ISOTOPE HYDROLOGY IN THE EXPLORATION OF THE KATWE-KIKORONGO, BURANGA AND KIBIRO GEOTHERMAL SYSTEMS, UGANDA

Godfrey Bahati
Department of Geological Survey and Mines
P.O Box 9, Entebbe, Uganda
Email: seismo@utlonline.co.ug, gbahati@gmail.com

ABSTRACT

Several sampling campaigns have been carried out in three geothermal areas in western Uganda, namely Katwe-Kikorongo (Katwe), Buranga and Kibiro. 118 water samples from hot and cold springs, dug wells, rivers, lakes and 13 rock samples from surface outcrops have been collected and analyzed for chemistry and isotopes of hydrogen (δ^2H_{H2O}, $^3H_{H2O}$), oxygen ($\delta^{18}O_{H2O}$, $^{18}O_{SO4}$), carbon ($\delta^{13}C_{DIC}$, $^{14}C_{DIC}$), sulphur ($\delta^{34}S_{SO4}$), and strontium ($^{87/86}Sr_{H2O}$, $^{87/86}Sr_{Rock}$). The results suggest a meteoric origin of the geothermal water with minimal secondary alteration. Based on isotope data, Katwe and Buranga are recharged from the Rwenzori Mountains while Kibiro is recharged from high ground represented by the Mukihani-Waisembe Ridge in Kitoba Sub-county 20 km to the southeast. Oxygen isotope geothermometry based on aqueous sulphate and water equilibrium fractionation, indicates a subsurface temperature of 200°C for Buranga, which is higher than that inferred from chemical geothermometry (120-130°C), but lower temperatures (140-160 °C) for Katwe and Kibiro that are similar to the results of chemical geothermometry. Tritium concentrations indicate some involvement of modern cold water close to the surface at Kibiro but not at Buranga and Katwe, where hot springs discharge tritium-free waters. Sulphur isotope ratios ($\delta^{34}S_{SO4}$) of hot water suggest magmatic contributions of sulphate in all the three areas, confirming results of earlier geochemical investigations. Strontium isotope ratios in water and rock samples ($^{87/86}Sr_{H2O}$, $^{87/86}Sr_{Rock}$) allow a preliminary identification of rock types that may have interacted with the thermal waters.

Key words: Isotopes; Recharge; Geothermometry; Salinity; Katwe-Kikorongo; Buranga; Kibiro; Uganda

1. INTRODUCTION

The geological and geotectonic setting of the Eastern Africa Rift System (EARS) suggests that it is very promising for geothermal development. Some areas, particularly in the eastern branch of the EARS in Kenya and Ethiopia, are already being exploited or are under exploration. In the western branch of the EARS, however, exploration has proceeded rather slowly, partly because of a limited scientific understanding of the geothermal systems.

Uganda is one the East African countries traversed by the western branch of the EARS, and, based on surface manifestations; its potential for geothermal energy development is high. For more than a decade, the Ugandan government has supported a geothermal exploration programme to provide electricity or direct heat for domestic power, industrial processing and agriculture in the rural areas.

Since 1999 the government of Uganda with support from the International Atomic Energy Agency (IAEA) has executed the Isotope Hydrology Project (UGA8003&5) on three most promising geothermal prospects of Uganda (Katwe-Kikorongo (Katwe), Buranga and Kibiro), located along the Congolese border (Figure 1) in the Western Rift Valley. The main objectives of this study were to: 1) elucidate the origin of the geothermal fluids, 2) identify the recharge mechanisms, 3) estimate subsurface temperature using isotope geothermometry, 4) trace the source of solutes, and 5) improve the conceptual geothermal models of the study areas.

This paper presents the results of this study.

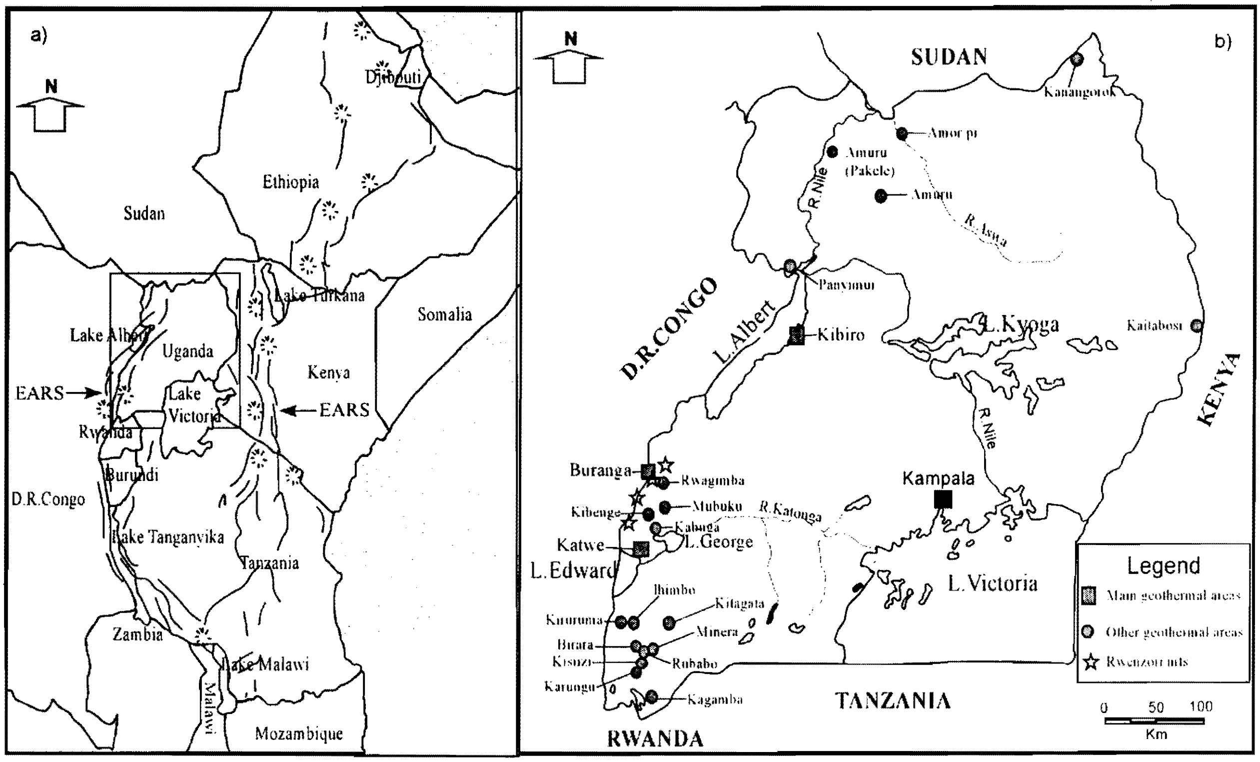

Figure 1: a) East African Rift System (EARS), b) Locations of the geothermal areas of Uganda

2. GEOLOGY OF THE WESTERN RIFT VALLEY

The geology of Uganda consists of an exposed pre-Cambrian basement dissected by the western branch of the East African Rift System in the western part of the country. In the Rift graben, the basement is overlain by intercalating tertiary sediments. The Western Rift starts to the north along the Sudan border, and then curves to the west and then southwest along the border with the Democratic Republic of Congo, and south to Rwanda, Burundi and western Tanzania. Spreading began at least 15 million years ago in Miocene time. The western Rift is considered at an early stage in the development, and is younger (late Miocene-Recent) than the more mature eastern branch, the Gregory Rift that runs north-south through central Kenya (Morley et al., 1999). The region of the Rift has a markedly higher heat flow than the surrounding Pre-Cambrian terrain. Within the Rift Valley there are thick layers of late Tertiary and Quaternary sediments; fresh water and saline crater lakes; volcanics; and plutonic bodies have been identified beneath L. Albert and L. Edward (EDICON, 1984).

3. STUDY AREAS

The study areas are Katwe, Buranga and Kibiro. The three areas were chosen as priority areas because of their volcanic and tectonic features that are indicators of a strong heat source and permeability.

The Katwe geothermal prospect is located in the Katwe-Kikorongo volcanic field between Lakes Edward and George and, the Rwenzori Mountains (Figure 1). The geothermal prospect covers an area of approximately 150 km^2. The geology is dominated by explosion craters and ejected pyroclastics and tuffs with abundant granitic and gneissic rocks of the basement. Minor occurrences of lava are found mainly in Lake Kitagata and Kyemengo crater areas. The age of the volcanic activity has been estimated at Pleistocene to Holocene (Musisi, 1991). Geothermal surface manifestations (hot springs) are relatively scarce, and found in two craters only, Katwe and Kitagata, both of which are host crater lakes. The maximum surface temperature is 70°C in one of the springs in the Lake Kitagata crater.

The Buranga geothermal area is located at the northwestern base of the Rwenzori Mountains in the Western Rift Valley (Figure 1). Unlike Katwe, Buranga shows no evidence of volcanism but is highly active tectonically. Geothermal surface activity is intense, with sprouting hot springs and high gas flow with a maximum temperature of 98°C. Recent surface and geological observations indicate the presence of extinct thermal features (travertine deposits) along a zone stretching for 10 km north of the Buranga hot springs. This indicates that the area of thermal activity has been shifting from north to south and that the underground geothermal activity in Buranga area may be somewhat larger than indicated by the present day surface manifestations.

The Kibiro geothermal area is located on the shores of Lake Albert on the eastern escarpment front of the Western Rift Valley (Figure 1). The escarpment, which cuts through the field from SW to NE, divides the study area into two entirely different geological environments. To the east, the geology is dominated by an ancient crystalline basement, characterized by granites and granitic gneisses, where as in the Rift Valley to the west there are sequences of sediments, at least 5.5 km thick. The surface manifestations (hot springs) are characterised by the presence of H_2S (10-15 ppm) with a maximum temperature of 86.5°C. Fumarolic activity has been located 500 m southwest of the hot springs, and sulphur deposits and crystals in cracks of escarpment rocks have been identified and mapped (Gislason et. al., 2004).

3. SAMPLING AND ANALYSES

A total of 118 water samples from hot and cold springs, dug wells, rivers and lakes, as well as 13 samples from surface outcrops of different types of rocks, were collected and analyzed for chemical and isotopic compositions. Isotopes analyzed included hydrogen (δ^2H_{H2O}, $^3H_{H2O}$), oxygen ($\delta^{18}O_{H2O}$, $^{18}O_{SO4}$), carbon ($\delta^{13}C_{DIC}$, $^{14}C_{DIC}$), sulphur ($\delta^{34}S_{SO4}$), and strontium ($^{87/86}Sr_{H2O}$, $^{87/86}Sr_{Rock}$). Field measurements of temperature, pH, electrical conductivity, analysis of volatiles (CO_2 and H_2S) etc., were carried out on site. The sampling procedure and results of chemical and isotopic analysis are recorded by Armannsson 1994; Bahati et. al., 2005; and UGA-IAEA, 2006.

4. RESULTS AND DISCUSSIONS

4.1 Stable isotopes of water, and recharge to the geothermal systems

Isotope ratios, especially $^2H/^1H$ (usually reported in delta notation as δ^2H, Craig, 1961a), tend to be conservative, and are good indicators of the origins of flow, mixing and evaporation processes. The $^{18}O/^{16}O$ ratio or $\delta^{18}O$ is similarly useful for cold waters, but in geothermal systems exchange may take place during water/rock interaction, causing an oxygen isotope shift to higher delta values, especially where the water/rock ratio is low, i.e. when general permeability is poor.

A general worldwide relationship between δ^2H and $\delta^{18}O$ has been established (Craig, 1961b), as the Global Meteoric Water Line (GMWL):

$$\delta^2H = 8*\delta^{18}O+10 \qquad \text{(i)}$$

Similarly the observed, Local Meteoric Water Line (LMWL) for precipitation at Entebbe (GNIP, 1999) has the same slope but higher deuterium excess with the equation:

$$\delta^2H = 8*\delta^{18}O+12.3 \qquad \text{(ii)}$$

Both lines have been drawn in Figure 2 and the stable isotope results for waters from the three areas plotted. All hot spring waters, groundwaters, and river waters plot close to the two lines. The thermal waters show isotopic compositions compatible with the LMWL, confirming the meteoric origin of the water circulating in the geothermal systems. The lake waters (enclosed in an oval) are higher in δ^2H and $\delta^{18}O$ as a result of evaporation, as shown by the dotted trend line, which represents a typical evaporation line.

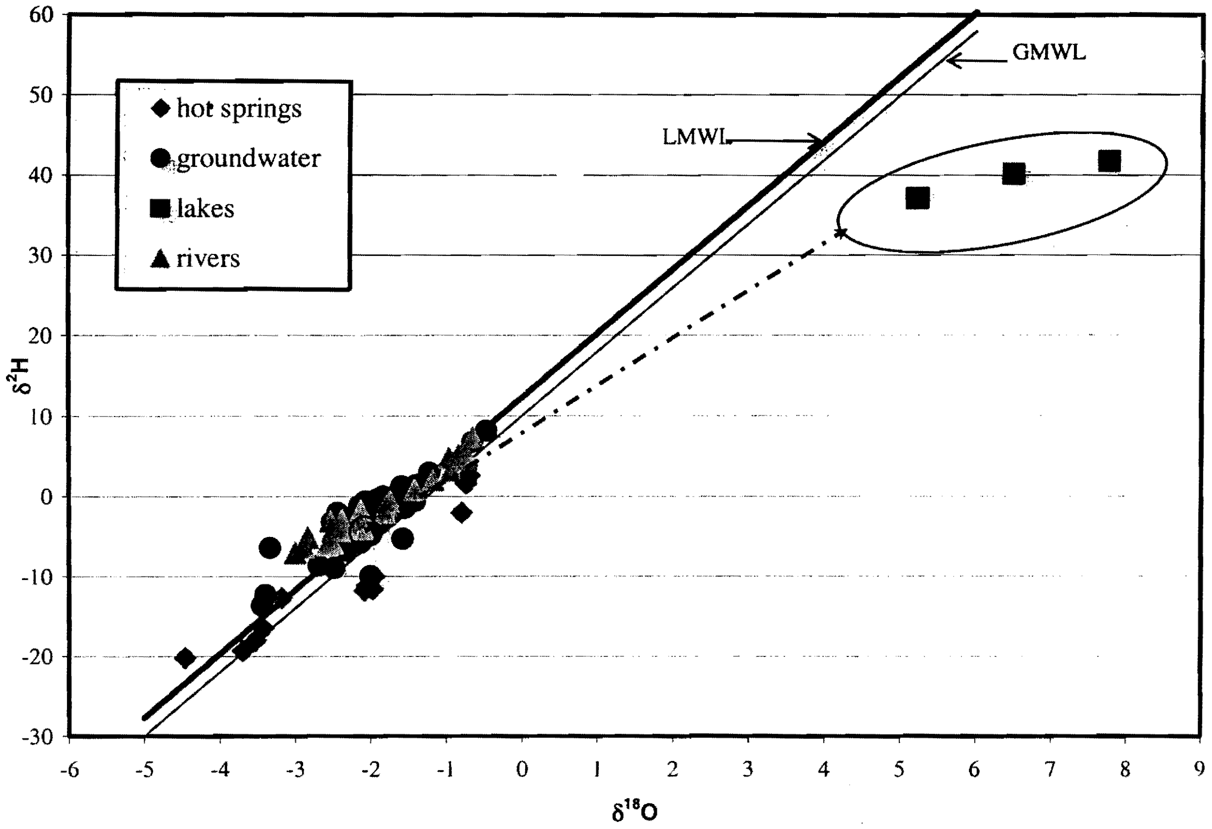

Figure 2: Katwe, Buranga and Kibiro: stable isotopic composition of hot and cold water samples.

In the Katwe area (Figure 3), there are signs of both oxygen and deuterium shifts of the hot spring waters from the potential source water, which results from slight mixing with lake water. The lake waters have been affected by strong evaporation, resulting in increased δ^2H and $\delta^{18}O$. The Katwe hot spring water is probably a mixture of a source water similar to the most depleted potential recharge water and water from lakes in the area. The mixing model for Katwe is also represented in the same diagram by a dashed line. This model indicates that the geothermal water is a mixture of the hot water component (represented by Kibenge-HS) with potential groundwater recharge and the lake water.

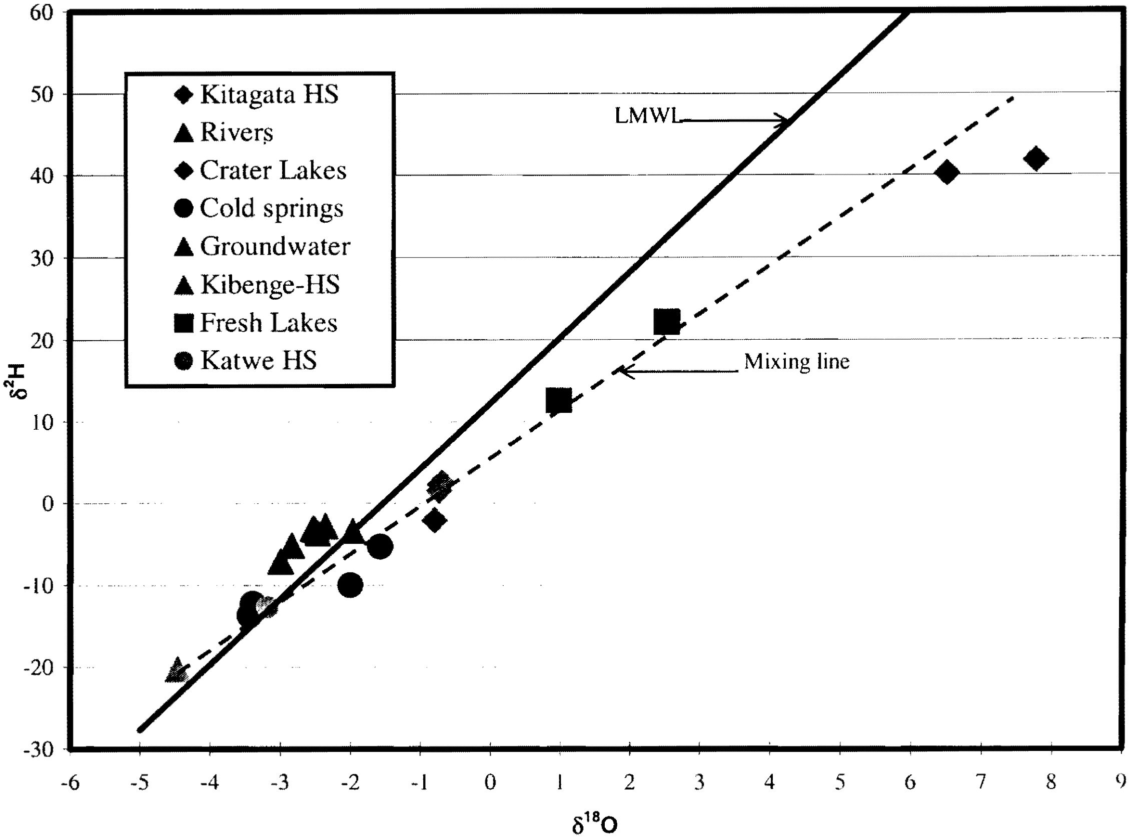

Figure 3: Katwe: stable isotopic composition of hot and cold water samples

In the Buranga area (Figure 4), there are no signs of an oxygen shift from the LMWL for hot spring waters, an indication of reasonable high permeability. All the groundwaters and river waters are more enriched in δ^2H than the hot spring waters by about 5 ‰, an indication that these cold waters cannot be a source of recharge for the thermal waters in this area. The diagram also shows the plot of the Kibenge geothermal area (Kibenge-HS) in relation to Buranga hot spring waters. As in the Katwe area, the source of recharge for Buranga is represented by the Kibenge hot spring although it is unlikely to provide the recharge for both areas considering its location and elevation. The recharge for the three areas, therefore, could be from the same source which is at a higher elevation.

Katwe, Buranga and Kibenge geothermal waters are most likely recharged from high ground in the Rwenzori Mountains. The Rwenzori Mountains are snow-capped and characterized by a number of lakes, at high elevation that are recharged from snowmelt. It is possible that some of these lakes are losing some of their waters through fractures (faults) that connect with the Katwe, Buranga and Kibenge geothermal reservoirs. The evidence for this is earthquakes that simultaneously affect the areas to the west (Buranga) and the areas to the east (Katwe and Kibenge) of the Rwenzori Mountains, indicating that both areas are connected by faults, possibly passing under the Mountains.

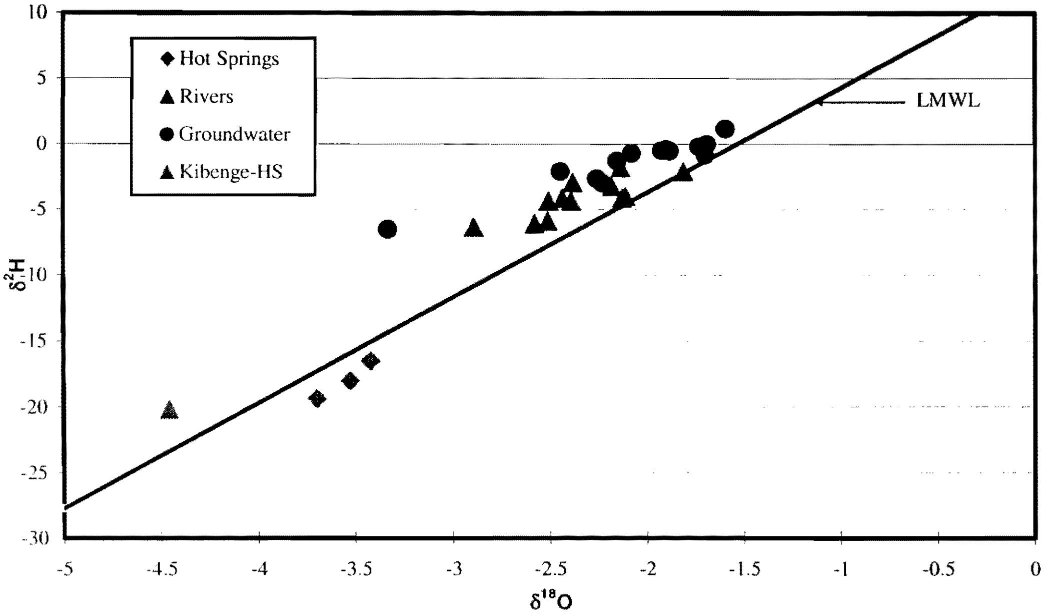

Figure 4: Buranga: stable isotopic composition of hot and cold water samples

In the Kibiro area stable isotope results indicate that there are two groups of hot springs namely Muntere which is highly enriched in $\delta^{18}O$ and δ^2H, and the Mukabiga/Mwibanda. This suggests that the hot spring water from Muntere could be from a different source than those from Mukabiga/Mwibanda. The groundwater that could be the source of recharge for the Kibiro hot springs is represented by two groups of waters located east and south of Kibiro (Figure 5).

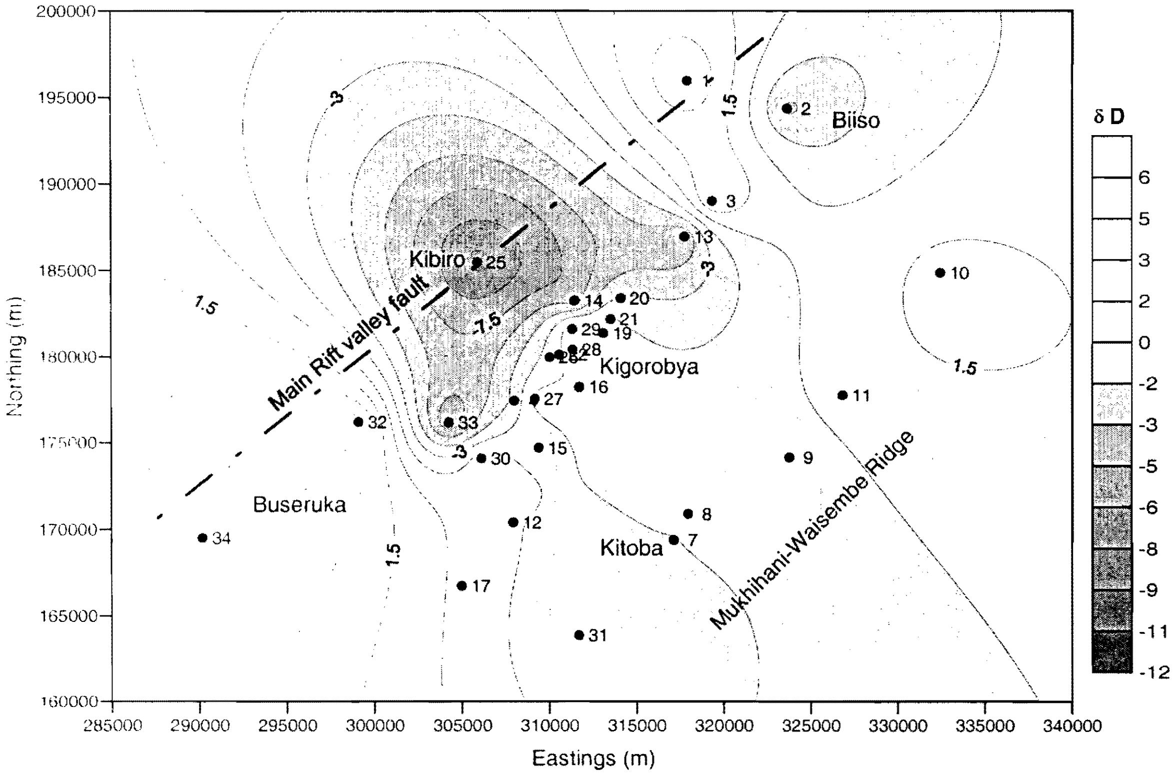

Figure 5: Kibiro: deuterium concentrations in water

The eastern and southern sources are probably feeding the Muntere and Mukabiga/Mwibanda hot springs respectively. Figure 5 also suggests that the Kibiro hot spring water is either recharged from the areas above the escarpment located east and south and closer to the thermal area or from a higher elevation than all the cold-water sampling points. This water is likely to be channeled through faults that have been identified in the area east and south of Kibiro. The only high ground close by is the Mukihani-Waisembe Ridge in Kitoba subcounty, located 20 km southeast of Kibiro.

4.2 Tritium (^3H) and possible mixing processes

Tritium (^3H) analyses indicate that there is no tritium in hot spring waters from the Katwe and Buranga areas. The Kibiro hot spring water has tritium content similar to that of the groundwaters, which indicates that the thermal water has some cold groundwater contribution and is therefore a mixture of a hot water component and cooler waters. Lack of tritium in the Katwe and Buranga hot spring waters suggests a residence time of more than 50 years BP.

4.3 Isotope and chemical geothermometry

Results of geothermometer temperature calculations are presented in Table 1. Four types of chemical geothermometer temperatures were obtained for the Kibiro samples, as well as the sulphate-water ($S^{18}O_4$-$H_2{}^{18}O$) isotope geothermometer temperature, which is well established for water-dominated fields (Lloyd, 1968; Mizutani and Rafter, 1969; McKenzie and Truesdell, 1977). This geothermometer gives a temperature of 180-210°C for Buranga and 140-160°C for Katwe and Kibiro.

Table 1: Chemical and isotope geothermometer temperatures (°C)

Area	Site	$T_{qz}{}^{a}$	$T_{KMg}{}^{b}$	$T_{NaK}{}^{c}$	$T_{NaKCa}{}^{d}$	$T_{S^{18}O_4-H_2{}^{18}O}{}^{e}$
Kibiro	Kibiro-5	160	148	217	220	137
	Kibiro-14	151	150	222	223	150
	Kibiro-3					160
Katwe	L. Kitagata-2	116		145		130
	L. Kitagata-5	134		162		140
Buranga	Kagoro-20	122		111		188
	Nyansimbe-17	104		113		189
	Mumbuga-5	117		111		212

[a] Fournier and Potter (1982)
[b] Giggenbach (1988)
[c] Arnorsson et al. (1983)
[d] Fournier and Truesdell (1973)
[e] Mizutani and Rafter (1969)
[f] Results from Armannsson (1994)

Ármannsson (1994) found that indicated geothermometer temperatures for samples from Kibiro fell into two groups, one about 150°C and another in the 200-220°C range. Lower temperatures were indicated by single-component solute geothermometers (e.g. quartz) and by geothermometers based on ratios of components that equilibrate rapidly (e.g. K-Mg). Higher temperatures were indicated by geothermometers based on ratios between components that equilibrate more slowly (e.g. Na-K and gas geothermometers). Mixing with cooler groundwaters may have affected the SiO_2 and K-Mg geothermometer temperatures. The use of mixing models (SiO_2-enthalpy, SiO_2-CO_2) and the construction of log (Q/K) diagrams supported this explanation. Exchange of oxygen isotopes between dissolved sulphate and water is exceedingly slow in neutral and alkaline solutions below 200°C (McKenzie and Truesdell, 1977), so equilibrium is probably not reached for the mixed solution and the $S^{18}O_4$-$H_2{}^{18}O$ temperatures are probably too low (Table 1). Therefore, the model suggesting a reservoir temperature in excess of 200°C still seems valid for Kibiro.

Solute geothermometers were a little difficult to use in Katwe because of the extreme salinity of the thermal fluid. The sulphate concentrations are relatively high and all indications suggest that the geothermal system is relatively old. Thus conditions for sulphur isotope determination and attainment of isotope equilibrium are good and the results compare reasonably well with those of the solute geothermometers (Table 1). In this case, however, it would be the geothermal component that supplied most of the sulphate. Thus a subsurface temperature of 140-160°C is predicted for Katwe on the basis of geothermometric data.

In the earlier study by Ármannsson (1994) a good agreement was obtained for all solute geothermometers tested for several hot springs and pools in Buranga and it was concluded that the subsurface temperature was 120-130°C. Log (Q/K) diagrams suggest about 135°C and there are few indications of mixing with groundwater. A gas geothermometer temperature based on the CH_4/C_2H_6 ratio (Darling et al., 1995) gave a higher temperature of 164°C, but H_2 was not detected in the gas, so the temperature of the system is likely to be well below 200°C. The present results reveal values from 180-210°C, which seem higher than could be expected. A more plausible explanation is that the Buranga geothermal system was hotter in the past and that the relative slowness of the exchange of oxygen isotopes between dissolved sulphate and water (McKenzie and Truesdell, 1977) has not changed the composition of isotopes in the fluid. The most reasonable interpretation seems to be that the reservoir temperature at Buranga is now 120-130°C, but that higher temperatures may have prevailed there in the past.

4.4 Sulphur isotopes and source of solutes

The isotopic composition of sulphur and oxygen in sulphates helps to differentiate between marine, evaporitic and volcanic sources of dissolved sulphate (Krouse, 1980; Pearson and Rightmire, 1980) and to determine its fate in the groundwater. The isotopic compositions expressed in $\delta^{34}S$ (SO_4) and $\delta^{18}O$ (SO_4) are important characteristics when origin of water and sulphates is discussed. The variety of possible sources of dissolved sulphates, complex fractionation mechanisms, non-equilibrium state and uncertainties about the permeability of the groundwater systems, however, make the interpretation of isotopic composition of sulphate and bound oxygen a difficult task. Figure 6 shows the ranges of $\delta^{34}S$ and $\delta^{18}O$ values for sulphates of various origins dissolved in groundwater (after Clark and Fritz, 1997). The hot spring waters from the three geothermal areas plot in different regions of the diagram. The figure shows that the source of sulphate for Katwe and Kibiro thermal water is magmatic and hydrothermal while for Buranga is minerals or rocks (terrestrial evaporites), with a possible magmatic contribution.

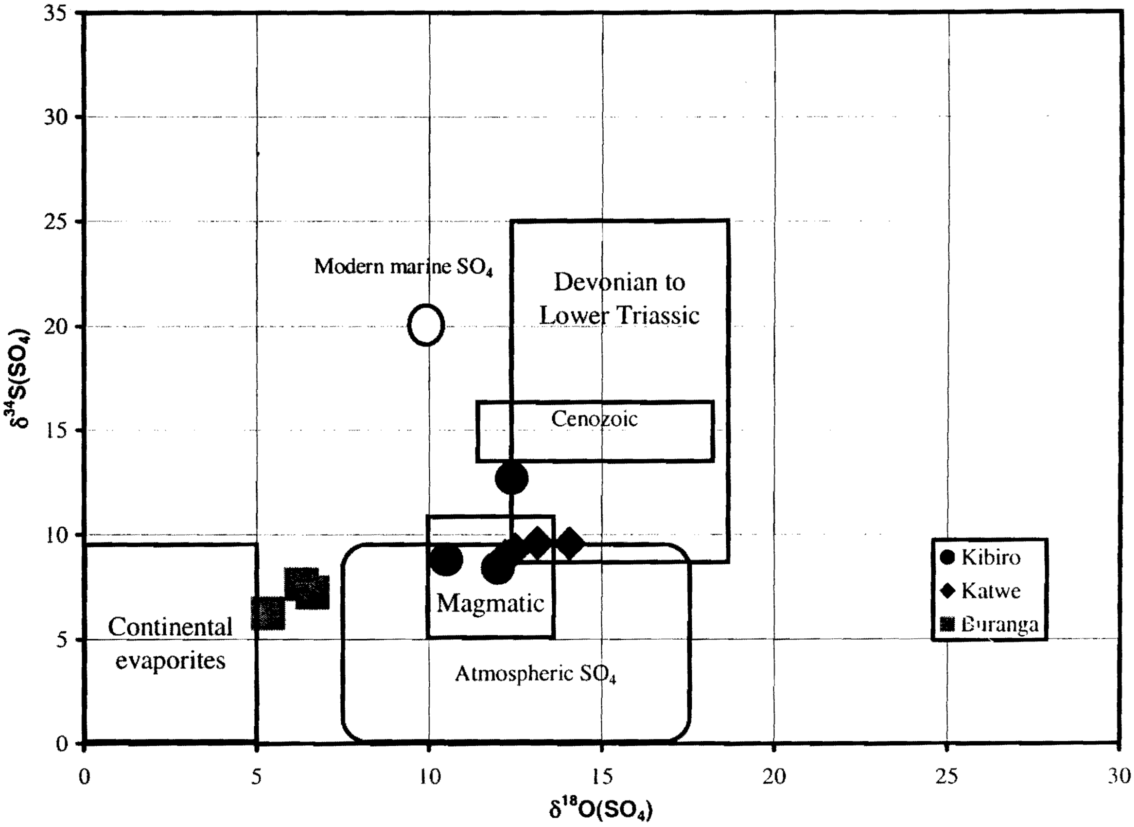

Figure 6: Katwe, Buranga and Kibiro: ranges of δ^{34}S and δ^{18}O of sulphates of various origins in groundwater

4.5 Strontium isotopes ($^{87/86}Sr_{H2O}$, $^{87/86}Sr_{Rock}$) and water-rock interactions

The concentration of $^{87/86}$Sr in most of the rocks and the thermal water in the same area are close suggesting a possibility of water-rock interaction between these rocks and the geothermal fluids. Comparison of strontium ratios in rocks and the corresponding geothermal waters indicates that the thermal water most likely interacts with basalt and ultramafic xenolith in Katwe and granites in Buranga and Kibiro.

5. CONCLUSIONS

The waters recharging the hot springs in the three Ugandan geothermal areas under study come from higher elevations, most likely in the nearby Rwenzori Mountains in the case of Katwe and Buranga. For Kibiro, the source is either from surrounding areas located east and south of Kibiro or from a higher elevation represented by the Mukihani-Waisembe ridge in Kitoba sub-county located southeast.

Subsurface temperatures predicted by isotope geothermometry are highest for Buranga (200°C), but these may be older temperatures in a cooling system which is probably now at 120-130°C. Lower temperatures of 140 – 160°C are predicted for Katwe and Kibiro. The Kibiro data probably reflect low temperatures resulting from a mixing with relatively sulphate-rich groundwater and thus do not conflict with the model previously proposed for Kibiro

(Armannsson, 1994) in which a geothermal water of about 200°C mixes with a brackish groundwater to produce a mixed water of about 150°C. The Katwe results probably reflect a true subsurface temperature.

Reservoir rock types are most likely basalt and ultramafic xenolith in Katwe, and granites in Buranga and Kibiro.

The major source of solutes in the waters of the three geothermal areas is rock dissolution, with magmatic input.

REFERENCES

Armannsson, H., 1994. Geochemical Study on Three Geothermal Areas in West and Southwest Uganda. UNDDSMS UGA/92/002 unpublished report.

Arnórsson, S., Gunnlaugsson, E. and Svavarsson, H. 1983. The chemistry of geothermal waters in Iceland III. Chemical geothermometry in geothermal investigations. Geochim. Cosmochim. Acta, 47, 567-577.

Bahati, G., Pang, Z., and Armannsson, H., Isabirye, E.M., Kato, V., 2005. Hydrology and reservoir characteristics of three geothermal systems in Western Uganda, *Geothermics 34 (2005)* 568-591.

Craig, H., 1961a. Standard for reporting concentrations of deuterium and oxygen-18 in natural water, Science, 133: 1833-1834.

Craig, H., 1961b.Isotopic variations in meteoric waters. Science, 133: 1702-1703.

Clark, I.D., and Fritz, P., 1997. Environmental Isotopes in Hydrology, Lewis Publishers, New York, 328 pp.

EDICON, 1984. Aeromagnetic interpretation of Lake Albert/Edward portion of the Western Rift Valley. Unpubl. report, EDICON inc., Denver Colorado, Sept. 1984.

Fournier, R.O. and Potter, R.W. II 1982. A revised and expanded silica (quartz) geothermometer. Geotherm. Res. Council Bull., 11, 3-9.

Fournier, R.O. and Truesdell, A.H., 1973. An empirical Na-K-Ca chemical geothermometer. Geochim. Cosmochim. Acta, 37, 1255-1275.

Giggenbach, W.F., 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. Geochim. Cosmochim. Acta, 32, 2749-2765.

Gislason, G., Árnason, K. and Eysteinsson, H., 2004. The Kibiro Geothermal Prospect. A Report on a Geophysical and Geological Survey. Prepared for the Icelandic International Development Agency and the Ministry of Energy and Mineral Development, Uganda. Unpublished report, June 2004. 109 pp.

GNIP, 1999. Data from the Global Network for Isotopes in Precipitation (GNIP) since 1960. Site Entebbe (Airport), Uganda; latitude 0°,05',0" N and Longitude 32°,45',0" E.

Krouse, H. R., 1980. Sulphur isotopes in our environment. In: P. Fritz and J.C. Fontes (Editors), Handbook of Environmental Isotope Geochemistry Vol. I, The Terrestrial Environment, Elsevier, Amsterdam: 435-471.

Lloyd, R.M., 1968. Oxygen isotope behaviour in the sulphate-water system. J. Geophys. Res., 73: 6099-6110.

McKenzie, W.F. and Truesdell, A.H. 1977. Geothermal reservoir temperatures estimated from the oxygen isotope compositions of dissolved sulphate and water from hot springs and shallow drillholes. Geothermics, 5: 51-61.

Mizutani Y., and Rafter T. A., 1969. Oxygen isotopic composition of sulphates, Part 3:-Oxygen isotopic fractionation in the bisulphate ion-water system. N.Z.J. Sci., 12:54.

Morley, C. K., and W.A. Westcott, 1999: Sedimentary Environments and Geometry of Sedimentary Dodies Determined from Subsurface Studies in East Africa, *in* C. K. Morley ed., Geoscience of Rift Systems – Evolution of East Africa: AAPG Studies in Geology No. 44, p. 211 - 231.

Musisi, J., 1991. The neogene geology of the Lake George-Edward basin, Uganda. PhD. thesis.

Pearson, Jr. F.J. and Rightmire, C.T., 1980. Sulfur and oxygen isotopes in aqueous sulfur compounds. In: P. Fritz and J. Ch. Fontes (Editors), Handbook of Environmental Isotope Geochemistry, Elsevier, Amsterdam: 227-258.

UGA-IAEA, 2006. Isotope Hydrology for Exploring Geothermal Resources II. UGA-IAEA TC-Project, UGA8005, Draft Terminal Report.