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Results of the Pre-Feasibility Study on Ngozi Geothermal Project in Tanzania

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ABSTRACT

Systematic field work of GPT in 2012 and 2013 revealed new indications concerning the geological setup of the Ngozi-Songwe geothermal system. The progress in respect of the high-temperature Ngozi conceptual model was achieved by analyses of two further travertine occurrences (complementing data to major Songwe travertine occurrence) as well as fluid and isotope analyses of formerly only poorly studied hot springs which also belong to the Ngozi-Songwe geothermal system. Beside newly sampled rivers and one water well, three new cold springs were discovered and sampled during the field surveys. Stable isotope analyses of those additional surface waters further constrained the different fault-related fluid pathways and were useful to define the recharge area of the system. Due to a second geophysical survey of BGR during GEOTHERM project phase II, 30 magnetotelluric soundings (MT) and 50 transient electromagnetic soundings (TEM) were used for the updated resistivity model. Based on that model and the new geological/geochemical results of GPT, the previous conceptual model was refined and a site was selected for the first deep slim-hole exploration well. GPT's well path planning objective is to penetrate the clay cap of the high-temperature reservoir to calibrate the resistivity model and perhaps even to tap the top part of the reservoir. Planning was also done on (i) selecting a suitable access road, (ii) preparation of the well pad incl. drilling water supply and (iii) technical drilling plan as well as (iv) putting-up a logging and testing program. A suitable drilling rig also for taking drill cores was acquired and is currently stored in Mbeya town about 12 km apart from the drill site.

1. INTRODUCTION

Tanzania is characterized by several high- and low-temperature resources which are reviewed e.g. by Hochstein et al. (2000) and Kraml & Kreuter (2013). One of the most promising geothermal areas is located in Mbeya Area, situated in the southwestern region of the country.

Mbeya Area is located within a rift-rift-rift triple junction (Rukwa Basin, Karonga Basin and Usangu Basin; Delvaux & Barth, 2010; for evolution of the rift see also Roberts et al., 2012) and characterized by the Rungwe volcanic province which is caused by mantle plume activity (up to ~15 R/Ra; Hilton et al., 2011) during Quaternary times (Fontijn et al., 2012). Four major geothermal areas with different characteristics can be distinguished: The northern high-temperature Ngozi-Songwe system (drowned fumaroles, hot springs, thermogene silica bearing travertine, CO_2 emanations etc.), the southern bisected area along Mbaka intra-basin fault and another area in the south with two prominent fault-related chemically similar hot springs (travertine, CO_2 emanations) near the western escarpment of the Karonga Basin (Mwampulo and Kasumulu).

Based on results of earlier investigations, the first geothermal project development by GPT focused on Ngozi volcano and on the southern section of Mbaka fault, respectively. The present paper describes the progress achieved in respect of understanding the high-temperature Ngozi-Songwe system.

During the Tanzanian/German technical cooperation project GEOTHERM phase I, a first conceptual model for the Ngozi-Songwe system was put up (Kraml et al., 2008) and presented at WGC 2010 (Kraml et al., 2010; Kalberkamp et al., 2010; Delvaux et al., 2010). During GEOTHERM phase II further resistivity measurements were done in July/August 2010 and jointly inverted to constrain the resistivity model as well as used for siting temperature gradient wells (Ochmann et al., 2012). Latest surface exploration in 2013 by GPT led to a refinement of the conceptual model which also considers the results of latest research activities in the Mbeya Area (e.g. Barry et al., 2013; de Moor et al., 2013) and the GEOTHERM phase II geophysical results. GPT's latest surface exploration in Mbeya Area, mainly comprising geological field work and geochemical sampling, took place between January 2012 and July 2013. Additionally, detailed on-site planning for the first deep exploration well including a well pad at Ngozi took place in August 2013. The main goal of GPT's latest field and analytical work was to refine the conceptual model and to define locations of deep exploration wells to tap the Ngozi System.

2. MATERIALS AND METHODS

During the geochemistry field surveys, rock, fluid and gas samples were taken in order to characterize the spatial structure, the flow paths and the recharge areas of the Ngozi Geothermal System. Geological investigations mainly included detailed (GPS supported) mapping of surface manifestations (mainly travertine and hot/mineralized springs). The concept of using travertine deposits to investigate active faults is described in Hancock et al. (1999). The strategy of the geology and geochemistry survey was to revisit poorly studied sites for supplementary sampling and to look for new springs predicted from the knowledge of the local fault pattern. The strategy of the isotope hydrology survey was to increase the number of sampling points for a denser data grid.

Rock samples were taken from representative fossil travertine outcrops. Samples of recent travertine with corresponding measured spring temperature were used to calibrate the precipitation temperature calculations. The influence of Mg-content in calcite and the influence of aragonite on the precipitation temperatures were corrected (Jiménez-Lopez et al., 2006; Tarutani et al., 1969 and Kim et al., 2007). Further details are given in Leible (2014).

Mineralogical, geochemical and isotopic composition of the travertine was determined using: (i) X-ray diffraction (XRD), (ii) wavelength dispersive X-ray fluorescence (WDXRF), (iii) energy dispersive X-ray fluorescence (EDXRF) and (iv) isotope ratio mass spectrometry (IRMS).

Systematically taken fluid samples include rivers, one water-well, as well as cold and hot springs. Field parameters (fluid and ambient temperature, pH and EC) were measured with a portable multi-parameter instrument (WTW Multi 3480) equipped with a NTC 30 kΩ temperature sensor, pH probe SenTix® 980 and electric conductivity probe TetraCon® 925. Chemical and isotopic analyses of the fluids were conducted by applying the following methods: (i) alkalinity titration, (ii) ion-exchange chromatography, (iii) ultraviolet visible (UV/Vis) spectroscopy, (iv) inductively coupled plasma mass spectrometry (ICP-MS), (v) inductively coupled plasma optical emission spectrometry (ICP-OES), (vi) thermal ionization mass spectrometry (TIMS) and (vii) cavity ring-down spectrometry (CRDS). The majority of the laboratory analyses mentioned above was performed at the Karlsruhe Institute of Technology (KIT), Germany.

Low-level Tritium analyses (mass spectrometrically via ^{3}He) and helium isotope analyses were done at the Institute of Environmental Physics (IUP) in Bremen, Germany (for full procedure see Sültenfuß et al., 2009).

During the geophysical survey magnetotelluric soundings (MT) have been carried out in the area of Ngozi-Songwe geothermal system. MT data are prone to galvanic distortions exhibited as frequency-independent static shifts of the apparent resistivity curves. The transient electromagnetic (TEM) method has been used as a shallow-depth (< 1,000 m) remedy in MT static shifts correction (Irfan et al, 2010; Rosenkjær, 2011).

3. RESULTS AND DISCUSSION

3.1 Field Evidence

Three new mineralized springs were discovered along known SE-NW directed faults (Sawa, Kagera and Nzovwe; Figure 1a), further confirming the established hydraulically active flow-paths in NW direction.

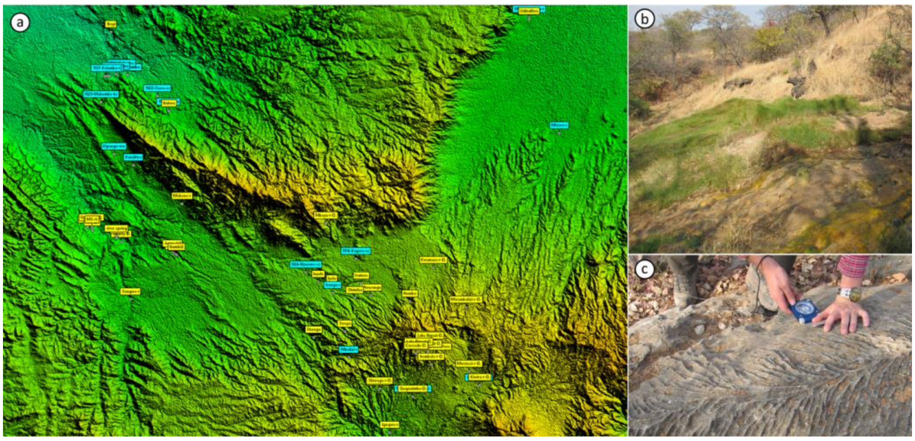

Figure 1 (a) ASTER GDEM with sampling locations relevant for Ngozi-Songwe geothermal system; yellow marked sites are from previous sampling campaigns (mainly Kraml et al., 2008 and Delalande 2009) and blue marked sites were sampled by GPT in 2013. (b) Mahombe hot springs with north-westernmost spring in the foreground (66.2°C). Second and third spring is situated in the middle-ground covered by "geothermal grass" (*Fimbristylis exilis*) and fourth spring is hidden in the little valley in the background. (c) Fossil Kalambo travertine with typical grooves on top of the massive layers was deposited on the slope at the termination of Mbeya Range.

Mahombe hot springs (Figure 1b) could not be fully analyzed previously (only major cations from an acidized sample sent to BGR laboratory). The first set of samples taken by GPT in July 2013 allowed for a full chemical and stable isotope analyses (see below). The low total flow rate of roughly estimated 5 l/s and fluid temperatures between 66.2 and 48.7°C (33.8°C ambient temperature) result in about 0.5 MW_{th} convective heat loss. Ikukwa mineralized spring is characterized by a fluid temperature of 28.0°C and an ambient temperature of 22.7°C adding only little heat discharge.

In contrast to Kalambo (Figure 1c), fossil Udindilwa travertine is weathered and occurs in form of one small mount beside active hot springs within a swampy area. Well known Songwe travertine was intensively studied by Pisarskii et al. (1998) and during the GEOTHERM technical cooperation program phase I (e.g. Wittenberg et al., 2007; Kraml et al., 2008) concerning its significance and implications for geothermal energy utilization.

To locate the leak of Lake Ngozi water at the southern flank of Ngozi volcano some rivers which originate at the uppermost part of the flank (Figure 2) were investigated during the dry season. The three rivers to the East of Gogozimba River were dried out and all other samples of flowing rivers were characterized by low chlorine concentrations (<4mg/l) except for the downstream part of Gogozimba (29 mg/l) and "Igogwe" (252 mg/l). This implies that the breached caldera wall (Fontijn et al. 2010) releases lake water most likely within the magenta encircled area at the origin of "Igogwe". An order of magnitude smaller contribution of Lake Ngozi water is leaking into Gogozimba River downstream of uppermost sampling point (orange encircled). Kiwira River sampled upstream of the confluence with Mwatesi river (Figure 2) is characterized by low solute concentrations (<4mg/l) in contrast to the downstream sampling point South of the confluence with "Igogwe" river (i.e. South of the map section shown in Figure 2; 42mg/l). A further field survey is recommended to precisely locate the first input of saline Lake Ngozi water into Gogozimba river and for tracing of the related fault.

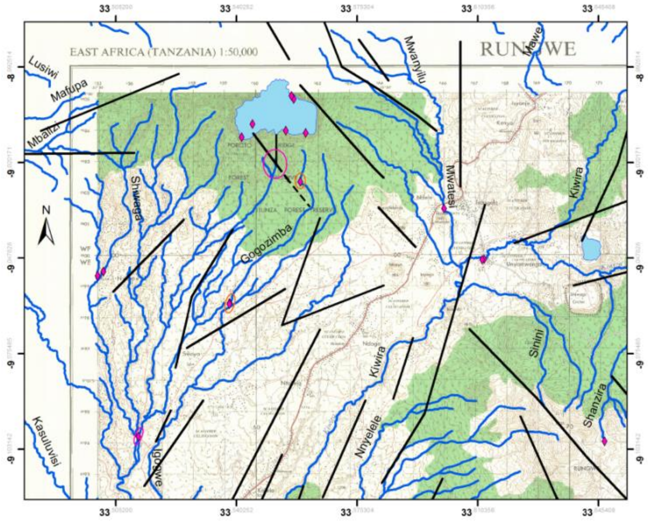

Figure 2 Rivers originating at the flank of Ngozi volcano. Magenta colored diamond symbols represent sampling points of Kraml et al., 2008, Delalande, 2009 and this work. The fault pattern is schematically adopted from Delvaux et al. (2010).

In this context earlier field observations are worth mentioning. During a bathymetric survey in 2007 by MEM/TANESCO/BGR during GEOTHERM project phase I, an 80 m high cone was detected in the middle of the lake almost reaching the water surface. This cone was interpreted as volcanic cone by Kraml et al. (2008) related to post-caldera activity of Ngozi. Maybe during the Karonga earthquake in 2009, at the same time when a part of the western rim of Ngozi caldera collapsed, the cone was wiped out and the central part of Lake Ngozi with water depths > 75 m was filled up with cone material and caldera wall material. A temperature survey done by MEM/TANESCO/BGR in 2009 at the bottom of the lake gave several temperature anomalies up to 90°C (Jolie 2009, oral communication). Those anomalies are interpreted as drowned fumaroles (this study). The hydrological budget (source of salinity) of Lake Ngozi is addressed in detail by Delalande et al. (2014, submitted).

2.2 Travertine Samples

3.2.1 Travertine's mineralogy, geochemistry and isotopic composition

The main mineral phase of the analyzed travertine samples is calcite with varying Mg-content. Additionally, minor components or traces of dolomite and ankerite (Kalambo), aragonite (Udindilwa) and quartz (Songwe) were proven by XRD analyses (this study and Kraml et al., 2008). In a systematic study of Pisarskii et al. (1998) it was shown that most Sr-rich Songwe travertines (Sr: 4.6 to 6.2wt.% !) are characterized beside Mg-calcite also by the minerals aragonite and strontianite forming a continuous isomorphous series. The content of most prominent trace element Sr in the travertine analyzed in the frame of this study ranges up to 1.7wt.% in case of Udindilwa sample due to the occurrence of aragonite as minor mineral phase. The high Sr content is in accordance with the finding of Whittaker and Muntus (1970) and Pingitore and Eastman (1984) that the trigonal calcite lattice is not able to accommodate Sr in its crystal structure in contrast to the orthorhombic lattice of aragonite. Pisarskii et al. (1998) interpret the high Sr content as being the result of Sr enrichment in the travertine precipitating fluid during the leach of Panda Hill carbonatite intrusion. This implies that Panda Hill is situated along the fluid pathway in the outflow zone of Ngozi-Songwe-System.

In contrast to all other samples, Songwe travertine contains microcrystalline quartz which is called 'onyx' by the local ornamental stone miners. Silica in massive Songwe travertine of up to 14% SiO_2 (up to 25% in porous samples) has also been documented by Pisarskii et al. (1998) implying a high-temperature reservoir above 175°C (Fournier & Rowe, 1966; compare also Lynne, 2013). Silica needs 10,000 to 50,000 years for changing from amorphous to microcrystalline phase (Herdianita et al., 2000) implying a Pleistocene age of the travertine deposit (see below).

There are no significant differences in major and trace element pattern of Kalambo, Udindilwa and Songwe travertine samples. However, Songwe travertine is more enriched in trace elements than Udindilwa and Kalambo. The enrichment of the same trace elements in Songwe Travertine as in the Panda Hill Carbonatite (e.g. Zr, Ce, F, Nd) can be attributed to the leaching process postulated by Pisarskii et al. (1998).

The stable oxygen and carbon isotope composition (Figure) of the three Ngozi-Songwe travertine occurrences points to purely thermogene travertine precipitating conditions (*sensu* Pentecost 2005). The trend to heavier isotopic compositions is caused by decreasing precipitation temperatures (see below). Songwe and Kalambo samples are defining a common trend with the carbonatites, whereas the Udindilwa sample is shifted to heavier oxygen and lighter carbon isotopic compositions. The latter can be attributed to the local precipitation conditions i.e. admixture of evaporated water of the swamp and CO_2 from abundant c4 plants (reeds and sedges) during a pluvial highstand.

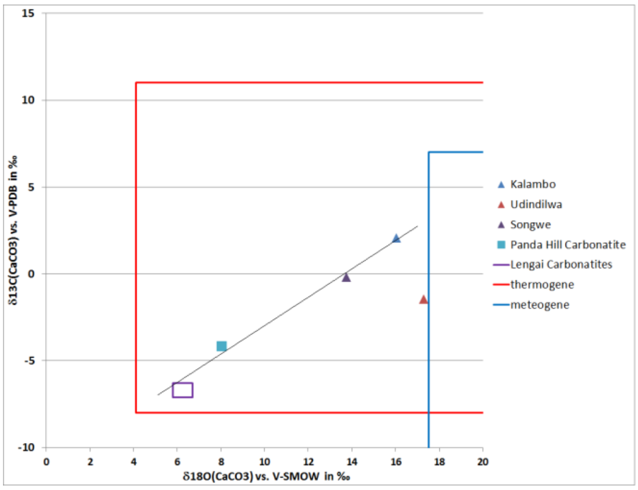

Figure 3 Stable isotope values of the travertine samples Kalambo and Udindilwa (Leible 2014), Songwe (Kraml et al., 2008), as well as Panda Hill and Ol Doinyo Lengai carbonatite box (Kraml et al., 2008 and Keller & Hoefs, 1995) for comparison. Limits of the red (thermogene) and blue (meteogene) travertine boxes are taken from Pentecost (2005).

3.2.2 Precipitation Temperatures of the Travertine

Songwe Travertine precipitated at 83°C (using equations of Friedman & O'Neil, 1977 and Démeny et al., 2010) and thus reflects the highest precipitation temperature of all fossil samples taken. This is in accordance with maximum temperatures of active hot springs reaching 80°C (Hochstein et al., 2000; Kraml et al., 2008). The longevity of the Ngzoi-Songwe high temperature geothermal system is documented by the occurrence of fossil Songwe travertine (>150 million m^3, Hochstein et al., 2000). U/Th disequilibrium dating of Songwe Travertine from different stratigraphic levels yielded 310±10 ka and 380±40 ka (Kraml et al., 2008). Kalambo travertine is characterized by a calculated precipitation temperature of 70°C. Dating of Kalambo travertine is recommended to reveal the age relation of the two major thermogene travertine fields of the Ngozi-Songwe system. Udindilwa travertine sample, located 43 km to the North of Ngozi Caldera in Usangu Basin, revealed 56°C.

3.3 Water Samples

3.3.1 Water Chemistry

First full chemical analysis of Mahombe hot spring confirmed that Mahombe belongs to Ngozi-Songwe geothermal system. Hot springs of Ngozi-Songwe System result from a common reservoir fluid which is diluted to a different degree. Mahombe hot springs are characterized by 27.1% and Songwe hot springs by 36.3% reservoir fluid. Detailed evaluation of conservative element ratios of all fluids of Ngozi-Songwe System revealed that carbonatites play an important role in fluid-rock interaction along the outflow zone but not in the area of the upflow zone (Figure 10).

The fluids of Songwe and Mahombe springs differ from those of Ngozi caldera lake, because of the special lacustrine environment (see Kraml et al., 2010) and the missing carbonatite in the subsurface of Ngozi, which would explain the lower Cs/Cl and Rb/Cl-ratios of Ngozi lake water. Furthermore, aragonite precipitation around the "hot vents" efficiently removes the Strontium in the lake water causing lowest Sr/Cl ratios (Figure 4).

Within the Ngozi-Songwe System the different fluid samples provide information concerning their flow paths in respect of trace elements (Figure 4). Carbonatite outcrops occur along possible flow paths of Songwe hot springs (Panda Hill & Sengeri Hill carbonatite) and Mahombe hot springs (Mbalizi & related Mbeya Range carbonatite).

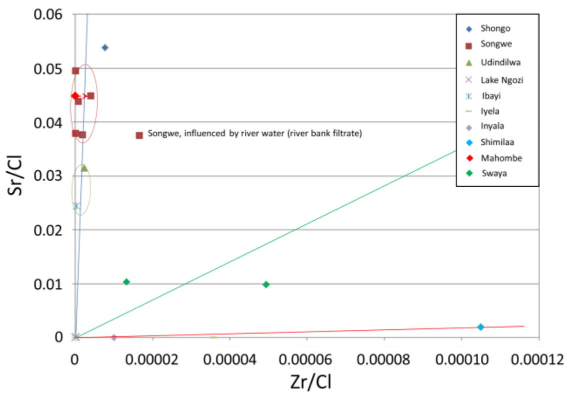

Figure 4 Sr/Cl vs. Zr/Cl diagram to distinguish between individual flow paths of the Ngozi-Songwe System.

3.3.2 Geothermometry

Ngozi-Songwe System is related to a high enthalpy reservoir (>200°C) as mentioned by previous authors (e.g. Hochstein et al., 2000; Mjnokava, 2007, Kraml et al., 2010). Mahombe hot springs further constrain the high reservoir temperatures. An intensive data assessment was recently done by one of the co-authors (Kling 2014) including silica-enthalpy mixing models. The latter indicate that fluids of the Ngozi-Songwe System significantly cool down (<150°C) along their long flow paths.

3.3.3 Isotope Hydrology

The newly analyzed samples have significantly enhanced the database for constraining the recharge areas of the Ngozi-Songwe geothermal system (Figure 5).

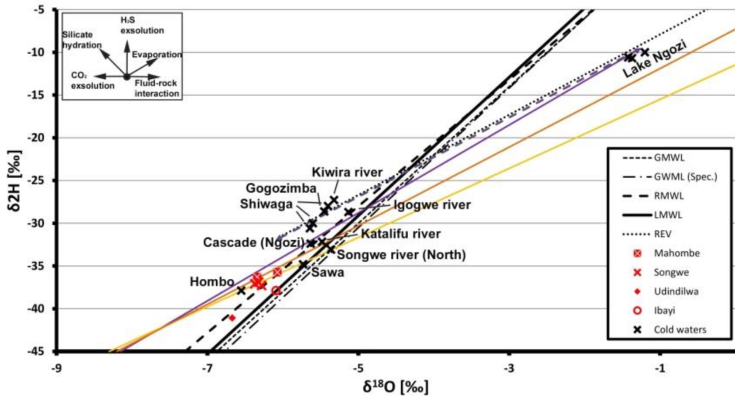

Figure 5 δ^2H vs. $\delta^{18}O$ diagram for the Ngozi Songwe System (dry & rainy season), considering hot springs and associated surface waters. Colored lines show the linear correlations between surface waters and associated hot springs: yellow = Songwe hot springs, orange = Mahombe, purple = Lake Ngozi. The dashed purple line starting from Lake Ngozi suggests an assumed trend of Ngozi Lake water to Kiwira river water due to a leakage on the southern slope.

In Figure 5 the linear trend (yellow line) defines the Northern Songwe River and Songwe hot springs, which are mostly located in immediate proximity to the river. A further linear correlation (orange line) can be observed for Mahombe springs and Katalifu River, which is supposed to represent surface waters of the northwestern flanks of Mbeya Range close to Mahombe. A third linear correlation (purple line) is assumed for Lake Ngozi, Igogwe River and Ngozi groundwaters ("Cascade"). Igogwe River, which is expected to be fed by Lake Ngozi water due to a leakage on the southern caldera-slope of Ngozi, is plotting between "Cascade" and the lake water. Additionally, a closer inspection indicates that the local evaporation line of Lake Ngozi slightly differs from the Regional Evaporation Line (REV) by exhibiting a steeper slope.

Based on the total data acquired in this study the recharge areas of the Ngozi-Songwe-System can be determined according to the isotope composition of the involved waters (Figure 6). All other possible fluid pathways could be excluded by contradicting isotopic compositions and due to structural reasons.

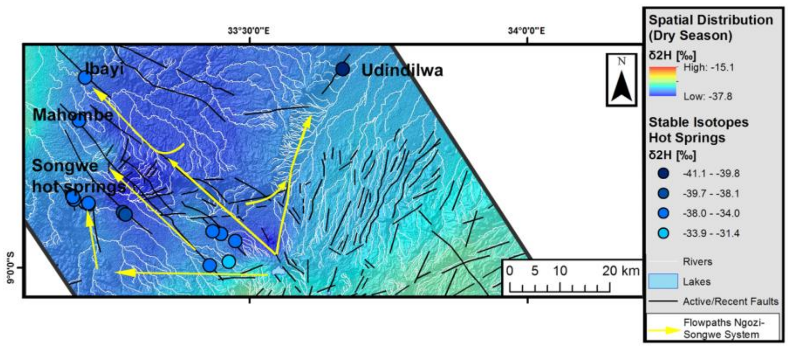

Figure 6 Schematic model of the reconstructed recharge areas and flow-paths of the Ngozi-Songwe geothermal system derived from isotope hydrological and geothermometrical data.

Regarding the Ngozi-Songwe-System, the recharge is provided only from the northern and eastern flanks of Ngozi volcano. Rivers of the southern flanks can be excluded due to their way to the south in direction of Lake Nyassa and due to their isotope values (cf. Figure 6). This setting is summarized in the new conceptual model below based on a fault connected fluid flow of all springs observed.

3.3.4 Isotope Geochemistry

The Sr and Nd isotopic composition of Songwe travertine as well as Sr isotopic compositions of fluids from Ngozi-Songwe geothermal system show that Ngozi geothermal reservoir is located in the lowest part of the Ngozi volcano at the contact to the crystalline basement. Without Nd isotope measurements of Songwe travertine sample it would not have been possible to identify the basement component (Figure 7).

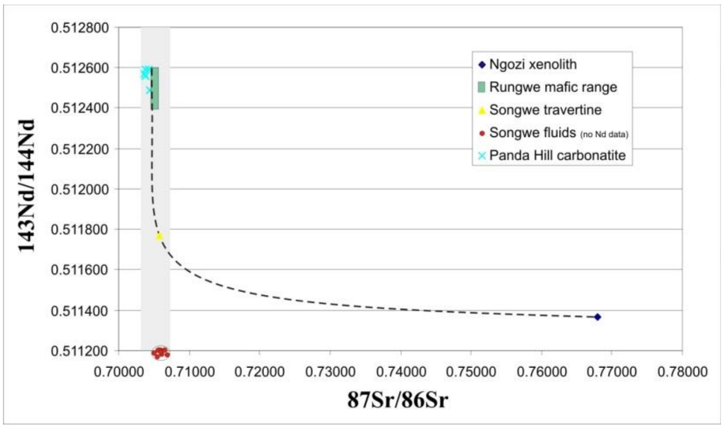

Figure 7 Nd versus Sr isotope diagram showing a small influence of the basement gneiss on the isotopic composition of Songwe travertine (data from Kraml et al., 2008). Data of Rungwe volcanic province are from Graham et al. (1995) and additional data of Panda Hill and Sengeri Carbonatite are taken from Bell & Blenkinsop (1987) and Morisset (1992). No Nd isotope ratios could be analyzed in the fluids due to too low Nd concentrations. The $^{87}Sr/^{86}Sr$ data range marked in grey color indicates mantle values.

3.4 Gas Samples

3.4.1 Gas species

Gas compositions of bubbling hot and cold springs in Mbeya area are dominated by the presence of volcanic CO_2 (Kraml et al., 2010; Delalande et al., 2011; de Moor et al., 2013). In the latest systematic gas study of de Moor et al. (2013) Songwe hot springs are characterized as travertine springs on the basis of the relation of gas species CO_2, H_2S and CH_4. The authors also intensively discuss CO_2-N_2-Ar-He systematics and nitrogen isotope compositions and conclude that samples collected from Songwe springs have highly variable He contents, N isotope compositions, and tracer gas ratios. The responsible processes modifying pristine mantle signatures are He loss, organic CO_2 addition, biogenic/sedimentary N_2 addition and/or removal of CO_2 due to travertine precipitation (de Moor et al., 2013). Organic CO_2 addition was especially found in samples with low gas flow-rate (e.g. Swaya) and could be detected by simple linear two component diagrams (CO_2 versus N_2) and carbon isotopic compositions (Kraml et al., 2010).

3.4.2 Noble Gases

The young-Quaternary Ngozi volcano (Figure a) is characterized by a mean $^3He/^4He$ ratio normalized by the atmospheric ratio and corrected for its atmospheric component (Rc/Ra) of 10.8 (up to 14.9) and are indicating a mantle plume component (Hilton et al., 2011).

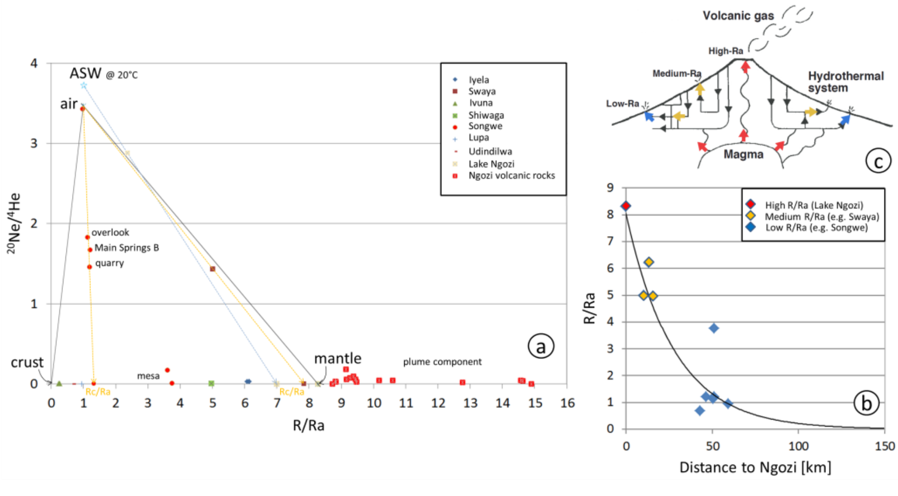

Figure 8 (a) Normalized He-isotopic composition vs. Ne/He ratio (data taken from Pik et al., 2006; Kraml et al., 2008; Delalande, 2009; Hilton et al., 2011; Barry et al., 2013). The straight line along the x-axis towards the origin represents mixing of mantle and crustal component. As mantle component the highest R/Ra of a fluid was taken i.e. Lake Ngozi water sample from 55 m depth (data from Delalande, 2009). (b) Trend of generally decreasing R/Ra which is related to longer (and or less permeable) fluid pathways within the Precambrian Basement. (c) Expected distribution of He isotope ratios of hydrothermal fluids with increasing distance to the volcanic crater (schematic; Sano & Fischer, 2013).

Barry et al. (2013) combined – in a first step – fluid discharges (50-70 l/s as reported in Hochstein et al., 2000) of the Songwe hot springs with measured CO_2 concentrations to estimate the CO_2 flux and – in a second step – measured $CO_2/^3He$ ratios with estimated CO_2 flux to calculate the ^3He flux of 2-4 × 10^{-5} mol/yr. As the final step these authors have combined heat output (10

MW_{th} as reported in Hochstein et al., 2000) with calculated ^3He flux to receive ^3He/enthalpy ratios which are believed to be controlled by the maturity of the magmatic system (Poreda & Arnórsson, 1992).

From above calculations Barry et al. (2013) concluded that Ngozi volcano hosts a cooled geothermal system. However, this conclusion contradicts volcanological evidence (last eruption approx. 1,000 years ago and caldera forming event approx. 12,000 years ago; Fontijn et al., 2012). From simple cooling calculations (following the approach of Smith and Shaw, 1975) it can be shown that the heat source (i.e. almost 20 km^3 sized Ngozi magma chamber) is still hot i.e. able to drive a geothermal system. The hot magma chamber is actively degassing as shown by MORB-like mantle helium isotope compositions of Lake Ngozi water.

Furthermore, it is expected that Songwe hot springs, which are located >40 km NW of Ngozi volcano, allow for multiple shallow processes to modify gas compositions from original pristine mantle compositions (de Moor et al., 2013). Such processes in respect of Helium can be different residence times in local reservoirs and different admixture of atmospheric helium prior to emergence at the spring. These effects might be responsible for the different isotopic compositions of Songwe samples “Overlook”/Main Springs B compared to Songwe sample “Mesa” located only a few hundred meters apart. Therefore, Kraml et al. (2008, 2010) suggested to sample gases from drowned fumaroles (at that time postulated and later proved by localized temperature anomalies of up to 90°C at the lake floor of Ngozi caldera; see above) which will deliver representative samples to assess the original composition of the mantle fluids.

In this context it is important to note that Andrews et al. (2006) have presented two- and three-dimensional simulations of heat and helium transport for a generalized rift system to systematically investigate how various interacting parameters influence coupling and decoupling of magmatic or mantle heat and helium signals in the Earth's crust. They have confirmed findings of previous studies by other authors including the occurrence of spatial decoupling of heat and helium due to variations in their respective diffusivities, entrapment of helium by low permeability layers, and the preference of helium for fracture flow.

Delalande et al. (2014; submitted) have reported normalized $^3He/^4He$ ratios of Lake Ngozi water sampled in 55 and 70 m water depth, yielding 8.3 and 7 R/Ra, respectively. Based on these results, which were achieved without being aware of localized hot emanations (sampling and measurements were done in 2005), we are convinced that it is possible to take an even more pristine sample by re-locating the highest temperature anomalies at the floor of Lake Ngozi. The less pristine and atmospherically contaminated sample in greater depth can be explained by sampling not exactly above a drowned fumarole.

It is of utmost importance to take gas samples from the hottest emanation at Lake Ngozi’s caldera floor also for reliable H_2/Ar temperature estimates. Gas geothermometry using the distant Songwe fluid of the outflow zone yielded a significantly lower H_2/Ar temperature than the fluid discharge temperature of sampled Songwe spring “Mesa” itself (de Moor et al., 2013; the location is equivalent to one of the “Main Springs” in Kraml et al., 2008), again showing the necessity of a pristine sample taken from the lake floor.

3.5 Geophysical Survey

In total 32 MT soundings have been carried out in the area of Ngozi-Songwe geothermal system. TEM data were used for static shift correction resulting in a jointly inverted resistivity model. A typical section through the resistivity model is shown in Figure 9.

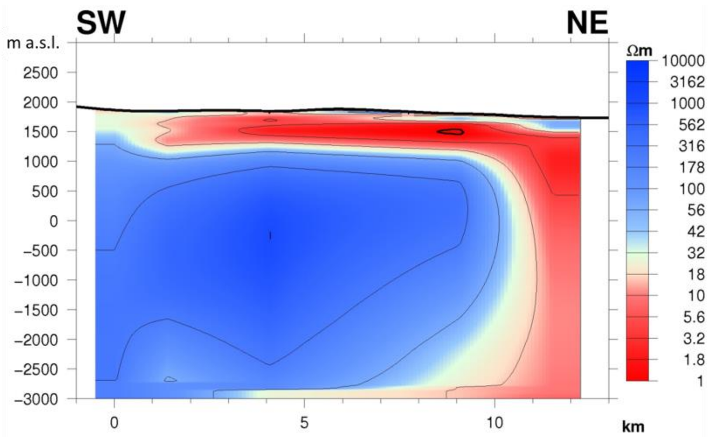

Figure 9 Resistivity cross section through Ngozi area down to 5,000 m depth.

Based on the geophysical results obtained from TEM and MT measurements at Ngozi crater, three sites for deep temperature gradient wells (approximately 500 m deep) were selected along a transect across the reservoir. Criteria for selection of drill sites were (a) accessibility and (b) thickness of clay cap mainly derived from TEM measurements. To achieve denser resistivity information an increased number of TEM/MT-soundings would be necessary. On this basis a site for a deep exploration well (>2,000 m) into the upflow zone could be suggested. An alternative strategy would be to drill one 1,500 m deep slim-hole well to penetrate the clay cap just outside of the upflow zone. The advantage of the alternative strategy favored by GPT is not only to prove the enhanced geothermal gradient below the shallow groundwater but also to continuously sample the clay cap for calibrating the resistivity model and to tap the reservoir fluid. Based on a calibrated model it would be easy to define sites for supplementary MT/TEM-measurements to reduce the risks in planning of the deep full-size exploration well (definition of the drilling location, well path, technical drilling plan etc.).

3.6 Refined Conceptual Model

The refined conceptual model (Figure 10) is based on the newly available data concerning the Ngozi Songwe system. Recharge is provided from the northern and eastern flanks of Ngozi (highest elevated areas). The outflow of Ngozi reservoir fluids is strongly fault controlled. There are four main directions of fluid flow: (1) to the West and at Panda Hill to the North (Songwe), (2) to the West and at the foot of Ngozi to the NW (Mahombe), (3) to the North (Udindilwa) and (4) to the North and to the NW (Ibayi). In contrast to flow paths to Songwe and Mahombe, no carbonatite intrusions are expected from field evidence to occur along the pathways to Udindilwa and Ibayi hot springs. The flow path to Kalambo travertine could be constrained by two newly discovered springs. All of the four recently active mineralized springs along Kalambo flow path are characterized by water temperatures exceeding ambient temperature by maximum 5°C. The three chemically similar hot springs (Figure 4) at the flank of Ngozi along the flow path between Kalambo and Mahombe show uniform chlorine concentrations (around 10 mg/l) and constant water temperature excesses of around 10°C. The two springs on a flow path first to the West and then to the NW are characterized by the highest observed temperature excesses of 16 and 19°C indicating already at the flank of Ngozi the major outflow of the geothermal system discharging at Songwe and Mahombe hot springs. Therefore, the first 1,500m deep slim-hole exploration well was planned to be situated as close as possible to the area with maximum convective heat loss at the flank of Ngozi volcano.

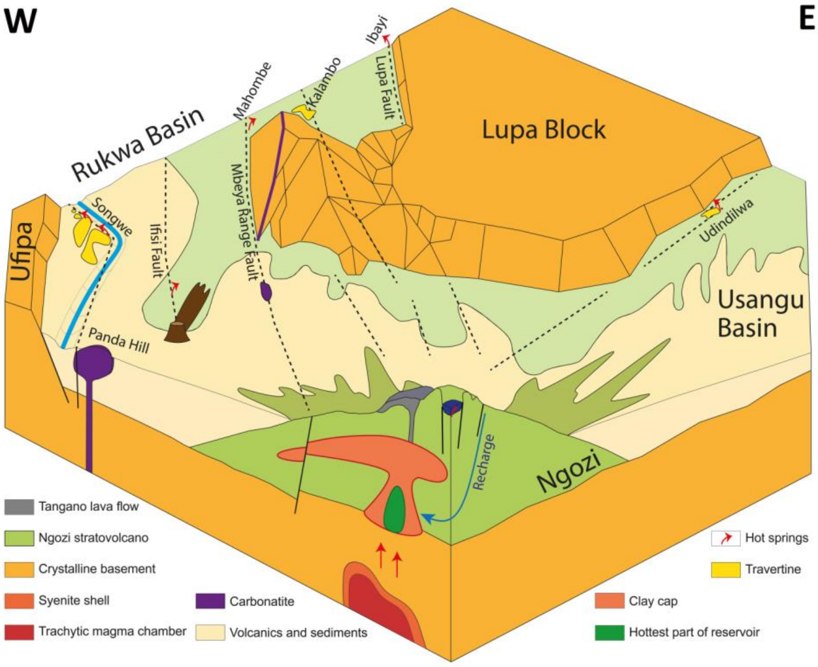

Figure 10 Simplified conceptual model of the Ngozi-Songwe Geothermal System. Faults are schematically adopted from Delvaux et al. (2010).

The drilling spot was chosen beside essential geoscientific arguments on the basis of a selection matrix comprising (i) slope angle of access road, (ii) availability of water for drilling, (iii) elevation of site, (iv) length of access road, (v) sections of access road in need of rehabilitation, (vi) flatness of drill pad area, (vii) cash crops cultivated at drill pad, (viii) distance to houses and (ix) sensitivity of local people.

4. CONCLUSION

In summary, it can be concluded that the Ngozi-Songwe-System is related to a high enthalpy reservoir (>200°C). Mahombe hot springs also belongs to the Ngozi-Songwe-System. Together with hot springs at the flank of Ngozi, the convective heat loss is higher than previously expected. This has implications to the estimated size of the reservoir.

Newly detected springs and geochemical differences in some trace elements of formerly known springs constrained individual fault-related flow paths of the outflow zone. In this context the carbonatites play an important role.

Further isotope hydrology data led to a more reliable definition of recharge areas of Ngozi-Songwe fluids.

Static shift corrected and jointly inverted resistivity data delivered the basis to plan temperature gradient wells and a deep slim-hole well. However, it might be suitable to further enhance the number of MT/TEM soundings to reduce the risks in planning of the deep full-size exploration well.

The expanded conceptual model of Ngozi can easily be proven by an approx. 1,500m deep slim-hole exploration well penetrating the clay cap. The location of the drilling spot is already determined, the well pad prepared, access and water supply clarified, technical drill planning including logging and testing program done and the drilling rig already transported to Mbeya.

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