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Stable Isotopic Composition of Geothermal Fields in Kenya; The Relationship Between Geothermal Fields and Kenya Rift Lakes Waters

Marietta W. Mutonga

Geothermal Development Company Ltd P. O. Box 17700-20100, Nakuru, Kenya

mariettamu@gmail.com/mmutonga@gmail.com;

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ABSTRACT

The results of the review of the stable isotopic composition relationship between the geothermal fields and the Kenya rift lake waters are presented. The Kenya rift Lakes Include; Lake Baringo, Bogoria, Nakuru, Elementaita and Naivasha respectively. Geothermal fields considered for this study are Menengai and Olkaria. Menengai is a major Quaternary central volcano dominated mainly by trachytic rocks it's located within the axis of the central segment and is host to one of the high temperature geothermal fields in the Kenya Rift while Olkaria is a rhyolitic volcanic complex located immediately to the south of Lake Naivasha in the Central Kenya Rift Valley. Olkaria is geothermally active and is being used to generate growing quantities of clean electrical power. Data from various workers has been used to try and discern the differences between the waters with a view to understanding the origin and isotopic relationships between them.

The results indicate that most of the Lake waters are varied in composition with some plotting on the Kenya Rift Meteoric water line (KRMWL) and some plotting slightly of this line on either side. Lake Baringo appears to be to be quite enriched in $\partial^{18}O$ and $\partial^{2}H$ isotopes which could be attributed to increased evaporation especially during the dry seasons, though some thermal input cannot be ignored. It may also be inferred that these waters have travelled long distances probable from the highlands to be discharged into the lake. One sample from Lake Nakuru is also very similar to one from Lake Baringo. The Olkaria geothermal field has been divided into four sectors which also show some varied compositions; Olkaria domes waters appear to be more enriched in both the $\partial^{18}O$ and $\partial^{2}H$ isotopes than the other fields this is attributed to high temperatures that may result in boiling or increased water interaction that results in rocks losing their isotopes to the geothermal wells. Olkaria East is more depleted in both isotopes and has fairly similar composition to Lake Naivasha waters. It was noted however is that Menengai geothermal field well waters are very different from the surrounding lakes i.e. Lake Nakuru and Elementaita. They appear to be depleted with respect to both $\partial^{18}O$ and $\partial^{2}H$. This is interesting and can be inferred to mean that either Menengai geothermal field is recharged mainly be rain water or by waters that have very little residence time.

1. INTRODUCTION

The increased cost of energy has many nations Kenya included seeking to diversify its sources by adopting an energy mix that includes Geothermal energy. Kenya is strategically located on the East African rift; endowed with numerous geothermal prospects with a potential in excess of 5000 MWe. Currently geothermal energy accounts for only 13% of all the electricity that's connected on the national grid. Currently Kenya is already producing from Olkaria geothermal field about 250 MWe which is set to increase to 400 MWe by 2015. In Menengai geothermal field, drilling is underway for the first 100Mwe power plant to be commissioned by 2015. This paper therefore will provide an insight into the stable isotopic composition our geothermal fields and how they relate with the surrounding water bodies i.e. the central rift lakes with a view of exploiting them sustainably.

Water is the major substance in the lithosphere implicated in convective heat and mass transfer, and any waters or aqueous fluids in geologic systems are involved in many chemical reactions. The isotopic composition of water (like other chemical compounds) is not uniform. This is because some chemical reactions discriminate between isotopes and the differences in volatility between compounds made of different isotopes. It's these differences that help us in deciphering the origin and different reaction paths followed by this waters. Oxygen and hydrogen are found in many forms in the earth's hydrosphere, biosphere, and geosphere. Oxygen is the most abundant element in the earth's crust. Hydrogen also is common in the biosphere and is a constituent of many minerals found in the geosphere. Most importantly, oxygen and hydrogen combine to form water, thus making their isotopic composition a powerful tracer of the hydrosphere. Isotope geochemistry has greatly contributed to the present understanding of geothermal systems. Ellis et.al., 1977 suggested that the detection of even small changes in the chemical composition of a geothermal fluid enables a precise assessment of the long term stability of the field. The isotopic composition of geothermal fluid components provides information on their origin, their recharge area and flow patterns, and may allow an evaluation of subsurface temperatures. Data from the Central Kenya Rift Lakes, Olkaria and Menengai Geothermal fields was analyzed with view to find out if there exist any relationship between these waters (Figure.1).

1.1 Geological Setting

Menengai is a major Quaternary central volcano located within the axis of the central segment north of Lakes Nakuru and Elementaita and South of Lake Bogoria and Baringo. It's one of the largest calderas in the world with a diameter of 12 x 9 Km which was formed around 29 Ka as a result of empting of the magma chamber.

The major structural systems in the area are Menengai Caldera, Molo tectonic axis and the Solai graben. Menengai caldera is elliptical with the major and minor axis measuring about 12 km and 8 km respectively (KenGen, 2004). The ring structure has been disturbed by the Solai graben faults on the NE end and one fracture at the SSW of the caldera wall extending southwards. The Molo TVA/Olrongai fracture system intersect Menengai caldera on the NNW part. Most of the caldera infill lavas are from fissure eruptions that flowed out of the fracture openings. The caldera host to one of the high-temperature geothermal fields in the Kenya Rift;The Menengai geothermal field, (Figure.2). The age of the youngest eruption episode (~1400 yrs.) indicates a possibility of a still active magma body below the caldera. Several geothermal wells have been and are still been drilled in this field.

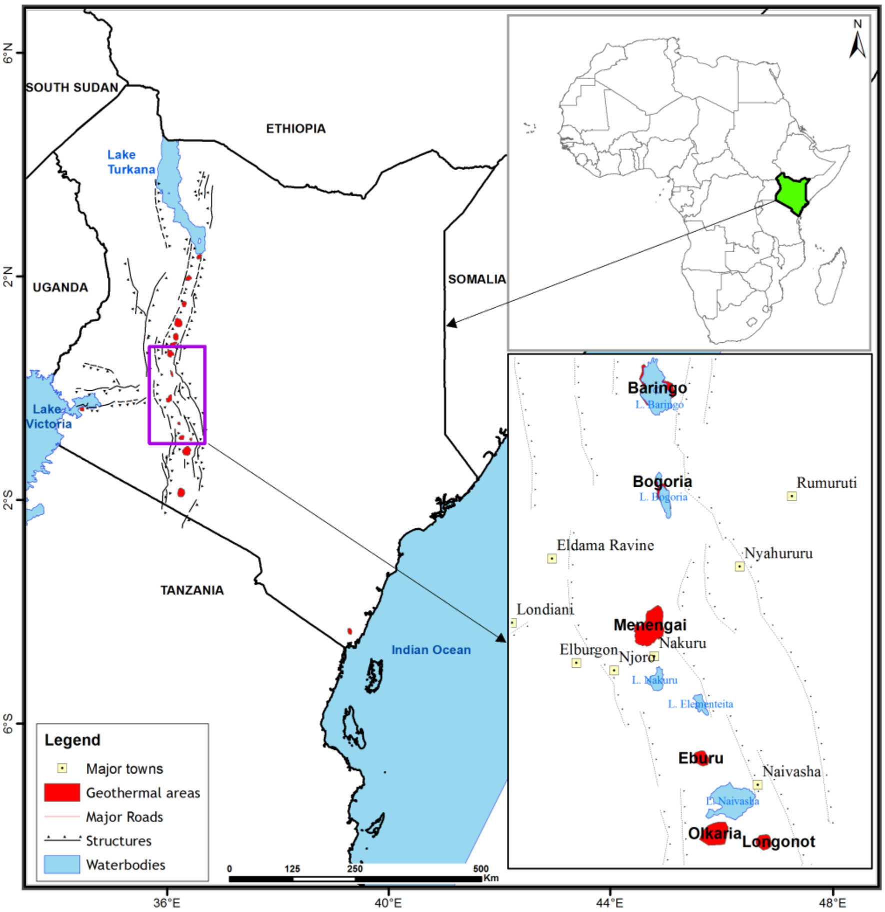

Figure 1: Map of Kenya showing the Central rift lakes, the Olkaria geothermal Field and the Menengai geothermal field.

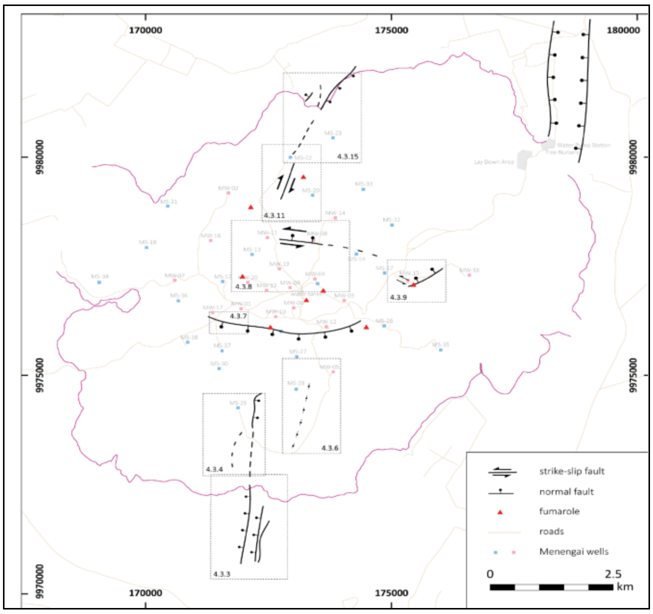

Figure 2. Menengai Geothermal field structural Map (Riedel et. al., 2013)

The surface at Olkaria Geothermal complex is dominated by a peralkaline rhyolite dome and lava field. The complex contains many centers of volcanic activity that often erupt in small volumes. There are at least eighty such centers of activity, mostly either thick lava flows or steep-sided lava and pyroclastic domes (Marshall et.al., 2009). A structural N-S running boundary passes through the Olkaria Hill that divides the Greater Olkaria area into east and west stratigraphic zones. Volcanic eruption centres are structurally controlled. The main centres are the Olkaria Hill, Ololbutot fault zone and the Gorge Farm area. Rock from a borehole 1,000 m deep at Olkaria is around 450,000 years old, but the surface features are no more than 20,000 years old (Marshall et.al., 2009). According to the oldest exposed sequence is the Ol Njorowa Pantellerite formation of pyroclastic rocks, lava flows and plugs. This is thought to be related to a caldera 11 Km by 7.5 Km that later collapsed but is indicated by traces of a ring fracture. The magma has a wide range of compositions representing the different phases after the caldera collapsed. The most recent volcanism is associated with the Ololbutot fracture zone. The youngest lava is the Ololbutot rhyolite flow, which is about 250 ± 100 years BP (Omenda, 1998; Clarke et.al., 1990). Olkaria is geothermally active and is one major field being used to generate growing quantities of clean electrical power.

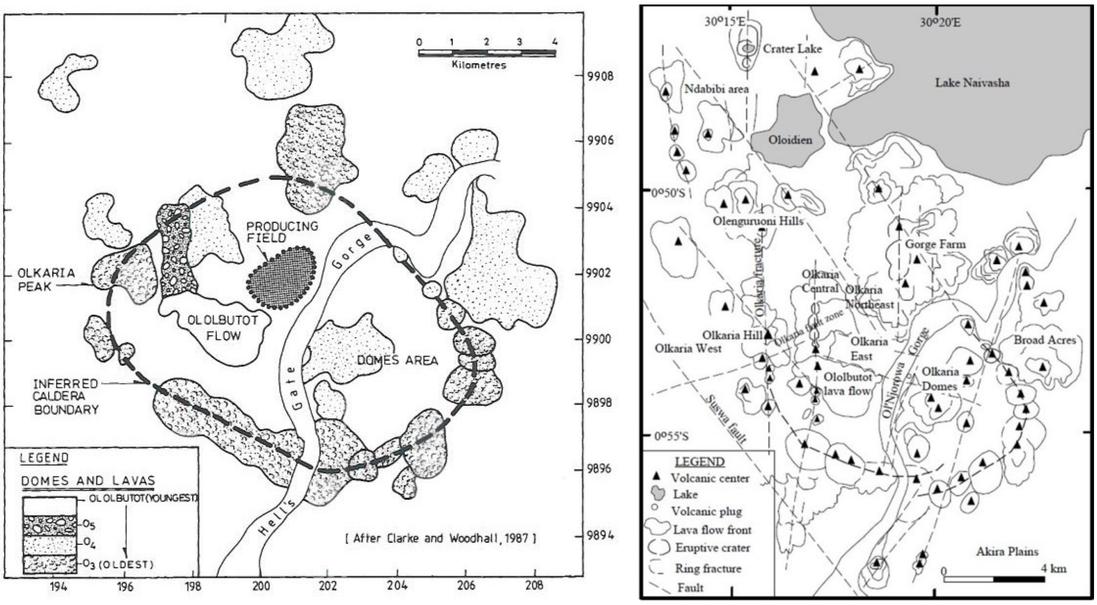

Figure 3: Volcanotectonic Map of The Great Olkaria and the Fields

Lake Baringo is, after Lake Turkana, the northern most of the Kenyan Rift Valley lakes, with a surface area of about 130 Km^2 and lies at an elevation of about 970 m. The lake is fed by several rivers, Molo, Perkerra and Ol Arabel, and has no obvious outlet; the waters are assumed to seep through lake sediments into the faulted volcanic bedrock. It is one of the two freshwater lakes in the Kenya Rift Valley, the other being Lake Naivasha which is at the highest elevation at 1,890 m in a complex geological combination of volcanic rocks and sedimentary deposits from a larger Pleistocene era lake. Apart from transient streams, the lake is fed by the perennial Malewa and Gilgil rivers. There is no visible outlet, but since the lake water is relatively fresh it is assumed to have an underground outflow (Harper, 2003). Lake Bogoria, Nakuru and Elementaita at an elevations of 990 m, 1759 m and 1670 m are alkaline lakes that at times host one of the world's largest populations of lesser and greater flamingos.

1.2 Materials and Methods

Stable isotope hydrology is a technique which can be used to trace groundwaters to their point of origin through analyses of their deuterium (∂D or ∂^2H) and oxygen-18($\partial^{18}O$) concentrations. The ∂^2H content of water has become an important tracer in mapping hydrological flows and in determining recharge for geothermal systems. In most cases, the technique is simple to apply and is usually consistent with other geochemical methods. The technique often presupposes a meteoric origin for the waters being traced, yet may be expanded to accommodate possible contributions from other sources. Meteoric water is by far the dominant contributor to the volume of most geothermal brines and hence will be considered in this study. Meteoric Water is water which has been recently involved in atmospheric circulation, including pluvial, vadose and other groundwaters. Recent means no more than a small fraction of a geological period. Rain waters which undergo changes in their solution chemistries as a result of hydrothermal alteration processes or other interactions with the ground in the course of their flows would still be considered meteoric.
A linear relationship between ∂^2H and $\partial^{18}O$ for most cold water of meteoric origin has been observed. Friedman (1953) first discovered the covariance between ∂^2H and $\partial^{18}O$ values of natural water, comparing his hydrogen isotope data with the oxygen isotope data of Epstein and Mayeda (1953). In this paper the GMWL (Global meteoric water line), The CARL Continental Average rain line and the KRVWL (Kenya Rift Valley Mean water Line) have been used to examine the relative relationships that exist between this waters the Kenya Rift Lake waters and the Geothermal fields.

The Global Meteoric Water Line (GMWL) is an equation defined by the geochemist (Craig, 1961) that states the average relationship between hydrogen and oxygen isotope ratios in natural terrestrial waters, expressed as a worldwide average.

$$\partial D = 8(\partial_{18} O) + 10 \qquad (1)$$

A meteoric water line can also be calculated for a given area, and used as a baseline within that area. With most of the samples being from Kenya the Kenya Rift Mean Water Line (KRVWL) was developed by Darling et.al.,1987 with a correlation coefficient of 0.94 is described as

$$\partial D = 5.56(\partial_{18}O) + 2.04 \quad (2)$$

Continental African Rain Line (CARL), Ármannsson (1994) $\partial D = 7(\partial_{18}O) + 11$ (3)

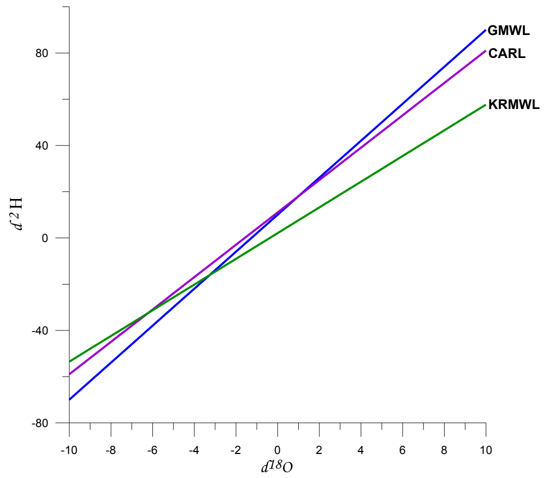

Figure 4: World Meteoric Water Line (Craig, 1961a), Kenya Rift Valley Meteoric Water Line (Allen and Darling, 1987), Continental African Rain Line, (Ármannsson, 1994), and Kenya Rift Valley Evaporation Line, (Ármannsson, 1994).

Geothermal fields are found in many parts of the world in a range of geological settings, and are increasingly being developed as a renewable energy source. Each of the different types of geothermal system has distinct characteristics which are reflected in the chemistry of the geothermal fluids and their potential applications.

According to (Nicholson, 1993), all the geothermal fields have one thing in common ,a common a heat source at a few kilometers depth which sets water present in the upper sections of the Earth's crust into convection (Figure.5) after (Nicholson,1993) was used to infer the sources and origin of various fluids under study. Data used for this study has been borrowed from previous samples by Darling et al.,1996, Tiercelin et al., (1987) and Cioni et al., (1992); Table.3), (Sekento, 2012; Table.2) and (Karingithi, 2000;Table.1).

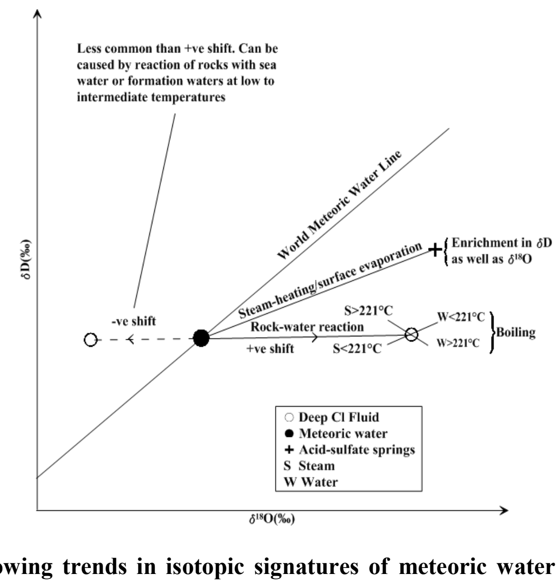

Figure 5: Schematic diagram showing trends in isotopic signatures of meteoric water and geothermal fluids with active processes (Nicholson, 1993)

Table.1 Stable Isotopic Composition of Geothermal Wells in the Greater Olkaria (Karingithi, 2000)

Location	δ^{18}O	∂^2H	Location	δ^{18}O	∂^2H
Olkaria East			Olkaria West		
OW-10	4.55	22.6	OW-301	-0.16	-1.7
OW-15	4.37	19.7	OW-302	0.87	7.6

OW-16	3.8	15.1	OW-304	-2.21	-9.3
OW-19	4.1	19	OW-306	-0.04	0.5
OW-23	4.59	21.7	OW-307	-2.02	-5.8
OW-25	5.03	27.4	OW-308	-4.55	2.5
Olkaria Central			Olkaria North East		
OW-202	0.21	5.5	OW-709	4.18	30.6
			OW-714	3.71	23.7
Olkaria Domes			OW-719	3.43	22.3
OW-901	4.97	32.2	Lake Naivasha	1.95	31.4
OW-902	3.22	21.8			
OW-903	3.09	21.7			

Table.2 Stable Isotope (Sekento, 2012)

Lake	**δ18O**	**δD**
Nakuru	3.1	18.9
Elementaita	2.8	21.6
Bogoria	5.7	29.7
Naivasha	1.3	10.4
Baringo	2.6	16.6
Geothermal well	**δ18O**	**δD**
MW-01	-0.2	2.6
MW-04	-0.3	1
MW-04_cond	-3	-15.7
MW-05	2.5	2.9
Calculated deep thermal fluid (MW-04)	-1.2	-4.5

Table.3 Darling et.al., 1996 are indicated by (*), ♦Tiercelin et al., (1987) and (●) Cioni et al., (1992),

Lake	**$\delta^{18}O$**	**δD**
*Naivasha[a]	6.6	36
*Baringo[a]	8.8	47
*Baringo[b]	2.8	21
*Baringo N[c]	5.3	32
*Baringo S[c]	5	34
*Baringo[d]	7.6	40
♦Bogoria[e]	6	40
●Bogoria[a]	9.5	48

2. ANALYSIS OF RESULTS

The Olkaria field is not all uniform in terms of geothermal fliuds. The field seems to partition in two distinct groups; for the sake of discussion groups A and B. group A is composed of Olkaria domes and Olkaria East (Figure.6) and group B is composed of Olkaria central and Olkaria West. Group B is more enriched w.r.t ∂^2H and $\partial^{18}O$ however its noted that Olkaria domes plots on the KRMWL while Olkaria East plots off this line to the right and is more enriched with respect to $\partial^{18}O$ with values between 4-6‰. Olkaria domes and the Olkaria west both plot on the KRMWL however Olkaria domes is more enriched w.r.t ∂^2H and $\partial^{18}O$. This could be an indication that the recharge is from a different source.

Menengai geothermal fluids plot on the KRMWL (Figure.7), this implies that the field is probably recharged by rain water also it's probable that the residence time is very minimal as a result water rock interaction is limited an indication that the waters have not travelled long distances and the isotopes have been formed at low intermediate temperatures. Apart from one sample from MW-04 which appears to be more enriched with respect to $\partial^{18}O$, according to (Sekento, 2012) this was a condensate sample from a discharging well,this is attributed to increased water rock interaction or boiling due to high temperature within the reservoir.

Off the Kenya central rift waters, Lake Naivasha plot slightly off the KRMWL, CARL and GMWL implying that there is some component of rain water, the enrichment in both isotopes is possibly due to its great potential for surface evaporation (Figure.8). Lake Bogoria waters both samples plot of the KRVML line on the left and on the right which implies that it has a big percentage of rain water (probably from a river that recharges it) and another sample plots off the KRMWL its enriched w.r.t ∂^2H an d $\partial^{18}O$ this is also attributed to the high evaporation rates within the lake due to its closed nature. In Lake Baringo most of the samples plot the

KRMWL while some plot slightly of the line implying that the lake is largely recharged by rain water from the flanks i.e. high altitude. The Lake Elementaita sample seems to be more enriched w.r.t ∂^{18}O than all samples from other lakes.

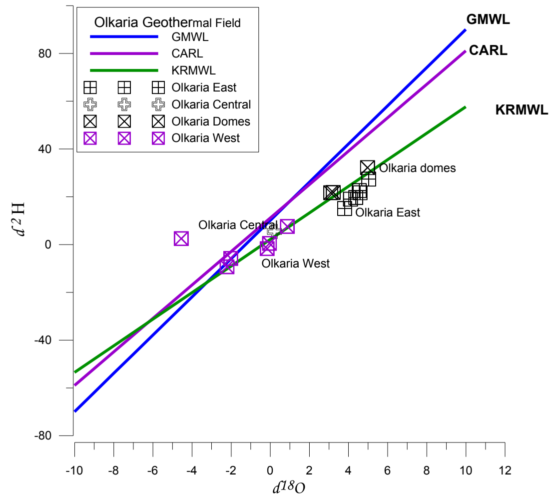

Figure 6: Isotopic composition of Olkaria Geothermal Field.

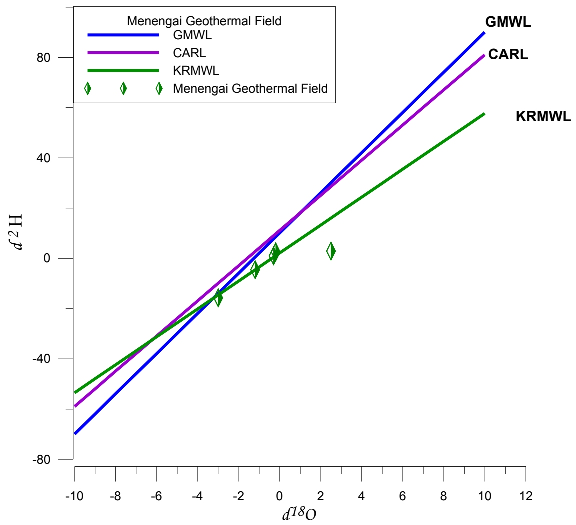

Figure 7: Isotopic composition of Menengai Geothermal Field.

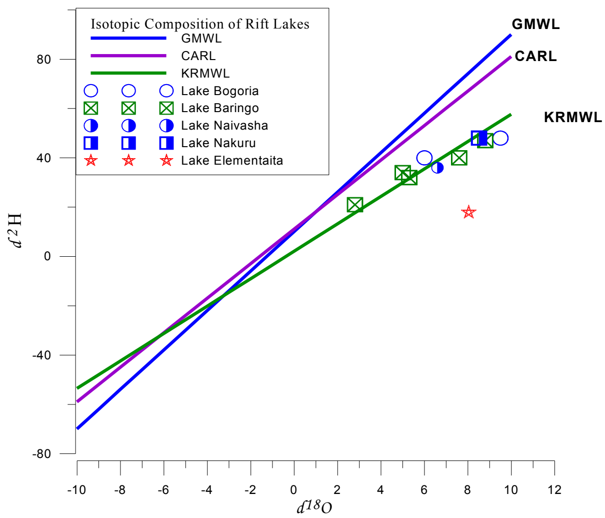

Figure 8: Stable Isotope Composition the Kenya Rift lakes

3.0 DISCUSSION

Water isotopes are generally used in geothermal studies to identify the origin of geothermal fluids and to define the physical and chemical parameters of the geothermal reservoir for optimal exploitation. In this paper data from Olkaria Geothermal field, Menengai Geothermal Field and the Central Rift Lakes which include; Lakes Baringo, Naivasha, Bogoria and Elementaita was analyzed to determine if any relationship exist.

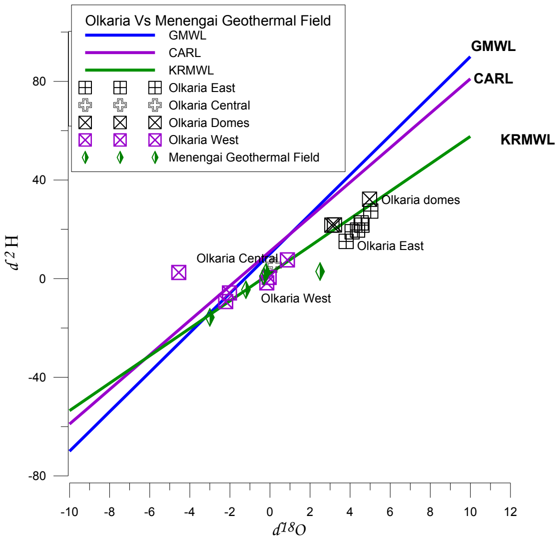

Figure 9: Olkaria Vs Menengai Geothermal fields.

From the analysis it's clear that the Olkaria geothermal field is divided into four fields which are quite distinct in their isotopic composition. The Olkaria West and Central cluster together while Olkaria domes and Olkaria East fields cluster together and are more enriched in ∂^2H and ∂^{18}O. The Olkaria East waters could be older than the Olkaria Domes waters as they have a more pronounced shift ∂^{18}O which implies that they have had more time to interact with the rocks and exchange ions. The Olkaria Domes seems to be largely recharged by rain water as opposed to the Olkaria East which seems to have undergone some evaporation before falling back as rain and interacting with the rocks.

There is a clear indication that Olkaria Central and West waters have different source, from the Olkaria Domes and East waters the recharge for this field could be from different sources. For the former this is attributed to increased water interaction as a result long residence time and also high temperatures within the reservoir. There exists a major difference between the fields to the West of Olkaria fracture and to the East of the Ololbutot fault (Karingithi, 2000), indicating that they have different recharge areas, recharge in this field probably structurally controlled.

The Olkaria west waters are very similar in isotopic composition to the Menengai field geothermal field waters. (Figure.9). These fields are fed by waters that haven't had long residence times, probably rain waters. A small shift from -3‰-0‰ is noted within these fields, implies the isotopes could have been formed at low intermediate temperatures, which are steadily increasing. One of the Olkaria west samples seems to be depleted w.r.t ∂^2H relative to the meteoric water line, it is probable that the system is fed from an aquifer originating in higher terrain where ∂^2H levels are lower or the well is tapping from a reservoir with high CO_2 values which results in depletion of ∂^{18}O.

Lake Elementaita exhibit's the highest Oxygen shift which is characteristic of chloride type waters this is attributed to boiling within the reservoir evidenced by hot springs in the lake. It's also a very shallow lake only about 0.5-1m deep making it a good candidate for evapotranspiration (Figure.10) The Menengai fluids have ∂^2H values that are 0‰ and below compared to the other lake waters (Nakuru, Naivasha, Baringo and Bogoria) within its vicinity which implies that the lake waters are much lighter than the Menengai waters. This is attributed to the fact that rain water that falls on the lakes is evaporated, condenses and falls back as rain again based on this assumption it's correct to say that Menengai is locally recharged by water from high humid areas i.e. the Bahati ranges to the East which forms part of the Aberdare ranges.

It's interesting to note Olkaria Domes waters and Lake Baringo waters have very similar isotopic composition (Figure.11) plotting on the KRMWL clustering at the same point. These are definitely not from the same recharge regime so what does this mean? the waters recharging the Olkaria Domes must be rain waters that have undergone some evaporation and haven't had much time to interact with the rocks or haven't attained temperatures that result in exchange of ions.

4. CONCLUSION

Water isotopes are generally used in geothermal studies to identify the origin of geothermal fluids and to define the physical and chemical parameters of the geothermal reservoir for optimal exploitation. Menengai and Olkaria west and central fields are similar in composition with ∂^2H and ∂^{18}O around 0‰. This can be inferred to mean that these fields are locally recharged from high humid areas i.e. the Aberdare ranges to the East of the fields. The Olkaria East waters could be older than the Olkaria Domes waters as they have a more pronounced shift ∂^{18}O which implies that they have had more time to interact with the rocks and exchange ions. The samples from all the Lakes have an average of 40‰ ∂^2H and 6‰ ∂^{18}O, they can therefore be assumed to have a great potential for high evaporation rates as most of the recharge is as a result of convectional type of rainfall typical of this lakes (Nakuru, Naivasha, Baringo and Bogoria) of course with some input from the rivers and highlands. The only exception of these lakes is Lake Elementaita which has a unique isotopic composition with the greatest shift in $\partial^{18}O$ which is similar to chloride type waters in other parts of the world.

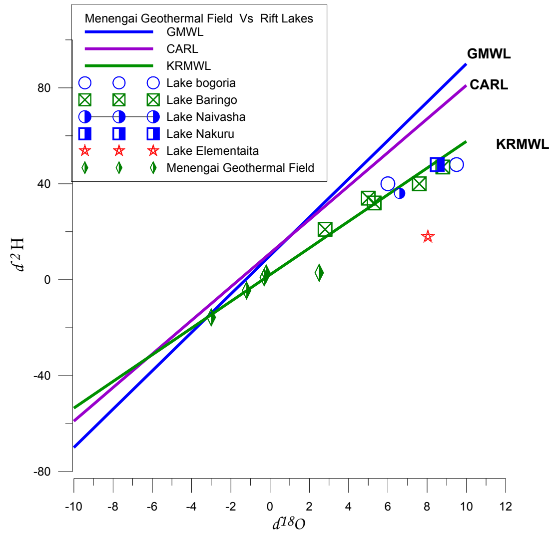

Figure 10: Menengai Geothermal Field Vs the Rift Lakes

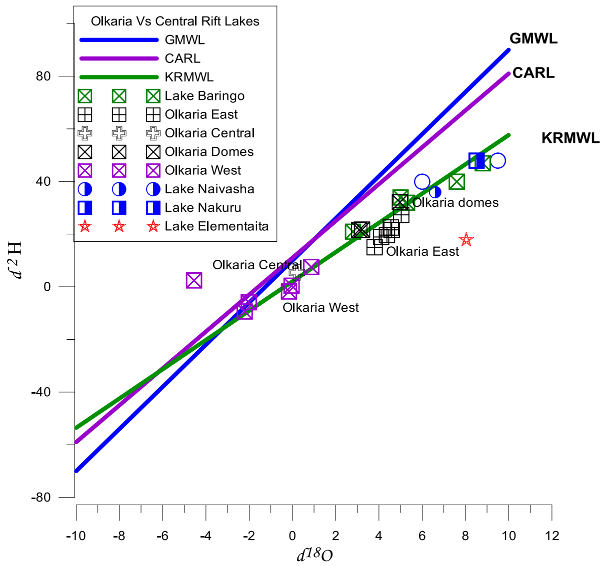

Figure 11: Olkaria Vs Central Rift Lakes

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