Geothermal Potential of the Amagmatic Aswa Shear Zone in Uganda: An Assessment Using Geochemical Signatures

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ABSTRACT

Okidi and Elegu, located in the Aswa Shear Zone of Northern Uganda are few of the amagmatic geothermal prospects situated outside the western arm of the East African Rift System. The two areas were first documented in 1935 and 2014 respectively. According to a reconnaissance survey done in 2023, Okidi thermal area is marked by hot springs issuing at a maximum temperature of 80°C from a riverbed covered with alluvial sediments. Conversely, Elegu is a blind system proven by shallow boreholes discharging mineralized anomalously warm fluids (44.7°C) and H_2S gas. Geological and geochemical data showed an extensional-type system controlled by tectonism and slightly alkaline (pH 7.5-8.3) thermal fluids with relatively low TDS compared to other areas of similar surface temperatures. Detailed geochemical and hydrogeological surveys conducted in 2024 show Na-Cl or Na-SO_4-Cl or Na-SO_4-HCO_3 type thermal fluids of meteoric origin and equilibrium reservoir temperatures of 150-170°C for Okidi and 90-120°C for Elegu.

1. INTRODUCTION

1.1 Background

Geothermal exploration in Uganda has been mainly focused on the Western Arm of the East African Rift System (EARS) along the Uganda border with Democratic Republic of Congo. The exploration studies have led to the identification of at least 24 geothermal areas mainly in Western Uganda**.** Four of these are priority areas, Kibiro, Panyimur, Buranga, and Katwe-Kikorongo, earmarked for cascaded development. According to exploration studies, the four areas host fault-controlled deep circulation systems rather than magmatically heated systems synonymous with volcanoes, akin to the Eastern arm of the EARS. The other geothermal areas most likely host similar systems. Thermal gradient hole (TGH) drilling, an exploration technique tailored to extensional type systems has been completed in two of the priority areas with deep exploration wells currently being planned.

The Aswa Shear Zone (ASZ) in Northern Uganda presents an alternative geothermal zone marked by two geothermal areas, Okidi and Elegu, aligned along its dominant structures. This paper presents the first geochemical study done for the two areas. Results of this study will inform subsequent exploration and development stages to confirm presence of the resource.

1.2 Geothermal Utilization in Uganda

Geothermal development in Uganda is regulated under a hybrid system. Electricity generation using geothermal resources will be regulated by the Electricity Act 2022 (as amended) and Energy Policy for Uganda 2023 while geothermal direct use is regulated by the Mining and Minerals Act 2022 (as amended). Electricity generation in the country is largely by hydroelectric power plants which generate at least 90% of the total power in the country. Thermal and solar energy also contribute a small percentage (about 3%). Geothermal power generation provides an opportunity to diversify the energy mix while also increasing electricity access to off-grid areas.

Geothermal direct use applications have been mostly limited to hot spas and balneotherapy. Other uses of geothermal resources include mineral extraction from geothermal brines (e.g., at Lake Katwe and Kibiro), tourism (e.g., Buranga hot springs in Semliki National Park). Development of the country's low to medium enthalpy resources for direct use will target the agro-processing and hospitality industries.

2. STUDY AREAS

2.1 Area Geology

Previous aerial and ground geophysical and geological studies conducted within these areas for purposes of mineral exploration helped in elucidating the subsurface controlling structure and geology of the two systems. Okidi geothermal springs issue from a riverbed underlain by quaternary alluvium, swamp, and sediments. The riverbed lies within a shear zone composed of Archean sheared granites and granitic gneiss. Banded gneiss is widespread across the study areas (Mawejje et al., 2023). Towards the NW (Elegu) the shear zone overprints the Kuju granitic and granodioritic gneiss, Adjumani granite, and Apuch granite migmatite. The thermal areas are underlain by crystalline basement rocks which include mylonite, migmatites, gneiss and granitic gneiss (Figure 1).

2.2 Okidi Geothermal Area

Okidi geothermal area is situated along Achwa River in the Aswa Shear Zone in Northern Uganda. The first reconnaissance and geoscientific surveys were done in 2023 and later again in 2024 by a team of geoscientists from the Geothermal Resources Department (GRD), the Ministry of Energy and Mineral Development (MEMD) in Uganda.

Geothermal surface manifestations in the area include hot springs, steaming ground, hydrothermal alteration, and geothermal grass. The thermal springs discharge from the Achwa riverbed (on a river island). More features are likely to be covered by the Achwa River. The hot springs issued at temperatures of 80.1 – 44.7°C. Two individual outlets with a low flowrate had surface temperatures of 80.1°C and 79.6°C. Several outlets emitting from fractured granites formed a pool with a maximum temperature of 76.4°C. A warm spring at the

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riverbank had an outlet temperature of 44.7°C. At 80.1°C, Okidi geothermal prospect has the third highest surface temperature in Uganda after Buranga (98°C) and Kibiro (86°C). Other prospects outside the rift in Northern Uganda include Amuru (49°C) and Kanangarok (47°C).

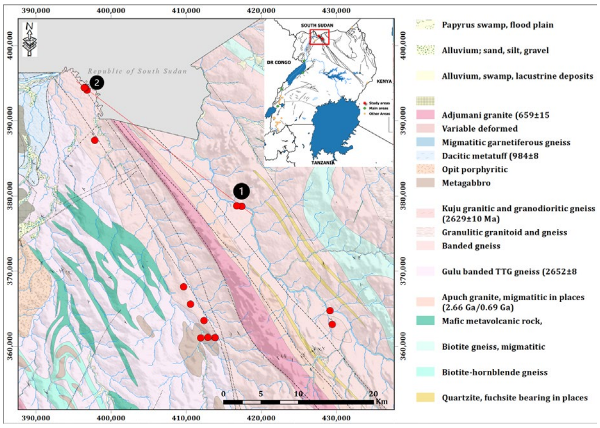

Figure 1: Geology of Northern Uganda surrounding the study areas. Modified after Westerhof et al., (2012). Red dots indicate locations of sampling points. Okidi and Elegu geothermal areas are numbered ❶ and ❷ respectively.

2.3 Elegu Geothermal Area

This blind geothermal system is found in Elegu town along the Uganda-South Sudan border. It has no natural surface manifestations, and the only indication of geothermal activity is anomalously warm fluids and H_2S gas discharged by shallow groundwater boreholes. In 2014, warm water containing solute minerals was encountered after drilling of shallow boreholes meant to provide water for domestic use (Kato et al., 2014). This was the first observed surface indication of geothermal activity in the area. At least two boreholes discharge warm water at temperatures 35 – 45°C.

2.4 Aswa Shear Zone

The Aswa Shear Zone (ASZ) is a major NW-SE trending sinistral strike-slip zone made up of complex ductile-brittle fabric (Westerhof et al., 2012). The ASZ stretches over 1000 km in length with ca. 11 km wide surface expression starting in South Sudan and terminating in Kenya against the rift. In Uganda, the ASZ begins at the termination of the Albertine–Rhino grabens (Katumwehe et al., 2016) and extends over a length of around 365 km between Elegu town in the North and Mount Elgon in the East (Saalmann et al., 2016).

The main ASZ structure is complemented by various sub-parallel lineaments, splay faults, and parallel shear zones showing similar fabrics and kinematics NE and SW of the main zone e.g the Lira-Gulu Domain. The shear zone is characterized by mylonitic gneisses and multiple stage brittle reactivation. Mylonitic foliation observed in mylonites and ultramylonites is a product of rock deformation caused by shearing. This high strain shear zone cuts across different granitoids and gneisses e.g., fine-grained banded gneisses of Neoarchaean age (Saalmann et al., 2016). The sinistral strike slip movement is shown by a 60 km horizontal displacement. This fault zone appears to be a sub-vertical topographic and density discontinuity that dips steeply towards the NE at an angle of 60° (Ruotoistenmäki, 2014).

Okidi and Elegu are also likely to be fault-controlled deep circulation systems of low to medium enthalpy. The two areas are aligned along major sinistral strike-slip faults of the ASZ which is likely to be the major controlling structure. Two theories are hereby postulated in Figure 2 that are likely to have increased permeability and allowed deep circulation of meteoric waters to reach rocks with high heat flow and thermal gradient forming a geothermal system.

1) Sub-parallel shear zones of the ASZ are likely to form a trans-tensional pull-apart zone or an accommodation zone (splay faults) of enhanced permeability.
2) Termination of the Rhino Graben against the ASZ formed an intersection of Quaternary faults and strike-slip faults or oblique slip faults likely to have increased permeability.

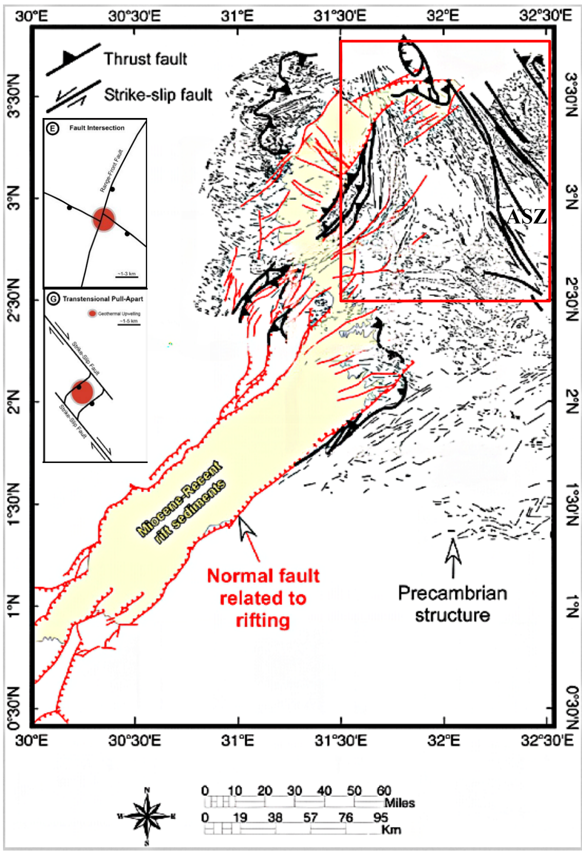

Figure 2: Red rectangle shows a possible fault intersection between the Rhino graben and ASZ, sub-parallel shear zones and splay faults of the ASZ forming a possible trans-tensional pull apart zone as illustrated (inset) by Faulds & Hinz, (2015)**. Modified after** Katumwehe et al., (2015)**.**

The main shock (M_w = 7.2) of the 1990 earthquakes in South Sudan was largely attributed to active sinistral strike-slip movement in a NW-SE planar direction along the ASZ fault trend (Moussa, 2008). The shear zone is therefore deemed to be tectonically active.

3. METHODOLOGY

3.1 Sampling and Analysis

Geochemical and hydrogeological studies were conducted in the two areas between 2023 and 2024. The field work campaigns were conducted by geoscientists from GRD-MEMD, Uganda. During the field work, geological mapping, mapping of surface manifestations, sampling of thermal and non-thermal fluids and measurement of physiochemical parameters, namely, temperature, pH, electrical conductivity (E.C) were conducted. In Table 1, hot springs (HS) and warm boreholes (WBH) represent thermal fluids (≥35°C) in Okidi and Elegu geothermal areas respectively. Non-thermal fluids (<35°C) are groundwaters represented by cold boreholes (CBH) and surface waters represented by rivers (RIVER) and rainwater (RAIN). Untreated samples were analysed for H_2S content and alkalinity (as HCO_3) on-site by titration. Samples collected were analysed in the laboratories at Kyushu University using IC (ion chromatography) for major cations and anions, and ICP-OES for trace elements. Untreated and acidified samples were used for analysis of anions and cations respectively. Total silica content was determined using the silicomolybdate yellow method and UV/Visible Spectrophotometry. Stable isotope ratios of water, $\delta^{18}O$ and δD, were analysed by IRMS.

Table 1: Thermal and non-thermal samples collected and their physiochemical parameters.

No.	NAME	TYPE	Sampling Date	TEMP (°C)	pH	E.C (µS/cm)	TDS (mg/L)
1	Elegu Police	WBH	Aug-24	35.5	7.56	1230	613
2	Elegu EGH	WBH	Aug-24	44.5	8.00	855	426
3	Elegu BH	WBH	Jul-24	37.0	8.50	1120	570
4	Elegu BH 2	WBH	Jul-24	43.5	8.47	877	437
5	Elegu Mosq.1	CBH	Aug-24	28.7	7.34	446	223
6	Elegu Mosq.2	CBH	Aug-24	30.1	6.64	849	425
7	Elegu Primary	CBH	Aug-24	29.6	6.85	760	380
8	Ogom A	CBH	Aug-24	29.8	6.49	372	185
9	Ogom Raa	CBH	Aug-24	28.9	6.11	208	113
10	Rwom Rwot	CBH	Aug-24	28.4	6.57	824	412
11	Okidi Centre1	CBH	Aug-24	28.2	6.46	604	301
12	Okidi Centre2	CBH	Aug-24	28.7	6.68	561	281
13	Okidi Centre3	CBH	Aug-24	28.1	6.34	455	227
14	Oroko	CBH	Aug-24	30.0	6.54	398	199
15	Unyama	RIVER	Aug-24	25.1	7.84	116	57
16	Achwa	RIVER	Aug-24	27.0	7.76	113	56
17	Gulu Rain	RAIN	Aug-24	25.3	7.34	14.6	7.6
18	Okidi HS	HS	Jul-24	70.0	8.04	1370	685
19	Okidi I	HS	Mar-23	80.1	8.02	1289	648
20	Okidi II	HS	Mar-23	79.6	8.02	1289	647
21	Okidi III	HS	Mar-23	76.4	8.02	1289	637
22	Okidi IV	HS	Mar-23	44.7	7.91	874	433

3.2 Data Treatment

Prior to data synthesis, the analytical results were subjected to a charge balance error calculation and all samples were within the acceptable limits of ±5%. A Schoeller plot was used to visualize variations of the different parameters in each sample. Biplots were used to help understand subsurface processes and sources of constituents. A piper diagram was deployed to aid in fluid classification based on major cations and anions. Subsurface temperatures were estimated using solute geothermometers. Stable isotope ratios of water were used to estimate the origin of recharge fluids.

4. RESULTS AND DISCUSSION

4.1 Physical and Chemical Characteristics

Geochemistry reflects the different geological settings of the areas where it is applied and considers numerous physical and chemical processes. Chemical aspects considered in this study for the two areas include fluid compositions and fluid-mineral equilibria. Physical aspects include hydrology and fluid flow.

Table 1 shows important physiochemical parameters measured to help characterize the fluids. pH of the thermal fluids was neutral to slightly alkaline. The temperature difference for Okidi hot springs was attributed to conductive cooling since chemical composition wasn't much affected (Figure 3). The EGH/BH2 borehole in Elegu and Okidi IV warm spring showed similarities in temperature and composition but had lower E.C and total dissolved solids (TDS) than Elegu Police/BH which had a lower temperature. The shallow boreholes were drilled to depths of less than 150 m probably tapping into shallow secondary warm aquifers or groundwaters that have mixed with geothermal fluids. Geothermal fluid composition has been used in fluid classification and solute geothermometry.

4.2 Sources of Constituents

The local system geology largely influenced chemical composition of the thermal and non-thermal fluids. Variations are likely due to differences in temperature, depth, origin and fluid flow path. According to reaction kinetics, reactions between the water and rock minerals proceed much faster at higher temperatures. Contact surface area, rate constants and prevailing equilibrium status also influence the reaction rate (Arnorsson, 2000).

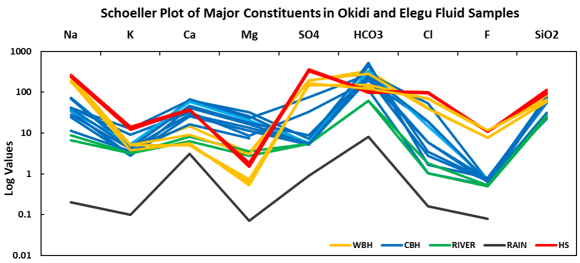

Figure 3: Variations of major constituents analysed in Okidi and Elegu fluid samples.

Despite the high surface temperature of 80.1°C, Okidi thermal fluids exhibit much lower TDS levels i.e. less chemically charged than fluids from volcanic systems e.g. those in the Eastern rift in Kenya due to minimal or no magmatic input. The same is true when compared to some systems in the Western rift in Uganda (Kato, 2000). The Western rift valley is covered by deep sediments that host sedimentary minerals, oil fields and oil field brines. Some influence of volcanism has also been reported (Kato, 2000; Mawejje et al., 2015). Conversely, Okidi fluids circulate in deep basement granitic formation where they interact with few primary minerals. The effect of temperature is shown by the difference in total solutes between thermal and non-thermal fluids. Major constituents of the thermal fluids (Na, Cl, SO_4, F, SiO_2) were obtained by fluids leaching rock minerals at depth. Others like Ca, Mg, HCO_3 were depleted due to removal from solution.

Most samples are enriched in Na (1 < Na/Ca < 42), especially the hot springs and warm boreholes reaching at least 165 ppm in excess over Ca. Na and Cl ions in the thermal waters were mostly obtained by dissolution of halite minerals. Excess Na (Figure 4A) and K were probably leached from weathered feldspar minerals in granitic rocks (Hounslow, 1995). In solution, the excess Na cations most likely conjugate with SO_4 or HCO_3 anions. Enriched Ca and HCO_3 in thermal waters were most likely removed by deposition of carbonate minerals in the surrounding rock hence the low concentrations. Aqueous speciation showed that thermal waters were oversaturated with calcite and aragonite. Precipitation of Ca^{2+} ions likely increased dissolution of CaF_2 mineral to replace lost Ca^{2+} ions (Hounslow, 1995). This subsequently increased the concentration of fluoride ions (7-12 ppm) in the thermal fluids vis-à-vis the F content in the non-thermal water (Figure 3). Augen gneiss and granitic gneiss in the host environment are likely to contain F-bearing minerals like fluorite (Hounslow, 1995).

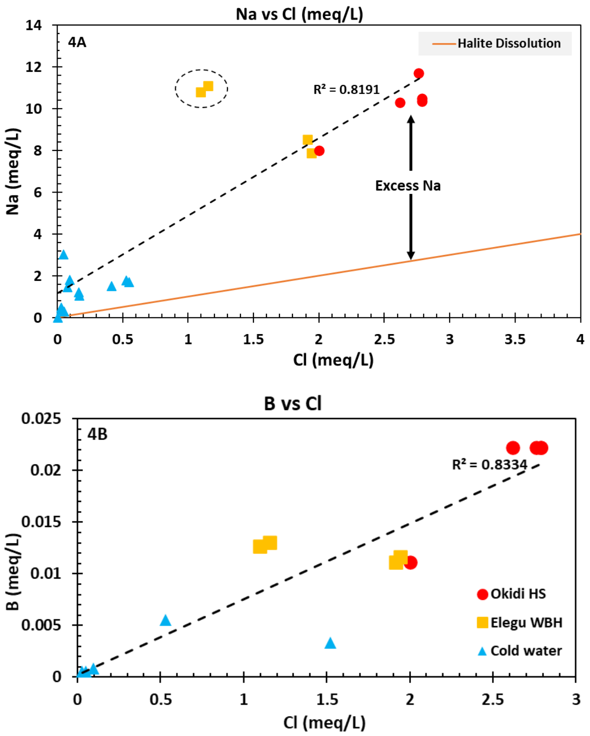

Figure 4A: Halite dissolution as a possible source of Na and Cl in the thermal waters. Excess Na is from other sources like feldspars, ion-exchange. 4B: B vs Cl linear relationship showing mixing.

The low Mg concentrations of Okidi (<2 ppm) and Elegu EGH/EBH2 (<1 ppm) thermal waters suggest they originate from deep formations and experience minimal mixing with shallow groundwater. Mg concentrations decline with increasing depth and temperature (Fournier & Potter, 1979) due to their uptake in formation of secondary minerals, altered clays.

The high concentrations of SO_4 ions, 145 – 195 ppm in Elegu and 320 – 360 ppm in Okidi thermal fluid samples are not expected for geothermal fluids from depth. SO_4-rich thermal fluids are associated with steam heated waters in the up flow of magmatic geothermal systems especially those in subduction zones (Giggenbach, 1988; Moeck, 2014). Westerhof et al., (2012) suggested that there was no active volcanism observed in our study areas. Low B, As and NH_3 concentrations confirmed the absence of magmatic input (Chiodini et al., 1996; Arnorsson, 2000). The abundant SO_4 ions are most likely sourced by microbial oxidation of sulphides like pyrite or pyrrhotite as shown by Equation 1 (Hounslow, 1995). This in addition to Ca-mineral deposition caused $Ca^{2+} < SO_4^{2-}$. Our thermal samples' results also fit the $Ca^{2+}/(Ca^{2+} + SO_4^{2-}) < 0.5$ criteria suggested by Hounslow (1995) for neutral waters. H_2S gas (at least 1 ppm) detected in the Elegu EGH borehole could be a product of microbial sulphate reduction (Hounslow, 1995).

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O + 4CaCO_3 \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4Ca^{2+} + 4HCO_3^- \quad [1]$$

Westerhof et al., (2012) analysed rock samples from the Lira-Gulu domain (splay faults of the ASZ) about 74 km south of the Okidi resource area, near Gulu city. They found biotite-hornblende gneiss of the Pongdwongo formation with high sulphur contents reaching 8860 ppm. Pyrite and chalcopyrite were observed in fractures and quartz veins in the rock. Fine-grained pyrite was also observed in quartzite of the Kinanga formation about 65 km ESE of the Okidi area. Both locations of these sulphur-rich rocks coincide with possible recharge zones for Okidi and Elegu systems (see Figure 10). Owor et al. (2021) also found dominantly SO_4-type groundwaters in the north-central part of Uganda east of the ASZ, around the Kinanga formation.

4.3 Fluid Classification

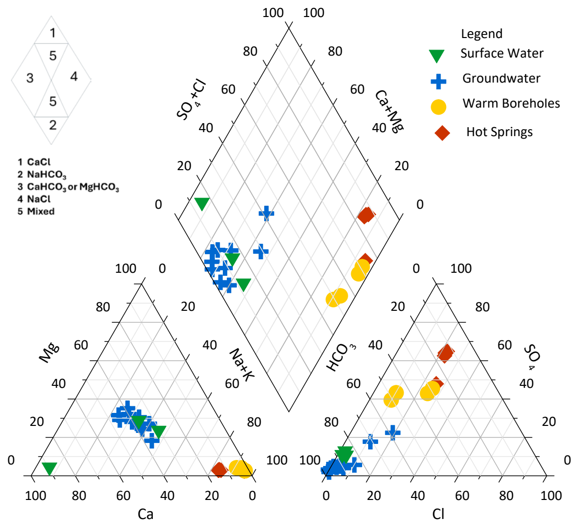

Figure 5: Classification of thermal and non-thermal samples. From the diamond plot, thermal fluids are classified as Na-Cl waters.

A piper diagram (Figure 5) was used to classify thermal and non-thermal fluid samples based on major anion and cation constituents. Major cations in Okidi thermal samples, are Na>Ca>K>Mg while the dominant anions are SO_4>Cl>HCO_3 dominantly reflecting a Na-SO_4-Cl type of water. Elegu thermal samples' major cations are Na>Ca>K>Mg while the dominant anions are HCO_3>SO_4>Cl dominantly reflecting a Na-HCO_3 type of water. On the other hand, major cations and anions in the non-thermal samples are Ca$\geqslant$Na>Mg>K and HCO_3>SO_4 $\geqslant$ Cl respectively, suggesting $CaHCO_3$-rich waters. Na exceeded Ca in a few of these samples making them $NaHCO_3$-rich waters.

5. SUBSURFACE TEMPERATURES

Chemical geothermometry for water samples was used to estimate subsurface temperatures in the two systems (Table 2). Chemical compositions of specific constituents used in geothermometry reflect the last point of equilibrium based on reactions between water and rock minerals in the subsurface. This last point of equilibrium usually refers to the geothermal reservoir or the source aquifer along the fluid flow path. Thermal fluids originating from shallow aquifers like those suspected in Elegu cannot provide information about the deep thermal reservoir (Arnorsson, 2000).

According to Arnorsson (2000), successful application of geothermometers is based on two assumptions. The first being temperature dependent chemical equilibria attained in the geothermal reservoir by specific mineral solutes. Secondly, no change in fluid composition has occurred as thermal fluids ascend to the surface because of chemical reactions or processes like conductive cooling, mixing, boiling. A change in fluid composition will cause a change in the final geothermometer results.

5.1 Silica Geothermometers

Silica concentrations in thermal waters were applied to the geothermometers to estimate temperatures. Quartz, the most stable form of silica approaches equilibrium with geothermal waters at temperatures greater than 180°C. It therefore controls silica solubility at these temperatures (Arnorsson et al., 1983; Fournier, 1977). At temperatures <180°C and neutral pH 6-8, other more soluble silica polymorphs like chalcedony control silica solubility (Arnorsson et al., 1983).

Table 2: Predicted subsurface temperatures (°C) for Okidi and Elegu geothermal areas. Chemistry data of Okidi HS, I, II, III, Elegu EGH, BH2 were used.

Geothermometer (Source)	Okidi	Elegu
Na/K (Arnorsson et al., 1998)	150 – 154	110 – 115
Na/K (Nieva & Nieva, 1987)	153 – 157	111 – 116
K/Mg (Fournier, 1991)	155 – 171	127 – 132
Quartz (Fournier, 1977)	131 – 145	117 – 128
Chalcedony (Fournier, 1977)	104 – 120	88 – 100
Na-K-Ca (Fournier & Truesdell, 1973)	141 – 145	123 – 125
Na/K (Fournier, 1979)	164 – 167	122 – 127

At 145°C (Okidi quartz geothermometer temperature), equilibrium with quartz maybe assumed for an amagmatic system. This is due to the slow rate of silica dissolution from granitic and sedimentary rocks which contain less reactive minerals compared to rocks in volcanic systems (Arnorsson, 2000). However, it seems much more reasonable to assume chalcedony equilibrium even in an amagmatic system since the highest possible temperature for Okidi (187°C by Giggenbach's Na/K geothermometer) is just close to the minimum quartz equilibration temperature of 180°C. Chalcedony geothermometer temperatures were considered for both systems since chalcedony attains equilibrium at a lower temperature than quartz (Table 2).

5.2 Cation Geothermometers

The Na/K geothermometer by Giggenbach (1988) estimated a reservoir temperature of 187°C. However, this temperature was disregarded since our samples plotted in the immature section of the Giggenbach triangle. Instead, the Na/K geothermometer by Fournier (1979) was considered with an estimated a reservoir temperature of 168°C for Okidi thermal area. It is suitable for geothermal waters which equilibrate above 100 to 150°C. Equilibrium with Na- and K-feldspars which control Na/K ratios of most geothermal fluids is closely approached at temperatures exceeding 100°C (Arnorsson, 2000). The Na-K-Ca geothermometer by Fournier & Truesdell (1973) was used alongside the Na/K geothermometer to ascertain the reliability of the predicted temperature as recommended by Fournier (1979). The Na-K-Ca predicted a temperature of 145°C. The two temperatures are not too far apart hence a reservoir temperature of 145-167°C can be expected for Okidi. Newer Na/K and K/Mg geothermometers all within 150-171°C also agree with this estimate.

Disparities between the silica and cation geothermometers can be attributed to mixing of the thermal waters with low concentration groundwaters in the up flow. Mixing models help to account for this effect of mixing (Arnorsson, 2000; Chiodini et al., 1996; Fournier, 1977). Chalcedony geothermometer temperature can therefore be assumed to be the minimum reservoir temperature hence 120-170°C can be expected for Okidi and 90-120°C for Elegu.

5.3 Mixing Models

Mixing of thermal fluids with shallow cold waters as they ascend from the reservoir causes cooling. According to Arnorsson (2000), variations in temperature and composition of conservative constituents between fluid outlets (hot springs, boreholes) are some of the indicators of possible mixing. These variations were observed in the Okidi and Elegu samples which showed a linear relationship between conservative constituents Cl vs B, Br (Figure 4B).

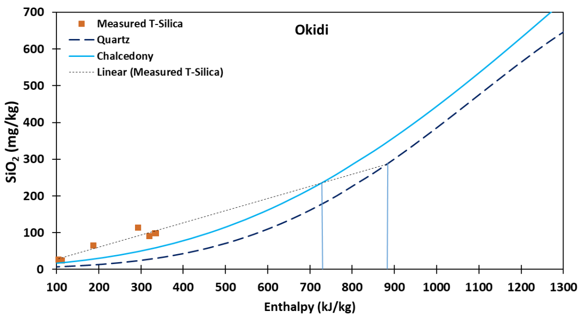

Figure 6: Silica enthalpy mixing model using chalcedony and quartz solubility curves. Chalcedony is more reliable for our medium temperature system.

The near linear relationship between silica and Cl for the same samples implies silica content was fixed after mixing. This silica behaviour is an underlying assumption of the silica-enthalpy model by Fournier (1977) in Figure 6. Concentrations of reactive constituents (e.g., Na) may increase to pre-mixing levels after dilution (Arnorsson, 2000) as observed in Elegu Police fluids (circled in Figure 4A). This is due to increased reactivity by addition of CO_2 in groundwaters which is converted to carbonic acid. More cations must be dissolved to counter the excess protons and return pH to neutral levels. This in turn increases the HCO_3 content (Arnorsson, 2014).

Reservoir temperature of unmixed Okidi fluid was estimated (Figure 6) at 171°C from chalcedony curve drawn using the chalcedony solubility equation of Fournier (1977). The quartz curve (Fournier, 1977) gave a temperature of 206°C. Steamtables were used to convert the enthalpies to temperature. The estimate by chalcedony curve is closer to estimates by Na/K and K/Mg geothermometers. This mixing model was not applied to Elegu waters because the samples fit line did not intercept the silica curves.

Figure 7 shows the iso-chemical geothermometric mixing model by Chiodini et al. (1996) used to find agreement between the different geothermometers for the temperature of the pure endmember feeding the Okidi hot springs. Three geothermometers agreed at a temperature of 152°C and chloride concentration of 152 mg/L, closest to 117 mg/L measured by titration in Okidi 1 sample. Other geothermometers were also in agreement at temperatures around 150°C to 160°C but higher chloride concentrations. The clearest observation is that the effect of mixing is less pronounced in the Na/K geothermometers compared to the silica geothermometers.

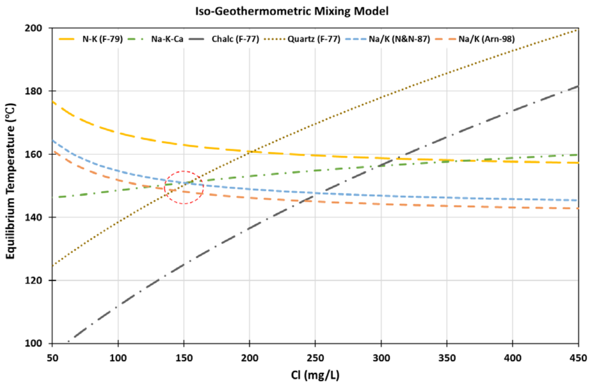

Figure 7: The iso-geothermometric mixing model

6. ORIGIN OF RECHARGE

6.1 Stable Isotopes

Stable isotope ratios for selected thermal and non-thermal water samples collected from Okidi and Elegu areas have been plotted alongside calibrated meteoric water lines as shown in Figure 8. Craig (1961) conducted experiments that established a general worldwide relationship between δ^2H and $\delta^{18}O$ represented by a Global Meteoric Water Line (GMWL). The local meteoric water line henceforth referred to as the Entebbe Meteoric Water Line (EMWL) for Uganda's precipitation at Entebbe by GNIP (1999) has a similar gradient but higher deuterium excess.

GMWL $\delta^2 H = 8\delta^{18}O + 10$ [2]

EMWL (GNIP) $\delta^2 H = 8\delta^{18}O + 12.3$ [3]

Isotopic compositions of the thermal waters are compatible with the GMWL and EMWL, confirming their meteoric origin. The primary source of water for both Okidi and Elegu geothermal systems is most likely local meteoric water. $\delta^{18}O$ and δ^2H values of Okidi and Elegu thermal fluids were slightly lower (more negative) than those of the groundwaters. Warm boreholes are an intermediate of the hot spring and cold boreholes which could be due to mixing of thermal and non-thermal waters. The order of depletion is rainwater > rivers > hot springs > warm boreholes > cold boreholes. The deuterium content of Okidi and Elegu thermal waters in relation to local precipitation and groundwaters can be used to determine our source of recharge.

Recharge precipitation to the respective geothermal field is expected to have a lower deuterium content i.e., more negative (Arnason, 1977). Precipitation sample, RAIN, collected in Gulu city (1100 masl), a nearby high-altitude area to the south of Okidi and Elegu resource areas (620-670 masl) was more depleted in deuterium (-40‰) compared to the thermal water samples (-4.0‰ for Okidi and -0.6‰ for Elegu). Gulu hill is likely to be the recharge area of Okidi and Elegu though the certainty is reduced by the big difference in deuterium contents. River water samples from Unyama (-4.0‰) and Achwa (-3.2‰) showed deuterium values that were slightly lower or close to those at Okidi and Elegu. However, they had a higher deuterium excess (Unyama 14.9‰, Achwa 14.3‰) compared to all the other samples (9.6-11.8‰). This deuterium excess (δD excess = $\delta D - 8*\delta^{18}O$) is shown by the two samples plotting above the two water lines. All the other samples plotted on these two lines. The rivers most likely carry waters from precipitation of a different climatic condition or season that differs from the current area or time (Arnorsson, 2000). They therefore may not be a potential recharge to the two systems.

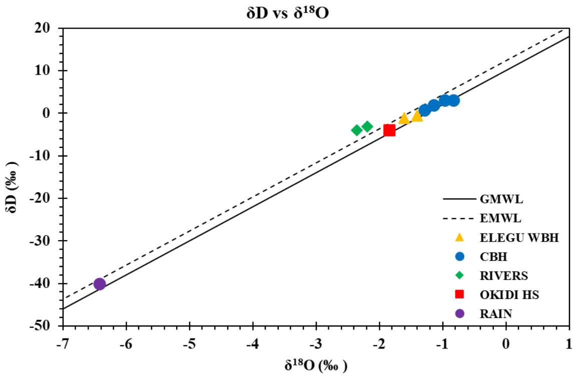

Figure 8: δD and $\delta^{18}O$ isotope ratios for selected water samples from Okidi and Elegu geothermal areas.

Low altitude regions close to the ASZ could be the source of recharge. Low altitude areas (<1000 masl) are expected to have fluids that lie between Gulu rainwater and hot spring fluids in terms of isotopic enrichment. This includes areas NE and SW of the ASZ as well as areas SE, ESE, SSE of the resource areas following the NW-SE orientation of the ASZ. Faults of the ASZ are assumed to control system recharge.

7. PROPOSED CONCEPTUAL MODEL

A conceptual model has been proposed (Figure 9) that shows two independent geothermal systems. The systems likely share a recharge area but not the reservoir. The sulphate composition of the thermal fluids provides some evidence on the possible recharge direction (Figure 10).

7.1 Origin of Recharge

Thermal fluids from the Okidi and Elegu geothermal systems are originating from meteoric (rain) waters falling in low altitude areas along or close to the ASZ (Figure 9). The meteoric waters circulate to the subsurface via steeply dipping faults of the ASZ to reach areas of anomalous heat flow where they obtain heat.

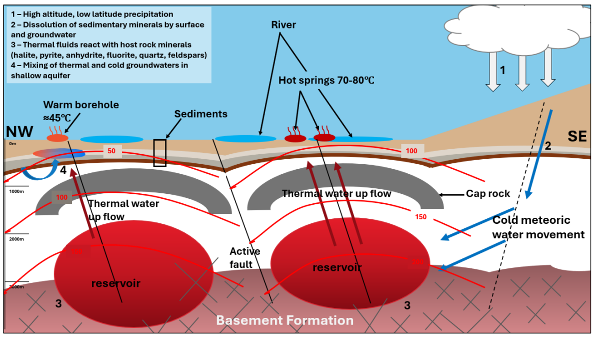

Figure 9: Proposed conceptual model of Elegu and Okidi geothermal areas. Orientation of this slice is shown by the thin red line in Figure 1.

7.2 Heat Source

Okidi and Elegu geothermal systems are likely to be extensional domain play type CV3 characterized by elevated geothermal gradient due to crustal extension and thinning and controlled by faulting and fracture zones (Moeck, 2014; Kato, 2024). Mantle elevated due to crustal extension and thinning transfers heat to the granitic basement rocks hosting the reservoir generating a high thermal gradient. This anomalous gradient facilitates the heating of meteoric waters circulating through deep faults or permeable formations.

7.3 Surface Manifestations

The heated fluids rise to the surface via conduits and deep faults to manifest as hot springs. Along the path, infiltration by cold groundwater may occur causing cooling as observed at warm springs and warm boreholes. Warm boreholes were drilled to a shallow depth and are likely to be tapping into shallow aquifers.

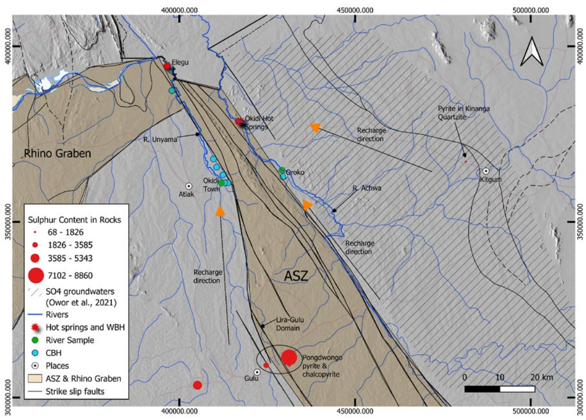

Figure 10: Areal conceptual model of Elegu and Okidi geothermal areas. Sulphur content (ppm) of Kinanga quartzite was not analysed (location only).

7.4 Host Rock

The host rocks which contain the geothermal reservoir are most likely fractured basement rocks e.g granites, granitic gneiss. High temperature fluids are stored within a network of interconnected fractures forming the geothermal reservoir.

7.5 Controlling Structures

The two geothermal areas are aligned along the NW-SE trending faults of the ASZ which control permeability and circulation of recharge fluids at depth. The main shear zone is accompanied by splay faults and parallel shear zones.

7.6 Resource Type and Fluid Type

Predicted reservoir temperatures for Okidi and Elegu are less than 180°C making them low to medium enthalpy resources. They are most likely liquid dominated with slightly alkaline Na-SO_4-Cl type and Na-HCO_3 type geothermal fluids respectively.

7.7 Reservoir Equilibrium State

A dynamic equilibrium likely exists where continuous recharge by meteoric water is heated and circulates throughout the system transferring heat by convection. Heated water is discharged at the surface as hot spring or into permeable zones in the subsurface.

8. CONCLUSION

Okidi and Elegu geothermal systems are fault controlled extensional type systems whose geothermal activity is controlled by faults of the Aswa Shear Zone. System permeability was likely increased by one or two possible scenarios that include a fault intersection, a trans-tensional pull apart zone or accommodation zone of splay faults. Geochemical analysis showed fluids from Okidi system are mainly of Na-SO_4-Cl type while Elegu fluids are mixed Na-HCO_3 type. High SO_4 concentrations in the thermal fluids are attributed to microbial pyrite oxidation. Solute geothermometry estimated temperatures of 120-170°C for Okidi and 90-120°C for Elegu. Mixing models applied to Okidi samples confirmed a temperature of 150-170°C. Aswa shear faults are also likely to control system recharge from low altitude regions in the SE, SSE and ESE of the resource areas. A conceptual model was proposed that includes high heat flow basement rocks as the heat source and host to the geothermal reservoir in inherent interconnected fractures.

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