Proceedings, 6th African Rift Geothermal Conference
Addis Ababa, Ethiopia, 2nd – 4th November 2016

THE SEARCH FOR VOLCANIC HEAT SOURCES IN TANZANIA: A HELIUM ISOTOPE PERSPECTIVE

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ABSTRACT

Tanzania is characterized by unique volcanoes. Most of those volcanoes are located within the eastern and western branches of the Cenozoic East African Rift. Latest helium and neon isotope investigations of lavas and xenoliths are indicating a super-plume beneath East Africa (Halldórsson et al. 2014). Additionally to the distinction between plume and non-plume related volcanism, helium isotope analyses are a versatile tool for relating geothermal resources to any type of volcanic heat source. In Tanzania there are several distinct areas with significant geothermal surface manifestations: (i) Mwanza region in the N, (ii) Arusha region in the NE, (iii) Dodoma region in central Tanzania, (iv) Dar es Salaam region in the E, (v) Kigoma region in the W and (vi) Mbeya region in the SW. Helium isotope data of Ruhoi hot spring in E Tanzania does not show any indications of a volcanic heat source in contrast to Ngozi-Songwe geothermal system in SW Tanzania (Kraml et al. 2014a,b).
In N Tanzania (data this study) the normalised $^{3}He/^{4}He$ ratio (R/Ra) of the Kogaja mineralized spring indicates crustal helium. Also the Maji Moto hot spring is characterized by non-volcanic gas as indicated by the carbon isotopic composition of CO_2. In NE Tanzania the R/Ra values of Ol Doinyo Lengai fumaroles indicates a mantle composition (Fisher et al. 2009, Barry et al. 2013). The Isotopic composition of Lake Natron hot springs (Barry et al. 2013) is dominated by crustal helium but show a small but significant mantle component due to the proximity to Ol Doinyo Lengai, whereas R/Ra of Lake Manyara hot spring (Pik et al. 2006) indicates crustal helium. In W Tanzania noble gas isotope data is only available for Lake Rukwa area (Pik et al. 2006; Danabalan et al. 2016) indicating crustal compositions. Hydrothermal emanations at the floor of Lake Tanganyika (D.R.C.) are characterized by a magmatic carbon isotopic composition of CO_2 (Botz & Stoffers 1993).The implications of a crustal or magmatic helium and/or carbon isotopic composition (and supporting evidence) are discussed concerning the existence of viable geothermal heat sources at individual sites of major Tanzanian geothermal areas.

1. INTRODUCTION

Tanzania is characterized by unique volcanoes like (i) Ol Doinyo Lengai, the only active carbonatite volcano, (ii) Kilimanjaro, the highest African volcano (5895 m) with a glacier on top, (iii) Ngorongoro Crater, the world's largest, intact, and unfilled volcanic caldera and (iv) Igwizi Hills, the youngest Kimberlite on earth. Most of those volcanoes are located within the eastern and western branch of the Cenozoic East African Rift. However, Igwizi Hills volcano is situated in the middle of the Tanzanian craton. Latest helium and neon isotope investigations of lavas and xenoliths (in conjunction with seismic tomography and Sr-Nd-Pb isotope studies) indicate a super-plume beneath East Africa (Halldórsson et al. 2014). Additionally to the distinction between plume and non-plume related volcanism, helium isotope analysis is a versatile tool for relating geothermal resources to any type of volcanic heat source. Isotopic ratios of noble gases ($^{3}He/^{4}He$, $^{40}Ar/^{36}Ar$) are very useful to determine the source of the gases, because they are unaffected by fractionation during degassing of the magma (Fischer et al. 2009).

Also noble gas isotope analyses are especially useful in case of blind geothermal systems (e.g. Dobson et al. 2015; Kraml et al. 2016). In case of samples from hot springs, the residence time of the fluid within the (Precambrian) earth crust will cause an addition of radiogenic helium (^4He) altering the ratio towards more crustal compositions. Therefore, the interpretation of fluid helium isotope data is not as straightforward as $^3He/^4He$ ratios of primary lavas lacking crustal contamination. However, this apparent disadvantage can be turned into an advantage: Within the TRACE research project in the Upper Rhine (non-magmatic) Rift, Germany we have found indications for a relation of residence time and permeability at depth, i.e. the shorter the residence time (→ high $^3He/^4He$ ratios) the higher the permeability (Kraml et al. 2016).

In Tanzania are several distinct areas with significant geothermal surface manifestations: (i) N Tanzania (Mwanza region) e.g. Maji Moto hot spring within the Precambrian Tanzania Craton, (ii) NE Tanzania (Arusha region) e.g. Lake Natron hot springs near Ol Doinyo Lengai within the eastern branch of the East African Rift System (EARS), (iii) central Tanzania e.g. Lake Balangida hot springs within the Manyara-Dodoma segment of the EARS (eastern branch), (iv) E Tanzania (Dar es Salaam region) e.g. Ruhoi hot spring within a sedimentary coastal basin, (v) W Tanzania (Kigoma region) e.g. Uvinza saline springs within the Precambrian basement and (vi) SW Tanzania (Mbeya region) e.g. Songwe hot springs downstream of Ngozi volcano within the western branch of the EARS. The interpretation of helium isotope data from E and SW Tanzania was already published by Kraml et al. (2014a,b). In this paper, only the implications of the helium isotopic composition for the existence of viable geothermal heat sources are discussed for the individual sites of the remaining Tanzanian geothermal areas considering further e.g. petrologic supporting evidence.

2. MATERIALS AND METHODS

Fluid samples include one cold groundwater-well, as well as cold and hot springs. Field parameters (fluid and ambient temperature, pH and EC) were measured with a portable WTW multi-parameter instrument. The soil temperature was measured with a Pt 100 (4-wire) high-precision temperature sensor in a 1 m long stainless steel rod (Greisinger electronic GmbH). Alkalinity was determined via titration on-site and in the laboratory. All samples were filtered (0.45 µm). Cation samples were acidified with concentrated HNO_3 to pH < 2 and analyzed via ICP-OES (Agilent 720). Anions were measured using an ion-chromatograph (Dionex ICS 1100) with a conductivity detector for Cl^-, NO_3^- and SO_4^{2-} and an absorbance detector for Br^-.

Total gas analyses (N_2, O_2, CO_2, CO, H_2, He, H_2S) were done via gas-chromatography with a Thermal Conductivity Detector (SHIMADZU GC-2014 TCD) using argon as carrier gas. Argon was analyzed with a CHROMPACK CP9002 gas chromatograph with micro Thermal Conductivity Detector (µTCD) using helium as carrier gas. Hydrocarbons were analyzed with a SHIMADZU GC-2014 FID gas chromatograph with Flame Ionization Detector. Carbon, hydrogen and oxygen isotopes of methane and carbon dioxide were analyzed via continuous-flow isotope ratio mass spectrometry (CF-IRMS) using helium as carrier gas. For oxygen and hydrogen isotopes of water samples a laser-based cavity ring-down spectrometry (CRDS; PICARRO L2120-i instrument) with liquid injection was used (Ahrens et al. 2013). Noble gas samples were analyzed using a GV 5400 mass spectrometer (Thermo Fisher, Waltham, Massachusetts) at the Institute of Environmental Physics (IUP) in Heidelberg, Germany. The GV 5400 sector field spectrometer including the initial extraction and preparation procedure is described in detail by Friedrich (2007). Further improvements of the procedure are given e.g. in Kaudse (2014).

3. RESULTS AND DISCUSSION

In this chapter the analytical results are presented and discussed together with published data.

3.1 N Tanzania

In Musoma area in northern Tanzania three hot and mineralized springs occur (Figure 1). Nyamosi (= Kogaja) mineralized springs and Maji Moto hot springs were visited and sampled in 2013 (Table 1).

Mananka hot springs near Kitandu, Nyarukamu and Ukiruruma villages are caused by upwelling thermal water along an antithetic fault of the major Utimbaru fault zone (James 1957, 1967).

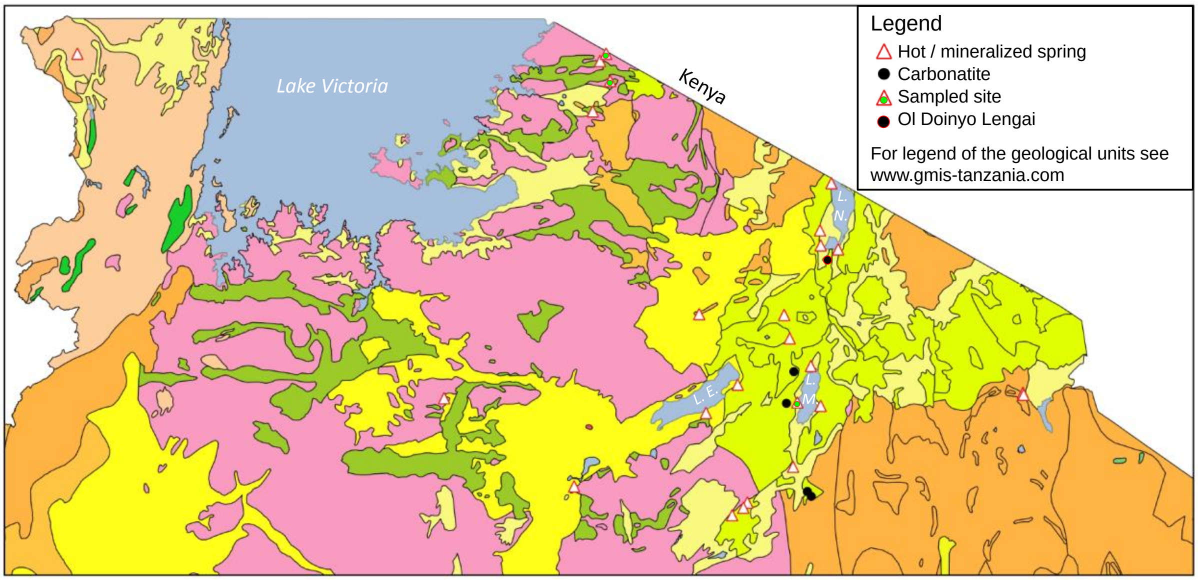

Figure 1: Geological map of northern and northeastern Tanzania (www.gmis-tanzania.com, modified) with sampled sites and further surface manifestations occurring in the region.

Table 1 Field parameters of Kogaja mineralized spring and Maji Moto hot spring. Kogaja mineralized spring is also called Nyamosi spring and is situated in Rorya district, N Tanzania

	Northing	**Easting**	**Elevation**	$T_{ambient}$	T_{fluid}	**El. conduct.**	pH_{field}
	Degree S	Degree E	m	°C	°C	mS/cm	-
Kogaja MS#	1°08.935’	34°16.272’	1330	26.7	26.7	0.97	7.4
Maji Moto HS*	1°37.880’	34°20.679’	1202	28.5	57.7	14.16	9.3
Maji Moto gas§	1°37.862’	34°20.677’	1204				
Maji Moto ww	1°37.780’	34°20.945’	1223				

Soil temperature in 90 cm depth: 24.75 °C; * Wellhead fluid sample (artesian outflow)
§ Gas sampling site (bubbling spring): Soil temperature in 40 cm depth: 59.6 °C

Full fluid chemistry of the Maji Moto and Kogaja samples of northern Tanzania, as well as one hot spring sample from Lake Manyara (NE Tanzania), and the geothermometric evaluation of these new and previously published data are fully presented elsewhere by the Tanzanian Exploration Team. Here only two aspects of the fluid chemistry are mentioned: (i) the implications of the bromine-chlorine ratio (Figure 2a) and (ii) the low-temperatures of the reservoir fluids (Figure 2b). Compared to seawater (0.0033, Hem 1992), the bromine-chlorine ratio of Kogaja mineralized spring as well as Lake Manyara and Maji Moto hot spring waters (0.0036, 0.0035, 0.0033) are equal or only slightly increased, while the Maji Moto shallow groundwater (0.0174) is significantly higher. Therefore, the source of salinity for those samples can be explained by silicate rock-water interaction/fluid inclusion leaching. The source of salinity of Maji Moto hot spring could alternatively or additionally be mobilized fossil seawater.

The chlorine-bromine relation (Figure 2a) even allows for assessing the type of reservoir rock in the basement. The compilation of basement fluids and leaching experiments shows a tendency that low Cl^-/Br^- ratios are indicating mica-rich meta-sedimentary rocks, whereas higher ratios (even up to seawater) indicate magmatic or metamorphosed magmatic rocks (Bucher & Stober 2010). Therefore, we conclude that only the groundwater well in Maji Moto village (= MM ww in 0.53 km distance to MM HS) is tapping water from a mica-rich metamorphic basement rock (e.g. phyllite). Whether the predicted basement rocks of the hot/mineralized springs Maji Moto and Kogaja are in line with mapped outcropping rocks and geophysical exploration data will be presented elsewhere by the Tanzanian Exploration Team.

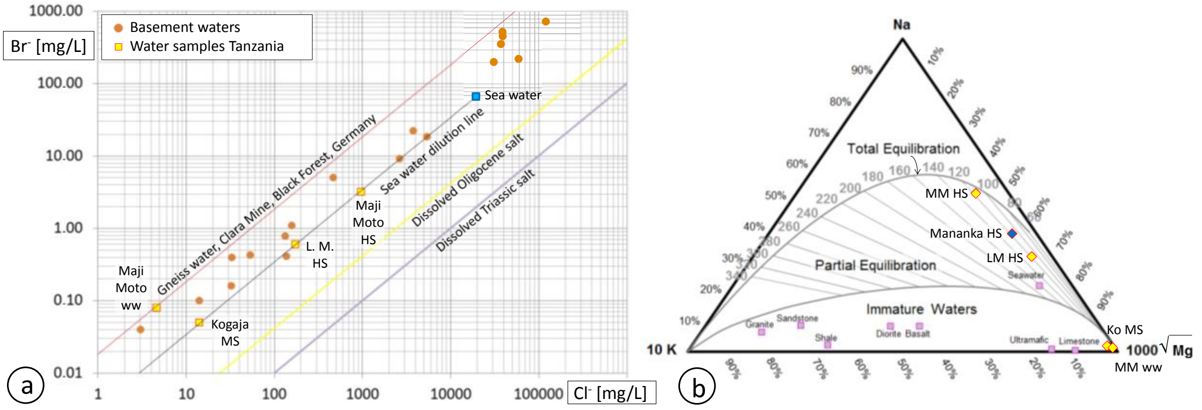

Figure 2: (a) Cl-/Br- ratio of analysed water samples (red line and brown dots representing basement samples (among others from Canadian and Scandinavian Shield) as well as other coloured lines representing dissolved salts are from Bucher & Stober 2010 and references therein). (b) Giggenbach diagram with analysed samples (yellow symbols) and literature data for Mananka spring (James 1957)

Figure 2b indicates low reservoir fluid temperatures <120 °C for the investigated sites. However, conventional geothermometers are developed for high-temperature geothermal systems, situated along convergent-plate boundaries and mid-ocean ridges, and not for the specific boundary conditions as found e.g. in Tanzania (Marini & Pasqua 2014). Reservoir temperatures revealed e.g. by silica geothermometers (chalcedony in the present case for Maji Moto, Mananka and Lake Manyara, respectively) have to be corrected for high pH (9.3, 9.5 and 9.5). Former analyses (not shown) might also be influenced by matrix effects suppressing the Mg signal and causing too low Mg concentrations (→ data points above full equilibrium line). In the special case of Maji Moto and Mananka, K-uptake by montmorillonite clay should be considered to explain the fluid composition. Assuming a minimal geothermal gradient of 3.2 °C/100 m and 20 °C mean ambient temperature, the maximal reservoir depth is 3000 m. The fluid is ascending along faults/fractures, which were encountered by well ddh2 in 35 to 40 m depth. The inflowing water had a temperature of 98 °C, even directly after the drilling had stopped (James 1967). The high initial down-hole water temperature and the initial flow rate dropped because the permeable fractures connected to the drill-hole sealed itself by the inflow of montmorillonite clay (James 1967). The latter was developed by the alteration of an ultrabasic country rock. A similar self-sealing effect was observed at natural Mananka springs (in meta-gabbro), where inactive springs are characterized by little mounts of montmorillonite clay (James 1967).

Table 2 Stable isotopes of oxygen and hydrogen

Sample	**Isotopes (H_2O)**	**Unit**	**Result**	**Standard**
Maji Moto HS	$\delta^{18}O$	‰	-3.90	V-SMOW
Maji Moto HS	δD	‰	-21.0	V-SMOW
Maji Moto ww	$\delta^{18}O$	‰	-2.54	V-SMOW
Maji Moto ww	δD	‰	-10.2	V-SMOW
Kogaja MS	$\delta^{18}O$	‰	-3.26	V-SMOW
Kogaja MS	δD	‰	-16.5	V-SMOW

Stable isotopes of oxygen and hydrogen are reported in Table 2. The Maji Moto hot spring fluid only consists of old depleted groundwater (high water/rock ratio), as also found in groundwater wells and two natural springs within the encircled areas near Kibara and Mwanza at the shore of Lake Victoria (Speke Gulf), but not from nearby Musoma (Figure 3a,b). The reservoir cannot be recharged by juvenile less depleted groundwater represented by the nearby groundwater well in Maji Moto village or recent surface water being affected by evaporation. The detailed structural interpretation of the origin and flow paths of Maji Moto's reservoir fluid considering NE-SW/ENE-WSW trending faults/basins north of Speke Gulf will be given elsewhere by the Tanzanian Exploration Team.

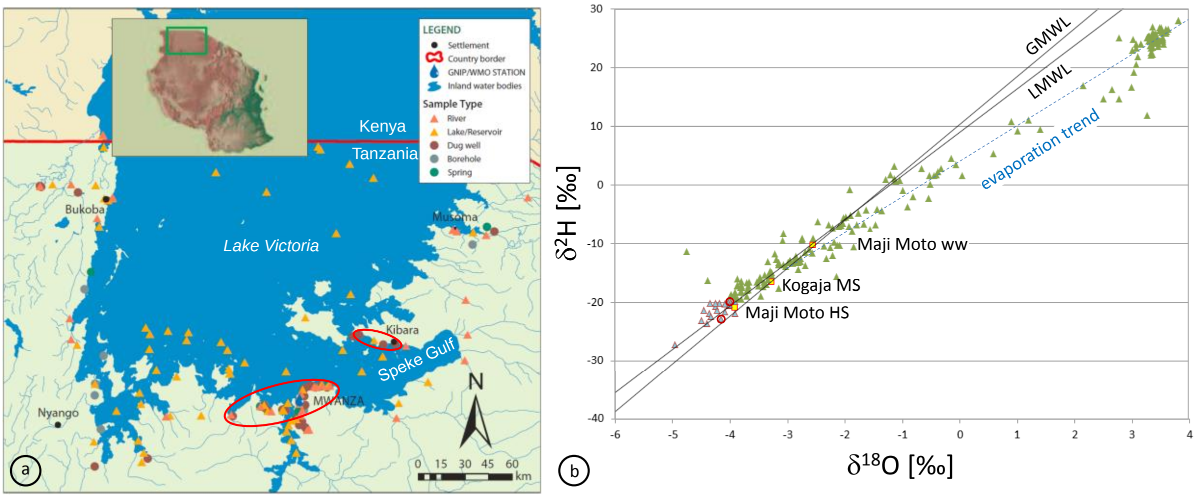

Figure 3: (a) Map of Lake Victoria area (IAEA 2007, modified) and (b) $\delta^{18}O$ versus $\delta^{2}H$ diagram of analysed samples (this study) and water isotope data of IAEA (2007). Encircled blue triangles are two springs (Kayenze-Angabo and Katunguru/Kitunguru) located at southern Speke Gulf near Mwanza. GMWL = Global Meteoric Water Line; LMWL = Local Meteoric Water Line

The composition of the free gas phase of Maji Moto hot spring is reported in Table 3.

Table 3 Results of gas species and isotopic analyses of Maji Moto free gas phase.

Gas species	**Chemical formula**	**Unit**	**Result** $_{measured}$	**Air free** $_{calculated}$
Hydrogen	H_2	vol%	<0.1	<0.1
Nitrogen	N_2	vol%	83.26	84.27
Oxygen	O_2	vol%	3.49	:= 0
Argon	Ar	vol%	1.73	1.89
Carbon dioxide	CO_2	vol%	0.21	0.24
Hydrogen sulfide	H_2S	vol%	<0.05	<0.05
Helium	He	vol%	9.97	11.96
Methane	CH_4	vol%	1.336	1.603
Ethane	C_2H_6	vol%	0.004	0.005
Propane	C_3H_8	vol%	<0.001	<0.001
Isotope analyses	**of gas species**	**Unit**	**Result**	**Standard**
$\delta^{13}C$	CH_4	‰	-33.3	V-PDB
δD	CH_4	‰	-263	V-SMOW
$\delta^{13}C$	CO_2	‰	-14.9	V-PDB
$\delta^{18}O$	CO_2	‰	-26.1	V-SMOW

The major gas species were used for the classification of the gas phase including former gas analyses of James (1956, 1967) and Walker (1969). There are three major groups (i) CO_2-rich volcanic gases, (ii) CO_2-poor, N_2-rich non-magmatic gases and (iii) CO_2-poor, CH_4-rich non-magmatic gases. Once the origin is known, the further evolution of the gas can be assessed (Figure 4). Figure 4a shows that all Ol Doinyo Lengai fumarole gas samples (and gases from other plume-related rift zones) are mixtures between the mantle component and air or ASW. The composition of the rift gases is completely different from subduction zone gases and slightly different to MORB gases. Figure 4b shows the uptake of crustal ^{4}He during increasing residence time within the Precambrian crust. The residence time (He accumulation) is roughly correlated with permeability in depth.

Maji Moto hot spring is characterized by non-volcanic gas (CO_2-poor, N_2-rich), as also indicated by the carbon isotopic composition of CO_2 ($\delta^{13}C$ -14.9 vs. PDB => C4 plants). The root respiration of the C4 plants (C4-Poaceae, Cyperaceae) growing in the near and far surroundings of Maji Moto geothermal site are fully responsible for the small volume of CO_2 (only 0.2 vol%) in the free gas phase. Additionally, the carbon isotopic composition of CH_4 and C1/[C2+C3] ratio (= 300±33; Figure 5a) points to thermogenic methane originating from Kerogen Type II of a marine source rock (meta-sediment?) in the subsurface.

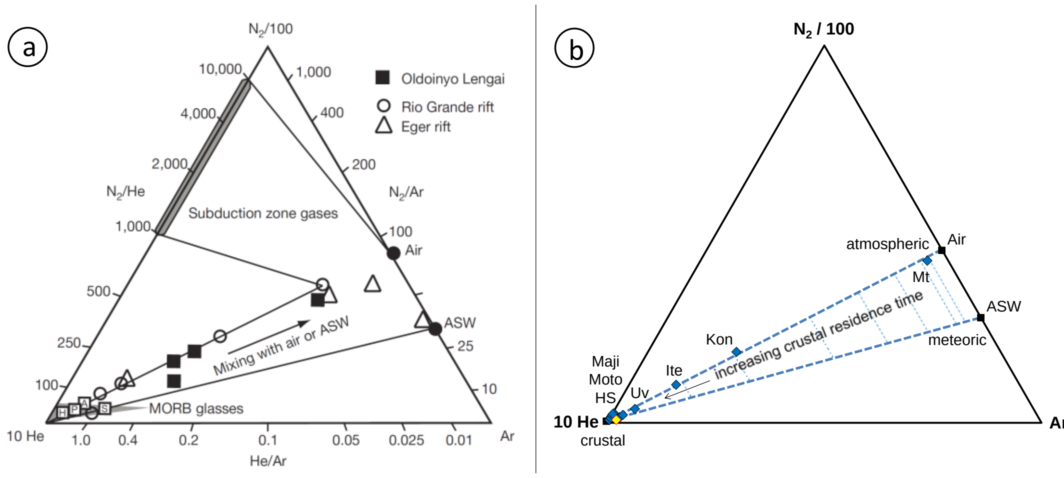

Figure 4: Gas composition of Ol Doinyo Lengai fumaroles (a; Fischer et al. 2009) as well as Maji Moto hot spring (b; data of MM HS this study; diagram after Giggenbach et al. 1983) and Uv = Uvinza; Ite = Itebu; Kon = Kondoa; Mt = Mtagata; The crustal cluster without labels at individual data points (Walker 1969) includes beside Maji Moto (13% He) also Nyamosi (=Kogaja; 18% He), Mananka, Golai (=L. Balangida), Hika, Eyasi, Ivuna, Gonga, Mponde, Takwa and Manyeghi.

In the Schoell-diagram, which is illustrating the hydrogen and carbon isotopic composition of methane (Figure 5b), the Maji Moto data point is within the field of abiotic gas near to thermogenic gas with condensate and microbial gas in an evaporitic environment. Therefore, the origin of methane cannot univocally be resolved solely based on methane isotopic composition. However, hydrogen and carbon isotopic composition of methane shows that the gas cannot be thermogenic with high-temperature CO_2-CH_4 equilibration, which excludes the application of gas geothermometers. High-temperature geothermal methane has a $\delta^{13}C$ generally ranging between -20 and -30‰ vs PDB, while methane, having a different lower temperature origin, shows much more negative values (Panichi et al. 1977).

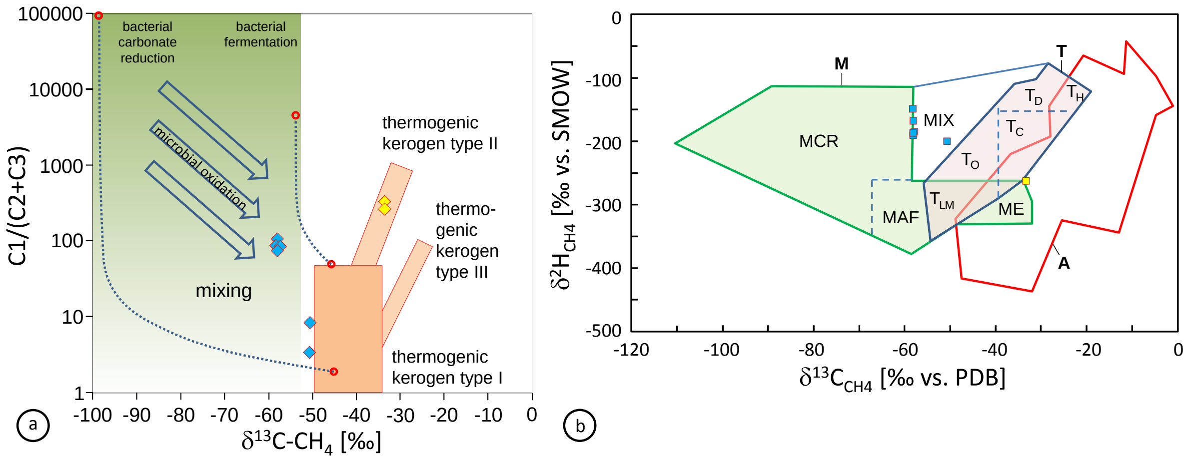

Figure 5: Maji Moto sample (yellow symbols) and data from Lake Tanganyika hydrothermal seepages for comparison (Botz & Stoffers 1993). (a) Bernard diagram, modified after Whiticar et al. (1986). Lake Tanganyika hydrothermal samples are CH_4 mixtures of microbial and Kerogen Type I origin

(from algae and bacteria in lacustrine mud) (b) Updated Schoell diagram (after Etiope & Sherwood Lollar 2013). M = microbial; T = thermogenic; A = abiotic; MCR = microbial carbonate reduction; MAF = microbial acetate fermentation; ME = microbial in evaporitic environment; TO = thermogenic with oil; TC = thermogenic with gas-condensate; TD = dry thermogenic; TH = thermogenic with high-temperature CO_2-CH_4 equilibration; TLM thermogenic low maturity

The noble gas isotopic composition of Kogaja mineralized spring is presented in Table 4 and Figure 6. The $^{3}He/^{4}He$ ratio normalized by atmospheric value R/Ra (= 0.2) is indicating a dominating crustal helium component. The $^{40}Ar/^{36}Ar$ ratio of 302±7 might indicate a small crustal component, but is indistinguishable from atmospheric composition within the analytical uncertainty. However, due to the four orders of magnitude higher atmospheric equilibrium concentration of argon in water compared to helium and a 5-times higher production of radiogenic helium compared to radiogenic argon (see below), argon is the less sensible isotope system and therefore the crustal signature of argon is less pronounced. Atmospheric neon is indicated by the $^{20}Ne/^{22}Ne$ ratio of 9.789 ± 0.004 and the $^{4}He/^{40}Ar^{*}$ ratio of 5 exactly resembles the value for 'average Upper Crust' (see Ballentine & Burnard, 2002).

Table 4 Noble gas isotopic composition of the water from Kogaja mineralized spring in ccSTP/g.

^{3}He	**^{3}He a.u.**	**^{4}He**	**^{4}He a.u.**	**^{20}Ne**	**^{20}Ne a.u.**	**^{22}Ne**	**^{22}Ne a.u.**
9.78 E^{-12}	3.68 E^{-13}	3.56 E^{-05}	2.89 E^{-07}	2.08 E^{-07}	7.30 E^{-10}	2,12 E^{-08}	7.81 E^{-11}
^{36}Ar	**^{36}Ar a.u.**	**^{40}Ar**	**^{40}Ar a.u.**	**^{84}Kr**	**^{84}Kr a.u.**	**^{132}Xe**	**^{132}Xe a.u.**
1.09 E^{-06}	2.64 E^{-08}	3.31 E^{-04}	1.09 E^{-06}	3.81 E^{-08}	5.29 E^{-10}	2.30 E^{-09}	5.53 E^{-11}

a.u. = analytical uncertainty; ccSTP/g = cubic centimetres at Standard Temperature and Pressure per gram fluid

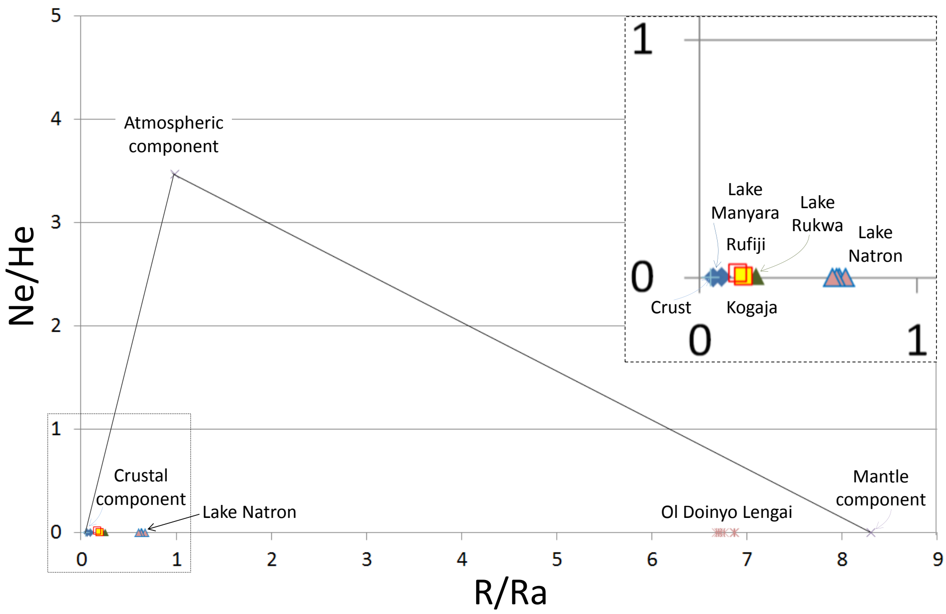

Figure 6: Normalized He-isotopic composition vs. Ne/He ratio (data this study, Pik et al. 2006; Kraml et al. 2014a; Barry et al. 2013; Fischer et al. 2009). The straight line along the x-axis towards the origin represents mixing of mantle and crustal component.

Nitrogen ($^{14}N/^{15}N$ = 270 ≙ $\delta^{15}N_{Air}$ = +7) and argon isotopic compositions ($^{40}Ar/^{36}Ar$ ~ 800) of Maji Moto gas are reported in James (1967). The $\delta^{15}N_{Air}$ of +7 can be explained by the release of nitrogen from old marine (meta-)sediments or an environment similar to the Precambrian crust of Kola Peninsula with its Devonian carbonatites (Dauphas & Marty 1999). The significantly higher than atmospheric $^{40}Ar/^{36}Ar$ ratio indicates the uptake of radiogenic ^{40}Ar during its long residence time in the Precambrian source rock and also implies a pure crustal helium isotopic composition.

3.2 NE Tanzania

The southern termination (splay) of the eastern branch of the EARS is characterized by saline lakes, prominent escarpments and young volcanoes like Ol Doinyo Lengai (Figure 1, 4a). The R/Ra values of Ol Doinyo Lengai fumaroles are indicating a mantle composition (R/Ra = 6.7-6.9, Fischer et al. 2009; R/Ra = 6.8-6.9, Barry et al. 2013). The isotopic composition of Lake Natron hot springs is dominated by crustal helium but show a small but significant mantle component (R/Ra = 0.6-0.7; Barry et al. 2013) due to the proximity to Ol Doinjo Lengai (41 and 43 km distance), whereas R/Ra of Lake Manyara hot springs is indicating crustal helium (R/Ra ≤ 0.1, Pik et al. 2006; see also Figure 6). The mantle origin of Ol Doinyo Lengai gases are supported e.g. by carbon isotopic composition of CO_2 ($\delta^{13}C$ vs. PDB = -2.4 to -4.0‰, Fischer et al. 2009; -2.4 to -2.8‰, Barry et al. 2013) and nitrogen isotopic composition ($\delta^{15}N$ vs. air = -4 to -5‰; Fischer et al. 2009). Lake Natron's carbon isotope values of CO_2 ($\delta^{13}C$ vs. PDB = -3.7 to -4.9‰, Barry et al. 2013) are also in the range of mantle composition and support the small mantle helium component. On the contrary, Lake Manyara's carbon isotope values of CO_2 ($\delta^{13}C$ vs. PDB = -11 to -12‰, calculated from $\delta^{13}C$ values of TDIC given by Casanova & Hillaire-Marcel 1992) are clearly indicating a non-volcanic origin. However, the information from $\delta^{13}C$ values is less straightforward than those of helium isotopes. This is due to e.g. kinetic isotope fractionation caused by preferential ^{12}C incorporation into HCO_3-ions, as long as no saturation of CO_2 is reached and time is not sufficient for establishing isotopic equilibrium (Puchelt 1982).

3.3 W Tanzania

A number of fault-related hot springs exist in western Tanzania (Figure 7). Only four of them (Ivuna, Uvinza, Maji Moto near Usevya, Bulongwe) are partly analyzed regarding the hydrochemical composition (Walker 1969, Pflumio et al. 1994, GMT 1999).

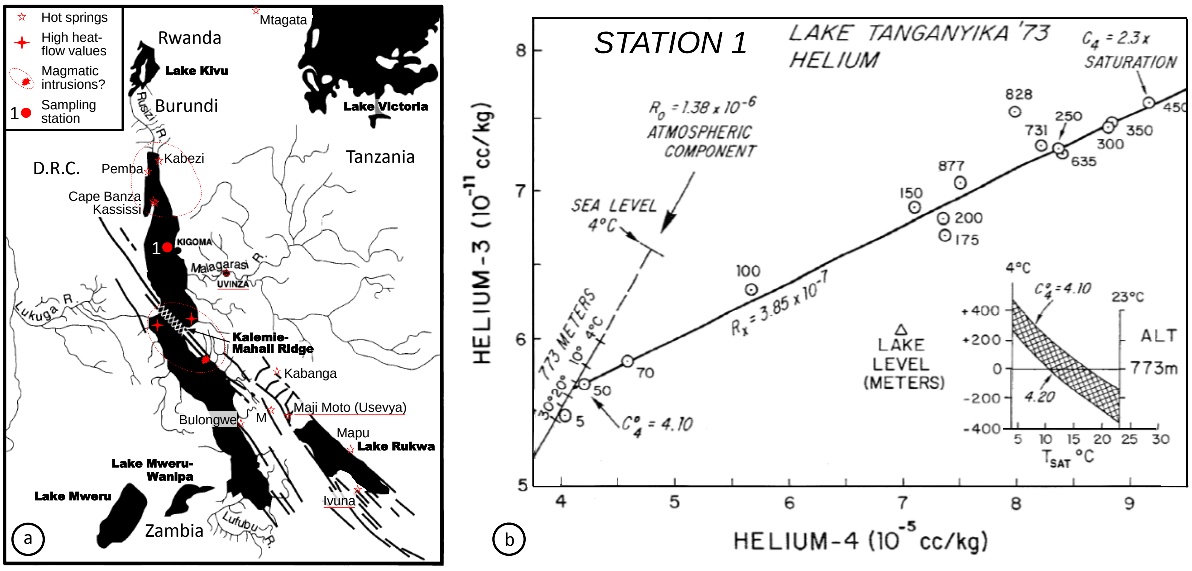

Figure 7: (a) Map of western branch of EARS (after Pflumio et al. 1994 and Coussement et al. 1994 modified and supplemented with locations of Tanzanian hot springs). Lake Tanganyika is showing offshore hydrothermal emanations Pemba and Cape Banza (D.R.C.) and onshore hot springs Kabezi (Burundi) and Kassissi (D.R.C.) as well as hot springs in Tanzania. M = unnamed hot spring at Mtose fault. The geothermal power plant Kapisya in Zambia (0.2 MW) is not shown at the southern tip of Lake Tanganyika. The red dot (station 1) marks the helium isotope profile down to 877m water depth (Craig 1974) and is shown in (b).

Helium isotope data are available for Lake Rukwa area (Ivuna hot spring: Pik et al 2006; Danabalan et al 2016) and Lake Tanganyika (Figure 7b), both dominated by crustal helium. Beside other gases (carbon dioxide, hydrogen sulfide and methane), which are present in the deeper anoxic part of Lake Tanganyika, helium reaches a maximum of 126% supersaturation at 450 m depth in the Kigoma sub-basin (Craig et al. 1974). Excess ^4He concentration is accompanied by a mid-depth minimum of the ^3He anomaly due to injection of Helium with a $^3He/^4He$ ratio (3.85×10^{-7}) lower than atmospheric but also higher than the crustal ratio (Craig 1974; Figure 7b). These findings point to a small mantle ^3He component (R/Ra = 0.28), which is characteristic for non-volcanic rifts (Kraml et al. 2016). However, so far no noble gas samples were taken from the hydrothermal emanations discovered at the floor of Lake Tanganyika (Cape Banza and Pemba).

Uvinza and Ivuna springs are both utilized for salt mining by evaporating the highly saline fluids (e.g. Uvinza: Cl^- = 105,690 mg/l, Walker 1969). Similarities exist not only between Uvinza and Ivuna fluids, but also to Cape Banza fluid and the more diluted Maji Moto (Usevya) fluid. The intensively studied Cape Banza Na-Cl fluids are derived from mixing between meteoric water and a deep-seated basement brine similar to the ones found in old continental shields all over the world (Pflumio et al. 1994; Bucher & Stober 2010). This is supported in case of Ivuna by a R/Ra-ratio of 0.23 and 0.26 (Pik et al. 2006), typical for non-volcanic extensional settings (Kraml et al. 2016; Kennedy & van Soest 2007).

3.4 Discussion of viable heat sources

The following Tanzanian geothermal systems are magmatically heated due to proven young activity of their host volcano: Kilimanjaro (Hochstein et al. 2000), Meru (not investigated so far concerning existence of a viable geothermal system), Ol Doinyo Lengai (see below) and Ngozi (Kraml et al. 2014b). The majority of the geothermal surface manifestations indicate fault-related low-temperature resources as discussed below.

3.4.1 Lake Natron area

In case of the active Ol Doinyo Lengai volcano it is evident that a magmatic heat source exists, as it is also indicated by the helium isotopic composition of the fumarole gas (Fischer et al. 2009). However, one has to take the following volcanological/petrological arguments into consideration. Carbonatite-related fenitisation provides evidence for an intrusive carbonatite body beneath Ol Doinyo Lengai, which has not previously been reported (Carmody 2012). Fenitisation processes require a carbonatite body with a long residence time within the crustal regions in order to release fluids capable of altering the surrounding rock units. Fenitisation takes place in 35 km at 600 °C and is caused by a CO_2-rich carbonatite melt (lack of amphibole and mica indicate water undersaturated conditions). Combining the results of Carmody (2012) with those of Morogan (1994) expands the depth range down to 50 km and the formation temperatures up to 800 °C. Additionally, a maximum depth of fluid trapping at 29 km was received adding the results from fluid inclusion studies (Carmody 2012).

In summary, an intrusive carbonatite body is expected roughly between 30 and 50 km depth at temperatures between 600 and 800 °C. However, this sustainable heat source is not located in shallow crustal depth and therefore not suitable for driving a geothermal system. Fischer et al. (2009) showed that the noble gases of Ol Doinyo Lengai were not released by the carbonatite melt but by the alkali-basaltic silicate magma, which is not forming a crustal magma chamber. Additionally, the amount of silicate melt injected into the crust is very limited and even the young surrounding maars are explained by gas explosions and not by the contact of ascending melt with shallow ground water (Berghuijs & Mattsson 2013). The latter was also suggested for the maars in Lake Balangida area further to the south (Delcamp et al. 2015). Therefore, those low volume injections of alkali-basaltic magma into the crust are not capable of driving a geothermal system in the subsurface, which can be reached by drilling. This is a fundamental difference to the high magma volumes of highly differentiated composition (trachytes, phonolites) forming high-level magma chambers, which are sustainably driving viable geothermal systems e.g. in Kenya and Ethiopia.

3.4.2 Lake Victoria area

The small fault-related geothermal systems in north Tanzania (like Maji Moto, Musoma) are located within the Precambrian basement (basic rocks) and are affected by self-sealing via expandable clay minerals. No magmatic heat source is indicated neither by exploration data of this study nor by evaluated data of the cited references. Therefore, the geothermal development potential is rather limited. Also the development potential for producing helium (the intention of the drilling activities in the 1950s) is sub-economic because the helium has no possibility to accumulate in contrast to sites being sealed by extended lacustrine clay layers in the rift basins (Danabalan et al. 2016).

3.4.3 Lake Manyara area

There is no indication for a magmatic heat source at Lake Manyara neither by the carbon isotopic composition of CO_2 (see above) nor by the He isotopic composition (Pik et al. 2006).

3.4.4 Lake Tanganyika and Lake Rukwa area

Geothermometric estimates of sublacustrine hydrothermal vents (53-103°C) at Lake Tanganyika have yielded reservoir temperatures of >200 °C for samples of the $NaHCO_3$-Pemba and NaCl-Cape Banza geothermal systems, respectively (Tiercelin et al. 1993, Pflumio et al. 1994). However, the fluid geothermometric data is not conclusive. Rare earth element patterns (only available for Cape Banza; Barrat et al. 2000) do not show a positive cerium anomaly as expected for high-temperature fluids. Crustal strontium isotope data of Cape Banza fluids are more radiogenic than those of the lake, confirming the basinal brine component in the fluid mixture (Barrat et al. 2000). The only indication for a magmatic heat source is the $\delta^{13}C$ range of CO_2 (Botz & Stoffers 1993), which might indicate a subvolcanic alkali-basaltic dike intrusion. However, this possible intrusion is not yet confirmed by high mantle helium concentrations. A magmatic helium signature at Pemba would have implications also for geothermal systems on the Tanzanian side of Lake Tanganyika (Figure 7a). Uvinza (crustal gas composition, Walker 1969; long residence time, Figure 4b) and comparable Ivuna basinal brines (dominating crustal He isotope composition, Pik et al. 2006) are without magmatic heat source. However, direct heat use could enhance salt production at Ivuna site during the rainy season.

4. CONCLUSIONS

Future fluid analyses should cover bromide to assess the origin of salinity of low-temperature brines. The major gas and carbon isotopic composition of CO_2 gives a first indication on a possible magmatic origin of the gas, but due to various and abundant fractionation affects, noble gas isotope analyses should confirm those preliminary findings (e.g. for Pemba, Lake Tanganyika). The investigated sites in northern and northeastern Tanzania (Maji Moto, Kogaja and Manyara) are characterized by the absence of a volcanic heat source. The geothermal systems are related to fluid flow along permeable fault zones (affected by self-sealing effects in case of Maji Moto). In north-eastern Tanzania Ol Doinyo Lengai represents only a weak magmatic heat source deduced from volcanological/petrological data. Mount Meru, which might host a volcanically heated viable high-temperature geothermal system, should be explored to close the data gap. Also the numerous fault-related low-temperature resources – which are not volcanically heated – can contribute to Tanzanian energy supply by delivering sustainable power via binary power plants with high supply security in rural and touristic areas.

ACKNOWLEDGEMENTS

We thank the Tanzanian Exploration Team, namely Taramaeli Mnjokava (GST) for inviting and organizing the field trip, Dr Jean Mujumba (UDSM) for fluid sampling and alkalinity titration in the field, Prof. Abdulkarim Mruma (head of GST) not only for providing a 4WD vehicle, technician Stephen Mjemah (GST) for support in sampling and soil temperature measurements, as well as the driver of GST for safe transport, and the local police for escorting our team near North Mara Mine. We also thank Dominique Leible (GeoT) for assistance with GIS and Marco Jodocy (GeoT) for polishing up the English text.

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