GEOCHEMISTRY OF EXTENSIONAL-TYPE GEOTHERMAL SYSTEMS IN UGANDA

Twesigye Benjamin[1]

[1]Ministry of Energy and Mineral Development

P.O BOX 9, Entebbe, Uganda

benjamin.twesigye@minerals.go.ug

Keywords: *geochemistry, deep circulation, amagmatic, extensional*

ABSTRACT

The purpose of this paper is to explain the geochemistry of Uganda's amagmatic extensional-type geothermal systems, particularly the origin of the chemical properties and corresponding reservoir properties. This type of system is a fault bound deep circulation system unlike magmatic systems which rely on shallow magma chambers. The fault zones are tectonically active which ensures deep circulation and high permeability. These amagmatic systems have low to medium temperature sources with subsurface temperatures ranging between 100ºC and 200ºC. Deep circulation geothermal fluids are less chemically charged compared to those from magmatic systems due to low temperature sources. Geothermal fluids from most of Uganda's geothermal areas are of neutral to slightly basic pH (6.0-9.0) and can be classified as fresh water to moderately saline based on their recorded TDS and conductivity values. Their TDS varies depending on the surrounding rocks through which the fluids flow from the reservoirs to the surface where they manifest as hot springs. Fluids from South-Western Uganda geothermal prospects have a relatively low Cl concentration and are mainly classified as HCO_3 type or SO_4 type. Fluids from Western Uganda geothermal prospects have a relatively high Cl concentration and are mainly classified as Cl-HCO_3 type or intermediate type with moderately high salinity in excess of 10,000 TDS. Possible subsurface temperatures for Uganda's hot springs range between 100ºC and 250ºC based on geothermometry and mixing models proving they are low to medium temperature sources. Soil-gas and gas-flux measurements along Kibiro, Buranga, Panyimur, Katwe and Ihimbo hot springs revealed concealed deep penetrating structures which control geothermal activity. The $^3He/^4He$ ratios of geothermal fluids from Kibiro fault-bounded geothermal system suggest no deep mantle signature. Stable isotopic studies of deuterium and oxygen-18 indicated high altitude fluid sources. Normally geothermal fluids contain <1ppm Mg content but most of Uganda's hot spring waters contain 1-10ppm Mg suggesting mixing with surface cold waters.

1. INTRODUCTION

Geothermal energy refers to heat of the earth and manifests in hot rocks or magma beneath the earth's surface. This heat is transferred to the surface by fluids like water, gases and steam. Geothermal fluids are emitted on the surface in form of hot and warm springs, fumaroles and geysers. Other surfaces indicators can be observed at a geothermal site besides the aforementioned ones. These include geothermal grass, steaming/hot ground, gaseous emissions, thermophilic algae, white clay and mineral deposits like salt, calcite, travertine cones/terraces/mounds.

Deep circulation systems also known as extensional-type geothermal systems in Uganda are located in the Western arm of the East African Rift System (EARS) and are controlled by the rift bound faults. These are the predominant type of geothermal systems that exist in the country. Boundary faults controlling a geothermal system are responsible for alignment of surface manifestations and enabling deep penetration of fluids to the geothermal heat source. It is imperative that faults in a deep circulation geothermal system be tectonically active to maintain open faults through which fluids can easily flow to and from the heat source. However, magmatic systems differ from the amagmatic systems. Magmatic heat sources are hot magma chambers close to surface and therefore do not rely on faults for deep penetration of fluids to the heat sources. Magmatic systems have hotter heat sources which are also closer to the surface hence geothermal fluids from magmatic geothermal systems are generally hotter than those from extensional type systems.

Fluids from extensional deep circulation geothermal systems are less chemically charged compared to those from magmatic systems. This is mostly attributed to their low subsurface temperatures and dilution/mixing with meteoric water. The chemical properties of geothermal fluids and gases tell much about the possible reservoir temperatures below the surface. This paper illustrates the chemical properties of Uganda's extensional type deep circulation geothermal systems. It explains the origin of these properties, what affects them and how they predict reservoir temperature.

2. LOCATION OF UGANDA'S EXTENSIONAL TYPE DEEP CIRCULATION SYSTEMS

The geothermal areas of Uganda are located in or in close proximity to the western branch of the East African Rift System along the border of Uganda with the Democratic Republic of Congo (Figure 1).

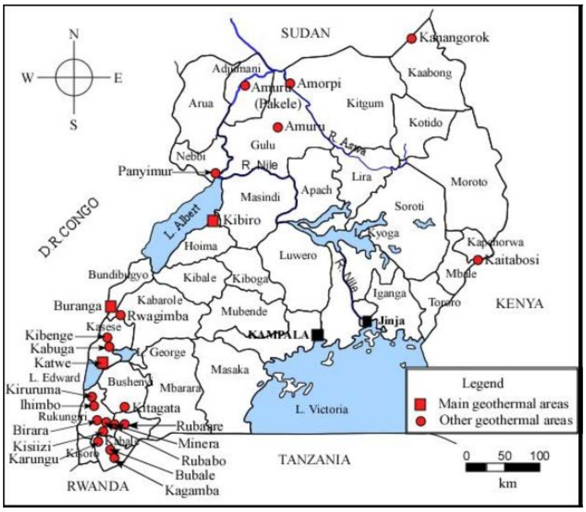


Figure 1. Uganda's geothermal areas (After Bahati et al., 2005).

Since 1993, four geothermal areas namely Katwe-Kikorongo (Katwe), Buranga, Kibiro and Panyimur have been studied in detail and are in advanced stages of surface exploration (Figure 2). Five areas namely Katwe, Kibiro, Panyimur, Buranga and Ihimbo geothermal areas have potential for geothermal energy development based on their geochemistry. All the discharges are characterized by gas bubbling and clear water. Geothermal systems in the sedimentary geological environments like Kibiro, Ihimbo and Panyimur are mostly affected by dilution due to mixing of cold ground water with geothermal waters and conductive cooling. On the other hand, the geothermal waters of Katwe and Buranga seem to be less affected by mixing.

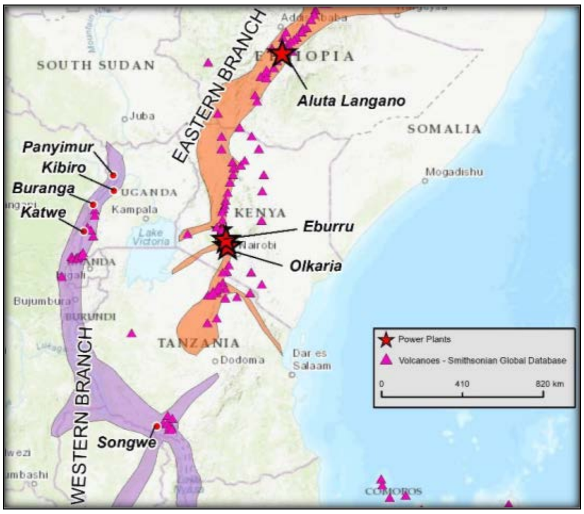


Figure 2. Location of four major geothermal areas of Uganda (After Hinz et al., 2016).

2.1 Buranga geothermal area

Located in the western border district of Bundibugyo district. Three hot springs exist at Buranga geothermal area i.e Mumbuga (the female hot spring), Nyansimbe (the male hot spring) and Kagoro (the son). The area is recharged by meteoric water from Rwenzori Mountains. The area is comprised of sedimentary rocks (clays and gravel) and no volcanic rocks. The hot springs are controlled by the NW trending Bwamba fault and located about 600m from this normal fault. Buranga geothermal area exhibits hot springs close to boiling (98^{o}C) with clear water, travertine terraces and cones and vigorous gas emissions.

2.2 Kibiro geothermal area

Located in the western district of Hoima in the Kibiro sedimentary basin. It is controlled by the Northern Tooro Bunyoro fault. It has three main hot springs namely Mukabiga, Mwibanda and Muntere with Na-Cl-HCO_3 waters of neutral pH, salt precipitation on the surface, travertine and calcite precipitation, CH_4 and CO_2 gas emissions and sulphur deposits at dry fumarole vents. The maximum temperature of the hot springs is 86˚C at Mukabiga and a weak fumarole (45˚C) approximately 1 Kilometer SW of the hot springs.

2.3 Katwe-Kikorongo geothermal area

Heated by intrusive magma, manifestations in this area include salt deposits, travertine deposits and a hot spring with maximum temperature 70^{o}C in the Kitagata crater lake. The hot spring water is characterized by a high concentration of HCO_3, SO_4 and Cl (over four times the concentration in seawater). Geothermometry puts maximum temperature of the hot spring water at 130 – 150^{o}C. The 30 – 40ppm H_2S concentration in Lake Katwe and Lake Kitagata waters suggests it could be of volcanic or hydrothermal origin.

2.4 Ihimbo geothermal area

Ihimbo is located in the Central Forest Reserve in Rukungiri district, South-Western Uganda. Ihimbo lies in a sedimentary basin characterized by gravel, clay, silt, sand and no volcanic rocks. The main Ihimbo rift bounding fault is characterized by travertine domes and cones. Ihimbo also has gaseous emissions in the hot spring waters and steaming ground. Maximum recorded temperature for Ihimbo is 68^{o}C.

2.5 Panyimur geothermal area

Located in the NW district of Pakwach on the North Eastern shore of Lake Albert. This area consists of three groups of hot springs namely Amoropii, Okumu and Avuka all along the escarpment of the Western Rift Valley. Other surface manifestations reported include deposits of travertine as cones/mounds, sulphurous algae and smell of hydrogen sulphide also seen as bubbling gas at the hot springs. Na-Cl-HCO_3 waters of neutral pH are emitted from the hot springs. The temperature ranges from 35˚C at Avuka to 58˚C at Amoropii.

3. GEOCHEMISTRY OF GEOTHERMAL FLUIDS

Amagmatic geothermal fluids are less chemically charged compared to magmatic fluids due to lower temperatures. They are of neutral to slightly basic pH (6.0-9.0) due to less ions in solution. They can be classified as fresh water to moderately saline based on their recorded TDS and conductivity values. The TDS values vary depending on the surrounding rocks through which the fluids flow as they transfer heat from the reservoirs to the surface. Most of Uganda's geothermal areas are synonymous with bubbling gas in the hot springs. Volatile components like CO_2, H_2S, CH_4 and Radon are sometimes released during the bubbling. The chemistry of the major components and isotopes is presented in Table 1.

Table 1. Chemical composition of Uganda's geothermal waters in mg/kg and and (‰) for stable isotopes (Compiled from Ármannsson et al., 2008).

Location	Elevation (m)	Temp. (ºC)	pH	EC (µS)	CO_2	H_2S	SiO_2	Na	K	Ca	Mg	SO_4	Cl	Br	$\delta^{18}O$	δD
Kagamba	1811	35	7.49	467	186	0	26	13.2	4.7	29	44	37	<20	<0.20	-4.7	-17.1
Karungu	1832	65	7.09	846	111	0	49	149	9.4	29	3.8	206	44	<0.04	-3.97	-9.6
Bubale	1820	34	6.29	578	406	0	19.2	61	5.7	60	38	73	<20	<0.02	-3.93	-9.1
Rubaare	1380	54	7.52	1600	85	0	106	285	14.9	70	1.4	417	177	1.2	-4.2	-12.1
Kitagata	1495	66	7.92	1110	56	0	76	203	10.7	36	0.28	346	55	0.36	-3.3	-3.1
Ihimbo	1028	70	9.2	893	45	0.92	66	186	5.6	3.8	0.02	219	71	0.42	-3.45	-4.1
Kanyinabarongo	999	38	7.37	992	58	0	34	173	9	31	4.5	280	92	0.54	-3.45	-5
Birara	1285	63	7.44	1072	647	0	103	210	13.6	70	10.5	208	80	0.35	-3.51	-7.2
Rubabo1	1316	58	7.14	1069	230	0	81	216	11.2	41	8.3	184	93	0.4	-3.61	-8.5
Kiruruma	994	36	7.09	609	124	0	57	110	9.4	36	2.9	182	22	<0.2	-3.28	-4.7
Kisiizi	1666	30.1	7.43	292	106	0	17.5	5.8	3.8	30	18.9	14.7	<20	<0.04	-3.69	-7.9
Minera	1345	58	6.88	2180	547	0	83	482	23	70	22	361	181	0.88	-4.13	-10.7
Kabuga	1005	42	7.42	3290	110	0	53	622	21	208	13.2	1071	474	3.5	-4.33	-11.4
Kibenge	1094	48	7.5	3300	79.2	0	46	581	26	233	6.5	889	589	3.9	-4.9	-15.7
Ndugutu	1234	22	8.5	17580	1918	0	40	4482	268	25	11.2	3469	2931	<0.2	-2.94	-4.4
Rwimi	1108	24	7.09	3160	1620	0	94	382	61	384	191	523	211	1.3	-2.61	1.9
Rwagimba	1555	69.2	6.87	6400	651	0	65	1481	46	75	5.1	1527	905	4.1	-4.8	-14.7
Amoropii	648	58	8.66	1790	71	5.61	73	352	10.9	4.5	0.36	26	470	1.5	-3.52	-7.7
Okumu	666	45	8.45	1590	109	2.48	69	321	9.5	8.5	0.68	36	379	0.93	-3.29	-5.5
Avuka-2	654	35	7.56	676	142	0	54	138	7.3	8.4	3.1	19	83	0.17	-2.5	1.9

3.1 Major constituents – Anions and Cations

Most hot spring waters in Uganda are classified as HCO_3 type or SO_4 type contrary to deep reservoir fluids which are Cl-types. Hot spring water from SW Uganda has a relatively low Cl concentration and is classified as HCO_3 type or SO_4 type. Hot spring water from Western Uganda geothermal prospects like Katwe-Kikorongo, Buranga and Kibiro have a relatively high Cl concentration and is mainly classified as Cl-HCO_3 type, Cl-SO_4 type with moderately high salinity in excess of 10,000 TDS.

Given that most of these are sulphate waters, it is unusual to find their pH high as evidenced especially by Katwe-Kikorongo. Bicarbonate is the main anion in all the waters except two (Okumu and Amoropii) for which chloride is the main anion. Bicarbonate waters generally tend to be cooler than other anion type waters like sulphate water and chloride water. Sulphates are mostly derived from oxygen driven oxidation of H_2S gas e.g at Kibiro geothermal area. Bicarbonates are derived from dissolution of CO_2 in meteoric waters at the edge of the reservoir e.g at Rwimi geothermal area. The chemical composition of the Rwenzori hot springs is presented in Table 2.

Table 2. Chemical composition of Rwenzori hot springs in ppm (mg/L) (Kato and Kraml 2005).

Location	Temp	Ph	Cond	SiO_2	HCO_3^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	Li^+	B	Al	Fe
Mumbuga	94	8.7	17900	70	2850	3133	3222	4716	166	6.24	1.94	1.2	14.8	0.015	0.02
Nyansimbe	75.4	8.4	22400	77.4	3630	4019	4186	5991	218	6.55	1.97	1.51	18.1	0.02	0.02
Kagoro	88	8.6	21000	76.6	3360	3735	3842	5561	199	7.01	1.97	1.41	17.2	0.71	0.91
Well-1	62	8.3	21500	73.5	3440	3839	4001	5738	209	7.11	1.77	1.45	17.5	0.031	0.16
L. Kitagata	64	8.7	31300	81.7	4160	2447	12959	9237	634	2.41	0.86	0.048	3.22	0.02	0.02
Kibenge	42.5	8.2	3580	44.5	98	585	894	550	24.3	226	6.4	0.221	1.89	0.163	0.3
Muhokya	41	8.2	8460	50.9	143	460	1075	586	18.8	206	13.1	0.062	1.42	0.039	1.05
Rwagimba	69	8.1	6390	62.5	800	838	1468	1480	41.6	74.1	5.38	0.452	2.77	0.01	0.48
Rwimi-1	25.9	7.2	3880	92.7	2100	232	693	424	60.7	380	198	0.071	0.94	0.154	6.42
Rwimi-2	24.6	7.1	3640	84.8	2020	189	523	356	56.8	361	181	0.056	0.73	0.031	6.25

The chloride and sulphates contents of Rwimi, Rwagimba, Mumbuga, Nyansimbe, Kagoro, Kibenge and Muhokya exhibit a high degree of covariance. Lake Kitagata has a unique composition possibly due to excessive evaporation. Buranga geothermal area and its sites (Mumbuga, Nyansimbe, and Kagoro) have water with the highest chloride and sulphates concentrations among the Rwenzori hot springs, possibly influenced by magmatic HCl and SO_2 input. These chemical similarities imply they are originating from the same source and along the same migratory path. The lowest values at Rwagimba, Rwimi, Kibenge and Muhokya reflect little input from lithological sources (evaporates, sulphate-enriched) (Kato and Kraml 2005).

Buranga's hot waters are equally rich in all three major anions (Cl-SO_4-HCO_3) which may be attributed to their source lithology, migratory path and mixing of different water types while Kibiro presents typical equilibrated Cl waters (Figure 3).

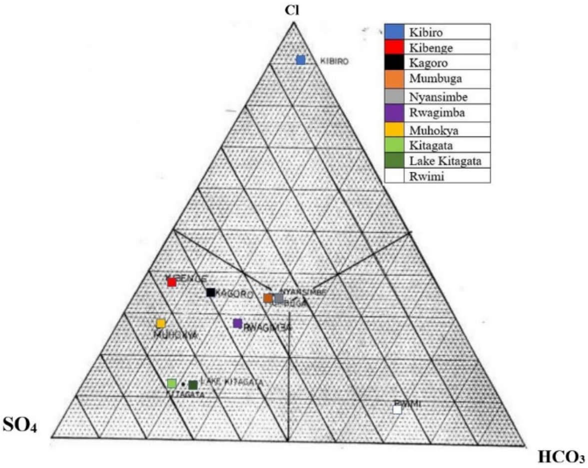


Figure 3. Relative contents of Cl, SO_4 and HCO_3 in Rwenzori hot springs (Kato and Kraml 2005).

Figure 3 also shows Lake Kitagata, Rwagimba, Kibenge, Muhokya to have alkaline waters with SO_4 as the major cation followed by Cl making them Cl-SO_4 type waters. Rwimi cold springs have bubbling CO_2 gas which accounted for the CO_2 rich waters with appreciable amounts of bicarbonate. Steam from the source is condensed into cool ground waters close to the margins of the resource where CO_2 is also absorbed to form bicarbonate waters. They are therefore a low temperature water type.

3.2 Relative Na, K and Mg Contents

The relative contents of Na, K and Mg in geothermal fluids show levels of dilution and mixing trend with meteoric Mg rich waters (Figure 4). Rwimi waters are low temperature meteoric waters that absorb CO_2 from cooling vapours. Rwimi water is therefore Mg rich, immature and plots close to the Mg corner. It is unjustifiable to use geothermometry on immature waters below equilibrium. Other areas with immature/partially equilibrated waters include Muhokya, Kibenge and Rwagimba. Buranga's high temperature waters at surface temperatures of about 98^{o}C (boiling) are rich in solutes due to increased solvent temperature and evaporation. These waters are slightly above equilibrium. Lake Kitagata waters also plot above the equilibrium line.

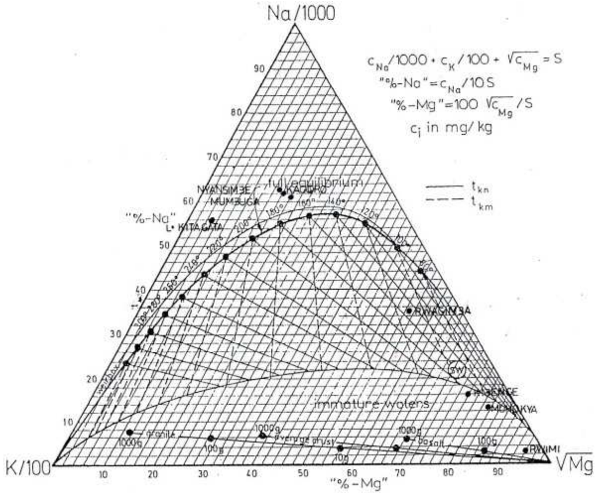


Figure 4. Ternary plot of Na, K and Mg for Rwenzori geothermal areas (Kato and Kraml 2005).

3.3 Deuterium and oxygen-18.

Isotopic studies in combination with other geochemical methods can be used to evaluate subsurface water systems. Isotopic studies assist in telling the depth of the system, altitude of the fluid sources, and levels of mixing (Figure 5).

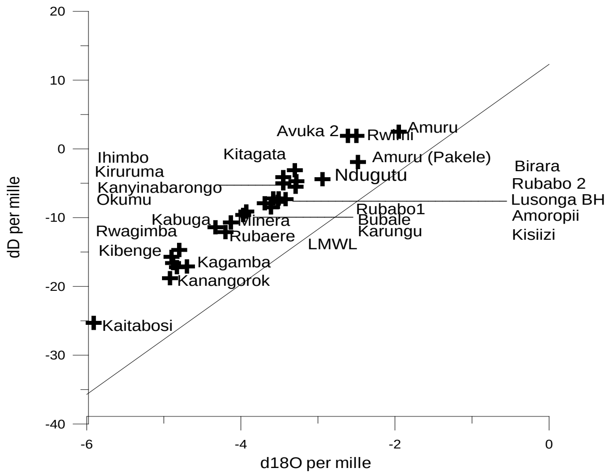


Figure 5. Deuterium and Oxygen-18 isotope ratios. Ármannsson et al (2008).

Hydrogen and oxygen isotope ratios relative to the Local Meteoric Water Line (LMWL) determined by the IAEA (GNIP 1999). The graph suggests a deuterium excess in all of Uganda's geothermal areas. This means all of Uganda's geothermal waters are sourced from the rain. It could also mean that the meteoric line for precipitation at Entebbe does not apply for the whole of Uganda and that one closer to the present results need be established (Ármannsson et al., 2008). The geothermal waters also show no signs of an oxygen isotope shift which implies good permeability while also reducing the likelihood of a high temperature geothermal system.

Water sourced from geothermal areas close to high altitude areas like mountain ranges showed low deuterium δ^2H values. This implies the water originates from a high altitude. These include Kagamba, Kibenge, Buranga, Kabuga, Rwagimba.

South Western Uganda's geothermal areas have meteoric waters from a moderate altitude. South Western Uganda is also known to be hilly geographically. These areas include Rubaare, Minera, Karungu, Bubale, Rubabo, Kisiizi, Birara, Kanyinabarongo, Kiruruma, Ihimbo, Kitagata.

Geothermal areas recharging locally, as well as cold springs exhibit slightly higher $\delta^{18}O$ values than areas with similar $\delta^{2}H$ values. Panyimur area's low deuterium values could be because the fluids are sourced from the rift escarpment or low mixing with lake water.

3.4 Cl/Br ratios

Cl/Br ratios help to indicate origins of thermal waters. Thermal waters from Western Uganda's geothermal areas like Kibiro, Panyimur, Katwe and Lake Kitagata have shown greater concentrations of chlorides than waters from other areas. Their Cl/Br ratios are a little higher than the rest of Uganda but below those of seawater. These ratios are reduced by precipitation of NaCl from brines e.g at Lake Katwe and Kibiro and dilution/mixing with meteoric waters. A mixture of geothermal end-member (full equilibrium water) and brackish (salty) water forms the geothermal fluids of most of western Uganda.

Alternatively, low Cl/Br ratio brines could come from gneisses and granite in basement rocks but such brines are known in fluid inclusions of such rocks. Through fracturing of these rocks by tectonic movements or by primary mineral dissolution small quantities of Br enriched brines could have been released into circulating ground water producing mixed water with low Cl/Br ratios (Alexander et al., 2016).

3.5 $^{3}He/^{4}He$ ratios

Deep geothermal reservoirs in amagmatic systems are presumed to be sources of high temperature fluids because of proximity to the mantle than the less deep reservoirs. A deep mantle signature can be deduced from the $^{3}He/^{4}He$ ratios of geothermal fluids. $^{3}He/^{4}He$ ratios help to determine depth of permeability of conduits and depth of the reservoir itself. According to Kato 2016, Elevated $^{3}He/^{4}He$ ratios for Buranga's geothermal fluids were believed to be evidence of deep permeability and possibly deeper, higher-temperature fluid reservoirs. The $^{3}He/^{4}He$ ratios could also be used to identify extensional faults with deep permeability. The low helium signature of Kibiro geothermal prospect affirms it as a deep circulation (amagmatic) extensional system (BGR 2007).

3.6 Soil gas and gas flux measurements.

Qualitative and quantitative analysis of gaseous emissions from Uganda's geothermal areas was done in some previous works to determine depth of penetrating structures. Analysis of gaseous emissions is also necessary for safety purposes and to determine if the gaseous resource can be utilised. Soil gas (Radon, Rn) and gas flux (CO_2) measurements have been done at Kibiro, Buranga, Panyimur, Katwe and Ihimbo geothermal areas. They revealed concealed deep penetrating fractures which control geothermal activity (Figure 6).

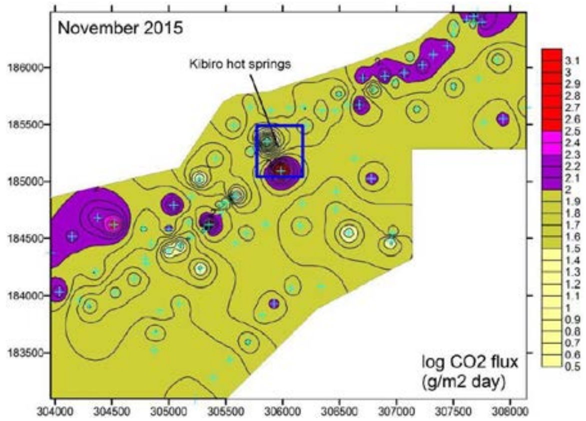
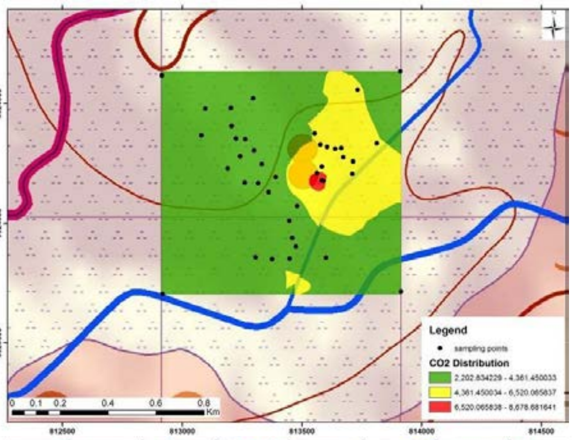
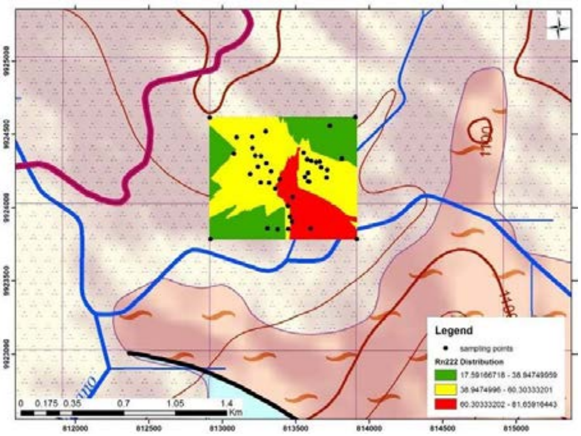


Figure 6: Gas flux measurements at Kibiro (Kato 2017).

Anomalous gas flux is presumed to indicate geothermal activity (permeable conduits). High flux are presumed to be indicative of anomalous flux associated with geothermal activity. It is used to locate active fault zones presumed to control geothermal activity. Anomalous concentrations of Radon-222 (soil gas) are presumed to indicate concealed faults that act as conduits for geothermal fluids.

The Ministry of Energy and Mineral Development undertook soil gas and gas flux measurements in Kibiro and other areas to aid in mapping active permeable fractures. Gas flux measurements (Figure 6) indicate high anomalies along main rift bounding fault complementing soil gas data and shallow temperature probe survey data (Kato 2017). The CO_2 flux measurement and ^{222}Rn activity in Ihimbo are represented in Figures 7 and 8 below (After Kato 2017).





3.7 Geothermometry

Geothermometers when applied to mature waters can be used to predict subsurface temperatures (Table 3).

Table 3. Measured temperatures and geothermometer temperatures for 25 geothermal areas in Uganda (Ármannsson et al., 2008).

Location	Measured °C	Quartz °C	Chalcedony °C	Na/K °C
Kagamba	35	73.9	41.8	338.9
Karungu	65	101.1	70.7	153.9
Bubale	34	62.6	30.3	194.7
Rubaere	54	138.8	112.1	134.6
Kitagata	66	120.1	91.4	136.1
Ihimbo	70	83.8	52.2	96.0
Kanyinabarongo	38	85.0	53.4	136.4
Birara	63	136.1	109.1	155.8
Rubabo1	58	125.0	96.9	136.2
Kiruruma	36	108.2	78.4	183.9
Kisiizi	30.1	58.6	26.4	n.a.
Minera	58	126.8	98.8	128.1
Kabuga	42	104.0	73.8	100.2
Kibenge	48	97.5	66.8	121.6
Ndugulu	22	79.7	47.9	141.3
Rwimi	24	133.2	105.9	250.3
Rwagimba	69.2	114.3	85.0	93.1
Amoropii	58	111.3	81.8	98.5
Okumu	45	112.9	83.6	95.4
Avuka-2	35	104.6	74.5	139.6

According to Ármannsson et al., 2008, the Na/K geothermometer is unreliable in such cases and so is the silica geothermometer for low temperature waters. In many instances there is not a good agreement between the Na/K temperature and the silica temperatures. Silica and Na/K geothermometers appear to be in agreement when predicting subsurface temperatures for Birara, Rubabo and Minera (Table 3). This suggests that the geothermal waters from these areas are close to equilibrium and are not a mixture of the hot component with cooler water.

4. CONCLUSION

Chemical composition of geothermal fluids from extensional type deep circulation systems is influenced mostly by temperature. The fluids are less chemically charged compared to the high temperature magmatic systems because they dissolve less chemical content from their contact rocks. Temperatures of Cl waters are greater than temperatures of SO_4 waters which are also greater than temperatures of HCO_3 waters. SO_4 waters and HCO_3 waters originate from areas with H_2S and CO_2 gases respectively. Hot springs around high altitude areas have low deuterium levels since the fluids are assessed as immature and partially equilibrated waters (shown by high Mg content), the use of geothermometry to predict subsurface temperature is not reliable. The high temperatures implied by measurable H_2S were not observed for Uganda's extensional type system. Soil gas and gas flux measurements at some of the major prospects revealed active fault zones and deep concealed permeable fractures that favour geothermal activity. Cl/Br ratios help to determine origin of fluids; the source rocks that grant them most of their chemical composition and the influence of mixing with surface meteoric fluids. $^3He/^4He$ ratios point to the depth of the subsurface reservoir by detection of a deep mantle signature.

ACKNOWLEDGEMENT

I acknowledge the input of Mr Bahati Godfrey and Mr Kato Vincent towards the writing of this paper. They told me about the workshop, encouraged me to write this paper and also fact checked it. Special thanks to the NZGW2020 and University of Auckland for granting me this opportunity.

REFERENCES

Alexander, K.B., Cumming, W., Marini, L.: Geothermal Resource Assessment Report, Kibiro Geothermal Prospect, Uganda, Final Report-September 2016. *Confidentially reported to UNEP and GRD/MEMD.* (2016).

Ármannsson, H., Bahati, G., and Kato, V.: Preliminary investigations of geothermal areas in Uganda, other than Katwe-Kikorongo, Buranga and Kibiro. *Papers presented at Second African Rift Geothermal Conference (ARGeo-C2)*, Entebbe, Uganda, 19 pp. (2008).

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

BGR.: Detailed surface analysis of the Buranga geothermal prospect, West Uganda. Final report, 168p. (2007).

Hinz, N.H., Coolbaugh, M., Faulds, J.E., Shevenell, L., and Stelling, P.: Regional quantitative play fairway analysis: Methodology, global examples, and application for the East African Rift System: *Proceedings, 6th African Rift Geothermal Conference*, Addis Ababa, Ethiopia, 2nd – 4th November, 2016, 12 p. (2016).

Kato, V., and Kraml, M.: Geochemistry of Rwenzori Hot spring Waters: *ARGEO-C3 Third East African Rift Geothermal Conference*, Djibouti, 22 – 25 November 2010, 12p. (2010).

Kato, V.: Geothermal Exploration in Uganda: *Presented at SDG Short Course I on Exploration and Development of Geothermal Resources, organized by UNU-GTP, GDC and KenGen*, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 10-31, 2016, 16p. (2016).

Kato, V.: Geothermal Exploration in Uganda-Status Report: *Presented at SDG Short Course II on Exploration and Development of Geothermal Resources, organized by UNU-GTP, GDC and KenGen*, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 9-29, 2017, 24p. (2017).