

# Geochemical Evaluation of Groundwater Flow Processes and Mixing in Menengai Geothermal Field, Kenya

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## Keywords

*Water, hydrology, groundwater, recharge, Menengai geothermal field*

## ABSTRACT

Intense geothermal development has occurred in Menengai geothermal field in the recent times. In this regard, it is imperative to understand groundwater movement and mixing within Menengai. Groundwater chemistry and isotopic data from boreholes, Lake Nakuru, and two geothermal wells, located in and around Menengai geothermal field in Kenya, were used to evaluate hydrological flow processes and mixing. Groundwater availability for recharge of geothermal systems depends primarily on hydrogeological factors such as recharge, transmissivity and storage. Geochemical data obtained from Menengai geothermal field indicates the fluids from Menengai region are predominantly of the Na-HCO<sub>3</sub> type, although a few of the wells may be classified as Na-HCO<sub>3</sub>-Cl to Na-Cl-HCO<sub>3</sub> waters. Stable water isotopes ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ ) were used to trace hydrological processes and tritium ( $^3\text{H}$ ) to evaluate the relative contribution of modern water in samples. Most groundwater samples are situated between the local meteoric water lines and are characterized by enriched  $\delta^{18}\text{O}$  values and depleted  $\delta^2\text{H}$  values suggesting variations of infiltration elevations. Available tritium data indicates that there are three major components contributing to local groundwaters, namely the low-salinity water from the sides of the Rift, the water discharged from the Menengai geothermal systems and the water of Lake Nakuru are old or relatively old waters. Chemical data from the study area are somewhat enriched in chloride with respect to local volcanic rocks, possibly due to presence of other chloride sources. Further assessment of the major anions and cations indicate a close relation between the geothermal reservoir liquids beneath Menengai, Lake Nakuru waters and local groundwaters. Input from Lake Nakuru into Menengai is suggested on the basis of high concentrations of Na and HCO<sub>3</sub> in the well fluids, and on isotopic composition. The ratio of the two components is, however, difficult to determine as the isotopic and presumably the chemical composition of the lakes vary with time, and the lake water influencing the wells is a mixture of present and older lake water.

## 1. Introduction

Menengai is a major Quaternary central volcano located within the axis of the central segment in the Kenyan Rift. It hosts one of the high temperature geothermal fields located in the Kenyan rift valley (Figure 1). The age of the youngest eruption episode (~1400 yrs.) indicates the possibility of a still active magma body below the Menengai caldera (Leat (1991) and Lagat et al. (2010)). Detailed surface exploration was carried out in 2004, with subsequent infill exploration studies being done in 2009, 2010 and 2011. This led to the first exploration well being sunk in 2011 and several wells have been drilled since then. 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. Knowledge of the origin of water is fundamental to understanding geothermal reservoirs. Isotopic composition of water provides a recognizable signature. During the passage of water through aquifers, the hydrogen isotope composition of the water is essentially a conservative property.

## 2. Geologic Setting

Two tectono-volcanic axes (TVAs), Molo and Solai, converge at the Menengai caldera (Figure 1) and are important in controlling the geothermal system. Numerous normal faults trending north-northwest form the greater Molo TVA, where eruption centres are also observed and volcanic eruptions have taken place (Figure 1). The Solai tectonic axis is a narrow graben that runs in a N-S direction from the eastern end of the Menengai caldera through Solai. It is comprised of numerous fault/fracture systems trending N-S (Lagat et al., 2010; Mungania et al., 2004). In the regional set-up, the Molo TVA structure extends northwards through Lomolo, the Goitumet volcanic centre, along the east side of Lake Bogoria to as far as southeast of Lake Baringo. At Ol'Rongai, the structure is marked by intense volcanic activity including explosive (pumice issuing) craters. This part of the structure is adjacent to the Menengai caldera and possibly extends into and through the caldera (Lagat et al., 2010). Geophysical surveys show that a distinct low-resistivity anomaly ( $<15 \Omega\text{m}$ ) occurs in the Menengai caldera and extends into the Ol'Rongai area to the northwest part of Menengai geothermal field, presenting a heat source inclining in the same direction as the Molo TVA. Gravity and seismology studies of the Menengai area identified a body, suggested to be a magma chamber that could constitute the heat source, directly beneath the caldera (Simiyu and Keller, 1997; 2001).

Most of the area around the caldera is covered mainly by pyroclastics erupted from volcanic centres. Young lava flows, infilling the main caldera, are of Holocene age. Older (Pleistocene) lavas, mainly trachytic in composition, are exposed in the northern parts and are overlain by eruptives from Menengai volcano (Figure 2, Mungania et al., 2004).

## 3. Hydrologic Setting

The possibility of groundwater availability for recharge of geothermal systems depends primarily on hydrogeological factors such as recharge, transmissivity and storage. According to Kanda (2013), groundwater data from 33 borehole logs were used in the analysis of aquifer stratigraphy (Figure 2). The drilling logs were obtained from boreholes tapping shallow groundwater aquifers distributed around Menengai caldera and areas neighboring Lake Nakuru. The features that were assessed include borehole depth, strike water level (i.e. the depth of the unit in which water was encountered) and static water level. Strike water level data indicated that the depths at which

water was encountered ranges between a few meters to 240 m below the surface. A shallower water-table is observed along the eastern and northeastern region and is attributed to the disappearance of River Ngosur and other seasonal streams from Bahati highlands into the sub-surface environments, subsequently, forming unexpected hydrostatic ridges that eventually raise the water-table significantly within the aquifer.

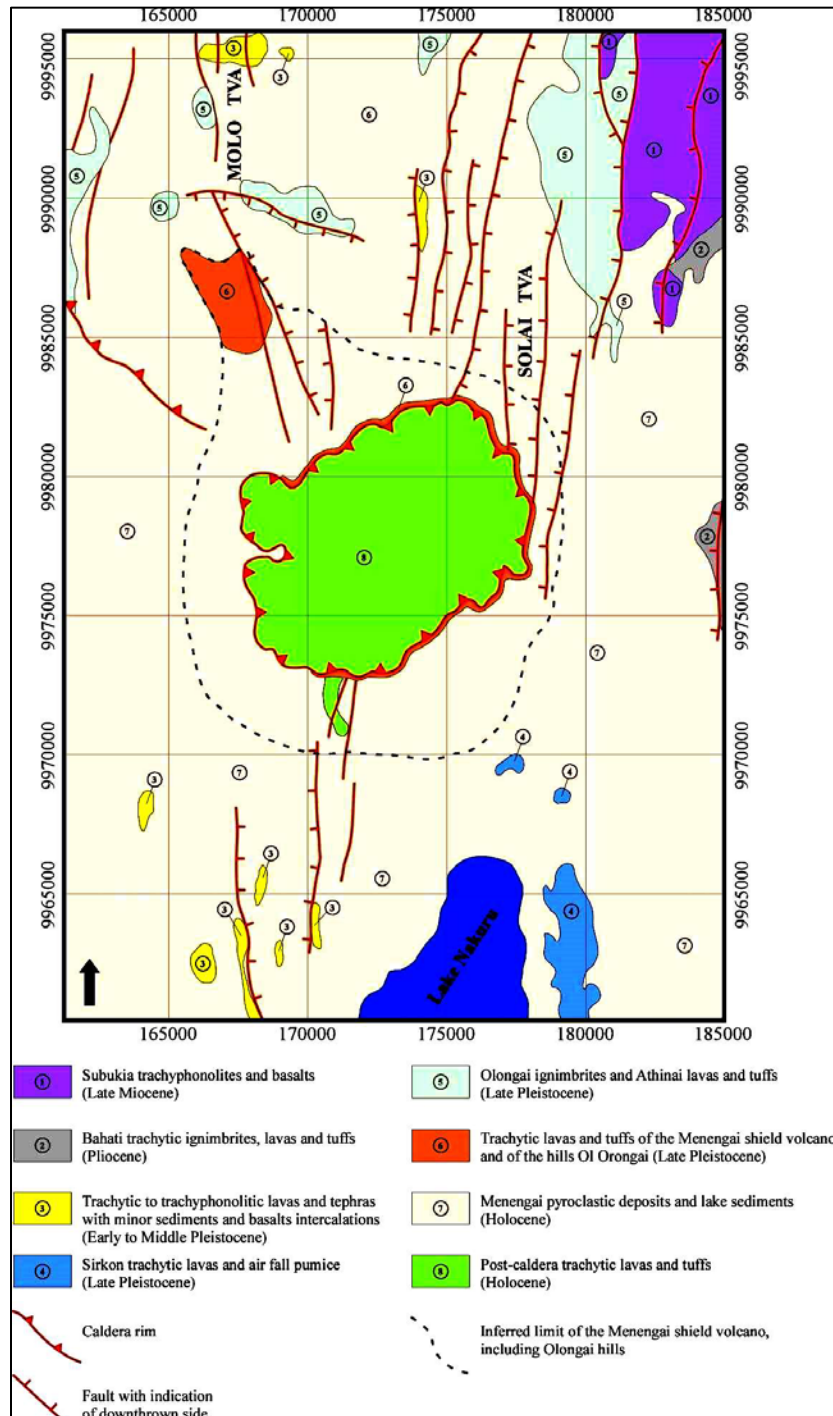


Figure 1: Geological and tectonics map of Menengai caldera region

Valuation of strike and static water level data shows that in the majority of the boreholes (> 80%), static levels are shallower than depth in which water was initially struck, and this may suggest the presence of confined shallow aquifers. More than half of the boreholes encountered multiple water intercepts with the static water level of the combined zone being the same after subsequent strikes, and therefore hydraulic connection between aquifer-bearing layers can be presumed. Aquifer lithological studies identified three types of aquifer matrices; sediments (including volcanoclastics), trachyte and tuffs. The origin of the trachytes and pyroclastics are believed to arise from a number of volcanic centers within the basin (and elsewhere), Menengai and Eburru volcanoes are the main eruption centers where most of volcanic pyroclastics and lava emplacement originated. Most of the aquifers having trachytic matrix occur where the rock is highly weathered or relatively fractured.

Lake Nakuru is one of the highest lakes in the central Kenya dome of the Rift Valley standing at 1,760 m asl, and its high altitude has hydrological implications on regional water flow pattern. Unlike other low-lying Rift Valley lakes that have abundant water supply through a series of hot and freshwater springs, there is minimal underground inflow into Lake Nakuru through the axial fault line system (Odada et al., 2005). The lake’s hydrology is reliant on catchment supply through rivers, demanding catchment integrity in order to sustain the lake water level. Five seasonal rivers (Makalia, Nderit, Naishi, Larmudiac and Njoro), and treated wastewater from Nakuru town, drain into the lake.

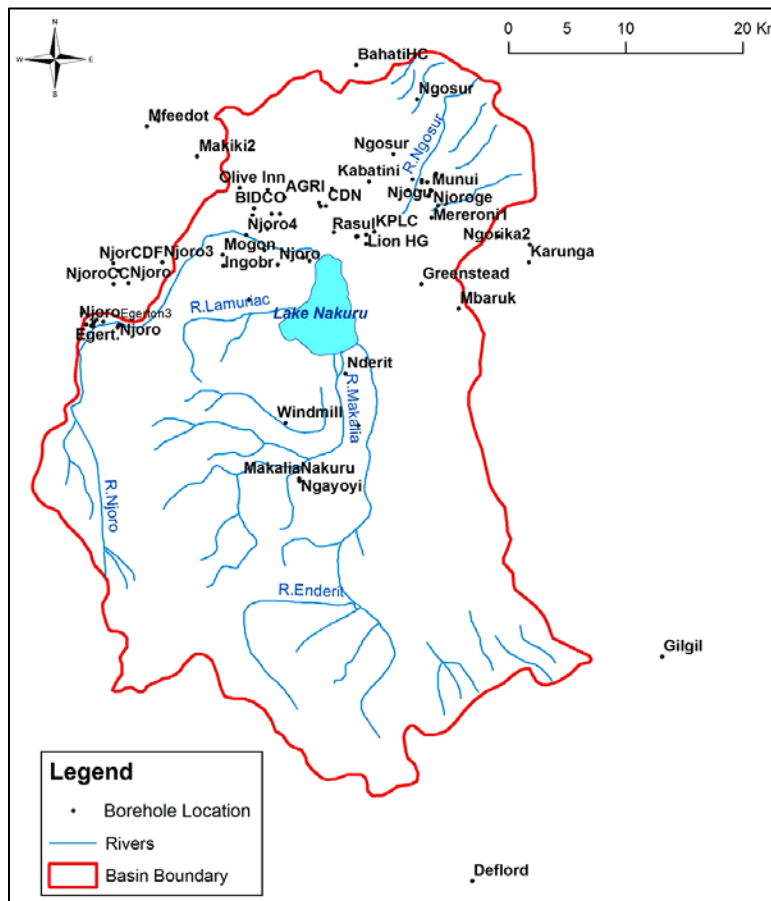


Figure 2: Local hydrogeology of Menengai area showing location of rivers, lake and boreholes

Lake Nakuru is said to be an enclosed lake, with only evaporation accounting for water loss from the lake. Some of the rivers (Njoro, Ngosur and Naishi) become influent, disappearing along the fault lines to recharge deep aquifers. These seepages of water possibly build on the regional flow pattern guided by the general gradient. According to Allen et al. (1989) and Dunkley et al. (1993) faulting has been considered to have a significant effect on regional flow in the central sector of the rift. In this central sector, flows along the rift are inhibited by major faults acting as zones of low permeability and in some areas the potentiometric surface is very deep. In addition, flows along the rift are affected by minor axial faults in the rift floor. These faults are considered to channel flows along the rift axis, either by acting as conduits if they are permeable or by inhibiting lateral flow if they are of low permeability.

#### 4. Chemical and Isotopic Characterization

##### 4.1 Chemical Groups

The triangular diagram of major anions has been adapted from Giggenbach (1988), maintaining the fields of Cl-rich mature waters, HCO<sub>3</sub>-rich peripheral waters, SO<sub>4</sub>-rich acidic steam-heated waters, as well as that of the so-called volcanic waters, which are acidic and rich in both SO<sub>4</sub> and Cl. Representative chemical analyses of the fluids from two well, MW-01 and MW-04 plot in the region of high HCO<sub>3</sub>, peripheral waters (Figure 2) and low chloride; therefore, the Menengai well fluids are of the Na-HCO<sub>3</sub> type. Waters that plot on the Cl region are usually associated with up flow zones, and are classified as mature waters according to Giggenbach (1991). The low silica suggests that the feed zone is below 200°C and it is decreasing with time during these initial days of discharge.

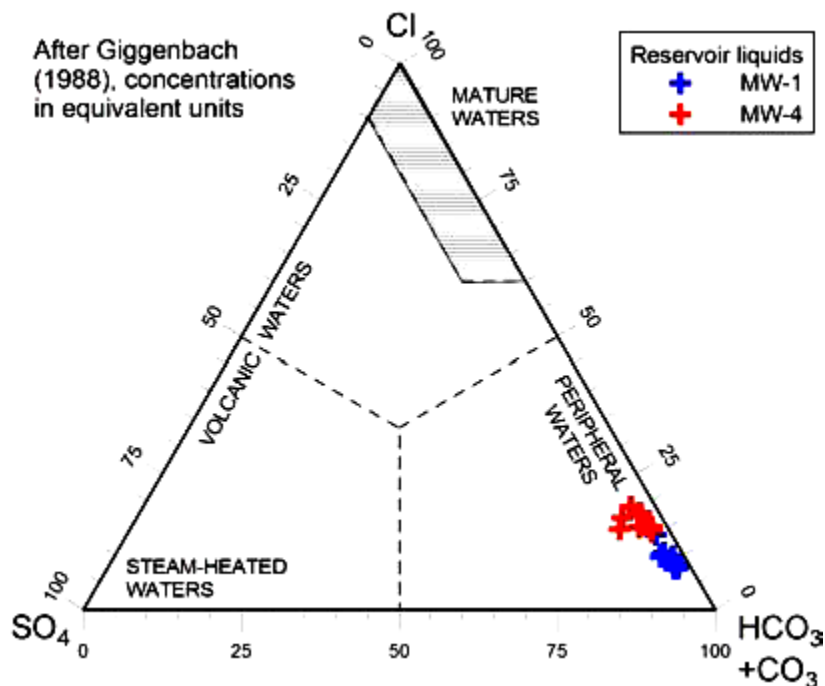


Figure 3: Triangular diagrams of major anions of fluids from Menengai

The available  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values for the groundwater samples from the Menengai area (Geotermica Italiana, 1987 and Clarke et al., 1990) are reported in the correlation plot of Figure 3, also showing; The worldwide meteoric water line, which is defined by the relation (Craig, 1961), the meteoric water line of the whole Kenyan Rift Valley (from Lake Magadi in the south to Lake Turkana, in the north), the Magadi-Silali (southern Kenya) meteoric water line and the meteoric water line of Chyulu Hills (south-eastern Kenya).

Most groundwater samples are situated between the local meteoric water lines according to Figure 4 and are characterized by  $\delta^{18}\text{O}$  values varying from -2.6 and -4.2 ‰ and  $\delta^2\text{H}$  values ranging from -8 and -20 ‰, suggesting variations of infiltration elevations in the order of 550 m, based on the  $\delta^{18}\text{O}$  values, or 810 m, on the basis of the  $\delta^2\text{H}$  values.

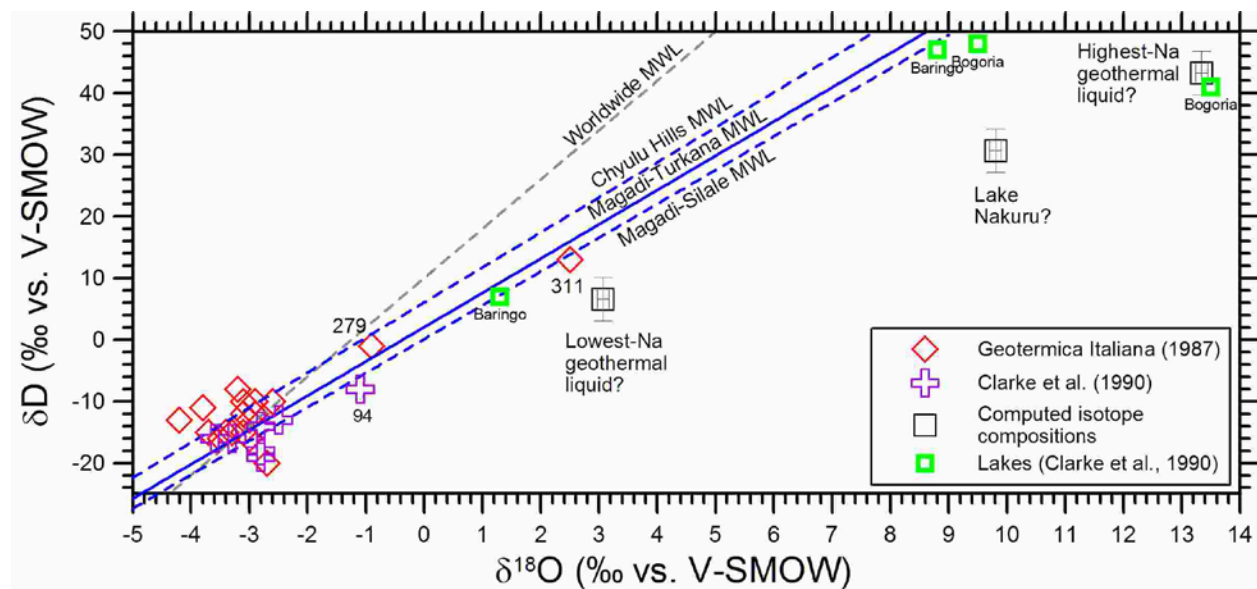


Figure 4: Correlation plot of  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  values for the groundwaters from Menengai

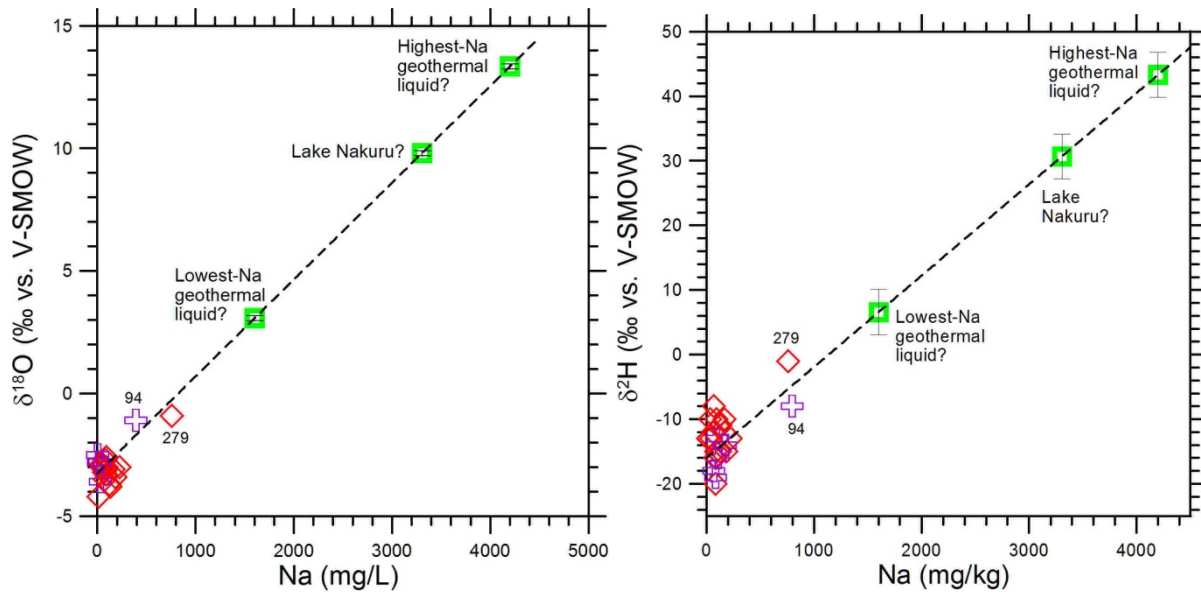
Accepting that samples 94 and 279 are mixtures made up of a high-salinity component (either Lake Nakuru or thermal water) and a low-salinity shallow groundwater component, inspection of the data using the correlation plots of Na vs.  $\delta^{18}\text{O}$  and Na vs.  $\delta^2\text{H}$  of Figure 5, samples constrain the following linear regression equations (Na in mg/kg):

$$\delta^{18}\text{O} = 0.00395 \cdot \text{Cl} - 3.25$$

$$\delta^2\text{H} = 0.0141 \cdot \text{Cl} - 16.1.$$

The average error of these computed isotope values are  $\pm 0.1$  ‰ for  $\delta^{18}\text{O}$  and  $\pm 3.5$  ‰ for  $\delta^2\text{H}$ . Errors are low for  $\delta^{18}\text{O}$  as there is a good correspondence between the two datasets, whereas errors are higher for  $\delta^2\text{H}$  as there is apparently a systematic deviation between the two dataset, with the data by Clarke et al. (1990) somewhat lower than those by Geotermica Italiana (1987). This is quite common for deuterium analysis. These computed isotopic compositions are

reported in the plots of Figures 3. Interestingly, the isotope composition estimated for Lake Nakuru is within the measured range for Lakes Baringo and Bogoria (data from Clarke et al., 1990). Although the isotope values evaluated for the geothermal liquids should be considered educated guesses, the large differences expected between distinct geothermal liquids suggest that  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values may be extremely important to understand the processes occurring in the Menengai geothermal reservoir and, in particular, to trace mixing and boiling relationships and to understand which waters are involved in the recharge of the geothermal system (Sekento, 2012).



**Figure 5: Correlation plots of Na vs.  $\delta^{18}\text{O}$  (left) and Na vs.  $\delta^2\text{H}$  (right) for the groundwaters from the study area (symbols as in Figure 4)**

Input from Lake Nakuru into Menengai is suggested on the basis of high concentrations of Na and  $\text{HCO}_3$  in the well fluids, and on isotopic composition. The ratio of the two components is, however, difficult to determine as the isotopic and presumably the chemical composition of the lakes vary with time, and the lake water influencing the wells is a mixture of present and older lake water. If the present value for Lake Nakuru is used as the lake end-member, the mixture is 20% lake water and 80% groundwater.

#### **4.2 Water Recharge Ages**

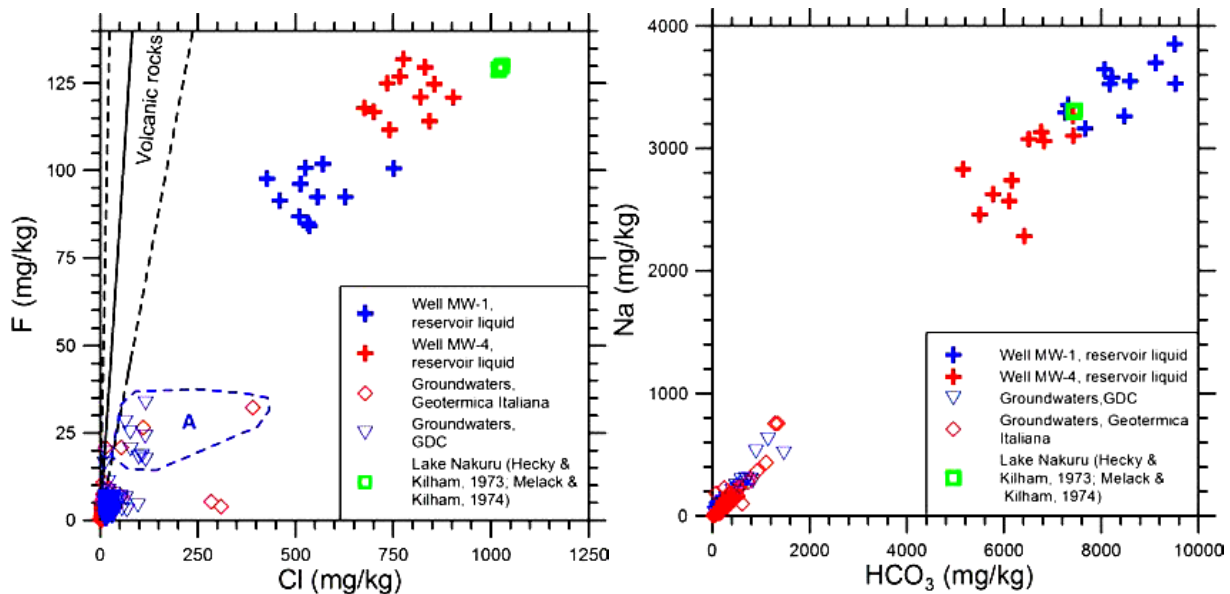
The Geotermica Italiana report gives the tritium values of ten groundwater samples (including sample 279), nine of which are lower than 3.6 TU, whereas sample 253 has a tritium value of  $4.4 \pm 3.7$  TU. In agreement with these indications, a low tritium value ( $1.64 \pm 0.16$  TU) was reported by Clarke et al. (1990) for sample 118.

These low tritium values suggest that the three major components contributing to local groundwaters, namely the low-salinity water from the sides of the Rift, the water discharged

from the Menengai geothermal systems and the water of Lake Nakuru are old or relatively old waters. Clarke et al. (1990) indicate an age higher than 25 years for waters containing less than 1 TU.

### 4.3 Evidence of Water Mixing

Proof of mixing between or within chemical/isotopic or age groups can be a guide to understanding hydrologic flow. Samples with intermediate chemical compositions are apparent on the figures. However, samples intermediate on one diagram are usually not those that are intermediate on other diagrams. Chloride plots and other binary diagrams between dissolved chemical constituents can be used to investigate the occurrence of mixing between geothermal liquids and shallow groundwaters. These diagrams divulge that liquids from Menengai geothermal reservoir, local shallow groundwater and Lake Nakuru waters are compositionally alike, and fit dominantly to Na-HCO<sub>3</sub> facies.



**Figure 6: Correlation plot of fluoride vs. chloride for the shallow groundwaters of the Menengai area. Geothermal reservoir liquids from wells MW-1 and MW-4, Lake Nakuru waters, and the range of values of local volcanic rocks are also shown. RIGHT: Correlation plot of sodium vs. bicarbonate for the shallow groundwaters of the Menengai area. Geothermal reservoir liquids from wells MW-1 and MW-4 and Lake Nakuru waters are also shown.**

Among the chloride plots, that of fluoride vs. chloride (Figure 6, left) is of special interest as the composition of groundwaters can be compared with that expected for leaching of local volcanic rocks, which are characterized by fluorine weight percentages of  $0.24 \pm 0.11$  (1s) on average, and chloride weight percentages of  $0.14 \pm 0.08$  on average (data from MacDonald et al., 1970 and Leat and MacDonald, 1984). The figure also shows that groundwaters from the study area are somewhat enriched in chloride with respect to local volcanic rocks, possibly due to presence of other chloride sources. Moreover, a number of samples are situated between the cluster of groundwaters (characterized by low contents of both Cl and F) and the aqueous solutions rich in Cl and F, comprising both the reservoir liquids and the Lake Nakuru waters, which cannot be

distinguished as their F and Cl contents are comparable. The samples occupying an intermediate position, enclosed in area A, seem to be the most likely candidates to be groundwaters affected by addition of either Lake Nakuru waters or aqueous solutions coming from the Menengai geothermal reservoir and entering the surrounding shallow aquifers.

A binary plots of Na vs.  $\text{HCO}_3$  (Figure 6, Right) was also used to investigate the occurrence of mixing. In the Na vs.  $\text{HCO}_3$  diagram, geothermal reservoir liquids, Lake Nakuru waters, and local groundwaters define a tight continuous alignment and therefore indicate that there is a relation between these three water bodies. The plot also indicates that MW-01 is richer in bicarbonate ( $\text{HCO}_3$ ) and sodium (Na) relative to MW-04, and the two elements correlate positively suggesting a possible common origin. These plots show the possibility of chemical relations between the two wells, meaning the aquifers may be partly interconnected, and the difference in chemistry can be attributed to the multiple feed zones.

## 5. Conclusions and Inferences

Based on the chemical and isotopic studies, there are several observations that can be made concerning the relations among the hydrochemical groups and regional hydrologic flow;

- Chemical analyses of the fluids from fluids of Menengai plot in the region of high  $\text{HCO}_3$ , peripheral waters and low chloride; therefore, the Menengai well fluids are of the Na- $\text{HCO}_3$  type.
- Most of the groundwater samples within Menengai are situated between the local meteoric water lines and are characterized by  $\delta^{18}\text{O}$  values varying from -2.6 and -4.2 ‰ and  $\delta^2\text{H}$  values ranging from -8 and -20 ‰, suggesting variations of infiltration elevations in the order of 550 m, based on the  $\delta^{18}\text{O}$  values, or 810 m, on the basis of the  $\delta^2\text{H}$  values.
- The groundwaters from Menengai area are somewhat enriched in chloride with respect to local volcanic rocks, possibly due to presence of other chloride sources
- In the Na vs.  $\text{HCO}_3$  diagram geothermal reservoir liquids, Lake Nakuru waters, and local groundwaters define a tight continuous alignment and therefore indicate that a close relation between these three water bodies.
- The groundwater samples from Menengai give tritium values which are lower than 3.6 TU1, these low tritium values suggest that the three major components contributing to local groundwaters in Menengai, namely the low-salinity water from the sides of the Rift, the water discharged from the Menengai geothermal systems and the water of Lake Nakuru are old or relatively old waters.
- Input from Lake Nakuru into Menengai is suggested on the basis of high concentrations of Na and  $\text{HCO}_3$  in the well fluids, and on isotopic composition. The ratio of the two components is, however, difficult to determine as the isotopic and presumably the chemical composition of the lakes vary with time, and the lake water influencing the wells is a mixture of present and older lake water. If the present value for Lake Nakuru is used as the lake end-member, the mixture is 20% lake water and 80% groundwater.

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