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Application of Gas Chemistry to Geohazard Investigation in the Central and North Rift Geothermal Prospects, Kenya

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ABSTRACT

Sampling of vapors from selected fumarolic vents in part of Central and North Rift geothermal prospects in Kenya was carried out with the aim of establishing a baseline for future monitoring of volcanic and/or geothermal activities in these areas. The fumaroles sampled were those that indicated relatively higher mass discharges, suggesting a rapid and direct migration to the surface. The survey program was undertaken towards the end of the dry season (March, 2014), just before the onset of major rains in the region in order to obtain samples least affected by mixing with surface/rain water. Two fumaroles in Silali, four in Paka, and one in Korosi, Chepchuk, Lake Bogoria and Arus were sampled. This paper also incorporates results from earlier surveys in Suswa, Emuruangogolak and Barrier geothermal prospects. The results indicate that fumarole KF-3 in Korosi and SF-6 in Silali experienced severe air contaminations, most probably due to inflow of atmospheric gases in the fumarolic conduits upstream of the sampling point given the relatively low flow rates witnessed. CO_2 is the dominant non-condensable gas in the fumarolic samples with H_2S being markedly low possibly due to secondary processes like oxidation that affect H_2S gas, the consequence of which is an increase in the CO_2/H_2S ratios. Hydrogen is present in varying amounts and notably appears to be unstable in air-contaminated samples. The results further indicate that Silali, Paka and Suswa reservoirs have redox conditions close to those governed by the fayalite-Hematite-Quartz (FHQ) redox buffer, with reservoir temperatures of between 250°C and 350°C being estimated. Moreover, two possibilities are deduced from mineral-gas equilibria; either vapor separation in the upflow of Paka and Suswa could have occurred at high temperatures ranging from 250 to 300°C, or that Paka and Suswa geothermal systems are vapor dominated.

1. INTRODUCTION

The composition of gases emitted from volcanic vents and fumaroles provide useful insights on the subsurface conditions of a volcanic area. Gas chemistry is normally used as one of the proxies in monitoring volcanicity and yields information on the status of the volcanic geothermal system as well as the risks associated with development of the geothermal resource in such areas. Temporal variations in gas compositions also give indications on the effects of fluid withdrawal during utilization of the geothermal resource. This is largely because reactive components tend to equilibrate with hydrothermal minerals, incorporating these components hence providing useful information on the physical state of the geothermal system (Giggenbach, 1991; Gudmundsson and Arnorsson, 2002; Giggenbach, 1987).

The composition of hydrothermal gases is dominantly water (usually higher than 90%) and significant CO_2 is present being the predominant non-condensable gas (Nicholson, 1990). For this reason CO_2 is considered a very useful tool for monitoring volcanic activity. Changes in CO_2 emissions can indicate magma movements and possible eruptions (Hanandez et al., 2001). Moreover, changes in the chemistry of fumarole discharges have been witnessed in other geothermal areas in the world (Kristmannsdottir and Ármannsson, 2003; Glover and Bacon, 2000; Oskarsson, 1984; Glover et al., 2001) and have been useful in arriving at key decisions relating to volcanic activity of an area and its implications on geothermal resource exploitation. Variations in outlet temperatures is also beneficial in identifying eruption precursors as well as understanding the volcanic system, hence monitoring of fumarole temperatures at several volcanoes has been practiced (Manyailov et al., 1986).

This paper presents findings of fumarole sampling carried out in the aforementioned geothermal areas (Figure 1). The objective of the sampling exercise was to obtain data to be used as baseline for future monitoring of these volcanic geothermal areas. Fumaroles earmarked for monitoring were selected on the basis of strength of discharge (flow rate) as guided by results obtained from previous surveys (Dunkley et al., 1993; Kanda et al., 2011; Kipngok and Nyamongo, 2013), as well as their spatial distribution. The fumarole sampling exercise was carried out towards the end of the dry season, before the beginning of major rains in the region. This was considered a reasonable strategy aimed at minimizing effects of mixing of the samples with surface/rain water. The monitoring work was done in line with Geothermal Development Company (GDC's) geohazard monitoring program of volcanic centres in the Kenya Rift. This paper also incorporates results of representative samples from previous works in Suswa, Emuruangogolak and Barrier for comparison purposes. Development of the geothermal resources hosted in these geothermal prospects is at an advanced stage hence the purpose for the monitoring program.

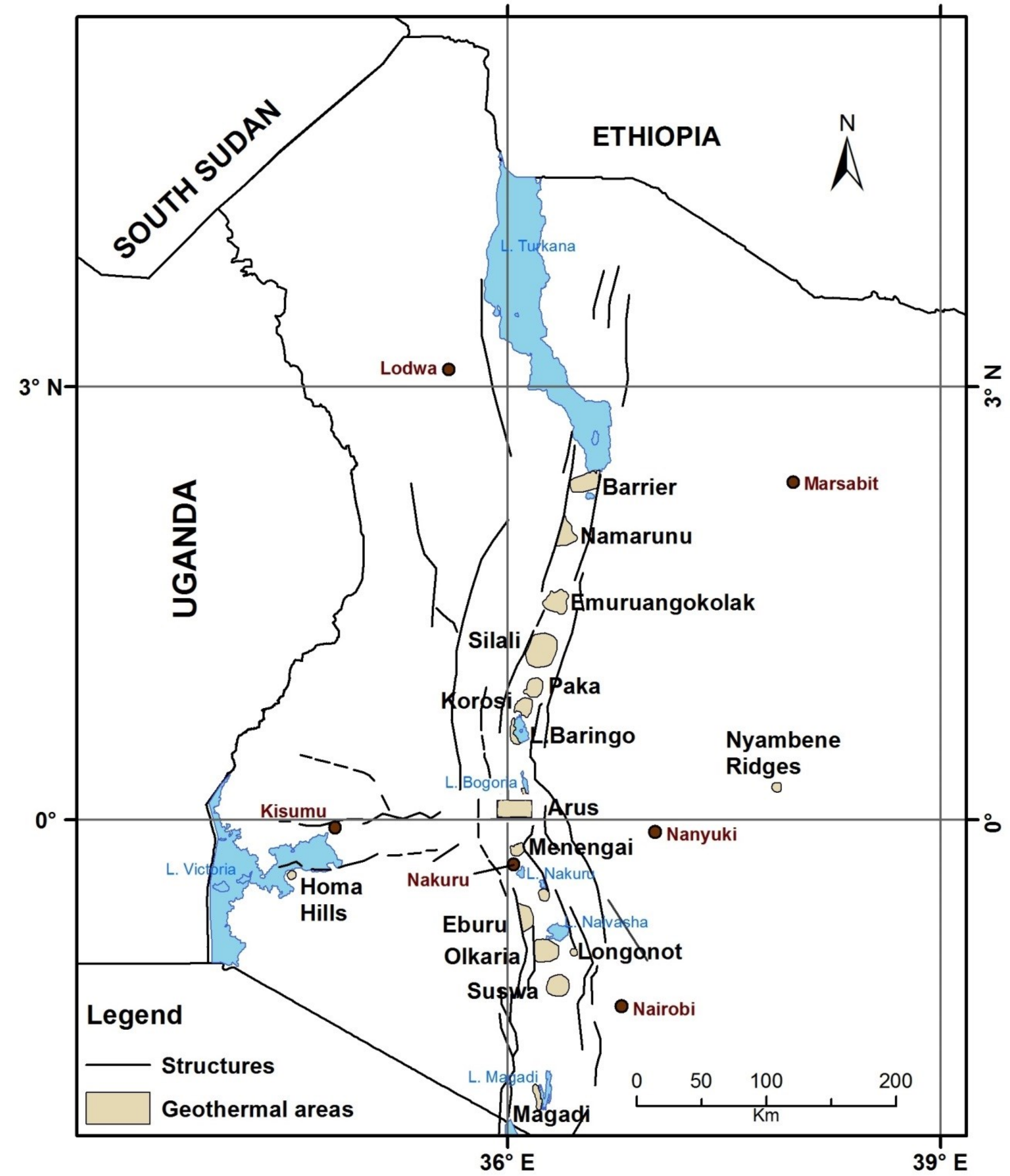

Figure 1: Location of geothermal areas in the Kenya Rift (GDC, 2012)

2. GEOLOGICAL SETTING

2.1 Arus-Bogoria

The geology of Arus-Bogoria area has been described by several authors (Jones, 1975; Griffiths, 1977; Jones and Lippard, 1979; Geotermica Italiana Srl., 1989). In the area between Arus and Lake Bogoria, the upper Plio-Pleistocene volcanism of the rift floor is characterized by large volumes of evolved lavas that consist mostly of peralkaline trachyte, trachyphonolite and phonolite. Small outcrops of basaltic lavas occur in isolated areas within the prospect. The northern sector of the area however, is dominated by fluvial and alluvial deposits within mini grabens.

2.2 Korosi-Chepchuk

Korosi is a trachyte-basalt volcanic complex though unlike many of the rift volcanoes is not marked by a summit caldera. The shield volcano is instead characterized by fault echelons, steep ridges, eruption centers and a superimposed horst and graben (Dunkley et al., 1993). Chepchuk on the other hand may have a caldera structure which is obscured due to down faulting (Lucy et al., 2011). Chepchuk is the name given to the highest point (1380 masl) in a series of prominent N-S trending ridges that rise 220 m above the plains to the NE of Korosi and SE of Paka (Dunkley et al., 1993). These ridges mark the faulted remnants of a large lower Pleistocene trachyte volcanic shield.

2.3 Paka

Paka is a complex multi vent low basalt-trachyte shield volcano dominated by a young central caldera at the summit, which is 1.5 km in diameter (Dunkley et al., 1993). The Paka volcano is dotted by a number of smaller satellite volcanic centers, which are linked to the main volcano by linear zones of basalt and trachyte cones and eruptive fissures. The volcano is generally composed of trachytic, basaltic lavas and pyroclastic deposits.

2.4 Silali

Silali is the largest Quaternary volcano in the Northern Kenyan Rift composed predominantly of peralkaline trachyte lavas, pyroclastic deposits and mildly alkaline to transitional basalts (Smith et al., 1995). The development of the volcano was initiated during the early Quaternary times with the eruption of largely basaltic lavas. Subsequent activity comprised both basaltic and trachytic volcanism, which resulted in the formation of a low shield volcano. The latest activity from a satellite vent on the northern slopes of Silali is basaltic in composition; these young lavas were erupted about 200-300 years BP (Dunkley et al., 1993).

2.5 Emuruangogolak, Barrier and Suswa

The geology of Emuruangogolak has been discussed in detail by Dunkley et al. (1993). Emuruangogolak is a large basalt-trachyte volcano situated about 20 km north of the Silali volcano. Extensive alluvial plains occur around the southern periphery of the volcano in the ground extending southwards to Silali. The northern part of the trough is floored by an expanse of fluvial, lacustrine and windblown deposits.

The Barrier volcanic complex (BVC) is a composite structure composed of four distinct volcanic centres i.e. Kalolenyang, Kakorinya, Likaiu West and Likaiu East (Dunkley et al., 1993). They are composed of a wide spectrum of lava types including basanite, basalt, hawaiitte, mugearite, benmorite, trachyte and phonolite. Kakorinya volcano forms the central part of the BVC with its summit dominated by a well preserved circular caldera to the west of which there are two arcuate ring structures. Trachytic pyroclastic deposits cover much of the western slopes of Kakorinya and the summit area of Likaiu west.

Suswa is the southernmost Quaternary shield volcano in the axis of the Kenya Rift. Its geology has been described by several authors (e.g. McCall, and Bristow, 1965; Johnson, 1969; Nash et al., 1969; Randel and Johnson, 1970; Hay et al., 1979; Skilling, 1993; Omenda, 1993; Macdonald et al., 1993). The volcano is unique in that it has two calderas, the outer and the inner calderas with an Island block (moat) at the center surrounded by an annular trench. The volcano is composed predominantly of trachyte and phonolite lavas, ignimbrite sheets and pyroclastic deposits. Petrographic examination by Macdonald et al. (1993) revealed that the rocks are carbonate-rich and that the carbonate was of mantle origin which separated from trachytic magma by liquid immiscibility.

3. STRUCTURAL FEATURES AND SURFACE GEOTHERMAL ACTIVITY

The main structural features in these geothermal areas of interest are mainly the generally NNE and N-S trending faults and fractures (Figure 2). Surface geothermal activity is associated with these structures and occurs in the form of fumaroles, hot and hydrothermally altered grounds, hot springs and sulphur deposition at some of the fumarolic sites. The highest temperature fumarolic sites are often characterized by white, purple and red clays. In most of the geothermal prospects however, steam vents and fumaroles have weak flows while areas of extinct surface activity are indicated by hydrothermally altered grounds with ambient to slightly above ambient temperatures.

4. SAMPLING AND ANALYSIS

A polypropylene funnel was inserted into the vent with its contact points with the ground sealed with mud, both to prevent any contact with atmospheric air in order to avoid contamination of the discharge as well as to provide necessary insulation so as to minimize steam condensation. The discharge end of the funnel is equipped with a short silicon tubing where the sampling bottle is connected. After the sampling train had been given sufficient time to heat up in order to purge it from air, the fumarole gases were then directed into two evacuated gas sampling flasks, one at a time, containing 50 ml of 40% w/v NaOH solution. The more soluble and acidic gases, H_2S and CO_2 were absorbed into the solution giving room in the evacuated flask for the minor non-condensable gases (H_2, CH_4 and to some extent, N_2) common in thermal fluids to concentrate to measureable levels. One flask was used for analysis of CO_2 and H_2S titrimetrically using HCl and mercuric acetate while from the second flask, analysis of H_2, CH_4, N_2 and O_2 was done using gas chromatograph. The condensate samples were obtained by passing the trapped steam through a stainless steel coil immersed in cold water to condense the steam. Sample treatment and analysis was done as described by Ármannsson and Ólafsson, 2006. Cl, F, pH, TDS/Conductivity, NH_4, SO_4, and B were determined in the condensate samples but the results are not included in this paper. All analyses were done at the GDC geochemistry laboratory, except for H_2S which was determined onsite. The location of fumaroles sampled in March, 2014 is shown in Figure 3 while Figure 4 shows the location of Suswa fumaroles used in this paper.

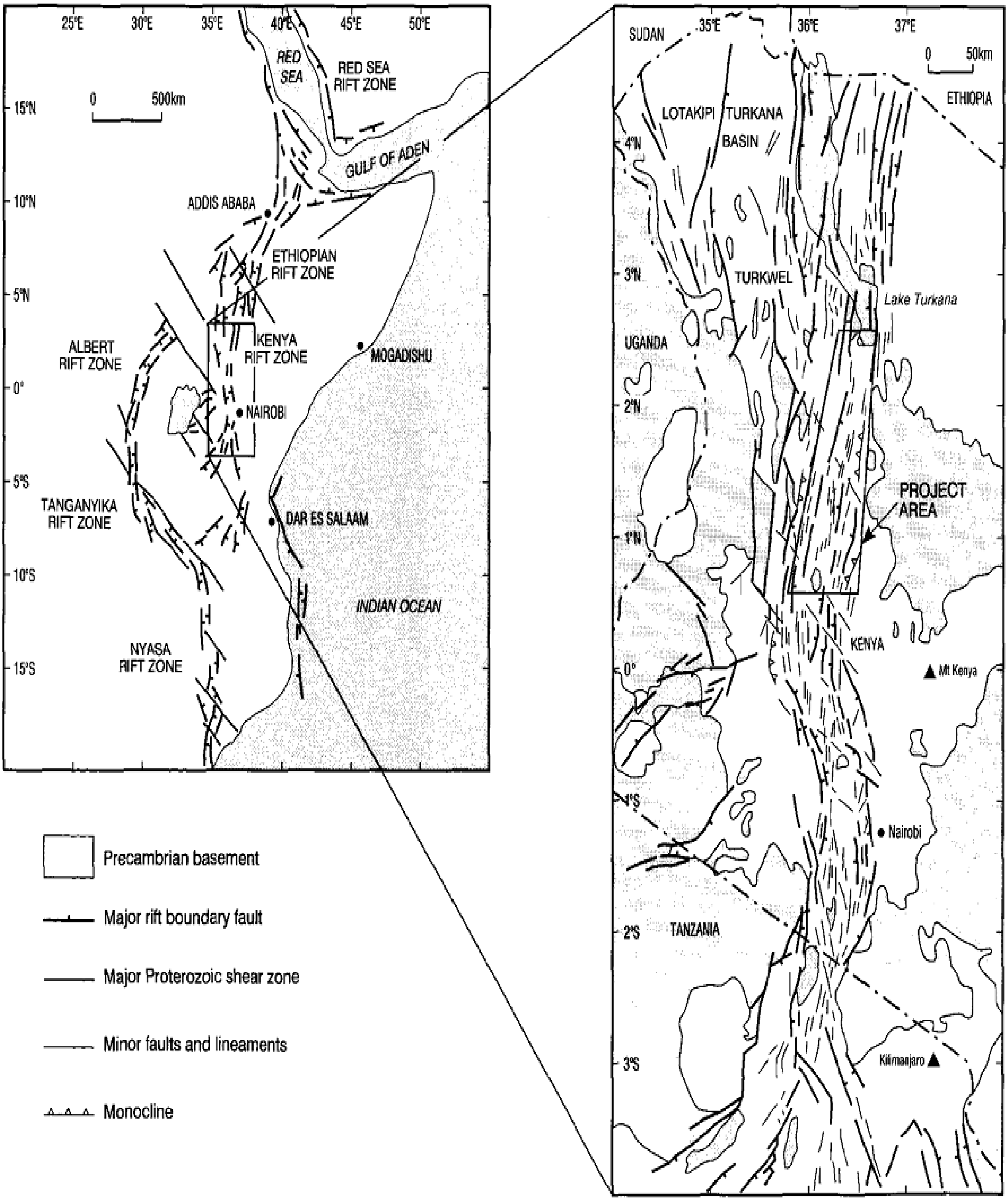

Figure 2: Simplified structural map of the Kenya Rift (Dunkely et al., 1993)

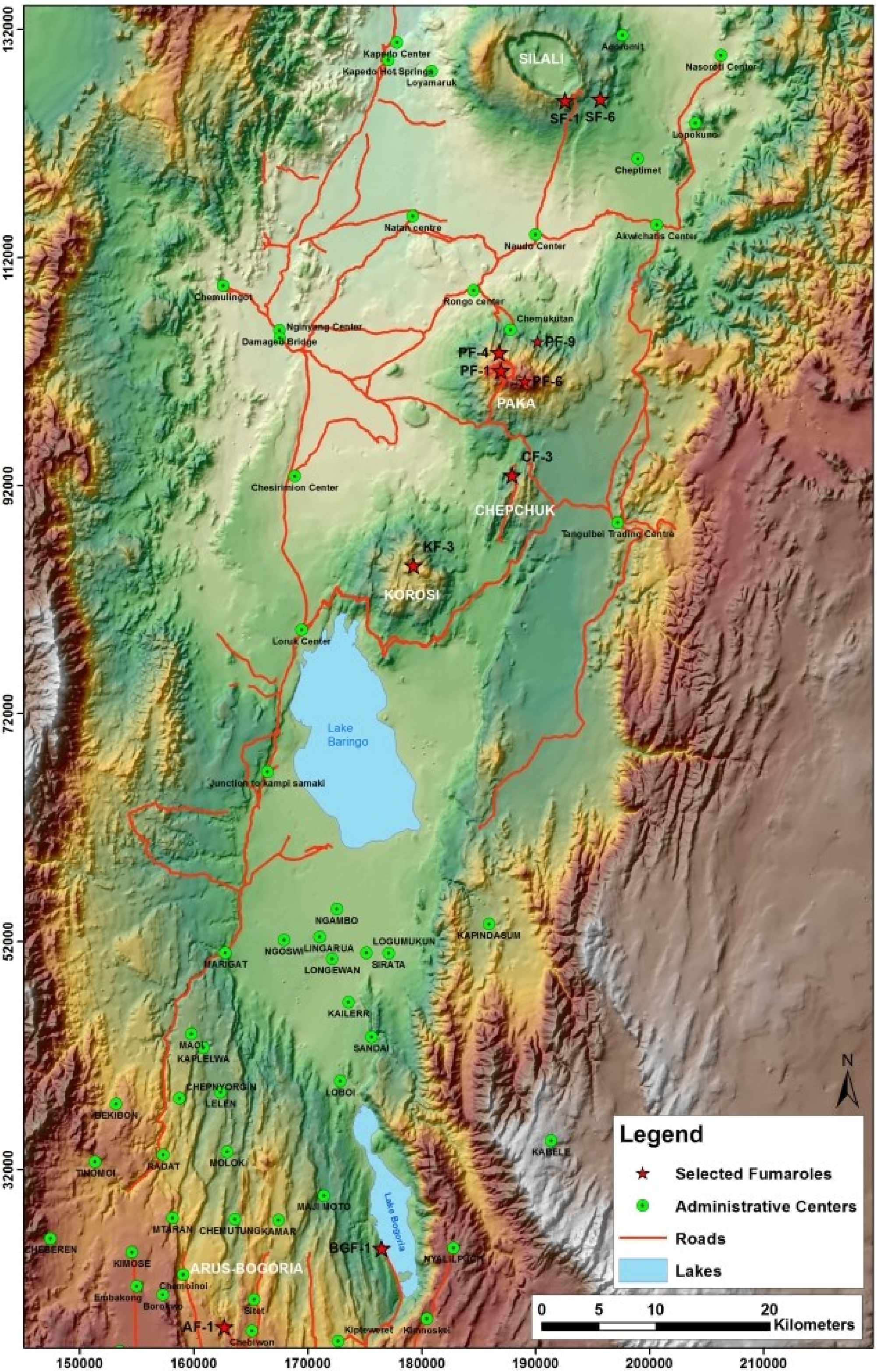

Figure 3: Location of sampled fumaroles in the Arus-Silali geothermal prospects (GDC, 2014)

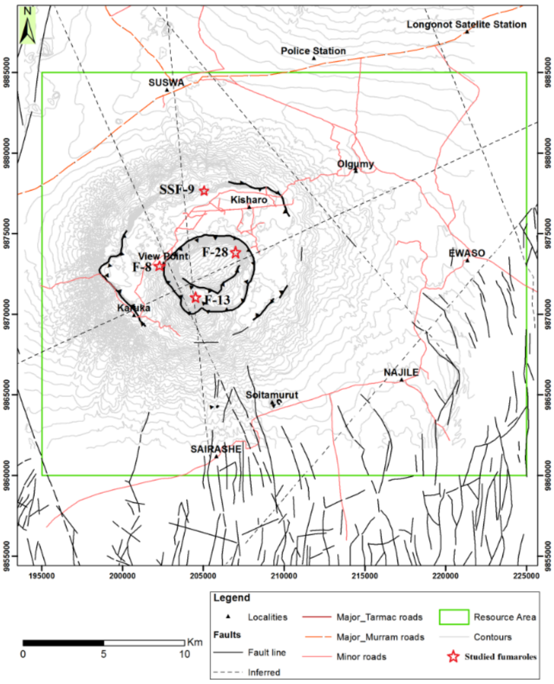

Figure 4: Location of studied fumaroles in Suswa (modified from Lagat and Malimo, 2013)

5. RESULTS AND DISCUSSION

The gas compositions of the fumaroles sampled (and those from previous works) are given in Table 1.

Table 1: Fumarole gas compositions

Fumarole	Geothermal prospect	Outlet Temp. (°C)	Elev. (m)	CO_2	H_2S	H_2	CH_4	N_2	O_2+Ar	Gas/steam (mole %)
				mmol/kg						
AF-1	Arus	94.1	1356	2041	0.006	0.13	4.0	3.9	0.4	3.71
BGF-1	L.Bogoria	96.6	967	417	0.067	0	4.4	4.4	0.3	0.78
SF-1	Silali	96.1	873	643	0.033	5.32	1.2	1.2	0.2	1.19
SF-6	Silali	94.2	1115	3458	0.083	0	4.8	2747	708	18.7
PF-1	Paka	95.1	1477	737	1.171	12.7	20.3	4.0	0.6	1.47
PF-6	Paka	94.2	1544	1460	0.755	11.6	34.5	6.7	0.9	2.83
PF-4	Paka	95.8	1327	147	0.017	5.43	1.7	1.1	0.2	0.30
PF-9	Paka	96.1	1073	167	0.011	0.46	0.1	1.7	0.4	0.31
KF-3	Korosi	94.5	1280	2719	0	0.00	6.9	1354	360	11.10
CF-3	Chepchuk	96	1073	1402	0.011	0.08	9.3	15.0	2.3	2.62
[a]SSF-9	Suswa	93.5	1878	745	0.11	0	2.18	298	72	2.68
[b]F-8	Suswa	94	nr	542	<0.03	0.74	5.14	<0.036	nr	0.99
[b]F-13	Suswa	94.6	nr	1019	0.88	6.70	15.4	<0.036	Nr	1.88
[b]F-28	Suswa	93	nr	3720	<0.03	34.99	53.65	0.036	nr	6.86
[c]EM-20a	*EM	96	nr	1545	29	0.05	13	850	207	4.76
[c]KR-11	Barrier	96	nr	208	0.03	0.10	0.54	788	219	2.19

[a] Sampled in 2012 (Sekento and Kipngok, 2013; Lagat and Malimo, 2013); [b] Ármannsson (1987), location of fumaroles shown in Figure 3; [c] Dunkley et al. (1993)· all the other samples were collected in March, 2014.

[nd] Not detected; [nr] Not reported; *EM Emuruangogolak

The results as shown in Table 1 generally indicate that the samples contain > 96% steam with the exception of fumarole SF-6, KF-3 and EM-20a that appear to have experienced significant atmospheric contamination, while F-28 on the other hand shows relatively high CO_2 content. It is further noted that the fumaroles least affected by air addition as shown by oxygen concentrations generally being near zero or below detection limit, discharged at the boiling point of water at the vent elevations implying that none of them was superheated. It is therefore inferred that some minor steam may have condensed during its ascent to the surface causing the remaining steam to become slightly (perhaps negligibly) enriched in non-condensable gas relative to the parent fluid. This therefore implies that the gas to steam ratios (mole %) given in Table 1 may not denote the exact representation of the compositions of the deeper and hotter parent fluids.

5.1 Triangular diagrams

Characterization of the fumarolic vapors has been done by means of triangular diagrams whereby the two major constituents (i.e. H_2O and CO_2), are considered together with other gas species i.e. N_2, H_2S, H_2 and CH_4. In the plot involving N_2 (Figure 5, left), samples distribute into two different groups i.e. the samples least affected by air addition, having $H_2O/N_2>3700$ and those that experienced significant contamination (KF-3, SF-6, EM-20a and BR-11) with $H_2O/N_2<70$. Fumaroles KF-3 and SF-6 had low flow rates implying that inflow of atmospheric gases in the fumarolic conduits upstream of the sampling point possibly occurred. The ternaries in Figures 3 and 4 also reveal that air contaminated samples have low H_2O/CO_2 values (with the exception of BR-11), expectedly though being the consequence of steam condensation, while samples that have high water content, indicated by high H_2O/CO_2 ratios, possibly represent later formed vapors (e.g. fumaroles PF-9 and PF-4 in Paka, particularly PF-9). Additionally, these fumaroles are characterized by relatively low gas content given that the further steam travels from the reservoir, the lower the absolute gas concentrations (Nicholson, 1993). Most samples however, occupy an intermediate position with H_2O/CO_2 ratios between 133 and 27. Contrary to this view is Suswa fumarole F-28 which shows a much lower H_2O/CO_2 ratio due to the observed high CO_2 content which could imply a magmatic flux of the gas to the hydrothermal reservoir.

Significantly low values of H_2S are however observed in the fumarolic discharges which could be the consequence of secondary processes i.e. O_2-driven oxidation to elemental sulfur or other oxidized species. Giggenbach (1996) and Yang et al. (2003) showed that sulfur species are easily affected by secondary processes, such as the formation of sulfides and elemental sulfur, and hydrolysis process of sulfur gases. In the triangular plot of H_2O-CO_2-H_2S (Figure 3, right), two fumaroles, PF-1 and PF-6 from Paka are displaced towards the H_2S vertex with a lower CO_2/H_2S ratio (≤ 630). These two fumaroles are possibly seated on the upflow in Paka, PF-1 being located inside the caldera and PF-6 on the eastern crater (see Figure 3). Furthermore, fumaroles with high gas concentrations and the lowest CO_2/H_2S, CO_2/NH_3 and CO_2/H_2 are fed by steam with the most direct route to the surface (Nicholson, 1993), of which these fumaroles are in agreement. The rest of the samples show higher CO_2/H_2S ratios, likely due to varying degree of entrainment of atmospheric gases and H_2S loss through oxidation. Moreover, it is worth noting that studies conducted in the Kenya Rift Valley (KRV) showed that it is a low sulphur province (Darling et al., 1995), which may further explain the significantly low H_2S values obtained.

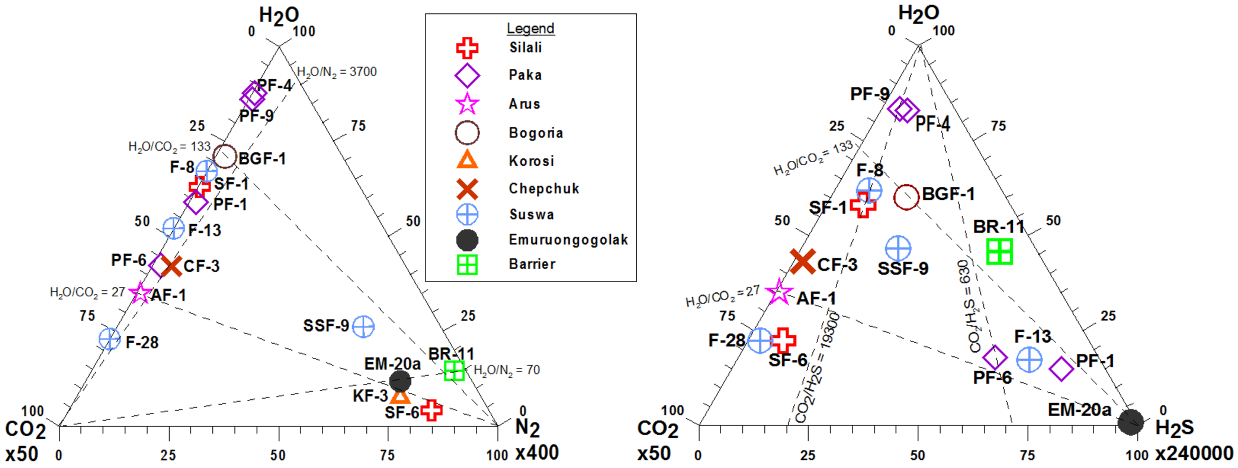

Figure 5: Triangular plots of H_2O-CO_2-N_2 (left) and CO_2-N_2-(O_2+Ar) (right) for the selected fumarolic samples from Arus-Silali, Emuruangogolak, Barrier and Suswa geothermal prospects.

Hydrogen appears to be unstable in air-contaminated samples as typified by fumaroles SF-6 and KF-3. However, H_2 is rather unexpectedly undetected in fumarole BGF-1 in Lake Bogoria, though this fumarole had a strong flow and discharged at the local boiling temperature. The most likely explanation for this is the possible interference by near surface ground water as was also observed in the condensate TDS which had a slightly elevated value as well as quite low aqueous H_2S. This postulation is further complemented by the fact that the fumarole is located at the shores of Lake Bogoria, with the intrusion of the lake water resulting from a recent rise in water levels in the lake a strong possibility. Overall, the H_2 content as seen in Figure 6 (left) distribute in two major groups i.e. fumaroles PF-1, PF-6, SF-1, PF-4, F-28 and F-13 which have high H_2/H_2O ratios (with F-28 indicating the highest value of about $6.3*10^{-4}$), while the rest of the fumaroles have lower ratios ($\leq 1.32*10^{-5}$). High hydrogen concentrations in dry gas correspond to high water vapor content and are often taken to indicate proximity to or strength of hydrothermal upflows. In this respect, vapors tapped by fumarole F-8 in Suswa appear to have the most direct route to the surface and could be sitting on or near the upflow in Suswa albeit recording very low H_2S. This argument is further supported by what is depicted by Figure 6 (left) where the gases from this fumarole seem to have equilibrated under two-phase conditions, at phase separation temperature of close to 300°C.

Interestingly, and rather somewhat expectedly, methane is detected in all the samples. Giggenbach (1997) recognized that methane has a sluggish behavior since it reacts very slowly, especially at low temperatures; hence the CO_2/CH_4 ratio is expected either to remain unmodified or to be slightly modified by steam condensation. Consistent with this expectation, and as depicted by Figure 6 (right), the CO_2/CH_4 ratios of both the water-rich and the water-depleted samples do not excessively vary.

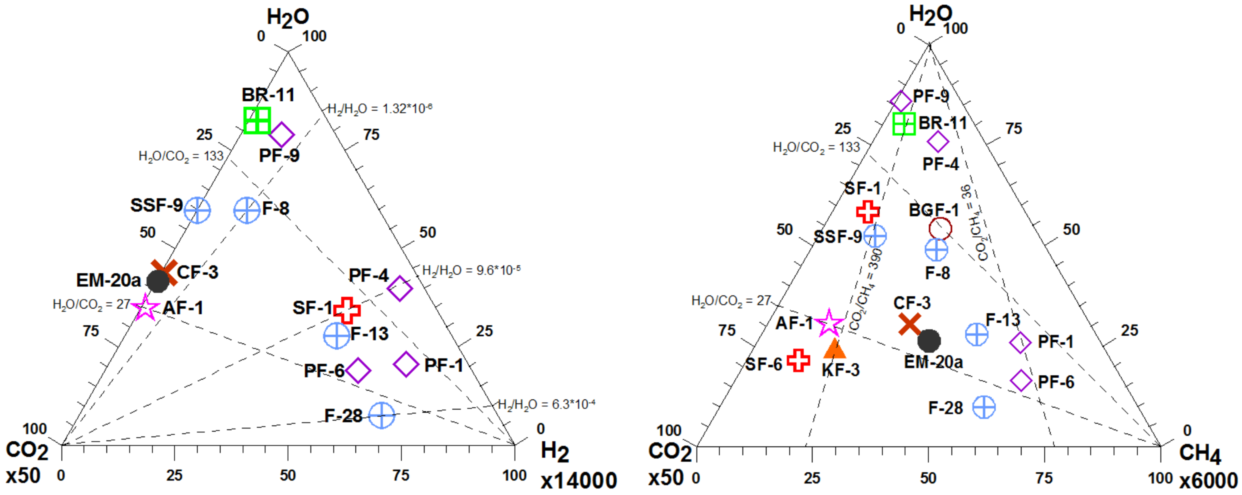

Figure 6: Triangular plots of H_2O-CO_2-H_2 (left) and H_2O-CO_2-N_2 (right) for the selected fumarolic samples from Arus-Silali, Emuruangogolak, Barrier and Suswa (symbols are as described in Figure 3)

5.2 Mineral-gas equilibria and geothermometry

Gas equilibria in the H_2-H_2O-CO_2-CH_4 system

Giggenbach (1987) showed that in most geothermal systems, the fayalite-hematite-quartz (FHQ) redox buffer:

$$Fe_2SiO_{4(S)} + H_2O = Fe_2O_{3(S)} + SiO_{2(S)} + H_2 \tag{1}$$

fixes the R_H ($R_H = \log (X_{H2}/X_{H2O})$) value at -2.82 ± 0.02, independent of temperature. Furthermore, Chiodini and Marini (1998) showed that as long as oxygen fugacity is known at any temperature, theoretical values of the log-ratios X_{H2}/X_{H2O} and X_{CH4}/X_{CO2} can be computed for equilibration both in the single vapor phase and, under consideration of corresponding vapor-liquid distribution coefficients, in the single liquid phase.

Equilibrium values for the log-ratios $X_{H2}/X_{H2O}$and X_{CH4}/X_{CO2} were, therefore, computed under the assumption that the FHQ buffer correctly describes the redox conditions in the Arus-Silali, Emuruangogolak, Barrier and Suswa geothermal systems. The plot of Figure 7 (left) presents a comparison between measured and computed values. The diagram also contains contour lines showing the chemical composition of vapors separated iso-enthalpically at temperature T_S from a liquid, whose gaseous constituents were in chemical equilibrium at temperature T_O prior to boiling as discussed by Chiodini and Marini (1998).

Silali, Paka and Suswa geothermal reservoirs appear to exhibit redox conditions that are very close to those governed by the FHQ redox buffer with reservoir temperatures given by the chemical equilibrium temperatures between 250°C and 340°C. It is further deduced from Figure 7 that vapor separation occurred at high temperatures (ranging from 250°C to 300°) in the Paka and Suswa upflows (inferred from PF-1, PF-6, F-28 and F-13) while those of Silali separated at a temperature close to the local boiling point of water. However, it is possible that vapors discharged by fumaroles PF-9 in Paka and F-8 in Suswa may have had similar parent fluid characteristics to those of PF-1 and PF-6 in Paka and F-13 and F-28 in Suswa, respectively, but were modified by secondary processes during fluid ascent to the surface. It is hence postulated that the difference could be attributable to the path taken to get to the surface. Arus, Chepchuk, Barrier and Emuruangogolak fumarole vapors may either have experienced some considerable air addition or that the redox conditions in these reservoirs are different and not closely controlled by the FHQ buffer.

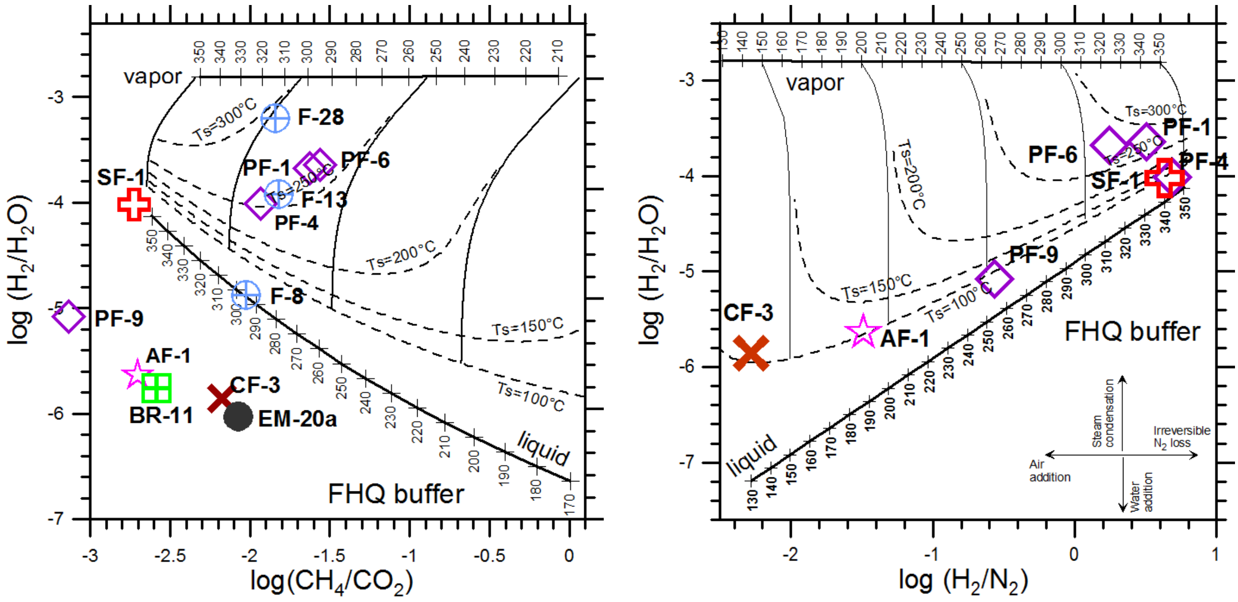

Figure 7: Diagram of log(CH4/CO2) vs. log(H2/H2O), left (from Marini and Fiebig, 2005), and diagram of log(H2/N2) vs. log(H2/H2O), right (from Brombach et al., 2003), in which the fumarolic fluids from Arus-Silali, Emuruangogolak, Barrier and Suswa prospects are compared with the theoretical compositions expected for gas equilibration in a single vapor phase and in a single liquid phase (pure water) under redox conditions controlled by the FHQ redox buffer (from Giggenbach, 1987). Also shown are the effects of steam separation at temperature TS on liquids initially equilibrated at temperature TO > TS. Symbols are as described in Figure 3.

The H_2-N_2 geothermometer

The X_{H_2}/X_{N_2} log-ratios of fumarolic gases are compared with corresponding X_{H_2}/X_{H2O} log-ratios in the plot of Figure 7 (right), also showing the theoretical compositions for gas equilibration in a single vapor phase and in a single liquid phase, as well as the effects of steam separation at temperature T_S on liquids initially equilibrated at temperature $T_O > T_S$. The theoretical grid was computed following the same approach adopted by Giggenbach (1991) for deriving the H_2-Ar geothermometer that is assuming that N_2 concentration of the geothermal reservoir liquids is equal to that of air-saturated groundwater at room temperature (Arnórsson, 1987; Brombach et al., 2003).

Similar to the previous diagram, also in this plot the fumarolic fluids least affected by secondary interfering processes are positioned close to the two-phase lines (for Paka PF-1 and PF-6) and the liquid line (for Silali SF-1 and Paka PF-4), indicating attainment of chemical equilibrium among gas species in both a two-phase and a single liquid phase at temperatures of 250-340°C approximately. However, fumarole EM-20a in Emuruangogolak and BR-11 in Barrier indicated significant air addition (see Figure 5, left) and therefore plotted outside the graph in Figure 7, (right). Samples from Suswa also plotted to the far right (outside the graph in Figure 7, right) being influenced by the very low nitrogen concentrations reported.

Other gas geothermometers

Table 2 presents estimated reservoir temperatures computed using other gas geothermometer functions as indicated. It is important to note that whereas these functions were developed assuming gas equilibration in a liquid reservoir, gases in Paka and Suswa reservoirs may have equilibrated under two-phase conditions as seen in Figure 7 (right) and subsequently discussed. Samples from fumaroles F-28, SF-6 and KF-3 indicate high CO_2 geothermometer temperatures, the latter (SF-6 and KF-3) due to condensation and are therefore not considered to be reflective of equilibrium conditions in the reservoirs feeding the fumaroles. However, fumarole F-28 gases suggest 'excess' CO_2 which may not be in equilibrium with hydrothermal minerals. Additionally, as explained in the previous sub-section, H_2S concentrations being notably low, give low estimates of reservoir temperatures that may not closely reflect the actual equilibrium conditions. Overall, the reservoir temperatures of the Arus-Silali geothermal prospects are reliably between 220°C and 350°C.

Table 2: Other gas geothermometers

Fumarole	$t^{ag}CO_2$	$t^{ag}H_2S$	$t^{ag}H_2$	$t^{ag}CO_2/H_2$	$t^{nd}H_2$-CO_2	$t^{nd}H_2S$-CO_2	$t^{g}CH_4/CO_2$
AF-1	350	157	264	222	233	238	328
BGF-1	305	205		-	-	-	276
SF-1	317	192	298	282	309	321	330
SF-6	>350	210		-	-	-	340
PF-1	320	261	306	291	331	347	250
PF-6	340	253	305	282	338	>350	254
PF-4	275	178	298	301	292	302	273
PF-9	279	171	276	269	234	239	>350
KF-3	>350	-	-	-	-	-	319

CF-3	339	171	259	220	216	221	289
SSS-9	321	204	-	-	217	222	315
F-8	312	178	274	260	181	185	279
F-13	329	244	295	279	271	279	266
F-28	>350	178	310	284	204	209	267
EM-20a	341	312	250	214	>350	>350	282
BR-11	286	218	256	247	219	224	319

$\mathbf{t}^{\mathbf{ag}}$: Arnórsson and Gunnlaugsson, 1985; $\mathbf{t}^{\mathbf{nd}}$: Nehring and D'Amore, 1984; $\mathbf{t}^{\mathbf{g}}$: Giggenbach, 1991

6. FUTURE MONITORING

Figure 8 shows the trends in gas results of the baseline data of March, 2014 (Table 1) and that of previous sampling in Silali, Paka and Korosi. It is recommended that future work should focus on more frequent and consistent monitoring in order to reveal any systematic trends in the gas compositions and subsequently establish the behavior of the geothermal systems, particularly that in Paka. It is however important to note that any observed minor differences over time in the gas compositions as depicted by the graphs presented in Figure 8 may have resulted from uncertainties in sampling and analysis.

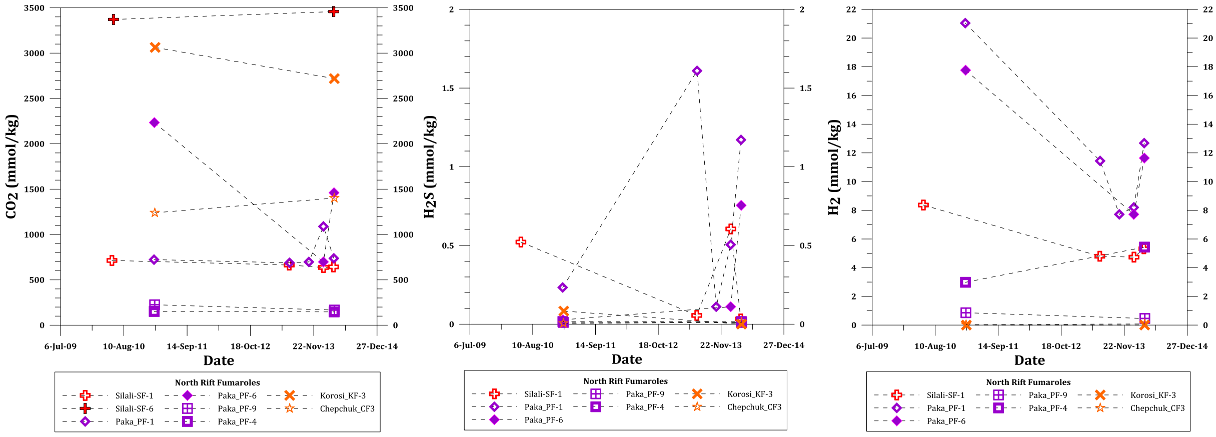

Figure 8: Variations in CO_2 (left), H_2S (middle) and H_2 (right) over different sampling periods

CONCLUSIONS

The fumaroles sampled in the Arus-Silali geothermal prospects had strong flow rates except fumaroles SF-6, located on the eastern part of Silali, and KF-3 in Korosi, which experienced severe air addition. Scheduled monitoring of the fumarolic vapors as per GDC's geohazard monitoring program is expected to reveal any trends, if present, before and after development of the geothermal areas.

CO_2 is the dominant non-condensable gas accounting for over 90% of the total NCG in the fumaroles least affected by air contamination (hence minimal condensation). Generally low H_2S is noted which could possibly imply the consequence of secondary processes, chiefly, oxidation. Notably, Paka fumaroles PF-9 and PF-4 indicate low gas content which signifies later formed steam i.e. steam that has travelled further from the reservoir, especially fumarole PF-9.

Reservoirs tapped by Silali fumarole SF-1, Paka fumaroles PF-1, PF-6 and PF-4 and Suswa fumaroles F-28, F-13 and F-8 show that Silali, Paka and Suswa geothermal reservoirs appear to exhibit redox conditions close to those governed by the FHQ redox buffer, with reservoir temperatures ranging from 250°C to 350°C. It also appears that phase segregation in Paka and Suswa geothermal systems occurred at high temperatures of about 250°C to 300°C unlike in Silali, which seems to have happened close to the local boiling temperature.

Gas equilibration in the upflow of Paka (as deduced from PF-1 and PF-6) and in Suswa (inferred from F-28 and F-13) appears to have been attained under two-phase conditions at separation temperatures lying between 250 and 300°C. It is also possible that these two geothermal systems are vapor dominated.

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