THE POTENTIAL RELATIONSHIP OF SOME GEOTHERMAL FIELD IN UGANDA.

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ABSTRACT

Detailed geological work has been concentrated on three main geothermal areas of south western Uganda that is Katwe-Kikorongo, Buranga and Kibiro Hot springs. This included geochemical exploration, isotope hydrology, geological mapping and geophysics. Resistivity located an anomaly in Katwe and Kibiro thought to be a geothermal reservoir. However, drilling to the depth gave no sign of geothermal activity hence a need to expand on the previously drilling targeted areas and probing deeper. Under this project, study has been made to correlate different geothermal hot springs with the aim of grouping them into geothermal fields. The characteristics of the geothermal fluids were studied using Cl-SO_4-HCO_3, Na-K-Mg , Cl-Li-B ternary diagrams, Speciation using WATCH 2.1 version, isotopes, ratio of conservative elements and mixing models. Cl-SO_4-HCO_3 ternary diagram classifies Amoropii, Okumu, and Kibiro as chloride waters, Kitagata and Kanangorok, as steam heated waters, Kibenge, Kabuga and Rwagimba as Volcanic waters, Amuru as bicarbonate waters while Amuru (Pakele) and Avuka as peripheral waters. The geothermal fluids come from old base rock rather than underlying sediments and are also partially or fully equilibrated. The δ^2H versus δ^{18}O plots, Cl/B, Cl/Li, Na/K, Na/Cl ratios and plots show that Kibenge, Rwagimba and Kabuga are correlated to Buranga with fluids of similar origin while Kibiro and Panyamur appear to be linked, with Avuka at the peripheral of Kibiro-Panyamur geothermal area. SiO_2-CO_2 mixing model show that there was no boiling in the studied hot springs but with some evidences of mixing. The log Q temperature plots of minerals shows Kanangorok, Kabuga, Kibenge, Rwagimba, and Okumu are saturated with calcite and could be prone to scaling if utilised.

INTRODUCTION

Uganda is one of the east African counties crossed by the East African rift valley. Several geological surveys, including shallow drilling have been carried out on three geothermal areas of Uganda which include Katwe-Kikorongo, Buranga and Kibiro. Preliminary work has also been carried out in other geothermal areas of Uganda, aimed at the development of geothermal energy for rural development. Biomass represents 93% of the energy used in the country, thermal power installed capacity is 100MW_e and installed hydro electric power is 380MW_e that has

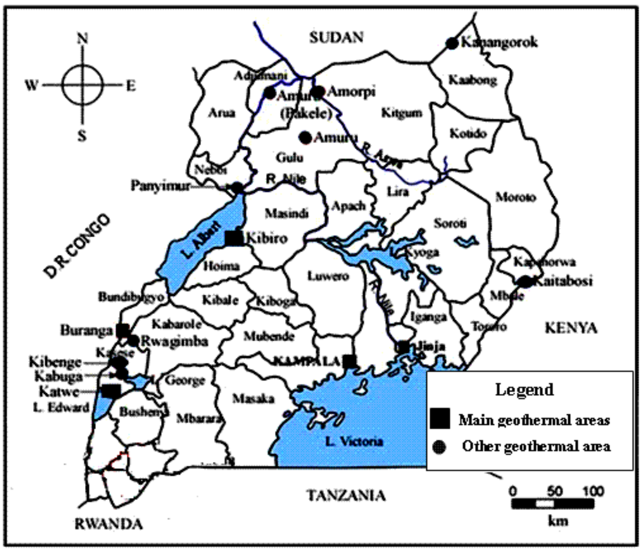


Fig. 1: Map of Uganda showing the hot springs studied

diminished to150MW$_e$ in the past few years due to climatic changes. This has made and unaffordable in addition to electricity expensive being scarce

Since all the oil products are imported. This has made the government consider the development of renewable energy among which is geothermal energy with an estimated capacity of 450MW$_e$ (McNitt 1982)

Study Areas

This study is of the main three geothermal areas, that is Katwe-Kikorongo (Katwe), Buranga and Kibiro, but also Kibenge, Kabuga, Rwagimba and northern Uganda hot springs i.e. Amuru, Avuka Amuru(Pakele), Amoropii, and Kanangorok. These are all located in the Western Rift Valley in the Albertine graben that runs along Uganda-Democratic Republic of Congo border (Fig. 1)

Aim / Scope of the Study

During geological, geophysical, and geochemical exploration anomalies for drilling have been located in the Katwe-Kikorongo, Buranga and Kibiro geothermal fields. However, drilling to a depth indicated by the geophysical methods in Katwe-Kikorongo and Kibiro gave a much lower geothermal gradient than expected and there was no sign of geothermal activity in the drill cores. It was however thought that the low resistivity could be due to an ore mineral body in the case of Kibiro and salt deposits in the case of Katwe-Kikorongo. It was therefore concluded that the source of heat is likely to be deep or outside the area previously interpreted as drilling target. The future plan is to use geophysical methods that probe deeper and compare geothermal hot springs to find if there could be a link between the main geothermal hot springs with other neighbouring hot springs to expand the study area.

The objective of the present project is to analyse and correlate the geochemical data for different hot springs, to find a possible potential with reference to geological location and structural controls. These were considered in two groups, Firstly, Buranga, Katwe-Kikorongo, Kibenge, Kabuga and Rwagimba, and secondary Kibiro and Northern Uganda hot springs (Amuru, Amuru(Pakele), Amoropii, Avuka and Kanangorok). To find out whether there is a relationship between fluids of different hot springs, their chemical composition was studied by looking at the conservative constituents that can be regarded as tracers. These include Li, Rb, that are highly mobile, Cl, B, and Br which form soluble minerals and their sources of supply to geothermal fluids limited to saturate it with any mineral (Anórsson,2000b).

Deuterium was also used as conservative isotope in the geothermal fluids due to its mobility. The formation of secondary minerals containing water can cause deuterium to fractionate between mineral and water. However the amount of water held in secondary minerals in insignificant compared to amount flowing through a given rock hence fractionation between the phases will have negligible effect on the deuterium content of the flowing water through it. Also water with temperature below100°C generally shows no oxygen shift and hence the ^{18}O isotope can be used as a tracer. Sulphate can also be reactive in some geothermal systems as it can react and be precipitated as anhydrite but conservative in others (Anórsson, 2000b)

BACKGROUND

The Geology of the geothermal fields

Geology of Kibiro

Kibiro geothermal field is divided into two geological environments by an escarpment of the western branch of the east African rift valley that runs from SW to NE. The eastern side is mainly crystalline basement with granites and granitic gneisses while the western part is characterised by rift sediments. The hot springs are found in the rift sediments (Fig. 2). Kachuru fault trending NNE is oblique to the main rift fault and intersects it at Kachuru and Kibiro Villages. Several surface manifestations are found at the intersection of the two faults (Fig. 3). The surface manifestations entail hot and warm springs, which include Mukabiga and Mwibanda; there are also salt gardens such as the Muntere salt garden. Other manifestations include smell of hydrogen sulphide in the air, steaming grounds, calcite and

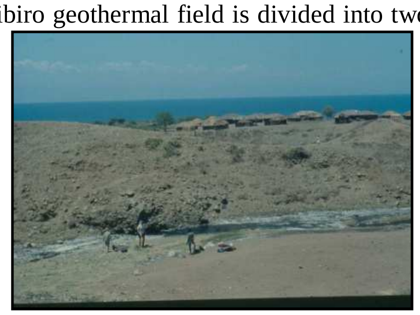


Fig. 2: Kibiro hot springs in rift sediments

sulphur deposits (Gíslason et al., 2004, Gíslason, 1994)

Geology of Katwe-Kikorongo geothermal field.

Katwe-Kikorongo volcanic field is located on the escarpment of the western branch of the East African rift valley south of Rwenzori massif. The field has a number of craters that lie on the NE-SW striking main fault. It characterised by basement granite and granite gneisses (Fig. 4) explosion craters, ejected pyroclasts and tuffs (Fig. 5). The craters are believed to have been formed by phreatic eruptions and in some of them like Lake Katwe, Kikorongo and Nyamunuka there are crater lakes with high salinity due to evaporation (Fig. 5) there are also minor occurrences of lava near Lake Kitagata and Kyemengo crater areas.

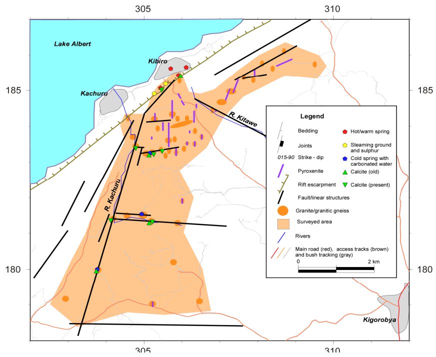


Fig. 3: Geology of Kibiro area

Geothermal surface manifestations are scarce and only found in the Katwe and Kitagata craters.

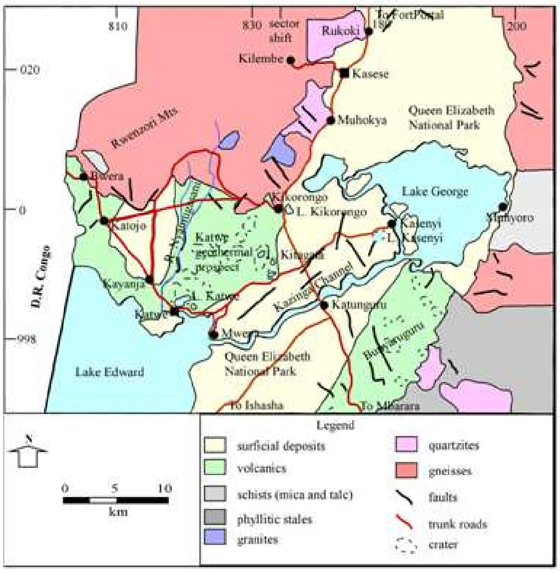


Fig. 4: Map of the geology of Katwe-Kikorongo area

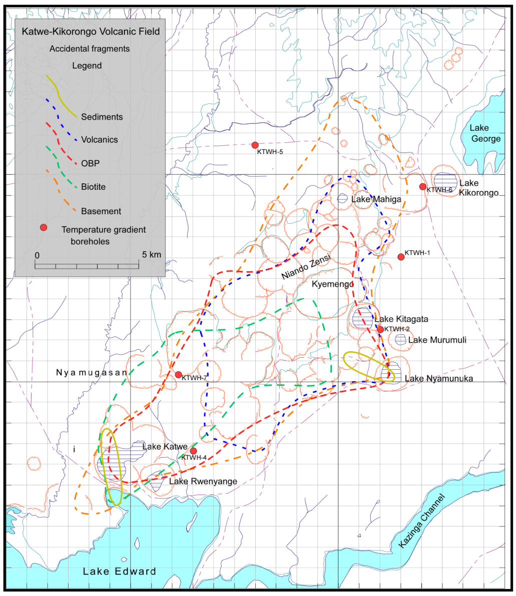


Fig. 5: Katwe-Kikorongo geothermal field showing springs and craters

Geology of Buranga geological field

This field is also in the western branch of the East African rift valley. It is situated in a sedimentary environment and despite the high tectonic activity; Buranga has no evidence of volcanism. It is a geothermal field with sprouting hot springs and high gas flow and travertine

Geology of other geothermal hot springs

Kabuga hot spring (also called Muhokya warm springs) has a temperature of about 40°C and a flow rate of 1 l/s. It has no rock exposure but the surface geology indicates that the springs issue from alluvial and pediment gravel material at the base of Rwenzori mountains. Kabuga is also thought that it is controlled by the major Rwenzori fault that extends from Lake Kitagata in the Katwe geothermal field (Ármannsson, et al., 2005).

Panyamur Hot springs are located on the escarpment near the shores of Lake Albert. They are divided into three hot springs which include Amoropii, Okumu and Avuka. All the three lie on the Rift Valley escarpment. They extend in a northwestly direction and are likely to be controlled by a major boundary fault.

The manifestations include hot springs, travertine deposits, and sulphurous algae and hydrogen sulphide smell. From the hot spring lies a gorge that dips into the escarpment in which fractured crystalline basement rocks like coarse hornblende gneiss, coarse hornblende garnet rock, talcose rock have been reported. There are two directions of foliation that is NNE-SSW and NE in the direction of the local major fault. Okumu is characterised by basement rocks of granitic gneiss and Pleistocene sediments to the east of rift fault boundary. Amur is underlain by fractured basement rocks with foliation trending in NNE-SSW and joints trending NE-SW in quartzite.

SAMPLING AND ANALYSIS

The analytical results used under this project were analysed in 1993, 2002, 2003 and 2005**.** In 1993 under UNDP project (UGA/92/002), geological work was done on Kibiro, Buranga and Katwe- Kikorongo geothermal areas. The samples were analysed both at the department of geological survey and mines (pH, conductivity, CO_2, H_2S and NH_3) while the rest of the results were an analysed at Orkustofnun (Ármannsson, 1993).

In 2005 under the project of the government of Uganda with support from World Bank and international development Bank, geochemical investigation involving sampling of hot springs was done. The collected samples which include water and rock samples were analysed at the institute of Geological and Nuclear science New Zealand (Ármannsson, 2005).The areas covered whose results are considered under this project include Kabuga, Kibenge, Amuru, Amuru(Pakele) Avuka Amoropii, Kanangorok and Okumu.

The project UGA/8/003(1999-2002) was renewed under isotope hydrology UGA/8/005(2005-2006) with the objective of obtaining origin of geothermal fluids, recharge mechanism, resident time, predicting of subsurface temperatures using isotope geothermometers and delineate source of salinity and mixing processes. The work was done by International Atomic Energy Experts (IAEA) and Ugandan professionals. It involved sampling of hot springs, groundwater boreholes and streams which started in 1999. Volatiles were measured in field for hydrogen sulphide and Carbondioxide, temperature and conductivity while environmental isotopes were measured by IAEA Isotope laboratory in Vienna. In 2001 more samples were collected and analysed for isotopes in the IAEA laboratory Vienna, Institute of Hydrology (GSF) in Munich, Germany and Institute of Geosciences and Earth Resources (CNR-IGG) in Pisa, Italy. In 2002 sampling was done in Katwe and Buranga geothermal areas as the last sampling during the project. This was done in 2005 in Kibiro, Buranga and environmental isotopes were also analysed in IAEA Isotope laboratory in Vienna.

DISCUSSION

Classification of geothermal waters

The CL-SO_4-HCO_3 triangular plot was used for the classification of geothermal fluid with respect to the major anions Cl, SO_4 and HCO_3 (Fig. 6). The Kibiro, Amoropii, and Okumu samples plot close to the chloride corner and are classified as mature neutral chloride water. These are likely to be formed from discharge from the geothermal reservoir associated with neutral chloride and represent equilibrated fluid from the upflow. Avuka and Amuru (Pakele) are peripheral bicarbonate waters likely to be spring waters with high Carbondioxide at the peripheral of the geothermal system. Kanangorok and Lake Kitagata plot in the field of steam heated waters. Steam heated waters are usually formed as a result of absorption of magmatic gases into ground water and are characterised by a low pH (Giggenbach, 1988). However, fluids of the hot springs considered here are neutral to alkaline (Kanangorok 7.37, Lake Kitagata 8.03 - 8.61) and

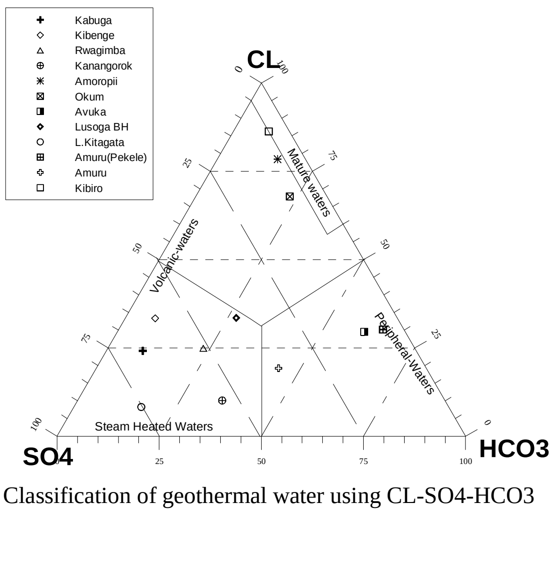


Fig. 6: Classification of geothermal water using CL-SO4-HCO3

are likely to be volcanic fluids in which hydrogen sulphide has been oxidised to sulphate by other processes other than oxidation by oxygen in ground water. Kabuga, Rwagimba, Kibenge and Lusoga borehole samples plot as volcanic waters but the Amuru sample is bicarbonate water.

The Cl-Li-B ternary plot, use Li as a tracer for rock dissolution processes and evaluating the possible origin of B and Cl. Kabuga, Kibenge, Rwagimba, Amoropii, Okumu, Lake Kitagata and Kibiro samples plot close to the chloride corner indicating that these constituents originate in old hydrothermal systems (Fig. 7). Due to either very low values of boron or lithium in geothermal fluid samples (below detection limit) Amuru (Pakele), Amuru, and Kanangorok (apart from waters from the Kanangorok borehole) waters could not be plotted on the diagram. However, they have almost 100% chloride and therefore would plot on the chloride vertex.

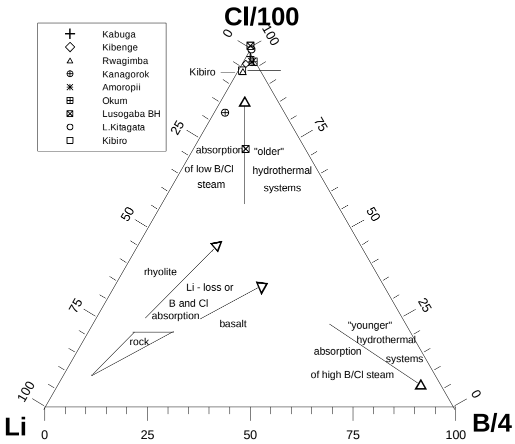


Fig. 7: Classification of geothermal waters using a Cl-Li-B ternary diagram

The low values of lithium and boron may be an indication that fluids come from old base rock rather than from the underlying sediments.

In the Na-K-Mg ternary plot, the geothermal fluids are divided into immature, partially equilibrated, and fully equilibrated waters. It shows which fluids are suitable for geothermometry that is partially and fully equilibrated fluids. Kibiro, Rwagimba, Lake Kitagata, Kibenge, Kabuga, Amuru, Amuru(Pakele), Amoropii, Kanangorok, Avuka and Kaitabosi waters are fully or partially equilibrated and therefore can be comfortably used for ion geothermometry(Fig. 8A). The equilibrium curve is based on Icelandic basalt results (Arnórsson et al., 1983). Lake Kitagata and Kaitabosi water samples plot above equilibrium line. The reason could be that they are derived from rocks that are not close in composition to the basalts used by Arnórsson et al. (1983). However, Kaitabosi plot on fully equilibrated curve based on andesitic rocks (Giggenbach, 1988), while

Lake Kitagata plots close to it (Fig. 8B). Na-K-Mg ternary diagram was used to estimate temperature of the geothermal springs (Table 3) using Na/K and K/Mg geothermometers. However there are some differences in the values from the two geothermometers. This could be due to the fact when geothermal fluids ascend and cool without boiling there is a decrease in pH and temperature. This causes undersaturation with respect to primary igneous rocks that eads to more dissolution lowering K/Mg compared to Na/K tending towards the ratio in the rock. This K leads to different values for Na-K and K-Mg geothermometers with K-Mg indicating a lower temperature (Arnórsson and D'Amore, 2000). The difference is also caused by the fact that the K/Mg geothermometer adjusts to changes in temperature faster than Na/K even for Carbondioxide rich waters. The K-Na geothermometer tends to preserve deep equilibrium of Na/K ratios (Giggenbach, 1991).

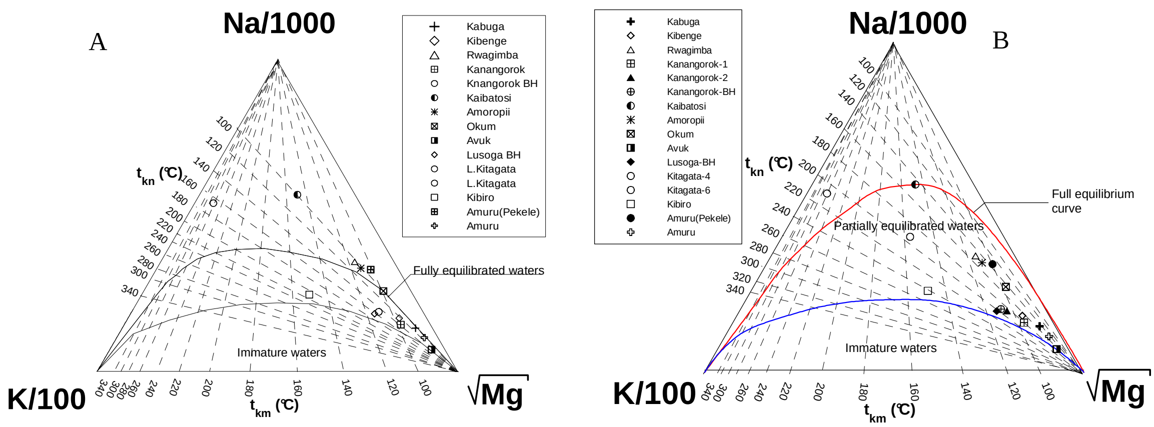


Fig. 8: Classification of geothermal waters using Na-K-Mg ternary diagram a) With Arnórsson et al. (1983) equilibrium line; b) With Giggenbach(1988)equilibrium line.

TABLE 1: Temperature estimated from the Na-K-Mg Triangular diagram.

Hot spring	Kabuga	Kibenge	Rwagimba	Kanangorok	Kaitabosi	Amoropii	Kitagata	Kibiro
Na/K	130	130	108	150	100	105	170	210
K/Mg	90	60	115	110	150	110	260	150

FLUID MINERAL EQUILIBRIA

The Cl-Li-B ternary diagram shows that Okumu geothermal water is fully equilibrated while Kabuga, Amuru, Amoropii and Rwagimba waters plot close to the full equilibrium curve. It would be expected for these fluids to give a clear convergence of minerals that are believed to be in equilibrium. This may be a test to prove that the fluids are in equilibrium with respect to some minerals in the rocks but not others. Due to relatively low temperatures, it takes a long time for the fluid to be in equilibrium with solutes. Water that is far from equilibrium with hydrothermal minerals shows no convergence of minerals at any specific temperature.

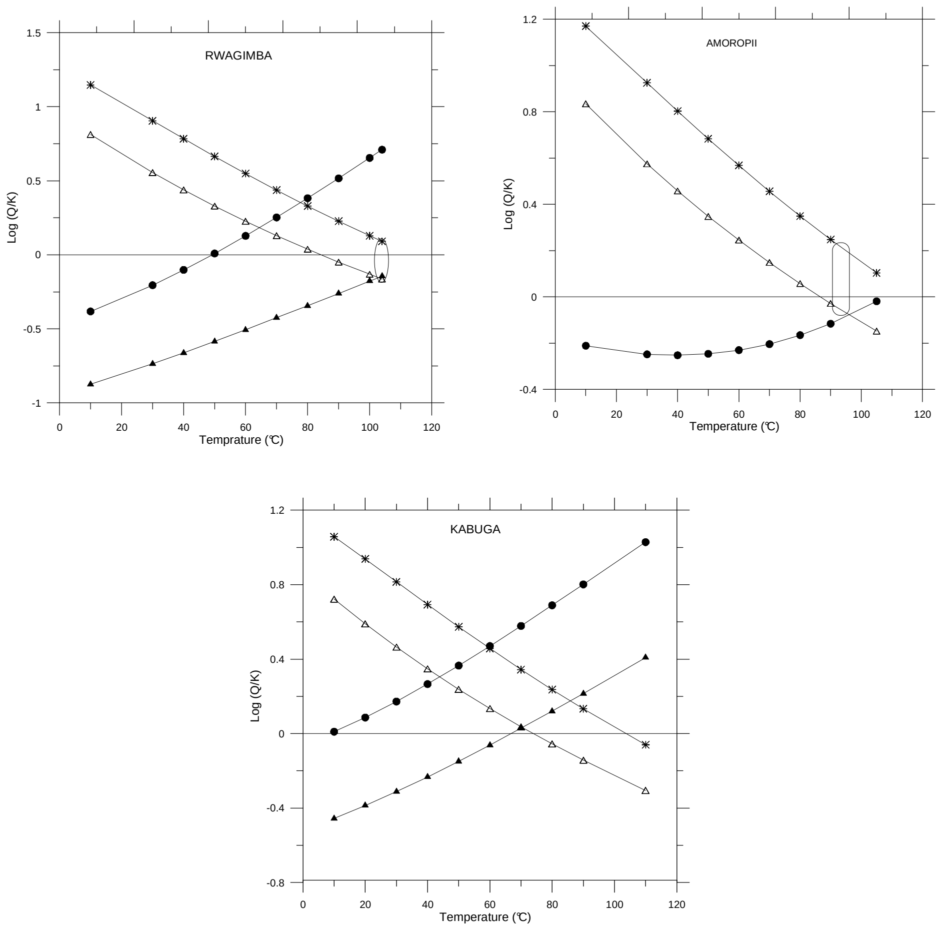


Fig. 9: Saturation index diagram log Q/K versus temperature

It differentiates between equilibrated geothermal fluids and those that have departed from equilibrium due to boiling or mixing with cold water. The geothermometer temperatures below are estimated by using the WATCH speciation programme (Table 2). In some geothermal fluids of Kibenge, Kabuga and Okumu the mineral curve intersect above the zero line giving a positive value of Log (Q/K). This can be possible if boiling happened before sampling due to loss of vapour and gases that leaves residual solution with a simple non volatile component (Arnórsson, 1985). However, this is not the case since the silica-carbonate mixing model indicates that there was no boiling in these hot springs. Amuru curves intersect below the zero line giving a negative log (Q/K). This happens when the mixing of the fluid with dilute solutions lowers the log (Q/K) value. The Amoropii sample shows no clear convergence of mineral curves. The geothermal fluid could have mixed with fluids of different composition which disturbs its equilibrium. Also if it mixes with fluid with solutes in a proportion very different from that of geothermal fluid there is a complete lack of any equilibrium (Fig. 9). In plotting Log (Q/K) versus temperature plots, minerals considered to be in equilibrium were considered. Amorphous silica was not was not used as equilibrium was thought to be controlled by quartz or chalcedony. Also because of dilute fluids of mainly northern Uganda hot springs, calcite and anhydrite were not used for locating the point of intersection or equilibrium point as there no enough calcium to saturate anhydrite and calcite. Few minerals are in equilibrium with the fluids. The low temperature of the fluids makes it require a long time to interact with fluids for equilibrium to be attained. Rwagimba and Kanangorok, geothermal temperatures from WATCH are higher than the average measured temperature using Quartz, chalcedony and Na/K geothermometers that was used in WATCH and the temperatures in the table was got by extrapolation.

Kabuga, Kibenge, Okumu and Amoropii show equilibrium at the chalcedony temperature while Rwagimba and Amuru show equilibrium at the quartz measured temperature. Kanangorok temperature is greater than the average measured temperature.

TABLE 2: Temperature estimated with WATCH and calculated temperature with geothermometers.

Location	**Sample No.**	**T(WATCH)**	**Ionic balance (%)**	**Quartz temp. °C**	**Chalcedony temp. °C**	**Na/K temp. °C**	**Mean temp. °C**
Kabuga	UG-05-29	62-70	2.53	104.0	73.8	100.2	102
Kibenge	UG-05-30	67-73	2.97	97.5	66.8	121.6	110
Rwagimba	UG-05-33	118	0.35	114.3	85.0	93.1	104
Kanangorok-1	UG-05-58	157	2.85	138.4	111.6	139.4	129.8
Kanangorok-2	UG-05-59			145.0	119.0	146.0	136.8
Kanangorok-BH	UG-05-60			144.9	118.9	153.2	139
Kaitabosi	UG-05-61	-		26.9	-3.1	93.7	-
Amoropii	UG-05-62	?	-0.28	111.3	81.8	98.5	105
Okumu	UG-05-63	70-90	3.05	112.9	83.6	95.4	104
Avuka-2	UG-05-64	-	15.21	104.6	74.5	139.6	
Amuru (Pakele)	UG-05-117		-17.76	78.7	46.7	82.5	81
Amuru	UG-05-118	100	-2.44	114.0	84.7	106.8	110

Kibiro, Panyamur, Amuru, Amuru (Pakele) and Kanangorok hot springs

Kibiro fluid flow is controlled by two intersecting faults, with the main one trending in the NE-SW direction and the other is oblique to it. Panyamur (Avuka,Amoropii, and Okumu) lie along the escarpment of the rift valley and appear to be controlled by it. The altitude of Kibiro and Panyamur springs is not so different that it will stop the flow in either direction

The isotope ratio plot (Fig. 10) shows excess hydrogen in Panyamur and other springs in northern Ugandan. However, samples from Panyamur hot springs (Okumu, Amoropii and Lusoga BH) plot together with Kibiro groundwater and close to Kibiro geothermal samples. The water samples plot in a line together with samples from other geothermal areas of Uganda apart from Katwe, Buranga and Kibiro. This together with a small oxygen shift could mean high permeability and interaction of geothermal fluids with Kibiro groundwater. The plotting of Panyamur samples close to Kibiro samples may be an indication of correlation between the geothermal fluids of Kibiro and Panyamur hot springs.

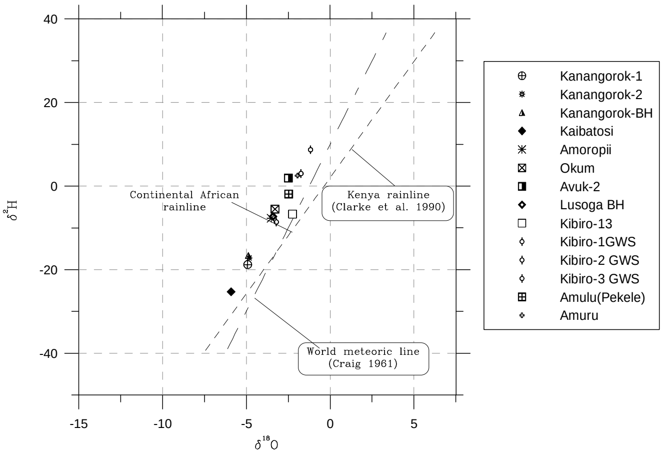


Fig. 10: Isotope ratios of Kibiro and northern Uganda hot springs.

The differences and similarities were further tested by studying conservative elements in the fluids from Kibiro (Mukabiga, Muntere and Mwibanda) and Panyamur. The conservative elements form soluble minerals and some of its supply is limited to saturate the fluids (Arnórsson, 2000b). The concentrations can vary as a result of dilution but the ratio remains the same. The ratios considered include Cl/B, Cl/Li, Na/Cl and fluids of similar origin should have same ratios.

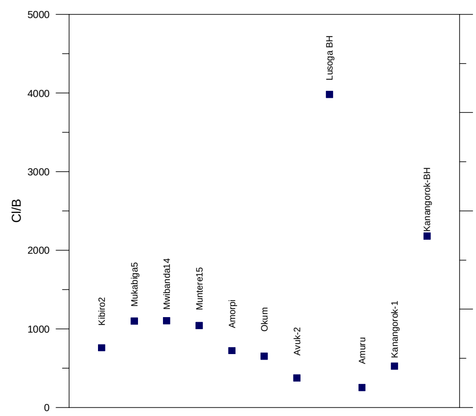


Fig. 11: Cl/B ratio in Kibiro and northern Uganda hot springs

Kibiro geothermal hot spring samples which including samples from Mukabiga, Muntere and Mwibanda have B/Cl ratios ranging from 759-1104(Fig 11). This is not very different from Panyamur hot spring samples with a range of 653-723 despite being analysed in different years, while others outside the rift have very low values. However boreholes samples have a high ratio due to high chloride values. Amuru (Pakele) has low detectable value of boron hence its ratio could not be calculated. The Lusoga borehole contains groundwater while the Kanangorok BH sample is likely to be intermediate between groundwater and geothermal water. The Cl/B ratio plot shows Amoropii and Okumu samples plotting close to Kibiro samples (Fig. 11) while Amuru and Kanangorok samples have considerably lower ratios except for borehole samples. Amuru (Pakele) samples have a low boron concentration, below the detection limit.

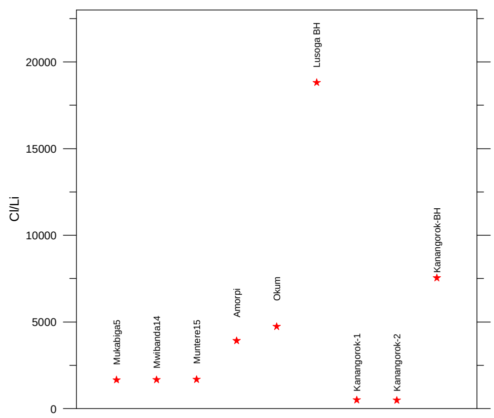


Fig. 12: Cl/Li ratio in Kibiro and northern Uganda hot springs

The concentration of boron is affected by both temperature and permeability of rocks in reservoirs. Literature shows that Cl is incompatible in alteration phases in all natural water-rock environments whether at ambient or elevated temperatures. It is also not adsorbed on a mineral surface (Hem, 1970). It does not enter any common forming mineral either due to its large size. Also when temperatures are high, B is mobile and incompatible as observed from many rock- water interaction experiments (Mahon, 1970). However at lower temperatures, below 100-150°C experiments have shown that B is incorporated in secondary minerals (Arnórsson and Andrésdóttir, 1995). It is adsorbed and incorporated in clay minerals, mainly illite (Harder, 1970) and behaves as incompatible in geothermal systems above 150°C (Ellis and Mahon, 1964, 1967, and Ellis 1970). These could be the reasons for the lower values of B in Panyamur geothermal hot spring water where temperatures are as low as 84 °C according to geothermometers. Therefore B might have been scavenged from the solution and even some samples have no detectable concentrations like Amuru Pakele and could be the cause of a slight variation in Cl/B ratios compared to those of Kibiro.

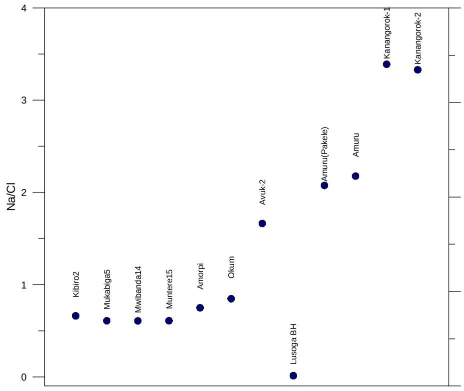


Fig. 13: Showing Na/Cl ratio in Kibiro and northern Uganda hot springs

The Cl/Li ratios are lower for Kibiro hot spring samples than Panyamur hot spring samples Okumu and Amoropii (Fig. 12.) The difference in Cl/Li can be attributed to very low values of lithium (Okumu 0.08 mg/kg) that may increase error in analysis.

Kibiro hot spring waters have a Na/Cl ratio close to that of Amoropii and Okumu waters samples while the rest have a high ratio due to a small concentration of chloride (Fig. 13). Okumu and Amoropii have the same range of Na/Cl ratios as Kibiro geothermal fluid samples.

From the Cl- SO_4-HCO_3 triangular diagram for classification of geothermal fluids (Fig. 6), Kibiro, Amoropii, and Okumu are classified as mature chloride waters, while Amuru, Amuru (Pakele) waters are classified as bicarbonate peripheral waters and Amuru bicarbonate geothermal waters.

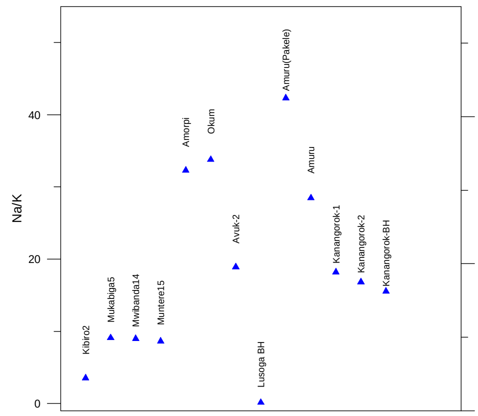


Fig. 14: Showing Na/K in Kibiro and northern Uganda hot springs

Another similarity between Kibiro, Amoropii, and Okumu waters is that they all contain hydrogen sulphide and ammonia whereas the rest of the hot springs in northern Uganda does not have detectable concentrations of these constituents.

However there appears to be no clear temperature gradient between Kibiro, Okumu and Amoropii. This could be due to short distance between Okumu and Amoropii. Kibiro has an estimated subsurface temperature of 200°C and its geothermal fluid has mixed with cold groundwater to give a subsurface temperature of about 150°C**.** Okumu quartz temperature 113.3, chalcedony 83.6, and Na/K 95.4 while Amoropii quartz temperature 113.3, chalcedony temperature 81.8, and Na/K temperature 98.4.

A Na/K plot (Fig. 14) shows that Kibiro water has low Na/K ratios and hence high temperatures while the Panyamur hot springs have high Na/K ratios suggesting that they are low temperature fluids. High temperatures tend to increase dissolution but give low Na/K ratios (Arnórsson, 1985)

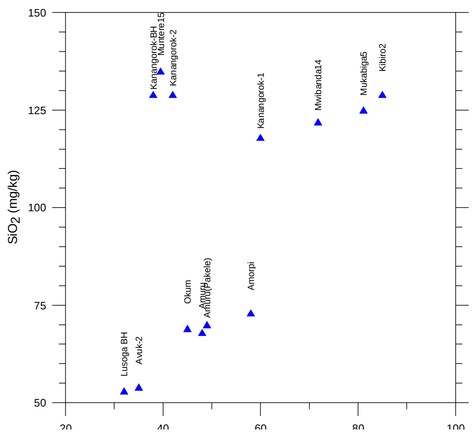


Fig. 15: Variation of SiO_2 with surface temperature.

Kanangorok1 and Kibiro (Mwibanda, Mukabiga) waters have high concentrations of silica and high surface temperature compared to other hot springs (Fig. 15). Kanangorok 2 and Kanangorok borehole waters have a low sampling temperature with relatively high silica.

This together with almost equal quartz and Na/K temperatures shows that the low surface temperature is a result of conductive cooling rather than mixing with cold ground water.

Kanangorok and Kibiro have high concentration of silica and high sampling temperature compared to other hot springs (Fig. 15). The low sampling temperature of Kanangorok with relatively high silica and almost equal quartz and Na/K temperatures (Table 2) shows the low sampling temperature is a result of cooling rather than mixing with cold ground water.

The plots of Cl versus B and Cl versus Li show a strong correlation between Kibiro, Okumu and Amoropii waters (Fig. 16). The Panyamur and other northern Uganda hot springs have lower concentrations. The lower concentrations can be attributed to low temperature of the fluids which require a long time to increase their concentrations through dissolution of rocks. The plots show that as you move away from Kibiro the concentration decreases.

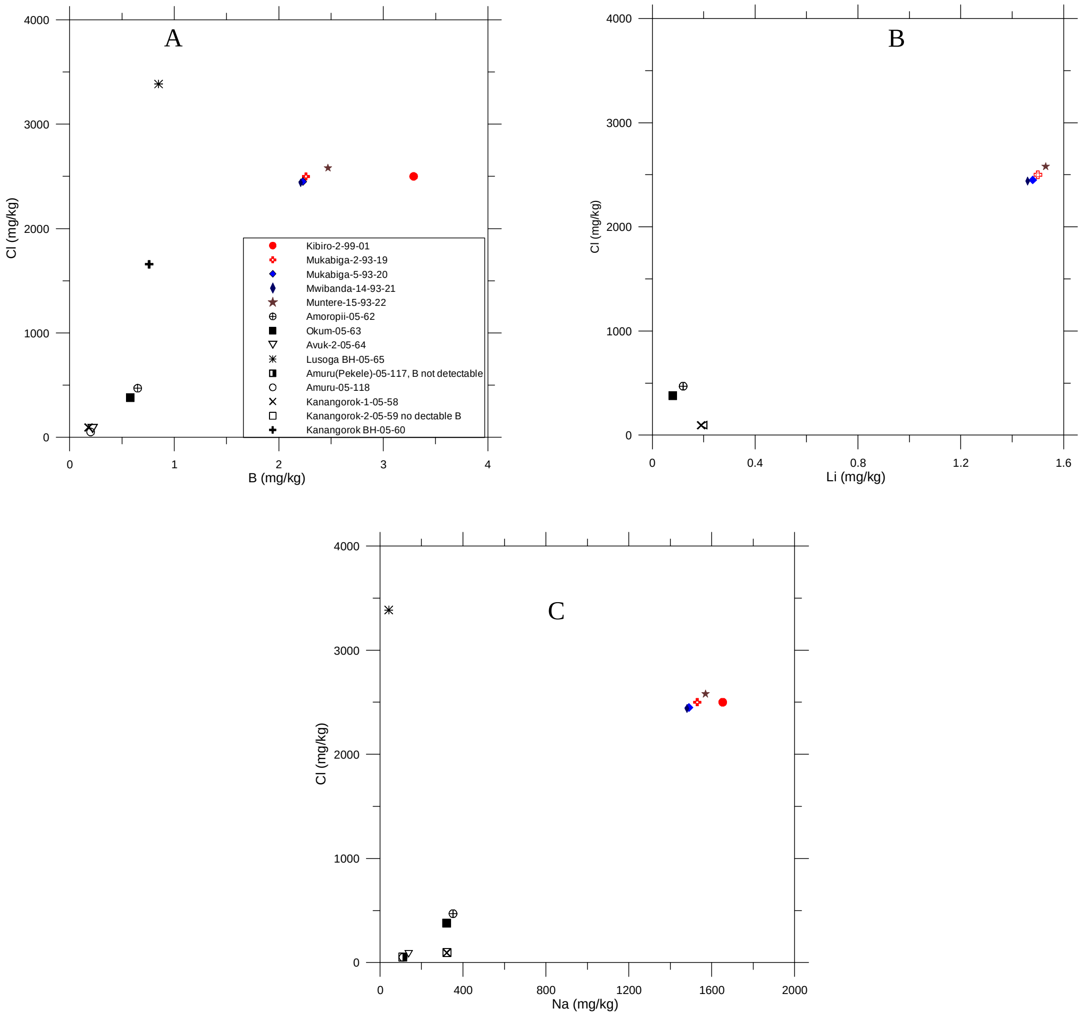


Fig. 16: Graphs showing a) Cl B, Cl versus Li, and c) Cl versus Na in Kibiro and northern Uganda hot springs

The results of geochemical study show that Kibiro waters are likely to be linked to Amoropii and Okumu waters. Carbondioxide rich waters have also been found to develop at the boundaries of geothermal reservoirs in New Zealand (Herderquist, 1989) and Olkaria geothermal field in Kenya (Arnórsson 1991**).** Therefore Avuka which is part of Panyamur which is one of the Panyamut hot springs is likely to be at the peripheral of the 'Kibiro-Panyamur' geothermal field. This is also supported by the Cl-SO_4-HCO_3 diagram in which the sample from Avuka, plots as peripheral water (Fig. 6)

Evidences of mixing

A positive correlation between the conservative elements and a linear relationship between them are typical of mixed waters (Fig. 16). However for fluid to be considered mixed the there is likely be a difference of about 50°C between the Na/K and quartz geothermometers (Fournier, 1981). Therefore using this criterion of measured temperature by the Na/K and quartz geothermometers it is Avuka water (Quartz temperature, 104.6 and Na/K temperature 139.6) that is considered to have mixed

The Na-K-Mg ternary diagram classifies geothermal fluids into immature, partial and full equilibrium (Giggenbach, 1991). However, most of the hot spring samples (Kibiro, Kanangorok) plot in partial equilibrium with only Avuka-2 plotting at the boundary of immature water and partially equilibrated water. The Log Q/K versus temperature diagram for the samples which plot close to equilibrium (Amoropii, Amuru, and Amuru (Pakele) does not show equilibrium with the minerals in the analysed geothermal sample (Okumu and Amoropii) at the expected temperatures. Lack of clear intersection of saturation mineral curves could be due to mixing with either solution of different concentration or ground water that is not dilute. Amuru, Kanangorok whose curves intersect at a negative value for Log Q/K, suggests mixing with dilute water.

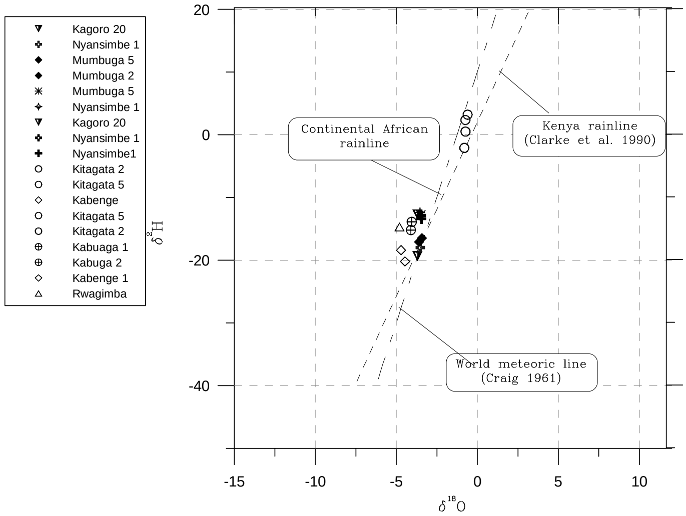


Fig. 17: Variation of ∂^2H with ∂^{18}O for Katwe-Kikorongo and Buranga geothermal field

Mixing also involves lowering of concentration without effectively lowering the CL/B ratio. The lowering of concentration of Amoropii and Okumu without too much lowering of the Cl/B ratio is also an indication of mixing. The mixed water is low in chloride relative to the water within the same reservoir it also tends to be high in CO_2/H_2S (Okumu 44, Amoropii 12.7) while the ratio for Kibiro waters varies from 9-14. This could be due to reactions caused by mixing that tend to remove H_2 and H_2S from solution relative to CO_2 (Hedenquist, 1990). The high value for Okumu water may also be an indication of mixing.

Avuka, Amuru, and Amuru (Pakele) waters have HCO_3 as a major anion. Carbon dioxide may form by mixing of fluid that has not undergone fluid phase separation with cold ground water (Arnórsson 1985). Carbon dioxide rich waters can also form by mixing of mantle derived magmatic or metamorphic CO_2 with ground or surface waters (Arnórsson and Barnes, 1983).

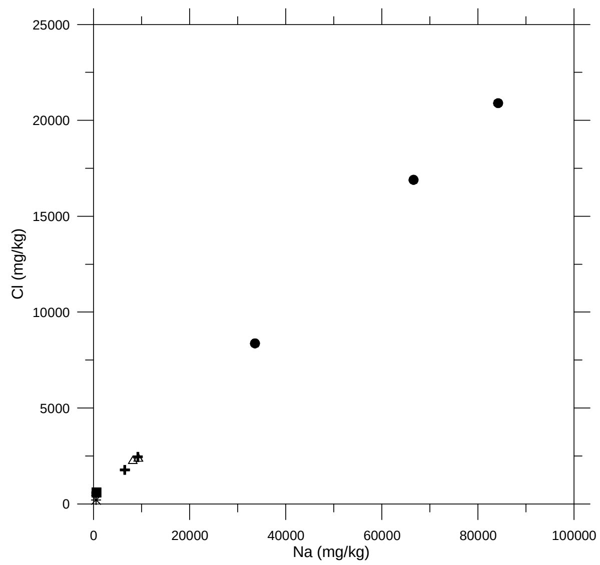
The dissociation constant of carbonic acid increases with increasing temperature and thus the H^+ concentration increases. Mixed waters have low pH with high carbonic acid and with a pH of 6-7 for chloride concentrations less than100 ppm. Avuka water has a pH of 7.56 with Cl of 83 ppm. The increased H^+ concentration also causes rock dissolution that may lead to a drastic change in initial equilibrium and approach the one dictated by rock stoichiometric dissolution. This leads to an increase of Mg and Ca concentrations (mainly Mg) relative to the Na concentration (Árnorsson, 1991). The cooling by mixing affects exchange reactions with rock minerals and thus causes increases in the Na/K and Mg/Na ratios (Truesdell, 1991). The Mg/Na ratio for the Kibiro water varies from 0.002 to 0.006, Kanangorok 0.008, Amuru 0.007 and Avuka 0.022 which is the highest of the samples studied.

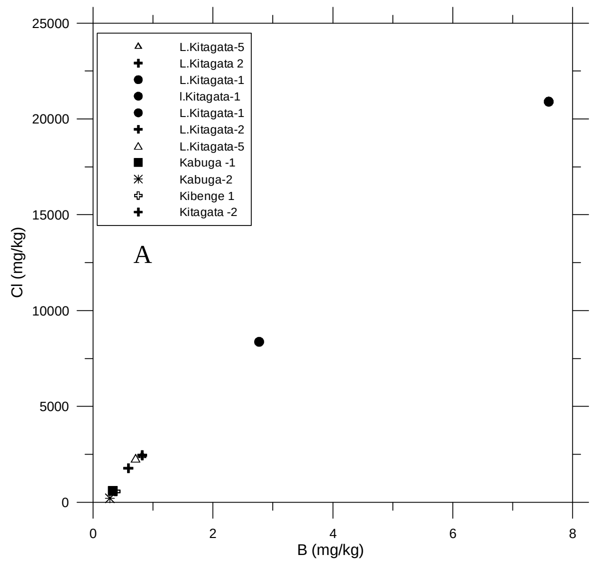
Geochemistry isotope studies have also shown that Avuka appears to be recharged locally or has a component of lake water while the values for Okumu and Amoropii are lower suggesting recharge from a higher altitude or mixing with local ground water (Ármannsson et al., 2005). Therefore the mixing model has only been considered for Avuka, Okumu and Amoropii by taking account of gas ratios, Log Q/K-Temperature plots, and difference between Quartz and Na/K temperatures.

However the interpretation of Avuka and Amuru (Pakele) waters needs more work since they have high ionic differences (Amur (Pakele) 11.9% and Avuka 15.12%) from WATCH speciation programme.

Katwe-Kikorongo, Buranga, Rwagimba, Kibenge and Kabuga geothermal springs.

Effort has been made to study the geochemistry of the above geothermal springs to see if there is any possible correlation between them. The Plot of δ^2H versus δ^{18}O (Fig. 17) shows that Buranga (including Kagoro), Kibenge, Kabuga can be grouped together as one geothermal field different from that of Katwe-Kikorongo field. For the isotope ratio plot, results of 1993, 1994, 2002 and 2005 were used. The results from plotting of Cl versus Li, Cl versus Li and Cl versus Na for Katwe-Kikorongo Kabuga and Rwagimba show that 1993 results from Kitagata-1 plot higher on the graph than the rest and once plotted with other results bring out a pseudo correlation mostly for Cl/B and Cl/Na plots. However, when these points are removed the other points scatter (Fig. 20).





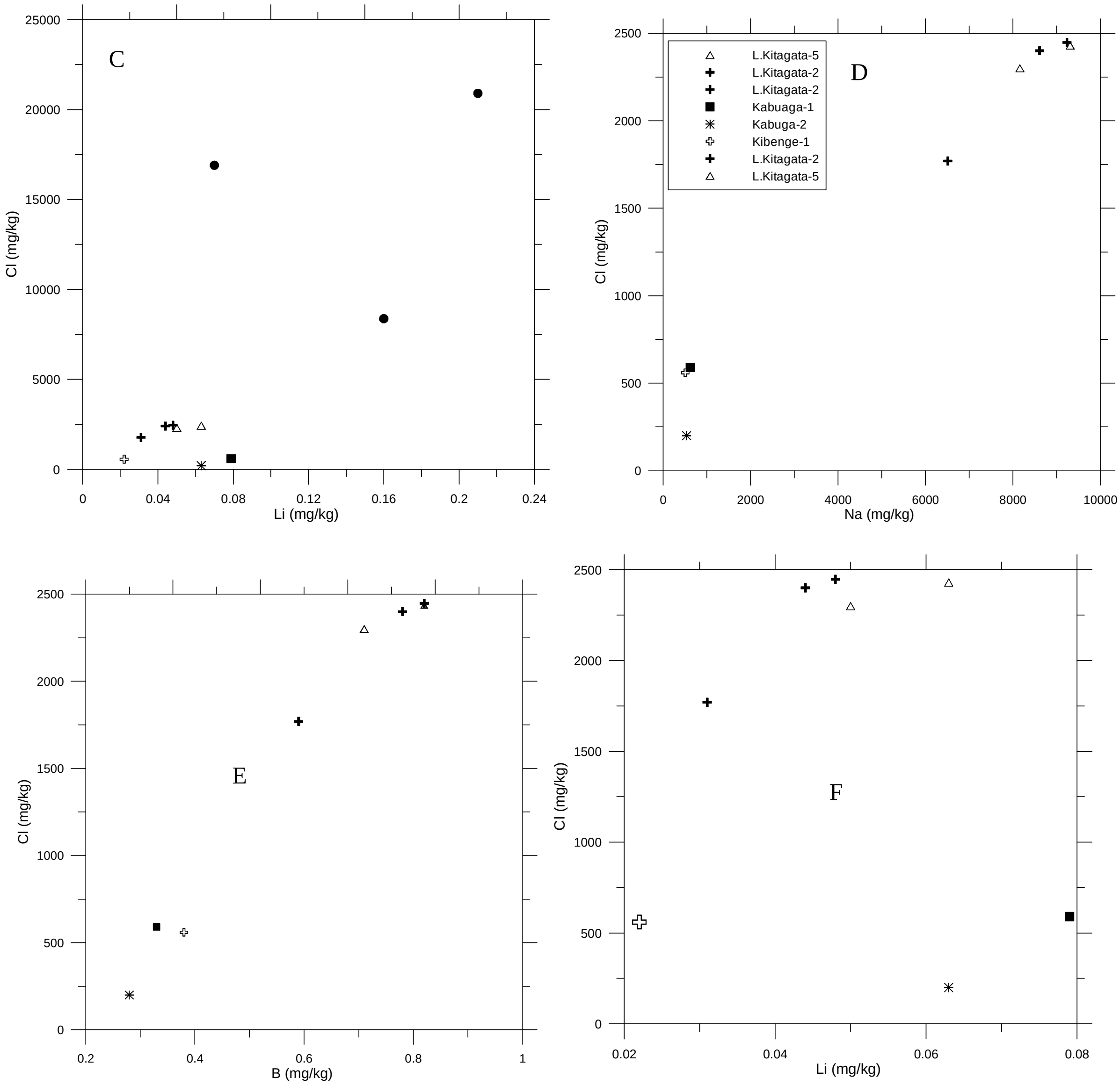


Fig. 18: Variation of Li, B, and Na with Cl in Katwe-Kikorongo, Rwagimba, Kibenge and Kabuga hot springs; graphs a-c) include the Kigata-1 1993 results, while graphs d-f) do not include these.

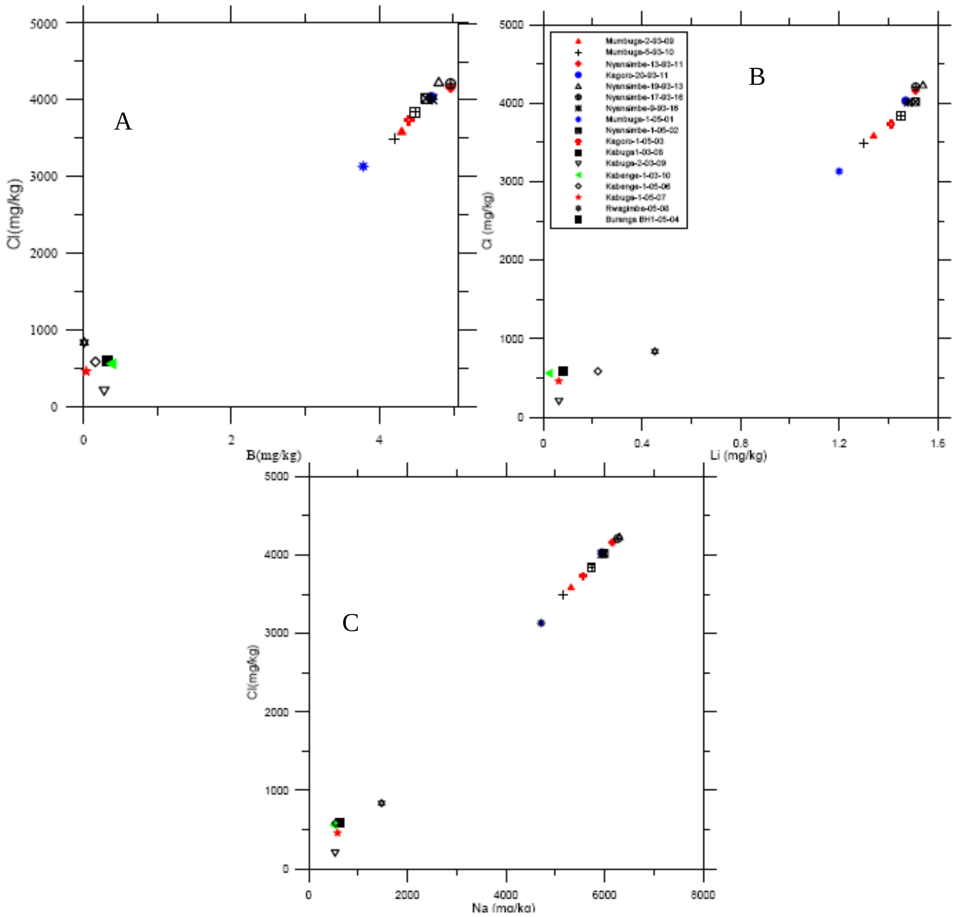


Fig.. 19 Graphs showing a) Cl vs. B, b) Cl vs. Li, and c) Cl vs. Na, in Kibiro and northern Uganda hot springs

However, the plots of Cl versus Na, Cl versus Li, Cl versus B for Buranga, Kibenge, Kabuga, and Rwagimba show a strong correlation (R^2 >0.995)between the conservative Cl, Li and B elements indicating that the different hot springs are genetically related (Fig. 18). Kabuga, Kibenge and Rwagimba waters are more dilute than those of Buranga and this is due to low temperatures and the long time needed for the fluids to interact with the rocks as earlier seen.

This grouping is also supported by different ratios between conservative elements. The ratios of different conservative elements from a geothermal fluid with a similar source of origin are constant or close despite changes in concentration. The conservative element ratios studied include Cl/B, Cl/Li, and Na/K. Katwe-Kikorongo Cl/B values vary from 2963.4 to 2984, higher than Buranga ratios varying from 830.95 to 868.03. The Kabuga1 water's Cl/B ratio varied from 1787.9 in the 2003

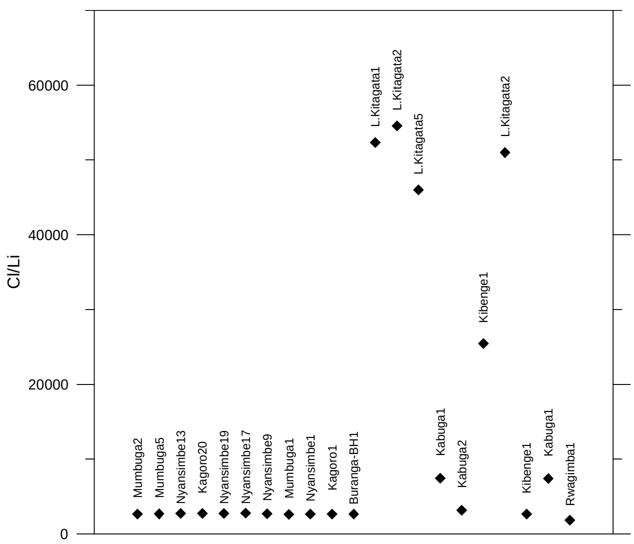


Fig. 20: Cl/B ratio in Katwe-Kikorongo and Buranga hot springs

analysis to 1277 in the 2005 analysis while Kabuga-2 water has a Cl/B ratio of 714.3, close to that of Buranga water. Kibenge values varied from 1218.75 to 1473.7 and the Rwagimba value is 1180.28, close to that of Buranga.

A plot of Cl/B ratios (Fig. 20) shows the geothermal field samples plotting close to Buranga samples with Katwe samples plotting at high ratios.

The Cl/Li ratio depicts a similar relationship. The Cl/Li ratio of Kibenge water (2647.059 analysed in 2005) is close to that of Buranga water (2610.83 to 2788.08) but lower than the high ratios of Katwe waters (46000-54545.5). The plot (Fig. 21) shows that Kibenge, Rwagimba and Kabuga and Buranga may be grouped together as one geothermal field. The K/Na ratio of Kibenge, Rwagimba and Kabuga (0.04 -0.05) waters is close to the Buranga water (0.04) ratio but lower than the Katwe water K/Na ratio of 0.06 to 0.09 with an average of 0.0714.

The Buranga Na/Cl ratio varies from 1.48 to 1.51 while that of Kitagata varies from 3.5 to 4.0. The rest of the hot springs vary from 0.9 to 1.77 close to Buranga than Kitagata (Katwe-Kikorongo) with Kitagata plotting above all other hot spring samples (Fig. 22).

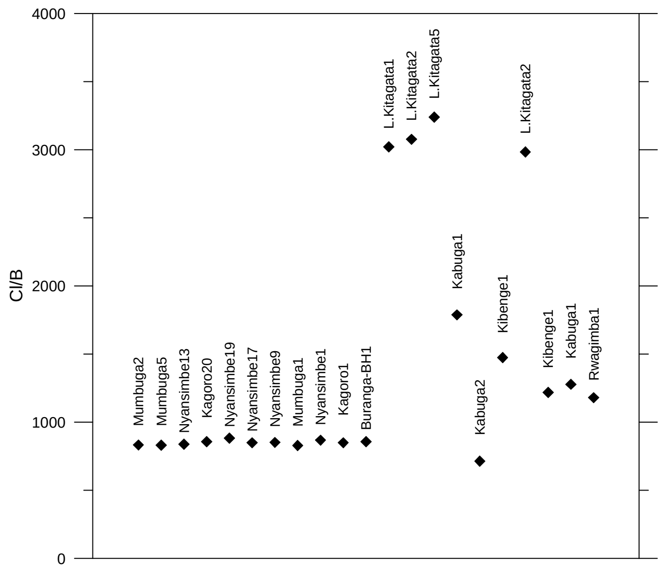


Fig. 21: Cl/Li ratio in Katwe-Kikorongo and Buranga hot springs

The Na/K ratio for Buranga waters varies from 26.68 to 27.8 in the 1993 to 2005 analysis which shows that they are consistent, Katwe water gives 11.8-19.0 in the 2003 analysis with an average of 15.98, Kabuga1 water 21.2 to 24.9 (in the 2003 analysis) and 31.2(in the 2005 analyses), Kibenge water 18.7 according to the 2003 results, but 22.6 in the 2005 analysis while Rwagimba water gives 35.6. Therefore Kabuga and Kibenge waters correlate more closely to Buranga than Katwe waters. The results show that Buranga hot spring (Nyansimbe and Mumbuga), and Ruwenzori hot spring (Kagoro) hot spring waters have Na/K ratios in the range 26.78 to 28.41 for the samples analysed in 1993 to 2005 thus showing consistence in the Na/K ratios. The plot of Na/K ratios (Fig. 23) shows that correlation although there are few discrepancies which could be due to results obtained in different years. This shows that Katwe-Kikorongo is a higher temperature geothermal field than Buranga.

Evidences of mixing

Whereas the concentration of other elements in the

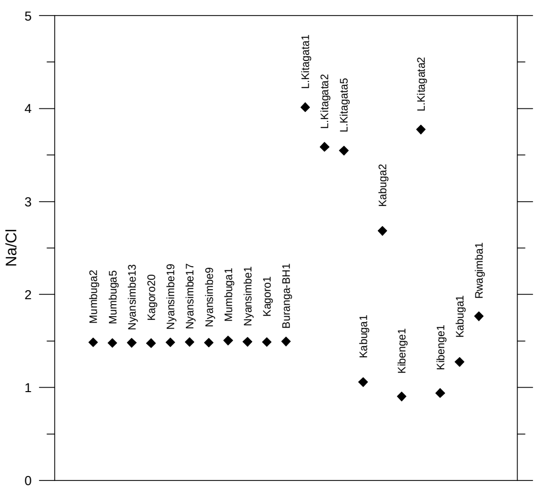


Fig. 22: Variation of Na/Cl ratio of Katwe -Kikorongo and Buranga hot springs

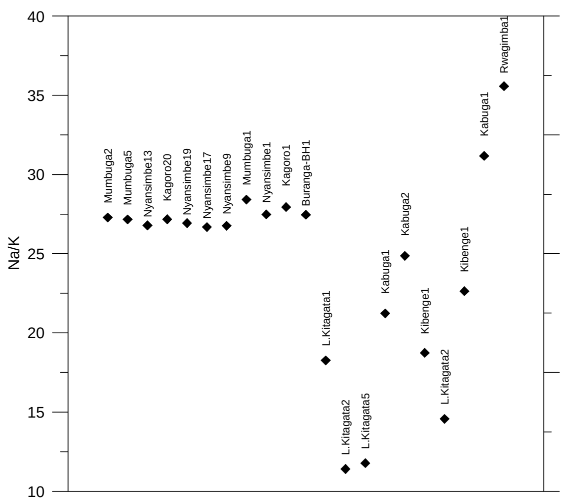


Fig. 23: Variation of Na/K ratio of Katwe-Kikorongo and Buranga hot springs

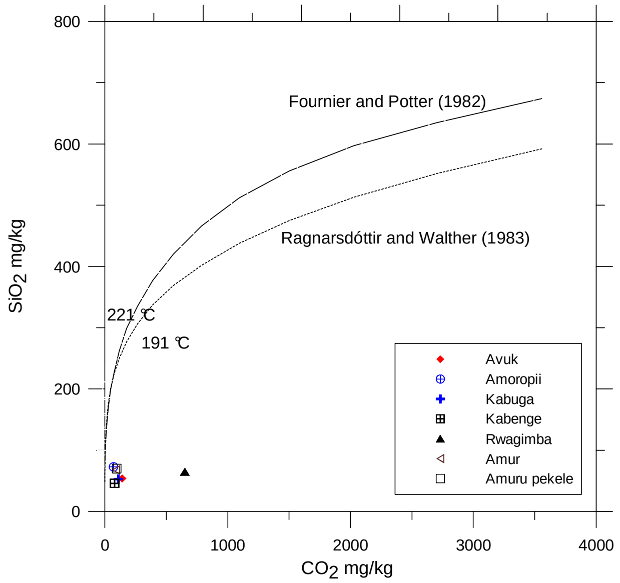


Fig. 24.The silica-carbonate mixing model

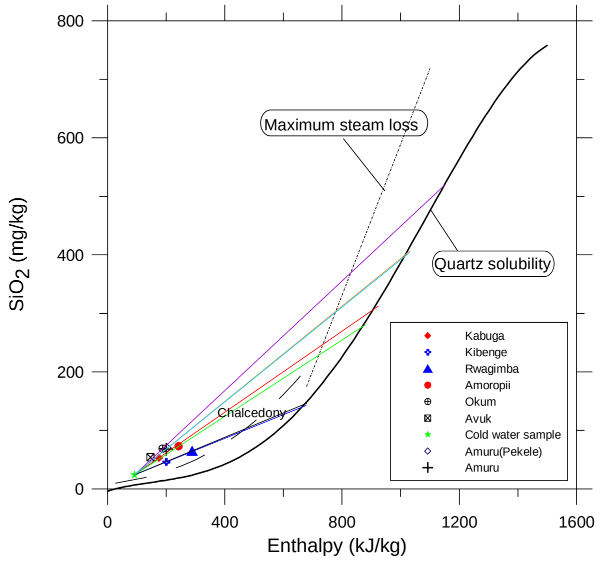


Fig. 25: Silica-carbonate mixing model for Buranga and northern Uganda hot spring samples.

geothermal fluids of Katwe and Buranga are higher than the concentration of Kabuga and Kibenge fluids, the concentration of Mg and Ca are higher in the two geothermal hot springs. This could be due to mixing with cold water and could be the reason why their predicted subsurface temperatures are lower than either that of Buranga geothermal field. Magnesium in geothermal fields rapidl y decreases as temperature increases. However as geothermal fluids flow from a high-temperature environment to a low temperature environment they pick up relatively easily and quickly significant amount of magnesium from rocks (Fournier, 1991). Therefore Kabuga, Kibenge and Rwagimba waters have been considered for mixing models.

Mixing models.

<u>Silica carbonate mixing model temperatures</u>

The silica carbonate model was used to determine whether the fluids boiled. The data plotted below the curve region representing unboiled or degassed waters (Fig. 24). It shows that Avuka, Amoropii, Kabuga, Kibenge, Rwagimba, Amuru and Amuru (Pakele) waters never boiled.Silica-Enthalpy model for calculating silica mixing model temperatures.

<u>Enthalpy silica model for calculating silica mixing temperatures.</u>

The silica concentration and the enthalpy of these unboiled samples were then plotted on a silica-enthalpy diagram together with the same parameters for a sample of cold water from the area (non thermal water). A line was drawn joining the cold sample point to each of the hot spring sample points. The line was extrapolated until it intersected the quartz solubility curve. The point of intersection represented the enthalpy and silica of geothermal water before mixing (Fig. 25). The maximum steam curve was not used since silica carbonate mixing model showed that there was no boiling. The Kibenge and Rwagimba samples give a reading reasonably close to the temperatures for the Buranga samples. The rest of the samples give very high values and even the extrapolated line for Avuka did not intersect the solubility curve. This could be due conductive cooling without loss of silica for the case of non boiling springs that shifts data points to the left giving a steep line, or boiling (Arnórsson, 2000). The boiling possibility is ruled out as silica carbonate models shows that there was no mixing. The higher temperatures of other geothermal samples could be due to dissolution of silica after mixing as this leads to estimation of high temperatures.

TABLE 3: Estimated temperature by SiO_2-Enthalpy mixing model

Location	Kabuga	Kibenge	Rwagimba	Amoropii	Okumu	Amuru(Pakele)	Amuru
T(°C)	214	160.5	161	205	263	238	238

CONCLUSION

The main objective of the study was to find possible potential relationships between geothermal hot springs in Uganda. The major conclusions of the study include:

- The geochemistry study of the geothermal fluids show that Kibenge, Kabuga, and Rwagimba are linked to Buranga and form one geothermal field.
- The Kibiro geothermal area is likely to be linked to Panyamur hot springs (Okumu, Amoropii, and Avuka) with Avuka likely to be at the periphery of the Kibiro-Panyamur geothermal field.
- Kabuga, Kibenge waters with measured temperatures of 100.2 and 126°C respectively are mixed with ground water and the SiO_2-Enthalpy mixing model indicates a temperature of 161°C.
- The geothermal samples studied come from old hydrothermal system rather than young underlying sediments since they plot near chloride corner on Cl-Li-B ternary diagram.
- Comparing the Na-K-Mg ternary diagram with Log (Q/K) versus temperature the geothermal fluids are in equilibrium with rocks rather than minerals since the samples that plot as partially and fully equilibrated on the Na-K-Mg ternary diagram do not show clear convergence of mineral saturation curves.
- The silica-carbonate mixing model shows that there was no boiling in Avuka, Amoropii, Kabuga, Kibenge, Rwagimba, and Amuru (Pakele) hot springs.

RECOMMENDATIONS

- More sampling should be carried out for Avuka and Amuru (Pakele) because of the poor ionic balance of the present samples and may reflect problems during sampling and analysis. The results from these two hot springs samples may not be reliable.
- More detailed work should be done on Kibiro and Panyamur hot springs to confirm their link and the possible common geothermal source. This is because correlation was done basing on a single analysis for every hot spring in Panyamur.

REFERENCES

Ármannsson, H., 1994: Geothermal studies on three geothermal areas in West and Southwest Uganda. UNDESD, UNDP project UGA/92/002, report, 85 pp.

Ármannsson, H., Bahati, G., Kato, V., 2005: Preliminary investigation of geothermal areas in Uganda, Other than Katwe-Kikorongo, Buranga and Kibiro.

Arnórsson, S., 1981: Mineral deposition from Icelandic geothermal waters, environmental and utilisation problems. Jour. Petroleum technology, 33, 181-187

Arnórsson, S., 1985: The use of mixing models and chemical geothermometers for estimating underground temperature in geothermal systems. J. Volc. Geotherm. Res., 23, 299-335.

Arnórsson, S., 1991: Geochemistry and geothermal resources in Iceland, In: D´Amore, F. (co-ordinator), Applications of geochemistry in geothermal reservoir development. UNITAR/UNDP publication, Rome, 145-196.

Arnórsson, S., 2000a: Mixing processes in upflow zones and mixing models. In: Arnórsson, S. (ed.), Isotopic and chemical techniques in geothermal exploration, development and use. Sampling methods, data handling, and interpretation. International Atomic Energy Agency, Vienna, 200-211.

Arnórsson, S., 2000b: Reactive and conservative components. In: Arnórsson, S. (ed.), Isotopic and chemical techniques in geothermal exploration, development and use. Sampling methods, data handling, and interpretation. International Atomic Energy Agency, Vienna, 200-211.

Arnorsson,S., Andresdottir, A., 1985: Processes controlling the distribution of Boron and Chlorine in natural waters in Iceland. Geochemi. Cosmochim. Acta, 59 4125-4146

Arnórsson S, Barnes I., 1983: The structure of Carbondioxide waters in Snaefellsnes, Western Iceland. Geothermics 12:171-176).

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

Bahati, G., 2007: Isotope hydrology for exploring geothermal resources. Dept. Geol. Surv. and Mines, Uganda, IAEA TC, project terminal report, UGA/8/005, 47 pp.

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

D'Amore, F., and Arnórsson, S., 2000: Geothermometry. In: Arnórsson, S.(ed.), Isotopic and chemical techniques in geothermal exploration, development and use. Sampling methods, data handling, interpretation. International Atomic Energy Agency, Vienna, 152-199.

Ellis A. J. (1970) Quantitative interpretation of chemical characteristics of hydrothermal systems. Geothermics 2, 516-527.

Ellis A. J. and Mahon W. A. J., 1964: Natural hydrothermal systems and experimental hot water/rock interactions. Geochim. Cosmochim. Actu 28, 1323-1357.

Fournier, R.O., 1973: Silica in thermal waters. Laboratory and field investigations. Proceedings of the International Symposium on Hydrogeochemistry and Biochemistry, Tokyo, 1, Clark Co., Washington D.C., 122-139.

Fournier, R.O., 1981: Application of water chemistry to geothermal exploration and reservoir engineering. In: Rybach, L., and Muffler, L.J.P. (editors), Geothermal system: Principles and case +

histories. John Wiley and Sons Ltd., Chichester, 109-143.

Fournier, R.O., 1991: Water geothermometers applied to geothermal energy. In: D'Amore, F. (coordinator), Application of Geochemistry in Geothermal Reservoir Development. UNITAR/UNDP publication, Rome, 37-69.

Fournier R.O and Rowe J.J., 1966: Estimation of underground temperatures from the silica content of water from hot springs and well steam wells. Amer. J. Mineral. 6, 459-464.

Giggenbach, W.F., 1988: Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. Geochim. Cosmochm. Acta, 52, 2749-2765.

Giggenbach, W.F., 1991: Chemical techniques in geothermal exploration. In: D'Amore, F. (coordinator), Application of geochemistry in geothermal reservoir development. UNITAR/UNDP publication, Rome, 119-142.

Gíslason, G. 1994: Geothermal Exploration – I, UGA/92/002 & UGA/92E01: Terminal Report. UNDDSMS – Geol. Surv. & Mines Dept., Uganda.

Gíslason, G., Árnason, K., Eysteinsson, H., 2004: The Kibiro geothermal report. A report on Geophysical and Geological survey prepared for the Icelandic international Development Agency and the ministry of Energy and Mineral Development, Uganda, unpublished report, p.109

Gíslason, S.R., Heaney, P.J., Oelkers, E.H. and Schott, J. 1997: Kinetic and thermodynamic properties of moganite, a novel silica polymorph. Geochim. Cosmochim. Acta, 61, 1193-1204.

Heaney P.J., 1995: Moganite as an indicator for vanished evaporates: A testament reborn? J. Sediment. Res. A65, 633-638

Heaney P.J and Post J.E 1992: the widespread distribution of a novel silica polymorph in microcrystalline quartz varieties. Science 255, 441-443

Hedenquist, J.W., 1990: The thermal and geochemical structure of the Broadlands-Ohaaki geothermal system, New Zealand. Geothermics, 19: 151-185.

Hem, J. D., 1970: Study and interpretation of the chemical characteristics of natural water. U.S. Geol. Survey, water supply paper 1473.

Henley, R.W., Ellis, A.J., 1983: Geothermal systems ancient and modern: a geochemical review. Earth-Sci. Rev. 19, 1–50.

Harder H. (1970) Boron content of sediments as a tool in facies analysis. Sediment Geol. 4, 153-175

McNitt. J.R., 1982. The geothermal potential of East Africa. In proceedings of the Regional Seminar on geothermal energy in Eastern and Southern Africa, Nairobi, Kenya. P. 3 - 8.

Paces, T., 1975: A systematic deviation from Na-K-Ca geothermometer below 75°C and above 10-4 atm PCO2. Geochim. Cosmochim. Acta, 39, 541-544.

Reed, M.H., and Spycher, N.F., 1984: Calculation of pH and mineral equilibria in hydrothermal water with application to geothermometery and studies of boiling and dilution. Geochim. Cosmochim. Acta, 48, 1479-1490.

Tole, M.P., Ármannsson, H., Zhong-he, P., Arnórsson, S., 1993: Fluid/mineral equilibrium calculations for geothermal fluids and chemical geothermometery Geothermics, Vol. 22pp. 17-37

Truesdell, A.H., 1991: Effects of physical processes on geothermal fluids. In: D'Amore, F. (coordinator), Application of geochemistry in geothermal reservoir development. UNITAR/UNDP publication, Rome, 71-92.

Truesdell, A.H., and Fournier, R.O., 1976: Calculations of deep temperatures in geothermal systems from the chemistry of boiling spring waters of mixed origin. Proceedings of 2nd U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, 1, 837-844.

Petrovic I., Heaney P.J., and Navrptsky A., 1996: Thermochemistry of the new silica polymorph moganite.Phys.chem. Minerals 23, 119-126