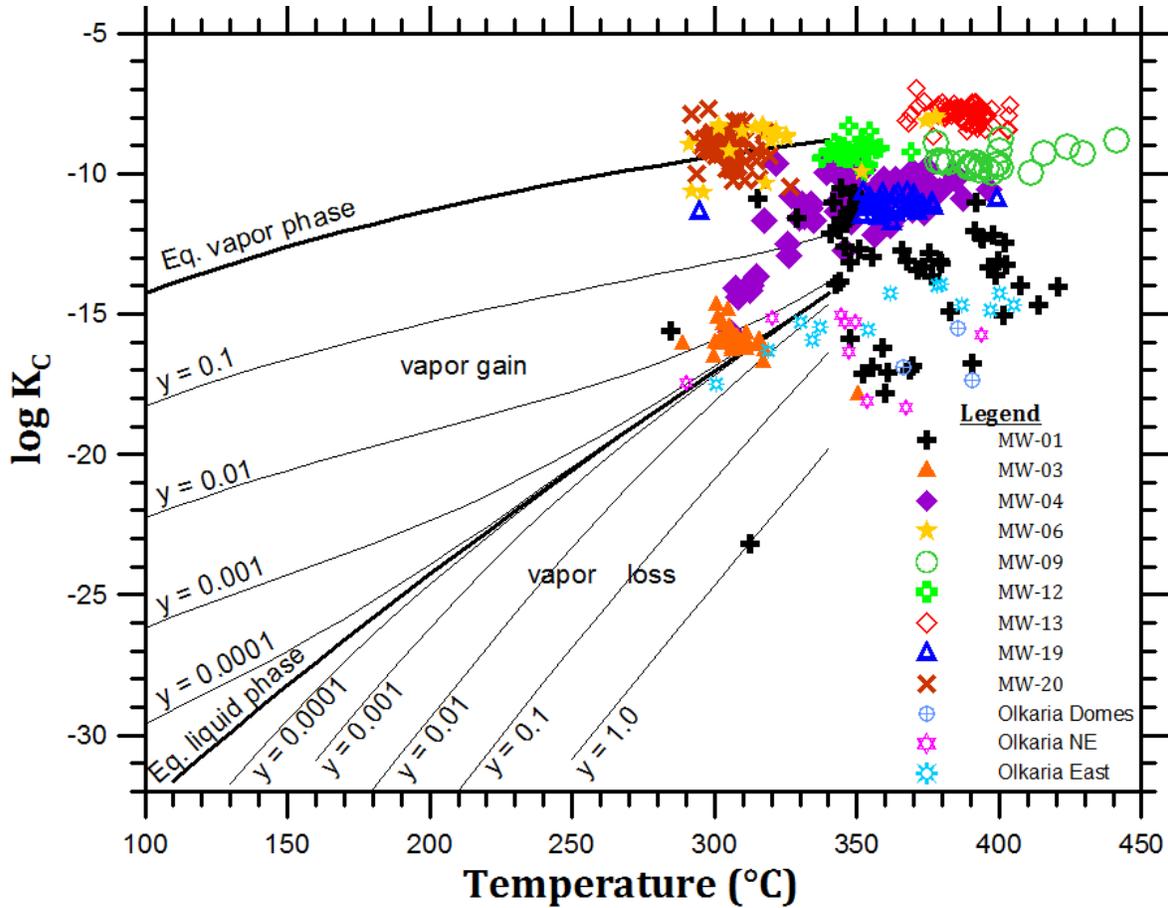
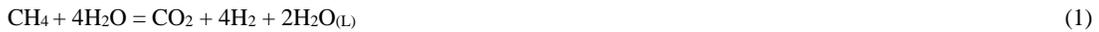


Figure 7: Graph of $\log K_C$ as a function of temperature and y , the fraction of steam showing the effects of vapor gain or loss with respect to the composition expected for the discharge of a pure equilibrium liquid phase (from Giggenbach, 1980). Also shown are the reservoir fluids tapped by Menengai and Olkaria wells.

The plot in Figure 7 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 6 are fully consistent with those obtained from the plot in Figure 7. It is further observed that the estimated temperatures are somewhat comparable to those measured in the deepest portions of most of Menengai as given in Mutura et al. (2014).

6. CONCLUSIONS AND RECOMMENDATIONS

- The chemistry of well discharge vapor shows that whereas Menengai and Olkaria are located within the same tectonic setting, the two geothermal systems appear to be very distinct. This is also evident from the geology of both geothermal fields.

- Generally high H₂O/CO₂ ratios are noted in the Olkaria geothermal reservoir which can be attributed to variations in the content of CO₂ gas.
- Wells tapping from vapor dominated zones as noted in most of Menengai wells are characterized by high H₂S gas content.
- The Fayalite-Hematite-Quartz buffer closely control the redox conditions in the Menengai geothermal reservoir indicating that the hydrothermal circulation into the Menengai reservoir buffers the inflow of magmatic gases entering from below. It is possible that different redox buffers are present in the Olkaria reservoir other than the FHQ.
- Well discharge gases indicate that the Menengai geothermal system has a significantly high vapor fraction in the reservoir indicative of enhanced boiling.
- Gases attain equilibrium in the Menengai geothermal reservoir in both a single vapor phase and under intermediate conditions (0.1 < y < 0.5 approx.).
- More studies crucial to establishing the source of the gases (i.e. CO₂, H₂S, H₂, CH₄ and N₂) are however recommended. These include:
 - Determination of He and Ar in the gas samples
 - Carrying out of carbon, helium and argon isotope studies

REFERENCES

- Ármannsson, H. and Ólafsson, M.: Collection of geothermal fluids for chemical analysis, *ISOR report* (2006).
- Arnórsson S. and Gunnlaugsson E.: New gas geothermometers for geothermal exploration-calibration and application, *Geochem. Cosmochim. Acta* **49**, (1985), 1307-1375. *Congress 2005, Anatolya, Turkey*, CD, 5 pp.
- Arnórsson, S.: Chemistry of gases associated with geothermal activity in Iceland: A Review, *Journal of Geophysical Research*, Vol. **91**, (1986), pp12261-12268.
- Arnórsson, S., Angcoy, E., Bjarnarson, J.Ö., Giroud, N., Gunnarsson, I., Kaasalinen, H., Karingithi, C., Stefánsson, A.: Gas chemistry of volcanic geothermal systems, *Proceedings World Geothermal Congress, Bali, Indonesia*, (2010), 6 pp.
- Chiodini G., Marini L.: Hydrothermal gas equilibria: The H₂O-H₂-CO₂-CO-CH₄ system, *Geochim. Cosmochim. Acta*, **62**, (1998), 2673-2687.
- Clarke, M.C.G., Woodhall, D.G., Allen, D., and Darling, G.: Geological, volcanological and hydrogeological controls of the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya, Ministry of Energy, *report* (1990).
- D'Amore, F. and Panichi, C.: Evaluation of deep temperatures in geothermal systems by a new gas geothermometer, *Geochim. Cosmochim. Acta* **44**, (1980), 549-556pp.
- GDC.: Kenya geothermal prospects map, *GDC internal database* (2012).
- GDC.: Location map of Menengai wells, *GDC Internal database* (2014).
- Geotermica Italiana Srl.: Geothermal reconnaissance survey in the Menengai- Bogoria area of the Kenya Rift Valley, UN (DTCD)/ GOK (1987).
- Giggenbach W.F.: Redox processes governing the chemistry of fumarolic gas discharges from White Island, New Zealand, *Appl. Geochem.*, **2**, (1987), 143-161.
- Giggenbach, W.F.: Geothermal gas equilibria, *Geochim. Cosmochim. Acta*, **44**, (1980), 2021-2032pp.
- Giroud, N.: A chemical study of arsenic, boron and gases in high-temperature geothermal fluids in Iceland, *Doctoral dissertation*, Dissertation for the Degree of Doctor of Philosophy, University of Iceland, (2008).
- Griffith P. S.: The geology of the area around Lake Hannington and the Perkerra River Rift Valley Province, Kenya, *PhD thesis* University of London, (1977).

- Griffith P. S.: Box fault systems and ramps: A typical association of structures from the eastern shoulder of the Kenya rift, *Geol. Mag.*, (1980), 579-586 pp.
- Griffith P. S., and Gibson I. L.: The geology and the petrology of the Hannington Trachyphonolite formation, Kenya Rift Valley, *Lithos*, **13**, (1980), 43-53pp
- Jones, W.B.: Discussion on geological evolution of trachytic caldera and volcanology of Menengai volcano, Rift Valley, Kenya, *Journ. Geop.l. Soc. Lon*, vol **142**, (1985), 711pp.
- Jones, W.B., and Lippard, S.J.: New age determination and geology of Kenya rift-Nyanzian rift junction, west Kenya, *Joun. of Geol. Soc.Lon* vol **136**, (1979), pg 63.
- Karingithi, C.W, Arnórsson, S., Gronvold, K.: Processes controlling aquifer fluid compositions in the Olkaria geothermal system, Kenya, *J. Volcanol. & Geoth. Res.*, **196**, (2010), 57-76.
- Kipng'ok, J.: Fluid chemistry, feed zones and boiling in the first geothermal exploration well at Menengai, Kenya, UNU-GTP *publications*, Report **15**, (2011), 281-302.
- Lagat, J., Mbia, P., Mutria, C.: Menengai prospect: Investigations for its geothermal potential, GDC Unpublished report (2010), 64 pp.
- Leat, P.T.: The structural and Geochemical Evolution of Menengai caldera volcano, Kenya Rift Valley, PhD *Thesis*, University of Lancaster, U.K, (1983).
- Leat, P.T.: Geological evolution of the trachytic volcano Menengai, Kenya Rift Valley, *J Geol Soc London*, **141**, (1984), 1057-1069.
- Leat, P.T.: Discussion on the geological evolution of the trachytic caldera volcano Menengai, Kenya Rift Valley, *Journal of the Geological Society*, **142(4)**, (1985) : 711 - 712.
- Leat, P.T., Macdonald, R, Smith, R.L: Geochemical evolution of Menengai, Kenya Rift Valley, *J Geophys Res*, **89**, (1984), 8571-8592.
- Macdonald, R., Navarro, J.M., Upton, B.G. J., Davies, G.R.: Strong compositional zonation in peralkaline magma: Menengai, Kenya Rift Valley, *J. Volc Geotherm Res*, **60**, (1994), 301-325.
- Macdonald, R., Davies, G.R., Bliss, C.M., Leat, P.T., Bailey, D.K., and Smith, R.L.: Geochemistry of high silica peralkaline rhyolites, Naivasha, Kenya rift valley, *Petrology*, **28**, (1987), 979-1008.
- Malimo, S.J.: Fluid Chemistry of Menengai Geothermal Wells, Kenya, Geothermal Resources Council *Transactions*, Vol. **37**, (2013).
- Malimo, S.J.: Interpretation of Geochemical well test data for wells 903B, 904B, and 909 Olkaria Domes, Kenya, UNU-GTP *Publications*, Report **17**, (2009), 319-344.
- Mbia, P.: Well MW-01 Geology Report. GDC Internal *Report*, (2012).
- McCall, G.J. H.: Geology of the Nakuru-Thomson's- Lake Hanningtons Falls area, Geological Survey of Kenya *Report No. 78*, (1967).
- Mibei, G.K.: Geology and hydrothermal alteration of Menengai geothermal field – Case study: wells MW-04 and MW-05, UNU-GTP *Publications*, Report **21**, (2012), 437-465.
- Ministry of Energy and Petroleum (MoEP): Draft National Energy Policy, Ministry of Energy and Petroleum, Kenya, (2014).
- Mungania, J.: Preliminary field report on geology of Olkaria volcanic complex with emphasis on Domes area field investigations. Kenya Power Company internal *report* (1992).
- Mungania, J., and Lagat, J., (editors), Mariita, N.O., Wambugu, J.M., Ofwona, C.O., Kubo, B.M., Kilele, D.K., Mudachi, V.S., Wanjie, C.K., Korio, R.K.: Menengai volcano: Investigations for its geothermal potential, KenGen Internal *Report*, (2004), 93 pp.
- Muturia, C.L., Suwai, J.J., Mibei, G.K. and Malimo, S.J.: Menengai Data Integration report, GDC Internal *Report* (2014).
- Nicholson, K.: Geothermal fluids: Chemistry and exploration techniques, Springer-Verlag Berlin Heidelberg New York, (1993) ISBN 3-540-56017-3 pp.

- Norman, D.I., Blamey, N.J.F. and Moore, J.N.: Overabundance of gaseous species and the source of organic compounds in geothermal fluids, *Proceedings*, Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2001).
- Omenda, P.A.: The geology and structural controls of the Olkaria geothermal system, Kenya. *Geothermics*, **27-1**, (1998), 55-74.
- Omenda, P.A.: Anatectic origin for comendite in Olkaria geothermal field, Kenya Rift; Geochemical evidence for syenitic protholith, *African J. of Science and Technology. Science and Engineering series*, **1**, (2000), 39-47.
- Omondi, C.: Borehole geology and hydrothermal mineralisation of wells MW-01 and MW-02, Menengai geothermal field, Central Kenya Rift Valley, UNU-GTP *Publications*, Report **30**, (2011), 737-773.
- Opondo, K.M.: Fluid Characteristics of the three Exploration wells drilled at Olkaria Domes, Kenya, *Proceedings of the 33rd workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, Ca, (2008), 6pp.
- Scott, W, S., Gunnarsson, I., Stefansson, A., Arnorsson, S., Gunnlaughsson, E.: Gas Geochemistry of the Hellisheidi Geothermla Field, SW-Iceland, *Proceedings Thirty-Sixth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, (2011) SGP-TR-91.
- Sekento, L.R.: Geochemical and isotopic study of the Menengai geothermal field, Kenya. UNU-GTP *Publications*, Report **31**, (2012), 769-792.
- Suwai, J.J.: Preliminary reservoir analysis of Menengai geothermal field exploration wells. UNU-GTP *Publications*, Report **20**, (2011), 481-509.
- Wambugu, J.M.: Assessment of Olkaria North-East Geothermal Reservoir, Kenya Based on Well Discharge Chemistry. UNU-GTP *Publications*, Report **21**, (1996), 437-465.
- Williams, L.A.J., Macdonald, R., Chapman, G.R.: Late Quaternary caldera volcanoes of the Kenya Rift Valley, *J Geophys Res*, **89**, (1984), 8553-8570.