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Geochemical investigation of geothermal power potential exploration of hot springs in South-western Tanzania

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Geochemical investigation of the power potential of Songwe geothermal prospect in south-western Tanzania within the East African Rift Valley was carried out. The thermal geochemistry was studied by collecting and analysing samples from 14 hot springs. The maximum discharge of thermal water occurs at the northern part of the prospect, at the bottom of a travertine cliff, 35 km above River Songwe level, at a rate of 26 kg/s ($T = 80^{\circ}\text{C}$, $\text{pH} = 6.7$). The southern springs are discharging between 30 to 50 m above river level. Degassed thermal water (CO_2 and H_2S) discharges at the river level and cause an increase of about 0.2°C above the ambient river water temperature (25°C in November), with a maximum spring temperature of 81°C ($\text{pH} = 6.9$). The lowest is Bwana Hutu (3 to 5 m above river level) thermal area where springs are degassing carbon dioxide gas with maximum temperature of 81°C ($\text{pH} = 7.6$). All springs in Songwe are depositing travertine except one spring degassing at (46.7°C , $\text{pH} = 6.8$). The total discharge rate of thermal fluid is between 45 to 75 kg/s with a median temperature of 60.5°C , and an estimated heat transfer of 10 MW. The results showed that the waters are of sodium-bicarbonate type, formed by steam heating below water table at the periphery of a geothermal system. The low predicted subsurface temperature of maximum 152°C (SiO_2 no steam loss geothermometer), compared to the earlier prediction of 270°C (unknown geothermometer) is due to great dilution of the deep fluid by percolating rainwater and encroaching ground water (July). This was indicated by high magnesium concentration in the samples of over 8 mg/l compared to deep fluid magnesium level of less than 1 mg/l and also by the chloride-enthalpy plot in which most of the data plotted along the dilution line. The total usable power potential is estimated to be 107 MWe.

Key words: Geochemistry, geothermometer, Mbeya prospect, geothermal power potential.

INTRODUCTION

Geothermal energy is a constant non-polluting source renewable natural heat that is emitted from within the earth's crust (McGee, 2007). It is used in a variety of diverse applications ranging from small domestic application to massive generation of electricity, which requires steam turbines (Rashid et al., 2012; Jaaskelainen, 2010). The type of conversion technologies include dry

steam, flash and binary type processes, which depend on the state of the fluid and its temperature (Jaaskelainen, 2010). Geothermal energy may be used directly for commercial, wastewater treatment or industrial applications (Vigrass et al., 1989; <http://www.paleoterran.com/journal/> 2012). Other uses include agricultural processes that require heat, and even residential conveniences such as

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home heating in the winter, heated pools, bathing and spas (Hepbasli, 2003; Alsuhaibani and Hepbasli, 2013; Reyes, 2010). Vigrass et al. (1989) reported that by heating the influent to 30°C on a year-round basis, the performance of activated sludge plant increases by 10 to 15% in terms of BOD₅ removal and approximately 30% for trickling filters. Low enthalpy geothermal energy resources are also used for recreational and cultural tourism (Pohatu et al., 2010; Carey, 2010; Neilson et al., 2010).

One of the major advantages of geothermal power is its renewability, unlike biofuels, whose reserves are rapidly dwindling. Jaaskelainen (2010) has reported that a substantial amount of geothermal power can be generated by steam turbine without substantial impact on the environment. Moreover, geothermal plants are not high value terrorist targets as an explosion would release only a small amount of steam (Jaaskelainen, 2010). Although geothermal energy is renewable, it is not readily available, and requires extensive drilling process and research before the plant is constructed (Mnzava, 2009). Kolditz et al. (2013) reported that access to groundwater reservoir by drilling is expensive and is associated with high exploration risks. The geographic region determines whether or not geothermal power will be feasible for a region, as it all comes down to how much heat is generated beneath the earth in that region. However, in recent years scientists have discovered that measurement of the helium isotope ratio in groundwater can be used to map the potential of geothermal areas (McGee, 2007). Moreover, hydraulic simulation has turned deep surface reservoirs into efficient heat exchangers or engineered geothermal systems (Kolditz et al., 2013).

With the recent increase in energy costs, rapid depletion of fossil fuel reserves, improvements in geothermal power investigation and generation technologies, geothermal power has been gaining popularity (Lund, 2007; Elhadidy and Shaahid, 2009; Calabro and Fazio, 2012). The world has a massive geothermal energy potential, but at the moment, only 25 countries are generating electricity from it (WEC, 2009; Huang, 2012). Wisniewski (2012) reported an increase of 12.5% global geothermal power capacity in seven years time from 8,000 MW in 1998 to 9,000 MW in 2005. By year 2010, the world's total geothermal generation capacity has exceeded 10,000 MW in 25 countries (Huang, 2012). In accordance with Huang (2012), United States of America, Phillipines, Indonesia and Mexico each has exceeded installed capacity of 950 MW. Indigenous renewable energy resources were estimated to contribute 84% of Iceland's primary energy, 66% of which was contributed by geothermal sources. Several countries, including oil-rich nations are planning to increase or introduce geothermal power generation. Reports indicate that Saudi Arabia, which possesses 20% of the world's proven petroleum reserve, and Iran,

another oil-rich nation, are prospecting for geothermal energy (Alsuhaibani and Hepbasli, 2013; Sharqawy et al., 2009; Abad et al., 2012).

East African countries are planning to dramatically increase electricity generated from 'hot rocks' by year 2020 to a challenging, yet achievable target of 1,000 MW, which is sufficient to meet power needs of about 3 million people (Science in Africa, 2003). Kenya, ranked 10th in the world, and Ethiopia, ranked 20th in the world, are the only two Eastern African countries in the world with installed geothermal power generation capacity (Huang, 2012). Reports from Kenya indicate that Government of Kenya is planning to increase its geothermal energy installed capacity of 198 MW in 2011 to 5,530 MW in 2030, which is over half of estimated geothermal potential of 7,000–10,000 MW (Kollikho and Rivard, 2013). Geothermal reserves in East Africa's Rift valley have a potential to provide an estimated 15,000 MW of power (US-EAGP, 2012), but potential of geothermal power in Tanzania is not adequately documented.

In Tanzania there are more than 15 locations with hot springs of temperatures greater than 40°C, which are found over and near the active rift segments with quaternary volcanism and over the Tanzanian (Archean) craton and its Precambrian surroundings (Figure 1). In southern Tanzania, in the northern extension of the Malawi Rift, about three prospects of high-intermediate temperature at Songwe, Kyela (Kasimulu and Mampulo) and Rungwe are indicated by the occurrence of hot springs. Songwe valley area is situated about 27 km west of Mbeya town and located between Latitude 8°50' S–8°56' S and Longitude 33°10' E–33°15' E. The geology of some part of the study area was studied by Spurr (1954), Brown (1959), McConnel (1972), Ebinger et al. (1989), Morley et al. (1992), Delvaux et al. (1992) and Delvaux and Hanon (1992). All these studies have established the surface geology, which consists of the Rift-related sedimentary basin is believed to have been formed by the three rifting episodes, the Permo-Triassic, the Cretaceous and the Cenozoic rift episodes (Delvaux et al., 1992). On studying the evolution of the Rukwa Basin, McConnel (1972) and Cahen et al. (1984) reported the basin is faulted into the Ubendian Tectonic domain. They further stated that this Tectonic basin, which forms the basement, is characterised by two facies, high-grade metabasic and meta-sedimentary sequences with intensive mylonitized shear zones. The Songwe basin is filled with a succession of sedimentary and volcanic rocks. The area was mapped by Brown (1959) during the regional mapping of Quarter Degree Square (QDS) 70SW. The hot springs are situated at the bottom of the wide gorge formed by River Songwe. All the springs rise through vents in the Pleistocene travertine limestone on the sides of the travertine cliff and at the bottom of the gorge. The hot springs are situated along a line followed by the river, running in a west-north-west direction (Spurr, 1954). The Songwe valley is bounded by a major fault to

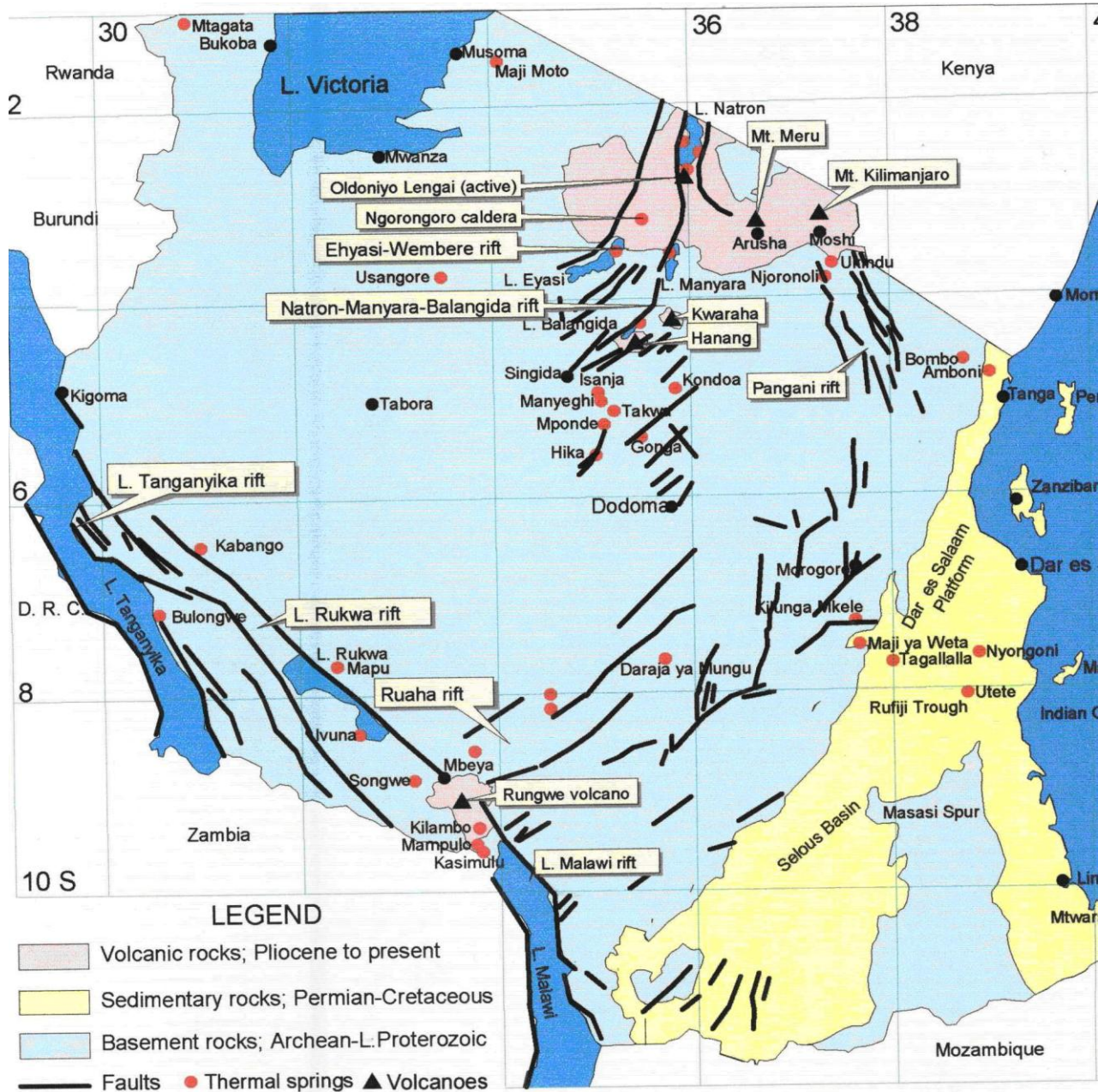


Figure 1. Geological map of Tanzania showing the locations of the geothermal prospects and the study area of South-western Tanzania (Songwe, Mampulo, Kasimulu and Rungwe).

the northeast, which is striking in a northwest-southeast direction while to the south-west, an escarpment bound it (Figure 1). Faulting has not been observed in the Karoo and Cretaceous rocks.

Tanzanian geothermal potential is estimated to be 650 MW (McNitt, 1982). A strong possibility of resumption of geothermal exploration programme in Tanzania in the near future is foreseen. The need to update major inferences drawn since the publication of a phase one reconnaissance survey (SWECCO-VIRKIR, 1982) have acted as a source of inspiration for presenting this case-

study of the most promising active hydrothermal system of South-western Tanzania along the African Eastern Rift Valley. Hochstein et al. (2000) reported that there are about 15 thermal areas with temperatures exceeding 40°C in Tanzania, but the largest prospect is that at Songwe River in Mbeya Region. Other notable attempts include more recent geochemical and geophysical investigation in South-western Tanzania covering Songwe, Rungwe and Kyela (Mnzava et al., 2004, 2006a, b). The objective of this research work is to estimate geothermal power potential of some hot springs in South-

western Tanzania.

MATERIALS AND METHODS

Sampling and examination of samples

Samples were collected from 15 locations in Songwe, Rungwe and Kyela of Mbeya prospect in south-western Tanzania (Figure 1) during dry season and at the end of rain season. At Songwe, sampling was possible in some springs, but impossible in deep fracture controlled springs and those springs that were very high up in the travertine limestone cliff. At Kyela sampling was done at Mampulo, Mwakalinga and Kasimulu while in Rungwe area, sampling was done at Kindandali, Ngungwisi and Makwehe. Sampling of both thermal and non-thermal waters within the study area was done using methods outlined by Arnorsson and Gunlaugsson (1975), Olafsson (1988) and Giggenbach and Goguel (1988). Four samples of one litre each for each source were sampled. Raw untreated for the determination of pH and conductivity, filtered untreated for the determination of anion, filtered and diluted and packed in plastic bottles for silica analysis and filtered and acidified with concentrated nitric acid to pH 2 for the determination of cations. Preservation of samples was done in order to retard the chemical and biological changes continuing after the samples are taken. Additional samples were later taken from some specific sources such as those with high temperature with high chloride concentration and less magnesium concentration.

Temperature of water was measured *in-situ* using thermometer. Electrical conductivity and pH were measured *in-situ* after cooling water to 25°C using pH meter (Orion) and electrical conductivity meter, respectively. Total alkalinity, HCO₃⁻, SO₄²⁻, Cl⁻ and hardness were measured titrimetrically in accordance with Standard Methods (1992). The examination of Na⁺, K⁺, Ca²⁺, Mg²⁺, B, Li were done using atomic absorption spectrophotometer in accordance with Standard Methods (1992). Total dissolved solids were measured gravimetrically after drying samples at 180°C and SiO₂ was determined using transmittance display photometer (640 nm) with calibration chart. Fluoride was measured using selective ion electrode (Orion) and gas chromatography was used to determine concentration of CO₂ and H₂S in accordance with Standard Methods (1992).

Degree of saturation of minerals in aqueous solution (SI)

Modelling was done with an aid of computer program to check if the minerals in the reservoir have attained equilibrium. Those indicating equilibrium were used in geothermometry to estimate subsurface temperatures and to construct mineral phase diagram in the reservoir showing minerals in equilibrium. The fluid-mineral equilibrium that is used in geothermometry to estimate subsurface temperatures in the study area was studied. The degree of saturation of minerals (SI), which gives an estimate of the fluid-mineral equilibrium state in aqueous solution, was determined using Equation 1.

$$SI = \log \left[\frac{Q}{K} \right] = \log Q - \log K \dots \dots \dots (1)$$

where Q is the ion activity and K is the equilibrium constants of the analysed ions to be calculated. This index is used for evaluation of the possibility of the co-existence of particular mineral assemblages in equilibrium in order to develop geothermometers for temperature prediction to suit our environment. It also helps to establish how the overall fluid chemistry can be quantitatively explained in terms of chemical equilibrium with minerals in the reservoir rocks.

Determination of ion activity Q

To calculate SI using Equation 1, activities and equilibrium constants of Na, K, Mg, Ca and SiO₂ on assumption that in dilute solutions, activities of dissolved constituents are about equal to the corresponding molalities and that in saline solutions, the molality of each species i (m_i) was multiplied by its activity coefficient (γ_i) to obtain the activity given by the Equation 2.

$$a_i = m_i \gamma_i \dots \dots \dots (2)$$

Activity coefficient for solutions with ionic strengths less than about 2 molal was calculated using an extended form of the Debye-Huckel (Equation 3).

$$-\log \gamma_i = \frac{Az_i^2 I^{1/2}}{1 + \frac{a}{a_i} BI^{1/2}} + bI \dots \dots \dots (3)$$

where z_i = ionic charge, I = ionic strength and A, B, a/a_i and b are constants. The coefficients A and B vary with temperature, and were determined to three decimal places from the standard tables in increments of 25°C from 100 to 350°C. The ionic strength is defined by Equation 4.

$$I = \frac{m_i z_i^2}{2} \dots \dots \dots (4)$$

Equation 5 was used to calculate I because in most hydrothermal waters I is approximately equal to the sum of m_{Na⁺} and m_{K⁺}.

$$I = m_{Na^+} + m_{K^+} \dots \dots \dots (5)$$

Values of a/a_i and z_i are listed in standard tables. Up to 250°C, b has values in the range of 0.03 to 0.05 when concentrations are up to 3 molal (Fournier, 1989). Substituting Equation 5 in Equation 3 results to Equation 6.

$$-\log \gamma_i = \frac{Az_i^2 (m_{Na^+} + m_{K^+})^{1/2}}{1 + \frac{a}{a_i} B(m_{Na^+} + m_{K^+})^{1/2}} + b(m_{Na^+} + m_{K^+}) \dots \dots (6)$$

RESULTS AND DISCUSSION

Observation and physical parameters

At the bottom of the travertine cliff in the northern part of the prospect about 35 km above river Songwe level, a maximum discharge of 26 kg/s of thermal water was recorded with a temperature of 80°C and a pH of 6.7. The southern springs discharge at lower level, about 3 to 50 m above the river level. Some degassed (CO₂ and H₂S) thermal waters discharge at the river level with a maximum temperature of 81°C and a pH of 6.9 causing

an increase of 0.2~2°C above ambient river water temperature (25°C in November). Simple field discharge assessment was carried out and a total discharge ranging between 47 to 75 kg/s was estimated with a median temperature of 60.5°C. The total heat transfer is approximately 10 MW.

The different surface discharge features of geothermal systems encountered in the field are:

- a) Diffused discharge: Thermal ground, steaming ground (Bwana Hutu area) and evaporation at a free water surface (e.g. water ponds).
- b) Direct discharge; warm and hot springs. These were encountered all over the study area localised. The discharge was approximately 2.5 to 10 Ls⁻¹ (estimation by simple field method calculations).
- c) Intermittent discharge; geysers was encountered at Songwe-Malonde in Mbozi.

Ion balance

Table 1 shows the results of the chemical examination of samples. The ion balance was done in order to check the reliability of chemical analyses and the neutrality of the samples. The sum of the product of molal concentration and valence of positive charged species was compared with the sum of the product of molal concentration and valence of negative charged species (Equation 7).

$$\sum_{cation} m_i z_i = \sum_{anion} m_i z_i \dots\dots\dots (7)$$

Where m is the molarity and z is valence charge of species i.

Essentially the milliequivalents [meq; millimolal concentrations (charge)] of each charged species in solution was calculated. In most hot spring waters the dominant ions are Na⁺, K⁺, Ca⁺², Mg⁺², Cl⁻, HCO₃⁻ and SO₄⁻². These cations and anions together with B and Li⁺ were analysed. Therefore,

$$m_{Na} + m_K + 2m_{Ca} + 2m_{Mg} = m_{CO3} + m_{HCO3} + 2m_{SO4} \dots\dots (8)$$

In the event that Equation (8) does not balance, then either the analysis is poor or all the important species have not been determined or the sources of the waters are of volcanic origin. An adequate ion balance is good to within 5%, using Equation 9.

$$\Delta \text{ charge } \% = \frac{\sum(cations + anions)}{|\sum cations| + |\sum anions|} \times 100 \dots\dots\dots (9)$$

Owing to the ion imbalance, the origin of water is

suspected to be Rungwe volcanic area.

The total dissolved solids varied from 276 mg/l at Songwe River to 3192 mg/l at Spring No. 6 located at Ilatire 2. About 64.3% of the samples have TDS values between 2000 and 2500 mg/l. Samples with concentrations above and below this range were 14.3 and 21.4%, respectively. The result points to a high temperature source.

Thermal water composition: The Cl-SO₄-HCO₃ ternary diagram

The three main anions present in geothermal waters are chloride, sulphate and bicarbonate. Chloride being the major anion for deep geothermal fluids is presumed to have concentrated from magmatic input and after leaching of minerals from the country rock. Chloride waters are normally encountered at the water table. Sulphate is the major anion in shallow geothermal fluids. It is formed when H₂S rises above the water table and become oxidised. The steam formed condenses to sulphuric acid. Bicarbonate anion is common in geothermal fluids, which form below the water table, and is derived from CO₂, which is released from deep fluid during ascent. Bicarbonate waters usually occur around the margins of an up flow zone. Both sulphate and carbonate waters are formed by steam heating, thus known as steam heated waters.

The most useful classification scheme of geothermal water based on their composition using Cl-SO₄-HCO₃ anions was used as a guide. The use of anionic components to distinguish waters is a convenient means of rapidly assessing water composition, as these are the most abundant solute components. Positioning of the data in mg/kg was done using Equations 10 to 12.

$$S = C_{Cl} + C_{SO4} + C_{HCO3} \dots\dots\dots(10)$$

$$\% Cl = \frac{C_{Cl}}{S} \times 100 \dots\dots\dots(11)$$

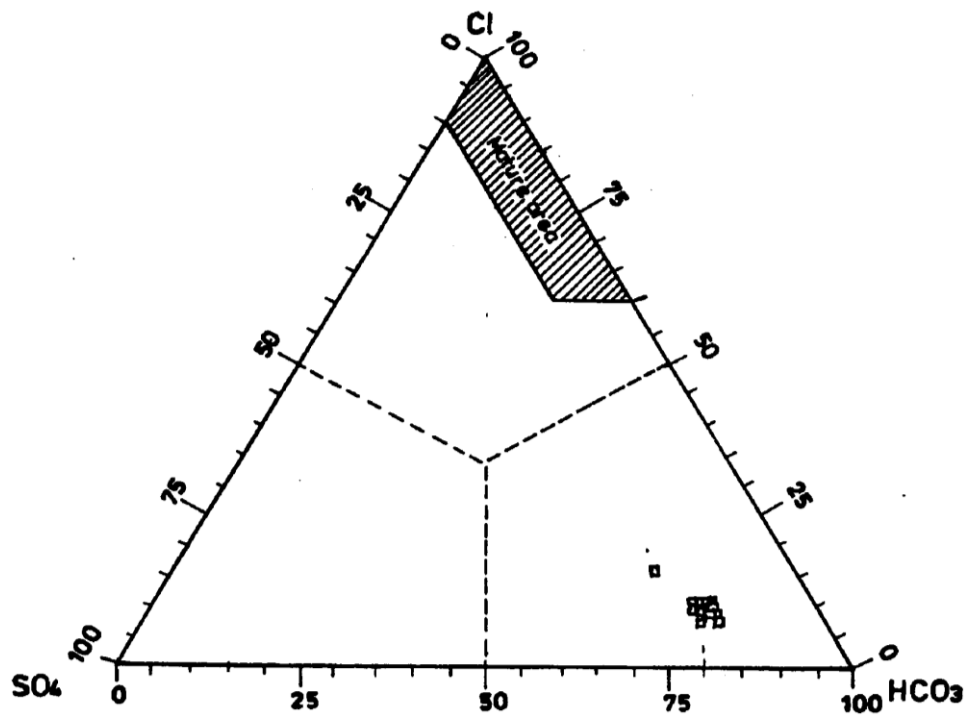
$$\% HCO_3 = \frac{C_{HCO3}}{S} \times 100 \dots\dots\dots (12)$$

Where S is the sum of the concentrations of (Cl + SO₄ + HCO₃) and C is their concentrations. The data was prepared from the original data (Table 1) and was plotted on the ternary as shown in Figure 2. From the results it is indicated that the thermal waters of Songwe Valley is of bicarbonate type, which is in line with earlier observation made by Hochstein et al. (2000).

Bicarbonate waters are normally associated with precipitation of dissolved solids and operational problems in hot water geothermal reservoirs. Development of

Table 1. Chemistry of Songwe Valley thermal discharge.

Spring name	Spring temperature (°C)	Chemical constituents (mg/l)											SiO ₂ T (°C)
		pH	K	Ca	Mg	Na	HCO ₃	Cl	SO ₄	B	Li	SiO ₂	
Na John	54.9	7.16	89.0	17.3	8.8	20.1	1780	270	190	31.1	0.86	2.4	-0.9
Ilatire 1	73.5	7.24	84.2	24.7	8.1	11.8	1720	280	184	30.0	0.90	112	144
Ilatire 3	80.3	7.93	86.8	47.3	8.4	9.2	1760	280	175	36.9	0.89	102	139
Songwe R. Springs	29.8	8.10	20.9	67.1	21.1	6.5	304	80	32	36.9	0.11	85	129
Ilatire 5	70.0	7.08	90.7	31.6	12.9	10.8	1780	275	180	40.8	0.88	129	152
Lower Na John	66.5	8.78	15.9	21.2	6.1	5.6	204	30	16	38.3	0.05	63	113
Songwe R. upstream	24.8	7.53	84.2	8.0	6.3	10.6	1760	290	170	38.4	0.91	120	148
Songwe R. downstream	24.9	8.79	16.5	17.8	6.1	5.4	244	25	20	40.2	0.05	16	55.4
Ilatire 4	74.0	7.30	94.8	12.1	6.8	10.8	1740	280	168	41.9	0.90	54	106
Bwana Hutu stream	50.0	8.50	94.0	17.4	5.6	19.0	1880	290	175	38.6	0.97	63	113
Bwana Hutu 1	81.0	7.63	92.5	12.2	7.6	19.1	1780	265	180	39.2	0.92	71	119
Bwana Hutu 2	46.7	6.81	97.8	40.3	8.0	11.8	1860	285	170	35.1	0.94	109	142
Mwalonde 1	70.5	7.08	10.4	47.1	20.6	10.4	1760	264	165	36.5	0.87	102	139
Mwalonde 2	73.7	7.14	10.4	26.4	13.9	11.1	1700	260	172	53.4	0.91	105	140
Mwalonde 3	67.4	7.17	10.6	31.2	16.9	41.6	1820	270	175	35.3	0.86	104	140

**Figure 2.** Ternary diagram of Cl⁻-SO₄²⁻-HCO₃⁻.

bicarbonate-rich geothermal fields may result into calcite scaling potential, which was evident at Songwe prospect. In systems dominated by volcanic country rocks, bicarbonate waters typically form on the marginal and subsurface region where CO₂ gas is absorbed and steam is condensed into cool ground waters. Sodium is generally the main cation since calcium carbonate (e.g. calcite) is not very soluble and potassium and

magnesium are fixed in clays. Bicarbonate waters are formed beneath the water table where they are weakly acidic as in spring No.10 of Mampulo; (pH is 6.6) and during the ascending process to the surface it increases the pH of the natural discharge to neutral or slightly alkaline due to loss of CO₂, (known as CO₂ flashing) as shown by other sources in the study area. Kruger (1976) have reported that geothermal waters rich in bicarbonate

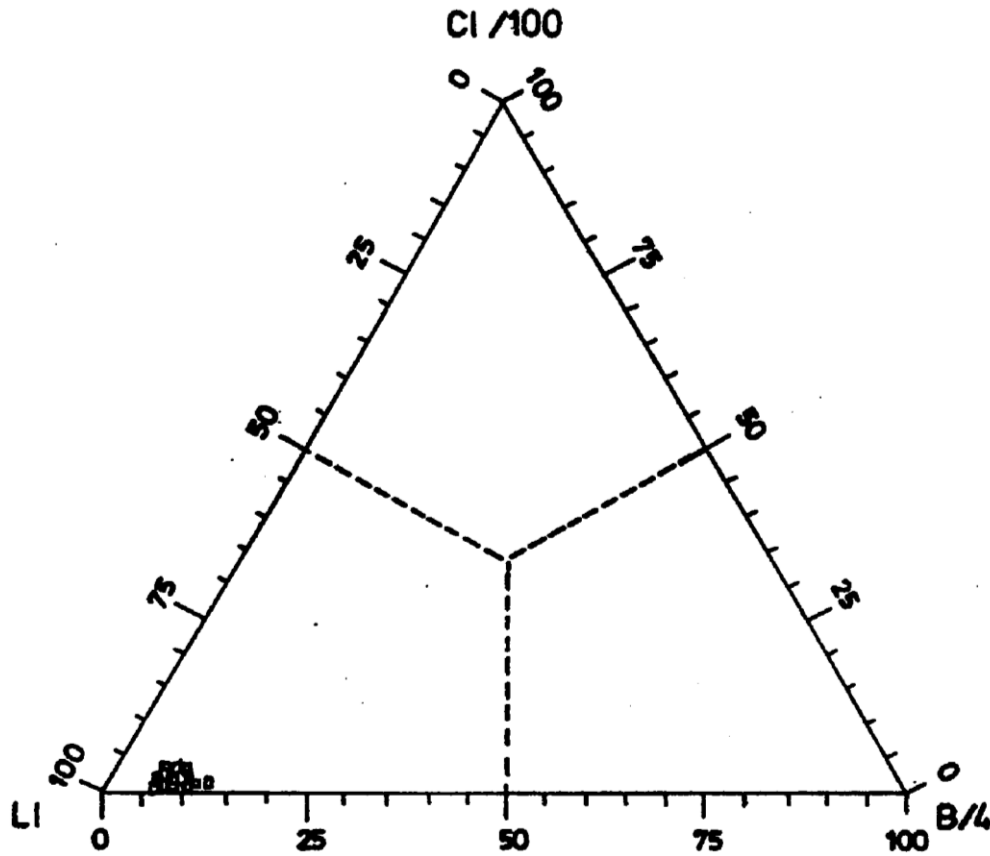


Figure 3. Ternary diagram of Cl-B-Li.

may cause severe problems associated with deposition of Calcium carbonate as a result of pressure reduction that causes release of CO_2 . A similar observation was reported by Reyes (2007) in New Zealand where a well rich in warm bicarbonate water ceased to allow flow of water because of deposition of carbonate.

The fluid original- Cl-B-Li ternary diagram

The relative proportion of Cl to B for fluid of similar origin is generally constant (Hochstein, 1982). Therefore, these two components were plotted against one another, to ascertain the origin of the fluids in the different springs (Figure 3). At temperatures greater than 400°C , Cl occurs as HCl and B as H_3BO_3 both of which are volatile and easily mobilized in steam of deep magmatic fluids. As the magmatic fluids rises to the surface, they cool slowly and the HCl is converted to NaCl through water-rock interaction while B may remain partly volatile in the steam phase. In contrast Lithium is probably incorporated into solution through deep rock dissolution on reacting with acid brines.

Due to the large difference in analytical values between Cl, Li and B, it required the use of scaling factors otherwise the data would have plotted close to the Cl

corner and compositional trends would not be apparent. Relative content of Cl and B were higher in comparison to Li suggesting either addition of the former two elements during or after the rock dissolution process or loss of Li, which seems unlikely as Li tends to remain in liquid as the magmatic waters, ascends. Therefore, results suggest that the source of the springs might be from systems closely associated to magmatic heat sources (Figure 4). These can be explained as products of rock dissolution by waters formed through absorption of high temperatures and pressure magmatic vapours in deeply circulating ground waters. These vapours may contain Cl and B in proportion to those of the rocks contacted by the ascending hot magmatic fluids.

The Na-K- $\sqrt{\text{Mg}}$ ternary diagram-Songwe

The ionic solute geothermometers based on Na-K and Na-K-Ca contents provide powerful tools for the evaluation of deeper conditions within a geothermal system. The Na-K- $\sqrt{\text{Mg}}$ Ternary diagram was used to distinguish between full equilibrated waters, partially equilibrated (including mixed) waters and immature waters. The positioning of the data was done using the input data from Table 1 and Equations 13, 14 and 15.

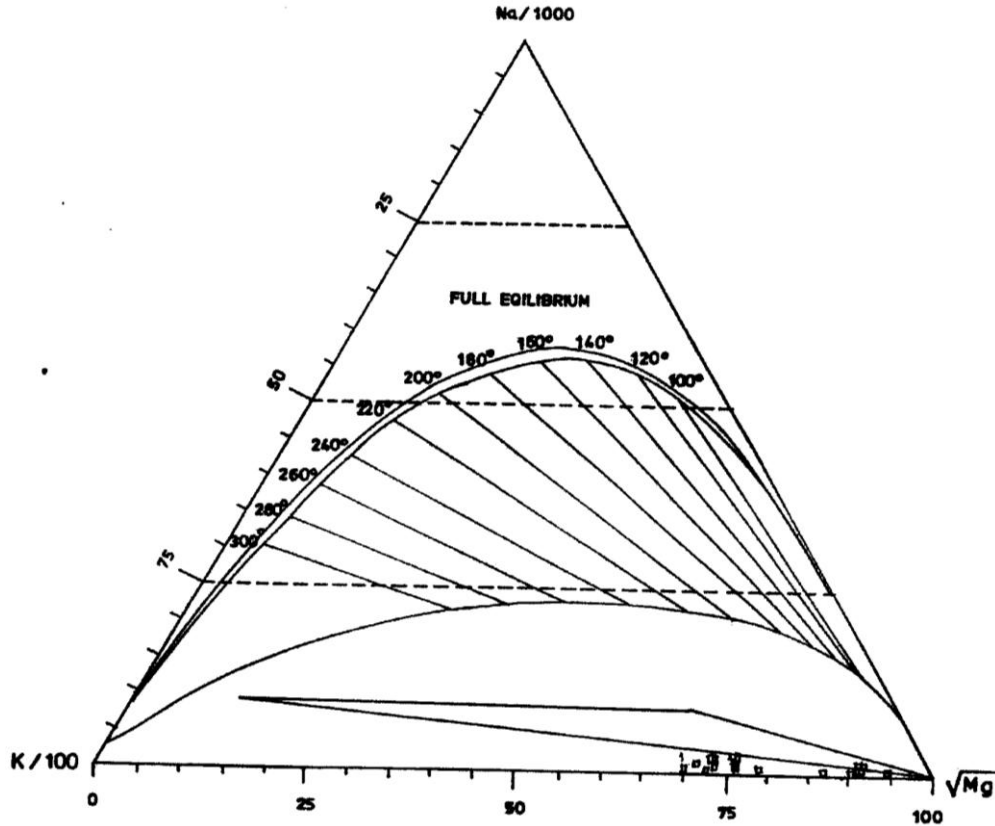


Figure 4. Ternary diagram of Na-K- \sqrt{Mg} .

Then the ternary diagram was plotted (Figure 4).

$$S = \frac{C_{Na}}{1000} + \frac{C_K}{100} + \sqrt{C_{Mg}} \dots\dots\dots(13)$$

$$\% - Na = \frac{C_{Na}}{10S} = \dots\dots\dots(14)$$

$$\% - Mg = 100\sqrt{\frac{C_{Mg}}{S}} \dots\dots\dots (15)$$

This was also used to distinguish waters that are suitable for the application of solute geothermometers (Giggenbach, 1986). Evaluation using this diagram also facilitated the delineation of trends and groupings among waters discharged. From these variations, the nature and intensity of processes affecting the rising hot fluids could be determined. However, in this case study samples were so much diluted with encroaching cold water and ground water during the month of July (end of rainy season). All the sources plotted in the immature water zone and they have high concentration of magnesium

(21.1 mg/l), which is an indication of dilution by ground water as deep fluids have magnesium concentration of less than 1.0 mg/l.

Influence of boiling and mixing on fluid compositions

This involved calculation of geothermal spring data to aquifer conditions. By using chemical data from geothermal springs of the study area, a more qualitative understanding of geothermal systems was developed. It was assumed that the geothermal system in the area is of a boiling one. The most complex hydrothermal system is a boiling one and recalculation of the fluid to reservoir conditions was done using steam fraction.

It is known that high temperature geothermal fluid rising rapidly to the surface through a fracture boils to produce steam and liquid. Non-volatile components such as silica and chloride remain in the liquid phase, whereas volatile components such as CO₂ and H₂S enters the steam phase. In this case an aquifer fluid at 260°C, rising to the surface and flashing to 100°C at 1 bar (abs) was considered (SWECCO-VIRKIR, 1982).

From the steam tables the following information was obtained: H_i 260_t = 1134.8 J/kg; H_i 100_t = 419 J/kg and

Table 2. The input data for chloride-enthalpy reservoir condition.

Spring name	Temperature (°C)	Cl (mg/l)	Y	HI	Hv	L	y.L	Hres	Cclres
Na John	54.9	270	0.307	230.2	2370	2140	679.4	910	184.4
Ilatire 1	73.5	280	0.307	297	2322	2025	643.0	940	191.2
Ilatire III	80.3	280	0.307	334.9	2308	1973	626.5	961	191.2
Songwe River springs	29.8	80	0.307	125.7	2430	2304	731.5	857	54.6
Ilatire V	70.0	275	0.307	293	2333	2040	647.7	941	187.8
Lower Na John	66.5	30	0.307	272	2346	2074	658.3	930	20.49
Songwe river upstream	24.8	25	0.307	104.8	2442	2337	741.9	847	17.1
Songwe river downstr.	24.9	290	0.307	104	2442	2338	742.2	846	198.1
Ilatire IV	74.0	280	0.307	313	2320	2007	637.2	950	191.2
Bwana Hutu stream	50.0	290	0.307	209.3	2382	2173	689.8	899	198.1
Bwana Hutu I	81.0	265	0.307	334.9	2308	1973	626.5	961	181.0
Bwana Hutu II	46.7	285	0.307	200.9	2387	2186	694.0	895	194.7
Mwalonde I	70.5	264	0.307	293.5	2333	2040	647.6	941	180.3
Mwalonde II	73.7	260	0.307	313	2321	2008	637.4	950	177.6
Mwalonde III	67.4	270	0.307	280	2333	2053	651.9	932	184.4
Bwana Hutu III	80.0	275	0.307	334.9	2308	1973	626.5	961	187.8

$H_v, 100_t = 2676 \text{ J/kg}$ in which H = enthalpy, subscripts l, v and t , refers to the liquid and vapour phases at specified temperature, t in °C. It was assumed that no heat is gained or lost by the fluid as it rises to the surface.

$$H_l, 260_t = x H_l, 100_t + y H_v, 100_t \dots \dots \dots (16)$$

Where x is the mass fraction of the initial fluid which remains as liquid at 100°C and y is the mass fraction that turns into steam at 100°C. Therefore from the mass balance of fluid Equation 17 is obtained.

$$y = \frac{H_l, 260_t - H_l, 100_t}{H_v, 100_t - H_l, 100_t} = \frac{1134.8 - 419}{2676 - 419} = 0.317 \dots (17)$$

This leads to enthalpy or heat balance equation, which is generally written as;

$$H_{reservoir} = (1-y) H_l + yH_v \dots \dots \dots (18)$$

Or

$$H_{reservoir} = H_l + y(H_v - H_l) \dots \dots \dots (19)$$

Cl is considered to be conservative constituent of the liquid phase assuming that Cl is not soluble in steam below 370°C. Therefore the chloride balance equation is similar to the heat balance;

$$Cl, 100_t = \frac{CCl_{reservoir}}{1 - y} \dots \dots \dots (20)$$

The calculated reservoir chloride concentration and enthalpy results are shown in Table 2 and its enthalpy-chloride diagram was constructed to assess the boiling and mixing situation and its resulting diluents (Figure 5).

Geothermometry

Subsurface temperature was estimated from the assumed mineral-equilibrium, which was put into consideration on selecting the geothermometer equation. Table 3 shows that the Na/K geothermometer registered very high unrealistic temperatures. This is because it is normally applied to high temperature reservoir of chloride waters as below 100°C the Na/K ratio of waters tends to depart from equilibrium controlled by feldspar. The result further confirms that water is of bicarbonate nature. The Silica and K/Mg geothermometers registered reasonable temperatures although they are very low compared to the predicted temperature of 270°C (SWECO-VIRKIR, 1982). The result of geothermometry indicated that the spring water temperature ranges between 55 ~ 152°C. The low temperature encountered is probably due to heavy rains that caused dilution of the samples by percolating into ground waters, which was further confirmed by high concentration of magnesium of 8 to 21.1 mg/l compared to hot springs magnesium concentration of less than 1.0 mg/l.

Estimation of potential power

The potential power was calculated from anomalous heat stored in the rocks, in the liquids and by the vapour. The

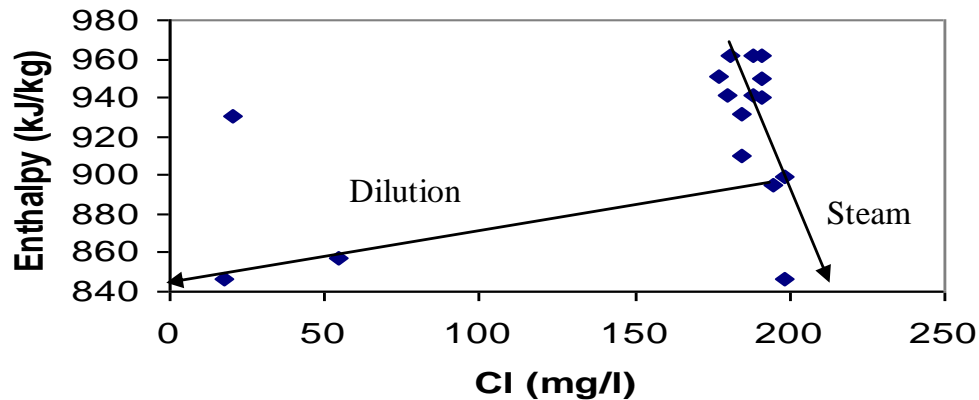


Figure 5. Chloride-enthalpy reservoir condition.

Table 3. Subsurface temperature prediction using the SiO_2 ; K/Mg and Na/K geothermometer.

Sample No.	Concentrations (mg/l)				Geothermometer temperature ($^{\circ}\text{C}$)		
	SiO_2	K	Na	Mg	SiO_2	Na/K	K/Mg
1	2.4	89.0	20.1	8.8	-0.9	987	126
2	112	84.2	11.8	8.1	144	1279	126
3	102	86.8	9.2	8.4	139	1521	126
4	85	20.9	6.5	21.1	129	847	75
5	129	90.7	10.8	12.9	152	1411	121
6	63	15.9	5.6	6.1	113	802	83
7	120	84.2	10.6	6.3	148	1359	130
8	16	16.5	5.4	6.1	55	827	84
9	54	94.8	10.8	6.8	106	1449	132
10	63	94.0	19.0	5.6	113	1043	135
11	71	92.5	19.1	7.6	119	1033	130
12	109	97.8	11.8	8	142	1397	131
13	102	10.4	10.4	20.6	139	521	59
14	105	10.4	11.1	13.9	140	508	63
15	104	10.6	41.6	16.9	140	320	62

details of the calculations are available elsewhere (Mnzava, 2009). The total usable energy potential usable energy of Songwe was then converted to power potential by taking into account the overall efficiency conversion factor and recovery factor, which is controlled by the efficiency of naturally induced recharge (hydrology and permeability structure outside the reservoir), permeability structure of the reservoir and fluid characteristic. From the calculations, the power potential of Songwe prospected was estimated to be 107 MWe.

Conclusions

Results of this work reveal that Songwe valley thermal waters are of Sodium-bicarbonate type, formed by steam heating at the periphery of a geothermal system. The reservoir of the steam is not within the studied area, but

the thermal waters travel through hidden fractures and show as surface manifestation at the toe of long distance fractures. From the huge deposited travertine (50 million tons) and the on going deposition of calcium carbonate at a rate of 5 g/s, it indicates that the reservoir feeding the spring must be big enough to account for this phenomenon. The chloride enthalpy and the chloride-temperature plots both indicated some boiling and cooling in the supposed reservoir and along the shallow reservoir. The total dissolve solids of over 2,000 mg/l point to a high temperature source. The power potential of Songwe prospected was estimated to be 107 MWe.

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