



GEOCHEMISTRY OF THERMAL WATER FROM THE THEISTAREYKIR GEOTHERMAL FIELD IN NE-ICELAND COMPARED TO THAT OF THE GEOTHERMAL PROSPECTS IN NW-RWANDA

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ABSTRACT

Geochemical methods were applied to the Theistareykir field in NE Iceland and the geothermal prospects in NW Rwanda. The results were then compared. Theistareykir was subjected to production drilling a decade ago, while in NW Rwanda, exploratory drilling started in August 2013. In Theistareykir field, Wells ThG-2, ThG-3, ThG-4 and ThG-5b discharge the characteristic enthalpy of a mixture of liquid and vapour (917 - 2661 kJ/kg). The discharged fluid was classified as mature Na-Cl-HCO₃ water and the maximum subsurface temperature calculated by the WATCH programme was 300°C. The chemical composition of the wells and warm springs suggests the presence of more than one aquifer drawing fluid from a single base reservoir; warm springs are the result of super-heated shallow water. When boiled, the deep liquid becomes super-saturated with amorphous silica; calcite saturation has been reached in most wells.

The geochemistry of the warm springs in the geothermal prospects in NW Rwanda suggests that the water is Na-HCO₃ water that has not attained full equilibrium. The thermal water might be steam heated groundwater, not necessarily reflecting subsurface properties.

Both in the Theistareykir field and the geothermal prospects in NW Rwanda there are warm springs on the surface which do not necessarily reflect the deep reservoir properties. Their presence simply indicates that the prevailing reservoir of the geothermal system is composed of many aquifers, some shallow, others deep.

1. INTRODUCTION

Geochemistry has a key role in the geothermal industry from earlier investigations, to utilization, and through development. Its application is only meaningful by assuming that the natural geothermal fluid arising to the surface preserves the signature of the deep subsurface where it formed. Most chemical species in aqueous solution are in equilibrium with their host rock minerals. As thermal fluid mines heat from the rock reservoir and the equilibrium is said to be temperature dependent, so it is possible

to predict the reservoir temperature based on the chemistry of the fluid collected at the surface. In the initial stages of surface investigations, geochemistry gives information on the sub-surface temperature with the help of geothermometers. Geochemistry is used for the classification of geothermal water and for the location of areas with enhanced permeability, by measuring carbon dioxide gas fluxes and performing radon counts. The origin of the fluids can be traced by analysing the fluids and looking into the composition of conservative constituents or isotope ratios. The geochemical data obtained during the production phase are used to predict the future response of the reservoir due to pressure decline, production load, boiling and recharge. Geochemical data are also used to forecast naturally occurring problematic geothermal processes such as scaling, corrosion and cooling of geothermal systems (Arnórsson, 2000). In this report, geochemical data from wells and hot springs in the Theistareykir geothermal field, NE Iceland, and some hot and warm springs in the NW-Rwanda geothermal areas are reviewed and interpreted to evaluate the surface and deep geothermal waters, mineral equilibrium conditions, and to estimate the subsurface temperatures. The results from the two geothermal fields are then compared.

Theistareykir is one of the high-temperature geothermal systems in Iceland situated in the northeast. This field has been subjected to several geothermal surface surveys and exploration drilling. Based on the outcomes of the surface studies, Ármannsson et al. (1986) presented a conceptual model of the Theistareykir field and divided it into five sub-areas out of which three are suitable for further geothermal development. The ongoing plan is to set up a geothermal plant of 90 MW electrical power by 2015 in the area. Four water samples from discharging wells and 2 from discharging springs were used in this study to characterize the chemistry of this field.

The northwest part of Rwanda is believed to host a substantial geothermal resource for generating economically viable electrical power. Yet, its development is still at an early stage. After extensive surface investigations, it was divided into three prospects, namely Karisimbi, Kinigi and Gisenyi. Exploration drilling started in the Karisimbi prospect in 2013 and is still going on. The drilling results will be used to conceptualize the reservoir regime that governs the geothermal system. Six samples from hot, warm and cold springs were selected to study this area.

The purpose of this paper is to apply geochemical methods to the results obtained from drilling and the information gained from surface springs to describe the properties of the deep aquifers. Theistareykir is a geothermal field where surface water properties do not reflect the reservoir conditions, as has been proven through the drilling results. Drilling was initiated at Theistareykir based on the results of studies on fumaroles. By comparing Theistareykir's characteristics to the geothermal prospects in NW Rwanda, where only information from surface water is available, the Theistareykir experience can lead to a better understanding of the reservoir properties of the geothermal system in Rwanda.

2. BACKGROUND OF THE GEOTHERMAL FIELDS STUDIED

2.1 The Theistareykir geothermal field NE-Iceland

Geological studies at Theistareykir have been carried out by several authors but the results were summarized by Gautason et al. (2010). Theistareykir is a high-temperature geothermal system situated in NE-Iceland (Figure 1). It lies in a fissure swarm some 25 km north of Lake Mývatn in NE-Iceland. The intense volcanic activity is very pronounced in the centre of the system, yet a true caldera structure has not developed. The most active parts of the area are related to active fractures which increase permeability and enable geothermal fluids to circulate and reach the surface. The bedrock in the area is divided into hyaloclastite ridges formed by subglacial eruptions during the Ice Age, interglacial lava flows, and recent lava flows (younger than 10,000 yrs), all of which are basaltic. Acidic rocks are found on the western side of the fissure swarm, originating from subglacial eruptions up to the last glacial period. Rifting is still active in the fissure swarm.

Geothermal interest in the Theistareykir area, as presented by Ármannsson (2012a), dates back several centuries to the mining of sulphur that was used for the fabrication of gun powder for the Danish king. Surface exploration started in 1972-1974, and a major geothermal assessment was carried out in 1981-1984. From 1991-2000, the area was occasionally monitored.

The findings of the surface exploration showed that the area has a reservoir of good permeability. Calculated heat loss and geothermometers were used to estimate the temperature of the aquifer and it was found to be at least 280°C. The recharge zone was located in the southeast, and the origin of the fluid is probably far to the south (Ármannsson et al., 1986; Ármannsson 2012a). The results of surface exploration in the Theistareykir area suggest that it can be divided into 5 distinct sub-areas (Figure 2), of which three (A, C and D) are suitable for drilling.

Based on the drill sites suggested by Gautason et al. (2000), the first well, Well ThG-1, was drilled in area C in the autumn of 2002 to a depth of 1953 m, with a casing to 614 m depth. The major inflows are at 620-640 m depth and 1620-1640 m depth. The measured enthalpy at the surface was 2180 kJ/kg and the total flow from the well was 16-17 kg/s. The calculated steam fraction at depth at 280°C was 0.611. In 2003, the second well, Well ThG-2, was drilled to 1720 m depth. This well made drilling a challenge with loss of circulation at several different depths. Extreme loss of circulation was encountered at 260 m depth, and inferred a powerful aquifer. In 2006, Well ThG-3 was drilled to a depth of 2659 m and the maximum temperature recorded was 380°C. Its flow oscillated with enthalpy varying from about 1600 to 2600 kJ/kg, but approached the higher value with time and eventually settled as a high enthalpy steam well, giving 10-12 kg/s of high temperature steam. In 2007, Wells ThG-4 and ThG-5 were both drilled directionally from the same well pad as Well ThG-1. The first one is a high enthalpy steam well with a steam flow of 30 kg/s of high temperature steam, but well ThG-5 is a low enthalpy well, similar to well ThG-2, with a large liquid water flow. In 2008, Well ThG-5 was redrilled as Well ThG-5b under



FIGURE 1: Location of Theistareykir geothermal field in NE-Iceland (modified from Georgsson et al., 2005)

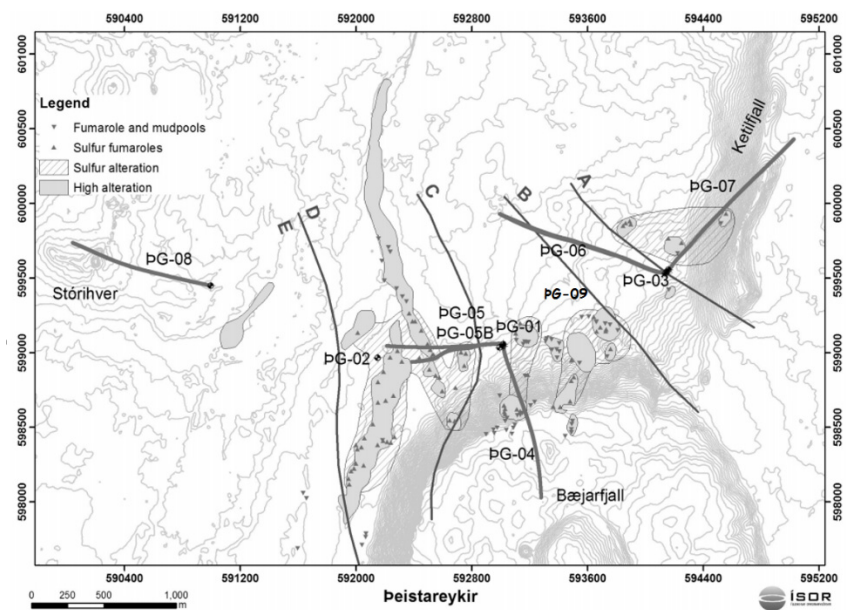


FIGURE 2: Location of deep wells and division of Theistareykir into five sub-areas (from Óskarsson et al., 2013)

a sharper angle and Well ThG-6 was drilled directionally from the well pad of Well ThG-3. The maximum temperature in Well ThG-5b was 300°C and 312°C in Well ThG-6 with respective enthalpies of 1485 and 2663 kJ/kg. Well ThG-7 was drilled in 2011 to a depth of 2509 m, with the highest measured temperature of 292°C. The enthalpy is about 2400 kJ/kg. Its isotopic characteristics suggest that it may produce from a different reservoir than the other wells in the area. Well ThG-8 was drilled in 2011, too, to a depth of 2503 m; it proved to be cool and has not been discharged. The latest is Well ThG-9, drilled in 2013 to a depth of 2194 m; its highest measured temperature was 338.5°C, with an enthalpy of about 2600 kJ/kg. Due to a short discharge period, representative samples have not been obtained (Óskarsson et al., 2013). Chemical compositions of ThG-2, ThG-3, ThG-4 and ThG-5b well fluids are discussed in this report as well as data from two warm springs. The current plan of Landsvirkjun (Iceland's National Power Company) and Theistareykir Ltd. (a jointly-owned municipal development company) is to build a geothermal power plant, with an electrical power capacity of 90 MW, at Theistareykir in two stages, starting in mid-2015.

2.2 Geothermal prospects in NW Rwanda

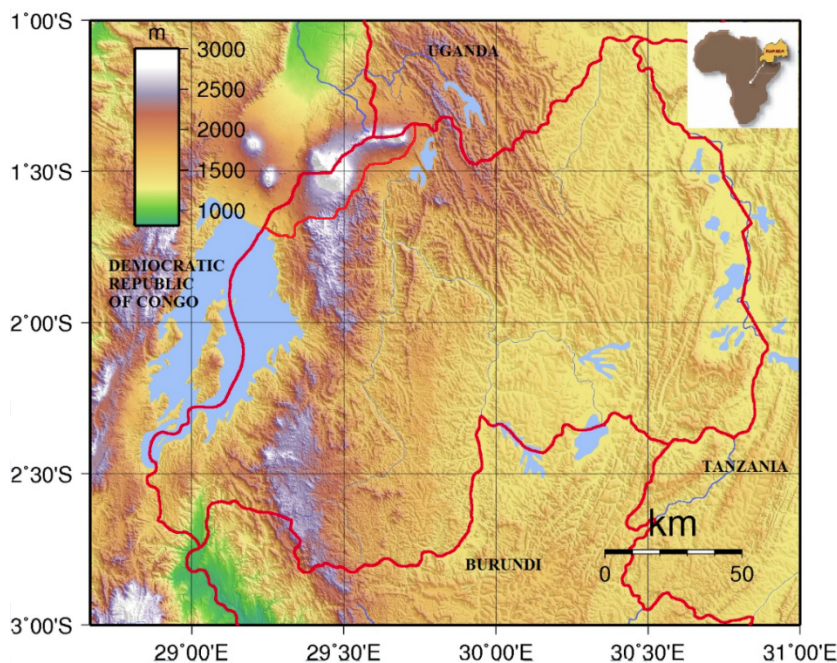


FIGURE 3: Topographic map showing the location of Rwanda and the geothermal area in the northwest

The geothermal prospects in NW-Rwanda (Figure 3) lie on the slopes of the Volcano National Park (VNP) and cover an area of 600 km², comprising 5 Strato volcanoes, i.e. Karisimbi, Bisoke, Sabyinyo, Gahinga and Muhabura, dating from the Quaternary period. Those massive volcanoes are a part of the Virunga Volcanic Range that forms a transverse chain in the western branch of the East African Rift (EAR). Those volcanoes were not active in historical time. Yet the Karisimbi volcano, the highest in the Virunga Volcanic Range with an elevation of 4507 m above sea level, is located approximately 22 km from

Nyiragongo and 30 km from Nyamuragira, both volcanoes in the eastern DRC that erupted in 2002 and 2010, respectively.

The geology of the geothermal prospects in NW-Rwanda, as well as the geology of the western branch of the EAR in general, is characterized by the abundance of potassic alkaline rocks that consist of basanites, leucitites, nephelinites, K-mugearites, K-benmoreiites and K-trachytes and other intermediate lavas in the Virunga area (Omenda, 2011). The geological setting consists of granite, migmatites, gneisses and mica schists of the Paleoproterozoic Ruzizian basement, overlain by the Mesoproterozoic Kibaran belt. The Kibaran belt, composed of folded and metamorphosed sediments, mainly schist and quartzite intruded by granite, covers most of Rwanda (BGR, 2009).

The geothermal prospects in NW Rwanda do not display many conventional surface geothermal manifestations. The thermal areas of Gisenyi and Karago are the only places where hot springs discharge water at the surface at 73 and 64°C, respectively. There is also a large amount of carbon

dioxide discharged through cold water springs in several places in both the Karisimbi and Kinigi prospects. Evidence of a large amount of carbon dioxide discharged in the past is expressed in the form of thick deposits of travertine exposed close to some springs in Musanze. However, the lack of surface manifestations does not mean a lack of potential geothermal conditions at depth. This is particularly true where an overlying non geothermal groundwater horizon masks the geothermal system. Where the top of a geothermal system is intersected by a large cold water aquifer, the heat will be swept down. Therefore, either no evidence of the geothermal system will appear on the surface, or large-volume warm springs may appear at large distances from the source (Gupta and Roy, 2007).

Reconnaissance surveys for geothermal energy in Rwanda were carried out in the 1980s, mapping areas of geothermal potential. Two prospective areas (Figure 4, associated with the Western Branch of the East African Rift), were identified and these comprise: the prospects in the northwest that are related to the Virunga volcanic chain, and the Bugarama prospect in the southwest of the country. Gisenyi and Mashuza hot springs, with surface temperatures of 73 and 53°C, respectively, were mapped as natural occurrences of surface manifestations. Intense exploration in the northwest area, which lies on the slope of the VNP from Lake Kivu in the west to Lake Ruhondo in the east, commenced in 2006. Since then, quite a number of geochemical, geophysical and geological investigations have been carried out in the above mentioned prospect and later led to the demarcation of the above field into 3 prospects, namely Karisimbi, Kinigi and Gisenyi, based on their developmental ranking (Figure 4). In early 2013, a geothermal review meeting was held in Kigali with the aim of integrating all existing data on the northwest prospect into one refined conceptual model. The data concerned was collected from the field in 2009 by the Kenya Electricity Generating Company (KenGen), and in 2011 by the Institute of Earth Science and Engineering (IESE) from New Zealand and KenGen (Mariita, 2010; Shalev et al., 2012). The outcome of this meeting was the siting of 3 geothermal exploration wells in the Karisimbi prospect, based on the conceptual model while

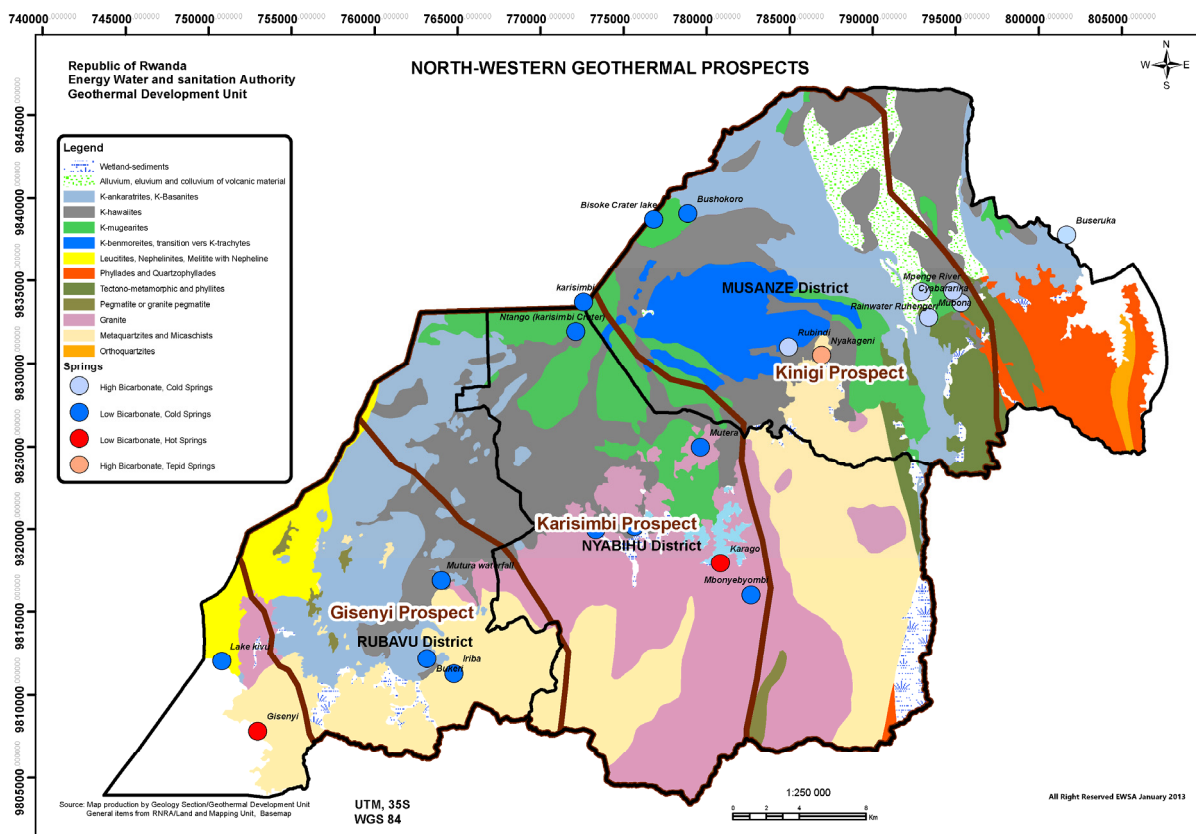


FIGURE 4: Geological map of geothermal prospects in NW-Rwanda

considering environmental aspects and infrastructure access. In mid-July 2013, Rwanda started drilling the first exploration wells (3 km deep) in the Karisimbi prospect and, hence, joined Kenya and Ethiopia in promoting the green and renewable energy resource in the region.

3. THERMAL WATER COMPOSITION IN THEISTAREYKIR AND NW-RWANDA

3.1 Thermal water composition in the Theistareykir field

The analytical data used in this report (Table 1) to classify the thermal water in the Theistareykir field consist of four composite samples from discharging wells (ThG-2, ThG-3, ThG-4 and ThG-5b) obtained from ÍSOR's database and two samples from warm springs from Ármannsson et al. (1986). Sampling and analysis were carried out by ÍSOR in conformity with sampling procedures described by Ármannsson and Ólafsson (2006). The wells discharged at the characteristic enthalpy of a mixture of liquid and vapour. Excess enthalpy for a discharging well is caused by boiling and phase segregation, explained in the following section. The water composition shows that Wells ThG-2 and ThG-5b tap fluid from a different aquifer than the rest of wells. The warm spring water is shallow steam heated groundwater.

3.1.1 Fluid aquifer assessment

After the collection of both water and steam samples with the aid of a Webre separator and recording the separation pressures, the steam fraction (water/steam ration) was calculated from the well discharge enthalpy. The aquifer fluid composition from wet-steam well data was assessed in two scenarios. In the first one, the well was considered to be a thermodynamically isolated system (no mass and heat transfer). In this case, only liquid water exists in the aquifer and the first level of boiling occurs within the well. The enthalpy of the total well discharge and its composition is the same as that of the water entering the well. Such situations are not always the case. When extensive boiling starts in a well's producing aquifers, both the discharge enthalpy and the total discharge composition may depart from those of the aquifer fluid. Under such circumstances, specific models are needed to connect well discharge and aquifer fluid composition (Arnórsson and Stefánsson, 2005).

The second scenario, in which the fluid is not regarded as an isolated system, may either be considered closed (heat is not conserved) or open (neither heat nor mass is conserved). In the former, the enthalpy is not a conserved quantity. Excess enthalpy (the discharge enthalpy is higher than that of liquid water at the aquifer temperature) would be produced by conductive heat flow from the aquifer rock to the fluid. In the latter, excess discharge enthalpy could result from the segregation of the flowing water and the steam in the aquifer. Difficulties in evaluating the relative importance of processes that result in excess discharge enthalpy lead to uncertainties in the calculation of the chemical composition of the aquifer fluid based on analytical data on water and steam samples collected at the wellhead (Arnórsson and Stefánsson, 2005; Arnórsson et al., 2007).

$$X = \frac{h^t - h^l}{h^v - h^l} \quad (1)$$

where X = Steam fraction;
 h^t = Total enthalpy of the fluid entering the well (kJ/kg);
 h^v = Enthalpy of vapour phase (kJ/kg); and
 h^l = Enthalpy of liquid phase (kJ/kg).

The steam fraction X is then used to calculate the deep liquid composition by using the following mass balance equation:

To calculate the steam fraction the Equation 1 is used:

$$C_i^t = C_i^v X + C_i^l(1 - X) \tag{2}$$

where C_i^t = Total concentration;
 C_i^v = Concentration in the vapour phase;
 C_i^l = Concentration in the liquid phase; and
 i = Chemical component of interest.

Some speciation and reaction path programs have been developed to compute concentrations of all chemical species present in deep aquifers. Among them are the WATEQ, PHREEQE, SOLVEQ and WATCH series. The last one was used in this report for the above mentioned purpose. WATCH is a computer programme that calculates the fluid aquifer composition based on the chemical analyses of samples collected at the surface and a reservoir temperature that may be arbitrary, measured or due to a suitable geothermometer. It computes the initial concentration of the chemical species present in the aquifer before they start ascending to the surface. Thus, it is possible to predict which minerals are likely to form or not from the knowledge of log Q (reaction quotient) and log K (equilibrium constant) values, calculated by WATCH. The programme gives two options for simulating the composition of aquifer fluids, i.e. by conductive cooling or boiling. The WATCH (version 2.4) technique was originally developed by Arnórsson et al. (1983), but the latest version is described by Bjarnason (2010).

3.1.2 Classification of geothermal water

It is useful to classify geothermal water before subjecting it to geochemical methods. The reason is that the water may not satisfy the premises of the geochemical computations. There are two common ways of classifying geothermal water, i.e. by the use of the Cl-SO₄-HCO₃, and the Na-K-Mg ternary diagrams (Giggenbach, 1991). The main purpose of this classification is to assess whether the sub-surface temperature can be predicted by the use of solute geothermometers. Geothermometers provide conclusive information if applied to what is denoted as “mature waters” that have reacted with bed rock minerals and reached equilibrium with them. They are characterized by high Cl concentrations compared to those of SO₄ and HCO₃. Cl is a conservative element that does not take part in mineral deposition and dissolution equilibria in geothermal fluids. Chloride-rich waters are generally found near the up-flow zones of geothermal systems. High SO₄ steam-heated waters are often encountered over the more elevated parts of a field. This diagram can be also used to assess possible mixing of groundwater and geothermal fluid as the degree of separation from the Cl corner towards the HCO₃ corner is the result of interaction of the CO₂ charged fluids at lower temperatures (Arnórsson, 2000).

TABLE 1: Representative chemical composition of wet-steam well discharges and springs in the Theistareykir high-temperature

Sample	Sample no	SP bar-g	h kJ/kg	Cond mS/cm	Liquid phase										Vapour phase							
					CO ₂ ppm	H ₂ S ppm	B ppm	SiO ₂ ppm	TDS ppm	Na ppm	K ppm	Mg ppm	Ca ppm	F ppm	Cl ppm	SO ₄ ppm	CO ₂ ppm	H ₂ S ppm	H ₂ %	N ₂ %	CH ₄ %	
ThG-2	20040276	6	917	636	66.1	29.7	0.53	380	750	139	14.5	0.003	0.83	0.73	43.7	40.6	2470	176	4.95	90.24	2.9	
ThG-3	20070023	25	1943	892	13.6	29.8	2.22	747	1258	166	41.2	0	1.34	0.76	225	5.53	1330	1177	94.89	4.36	0.58	
ThG-4	20080095	15.7	2661	432	24.4	26.5	3.95	663	978	76.1	17.1	0.019	0.22	1.42	88.3	3.22	155	820	94.38	5.47	0.04	
ThG-5b	20080503	15.3	1485	580	20.7	45.6	0.74	718.5	1027	120	30	0.002	0.37	1.07	49.3	18.3	4205	394	21.7	76.02	1.12	
V-1	19820630				191	0.1		104	400	76.3	7.48	11	49	0.1	9.3	105						
V-1					56.01	0.1		35.5	124	7.45	0.63	5.22	12.1	0.06	13.5	5.01						

SP = Sampling pressure; h = Enthalpy; ThG = Well; V = Spring

In the Theistareykir field, the samples from the warm springs exhibit bicarbonate waters. They plot in the peripheral waters zone, as shown in Figure 5. The presence of Mg in the springs indicates that they result from a mixture of thermal water and groundwater (Figure 6). Water samples from the wells plot at equilibrium and may be classified as Cl waters, except for the samples from Well ThG-2 which has HCO₃ water. The substantial HCO₃ concentration in the well water suggests that the water may derive from CO₂-rich steam condensing or mixing with water. This is sometimes the case with old geothermal waters or on the peripheries of geothermal areas in outflows. Such waters are commonly at equilibrium and may be used to predict subsurface properties (Ármannsson, 2012b).

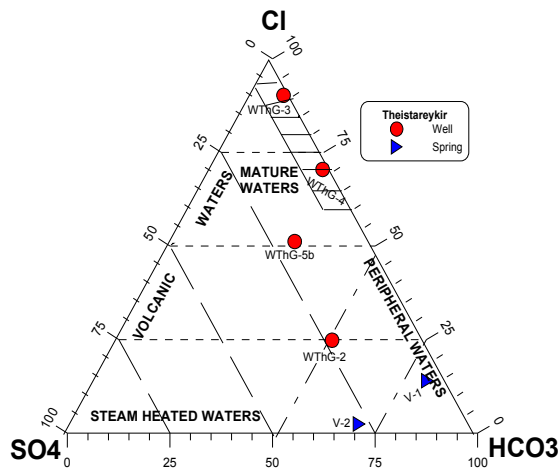


FIGURE 5: Cl-SO₄-HCO₃ ternary diagram for selected samples from the Theistareykir field

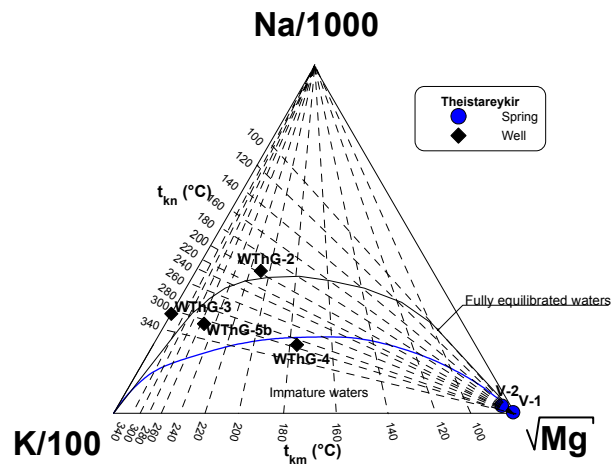


FIGURE 6: Na-K-Mg equilibrium diagram for Theistareykir water samples

3.1.3 Subsurface temperature estimation

Geothermometry is a technique used to predict sub-surface temperature in geothermal systems. It is based on the assumption that there is a temperature dependent equilibrium of the fluid in the aquifer with the rock for a given chemical or isotope composition that has been reached. A large number of geothermometers has been developed by several authors; the most used ones are the silica (quartz and chalcedony), Na/K and Na-K-Ca geothermometers (Arnórsson, 2000). The reservoir temperature was estimated by the help of WATCH and below there is a list of the geothermometers used in this report:

Chalcedony geothermometer, 20-330°C (Arnórsson et al., 1983):

$$t^{\circ}C = \frac{1112}{4.91 - \log S} - 273.15 \quad (3)$$

Quartz geothermometer, 20-330°C (Fournier and Potter, 1982):

$$t^{\circ}C = \frac{1309}{5.19 - \log S} - 273.15 \quad (4)$$

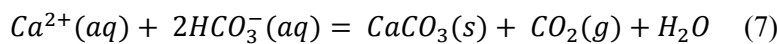
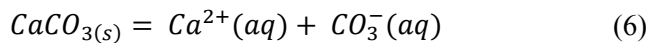
Na/K geothermometer, 25-250°C (Arnórsson et al., 1983):

$$t^{\circ}C = \frac{993}{0.993 + \log(Na/K)} - 273.15 \quad (5)$$

The values for subsurface temperatures (Table 2) range from 200 to 300°C for the wells and from 55 to 199°C for the springs. The chalcedony geothermometer yielded slightly low values, whereas the Na/K geothermometer produced relatively high values, except for Well ThG-2. For wells, the quartz geothermometer seemed to provide a reliable temperature, close to equilibrium with the deep liquid composition. Hence, Theistareykir area can be categorised as a high-temperature geothermal field.

3.1.4 Silica and calcite scaling assessment

Scaling is one of the problems encountered during geothermal utilization, caused by the nature of the fluid aquifer; the magnitude varies from one field to another. The best known scales are amorphous silica and calcite in producing wells, surface equipment and reinjection wells. Calcite starts to form within the well when boiling starts and its solubility decreases with an increase in temperature, contrary to silica solubility. The calcite solubility is dictated by Equation 6 while the precipitation reaction of calcite can be described by Equation 7.



Once the boiling has become intense, the CO₂ enters into a vapour phase, raising the pH of the fluid. When the fluid becomes oversaturated with respect to CaCO₃, scales start to form. The dissolved silica in a geothermal system can lead to quartz and amorphous silica precipitation. However, it has been found that scaling from quartz never occurs because of its slow formation process. On the other hand, amorphous silica is of considerable concern in surface equipment and reinjection wells.

From the WATCH program results, it can be predicted whether a given mineral is likely to form or not by using the equation:

$$SI = \log\left(\frac{Q}{K}\right) \tag{8}$$

where *SI* = Saturation index;
Q = Quotient of ionic activities; and
K = Solubility product constant (function of temperature or pressure).

If *SI* < 0 under-saturated, mineral dissolves;
SI = 0 saturated exactly, no mineral reaction; and
SI > 0 supersaturated, mineral precipitates.

The water samples from the Theistareykir field have been scrutinized with respect to amorphous silica and calcite scaling and all probable scenarios were drawn in Figures 7 and 8. The saturation index was calculated for temperature values ranging from 100 to 287°C. The fluid from Well ThG-2 remains under-saturated with respect to amorphous silica for both adiabatic boiling and conductive cooling processes. However, upon adiabatic boiling, it became supersaturated with calcite; scaling is likely to occur in the well if the fluid boils at a temperature higher than 198°C.

Amorphous silica and calcite saturation with respect to the fluid is reached at 178°C and 220°C, respectively, in Well ThG-3 for adiabatic boiling. If the fluid is boiled below 178°C, amorphous silica scaling may take place, and calcite scaling at temperatures higher than 220°C. Conductive cooling below 150°C is likely to cause amorphous silica scaling. Regarding Well ThG-4, no calcite scaling is expected to take place; only boiling the fluid to below 160

TABLE 2: Calculated composition (in ppm) of the deep liquid for the representative samples from the Theistareykir field

	T (°C) Qtz	T (°C) Chal	T (°C) Na/K	B	SiO ₂	Na	K	Mg	Ca	F	Cl	SO ₄	Al	CO ₂	H ₂ S	NH ₃	H ₂	O ₂	CH ₄	N ₂	TDS	
ThG-2	218	201.8	204.8	0.5	336.3	123.0	12.8	0.0	0.7	0.6	38.7	35.9	1.0	342.8	46.5	0.0	0.1	0.0	0.4	21.4	663.7	
ThG-3	287.3	271.6	290.7	1.9	632.9	140.6	34.9	0.0	1.1	0.6	190.6	4.7	1.3	712.4	638.7	0.0	22.8	0.0	1.1	14.5	1065.8	
ThG-4	270.3	257.2	301.3	3.4	566.2	65.0	14.6	0.0	0.2	1.2	75.4	2.8	1.6	146.0	765.6	0.0	36.4	0.0	0.1	29.2	835.3	
ThG-5b	273.6	260	300.1	0.6	592.1	98.9	24.7	0.0	0.3	0.9	40.6	15.1	1.7	1370.0	158.0	1.4	1.1	0.0	0.4	52.2	846.3	
V-1	139	112.3	199.2																			
V-1	86.8	55.3	184.9																			

T (°C) Qtz = Quartz geothermometer; T (°C) Chal = Chalcedony geothermometer; T (°C) Na/K = Na/K geothermometer

and 140°C may cause amorphous scaling for boiling and cooling, respectively. Finally, for Well ThG-5b, scaling by amorphous silica is possible for both boiling and conductive cooling below 160 and 140°C, respectively. Calcite is supersaturated, with respect to the fluid, up to 160°C upon boiling and to 240°C upon conductive cooling.

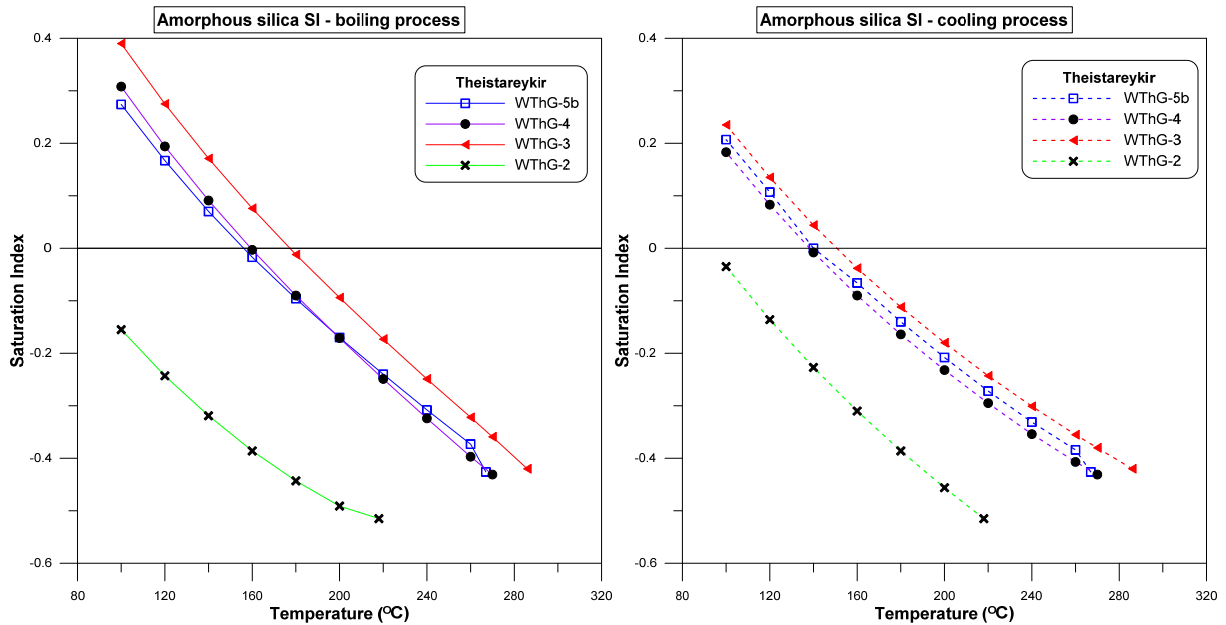


FIGURE 7: Amorphous silica, SI vs. temperature diagram for fluid from Theistareykir field

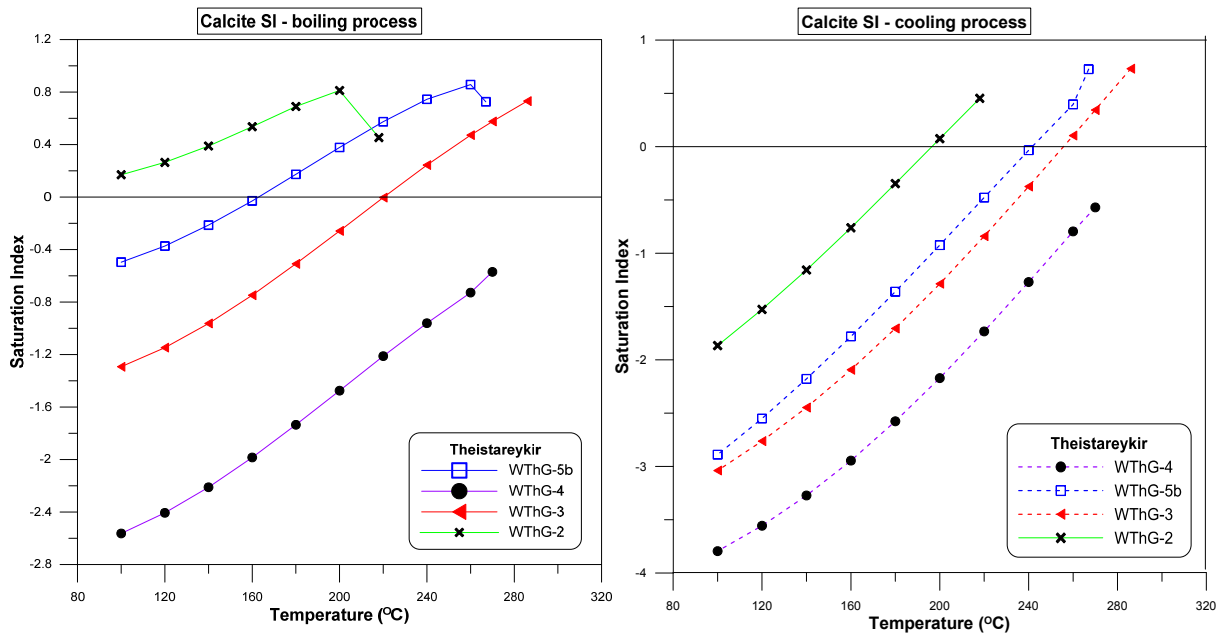


FIGURE 8: Calcite, SI vs. temperature diagram for fluid from Theistareykir field

3.2 Geochemistry of geothermal water in NW-Rwanda

The spring water samples, from northwest Rwanda, that were used in this report were collected by the Federal Institute for Geosciences and Natural Resources (BGR), Germany, in 2008 and were analysed by Iceland GeoSurvey (ÍSOR). The analytical data (Table 3) are reviewed and interpreted in this section.

TABLE 3: Water composition of selected springs in NW-Rwanda; the concentrations are in mg/kg, unless otherwise stated

Sample	T°C	pH	Na	K	Ca	Mg	SiO ₂	B	Cl	Al	F	SO ₄	HCO ₃	Fe	Mn	δ ¹⁸ O	δ ² H
Gisenyi	73.1	6.68	495	38	35	11.2	56.2	2.1	195	0.016		55.8	1140	0.3		-3.5	-9.7
Karago	64.1	7.12	253	15	21	2.4	84	0.3	77	0.011		77.9	537	0	0.17	-3.72	-12.4
Mpatsi	31.2	6.75	208	23	144	16.8	86.3	1.3	41	0.006		31.2	1050	0.2	0.14	-3.61	-11.2
Iriba	22.3	7	394	17	77	23.2	58.3	0.4	287	0.051		67	846	2.2	0.23	-3.44	-8.8
Mbonyebyombi	34.5	7.04	187	12	20	2.4	60.3	0.2	52	0.02	5.48	44.2	414	0.7	0.16	-3.86	-12.8
Nyakageni	20.5	6.9	229	43	71	23.2	62.7	0.7	73	0.444	3.1	31.5	854	12	0.3	-2.7	-5.7

According to the classification of geothermal water made by Giggenbach (1991), the selected springs are mainly characterized by HCO₃⁻ rich waters and low Cl, as shown in the Cl-SO₄-HCO₃ ternary diagram (Figure 9). Thus, the springs are probably the result of a heated geothermal fluid from the deep reservoir reaching the surface and mixing with shallow groundwater. This is confirmed by the presence of magnesium in the spring water (see Na-K-Mg diagram in Figure 10). Depleted in geothermal water, its presence reveals the cold groundwater inflow into the system. The water classification above does not confirm whether the given water is of geothermal origin or not. However, when waters are classified as Cl-rich or mature, there is an increased assurance that the use of geothermometers to estimate the reservoir temperature will give reliable results. This classification of hot and warm springs from NW Rwanda is consistent with the classification made by Ármannsson and Eyjólfsson (2009).

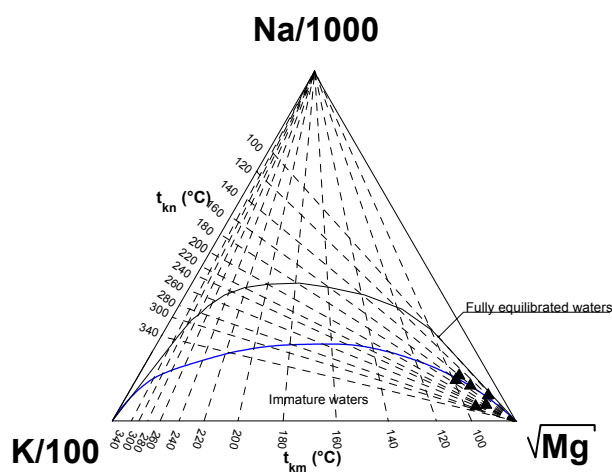


FIGURE 9: Cl-SO₄-HCO₃ Ternary diagram for selected springs in NW Rwanda

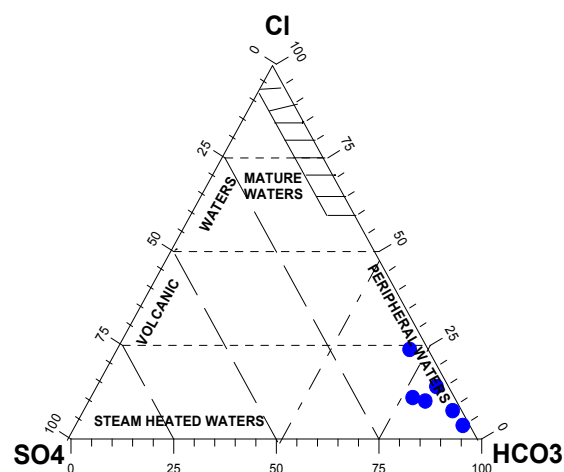


FIGURE 10: Na-K-Mg Ternary diagram for selected springs in NW Rwanda

The quartz (Fournier and Potter, 1982) and chalcedony (Fournier, 1977) geothermometers gave temperature values ranging from 80 to 129°C. The Na/K geothermometer (Arnórsson et al., 1983) yielded higher values from 142 to 270 °C. The discrepancy could arise because the selected water samples may not yet have reached full equilibrium, confirmed in Figure 10. The temperature values for the selected samples are shown in Table 4. In most cases, the chalcedony geothermometer seems to give reliable temperature values, as it is close to equilibrium with all waters.

The results of the stable isotope determinations (δ¹⁸O and δ²H) suggest that the spring water is of meteoric origin as they plotted near the world meteoric line and the Kenya rain line in Figure 11. This means that the thermal water was derived from local surface water that infiltrated deep layers and then mined the heat from the host rocks (Craig, 1963). However, the isotope composition of NW Rwanda waters needs to be studied to improve the accuracy of these analyses because the meteoric lines used might not tell the whole story. In order to estimate the thermal water content of the mixed water, we

used the silica enthalpy model (Figure 12). Unfortunately, the results plot horizontally, making them unsuitable for use in the model. Drilling results will help to elucidate the thermal water composition.

TABLE 4: Measured surface temperatures and calculated subsurface temperatures for selected springs in NW Rwanda

Sample	Measured T (°C)	Qtz T (°C)	Chal T (°C)	Na/K T (°C)
Gisenyi	73.1	107.7	77.8	172.7
Karago	64.1	127.8	99	142
Mpatsi	31.2	129	101.6	212.5
Iriba	22.3	109.4	79.7	122.2
Mbonyebyombi	34.5	111	81.4	149.2
Nyakageni	20.5	112.9	83	270.4

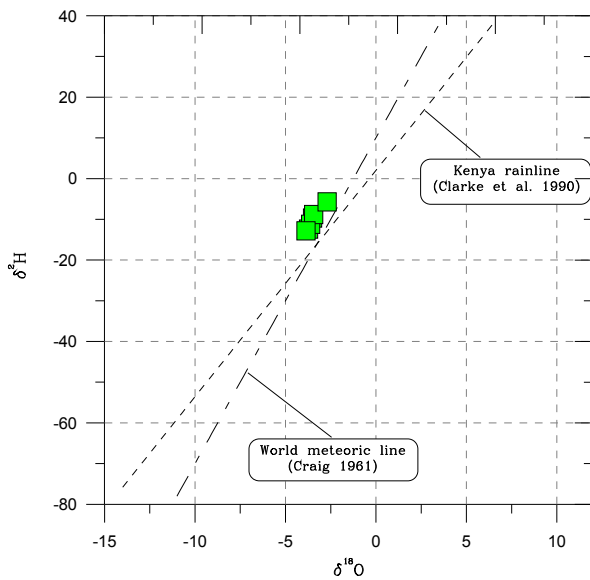


FIGURE 11: Isotopes for selected springs in NW Rwanda

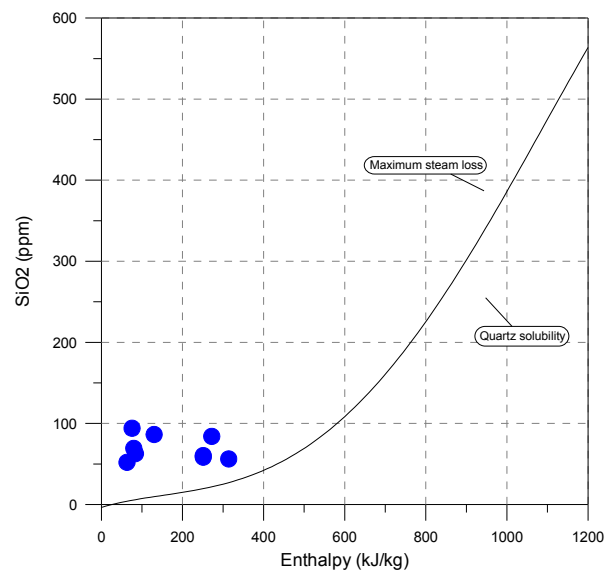


FIGURE 12: Silica mixing model for selected springs in NW Rwanda

4. RESULTS, DISCUSSION AND COMPARISON

In the Theistareykir field there is a fundamental difference between the water composition of the warm springs and the discharge wells. The spring waters are rich in Mg and HCO₃ whereas well waters are not. The presence of Mg implies groundwater origins, but the fact that the springs' temperatures at the surface are 24 and 34°C suggests that the springs are getting their water from steam-heated groundwater. This difference has been proven by isotope analysis where the warm spring water plots close to local rainwater and the geothermal fluid is not of local origin, as discussed by Darling and Ármannsson (1989). The thermal water is considered to originate from precipitation far to the south, flowing along the fissure swarm and conductively heated. There were differences in the water composition between the wells, suggesting that different aquifers provided their fluid. Thus, there are shallow and deep aquifers in the Theistareykir system. This is in agreement with the subdivision of Theistareykir into 5 sub areas, dependent on the discharge fluid and the conceptual model of the system (Gudmundsson et al., 2008).

On the other hand, the thermal water from the northwest prospects of Rwanda appears to originate from local precipitation, as indicated by isotope analysis. Two scenarios may explain the thermal activity of the few warm springs encountered there. In the first one, the warm water may result from heated groundwater, as is the case in Theistareykir field. The second scenario proposes the mixing of shallow groundwater with geothermal fluid ascending from a deep aquifer. The nature of the water samples did not allow any use of common mixing models to estimate the amount of the hot water content in the mixed waters. When trying to use the silica enthalpy model, all samples plotted horizontally, making it difficult to apply this model. Presently, the two scenarios remain debatable. Most likely the drilling results will help to decide which model is applicable.

4.1 Comparison between the Theistareykir field and the geothermal prospects in NW-Rwanda

The reservoir regime of the Theistareykir field is complex; there exist several aquifers, all drawing fluid from the same reservoir. In addition, there is mixing of geothermal fluid and shallow ground water in some aquifers. Water discharged at the surface by springs is different from that of the deep fluid. In the geothermal prospects in NW Rwanda, the surface manifestations do not seem to reflect deep aquifer properties. A convective geothermal system may have been formed in such a tectonically active environment. The high rainfall and pronounced rock permeability in this volcanic prospect could certainly suppress the surface manifestations of a geothermal system below.

In contrast with the Theistareykir field, where the geothermal activity is related to the most recent volcanic activity in the area which took place some 2500 years ago (Óskarsson et al., 2013), the prevailing geothermal systems in the prospects in NW Rwanda are associated with Quaternary activity. The geothermal fluid would probably be derived from local precipitation, which is not the case for Theistareykir. The drilling results in NW Rwanda will give a considerable clarification, as far as similarities and dissimilarities with regard to Theistareykir are concerned.

5. CONCLUSIONS

The chemical composition of spring waters and well discharges in Theistareykir shows that the geothermal water can be classified as Na-Cl or HCO₃ rich water, in general. All wells and springs discharge distinct fluid in chemical composition. This simply indicates that the prevailing reservoir of the geothermal system consists of many aquifers, some shallow, others deep. The warm water in the springs might be steam-heated shallow water. The subsurface temperatures confirm Theistareykir as a high-temperature geothermal field, as the calculated temperatures for the geothermal fluids are higher than 270°C, except for those from ThG-2 which draws fluid of 218°C, taking the quartz geothermometer temperature as the reference temperature. From the WATCH programme calculations, scaling from amorphous silica on surface materials and in reinjection wells is, in most cases, likely to take place if the fluid is separated at temperatures below 160°C. Calcite may pose problems in wells, too.

The thermal waters from the geothermal prospects in NW Rwanda are characterized as Na-HCO₃ waters that have not reached full equilibrium. The significant HCO₃ and Mg concentrations suggest the water to be of groundwater origins. The thermal water might be steam heated groundwater and may not necessarily reflect subsurface properties. Mixing of geothermal fluid with shallow water is not excluded from the likely scenarios, unless drilling results prove otherwise. When trying to apply mixing models, the results were not conclusive.

The Theistareykir field and the geothermal prospects in NW Rwanda host warm springs at the surface that do not necessarily reflect the deep reservoir properties. Mixing of geothermal fluid with shallow groundwater may take place in NW Rwanda.

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