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Small-Scale Rural Electrification and Direct Use of Low-Temperature Geothermal Resources at Mbaka Fault in SW Tanzania

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ABSTRACT

The objective of the paper is to present first evidence for suitability of Mbaka fault's low-temperature geothermal systems for rural electrification projects.

The Karonga basin north of Lake Nyasa in the southwestern part of Tanzania is characterized by the prominent NW-SE trending Livingstone border fault and the parallel major intra-basin Mbaka fault. Several hot springs emanate along the highly permeable Mbaka fault with temperatures of up to 70°C, flow rates of up to 20-40 l/s and partly artesian outflow. Three license areas are currently under geological, hydrological and geochemical exploration by Geothermal Power Tanzania Limited and include both Mbaka and Livingstone faults. Fluid geothermometric results indicate anticipated temperatures of the deep reservoir(s) of ≥160°C. The recharge area of the Mbaka hot springs is located mainly in the elevated region of Kiejo volcano N to NE of the hot springs and is characterized by humid climate.

A first conclusive conceptual model is presented for the southernmost Kilambo prospect at Mbaka fault as basis for identification of sites for drilling of exploration wells and planning of well paths. After successful drilling of a more than 600m deep exploration well and a shallower injection well, a wellhead generator will be used for early power generation. In addition direct heat utilization will be considered mainly for use in drying of agricultural products by constant and reliable conditions to enhance the quality of the products (e.g. tea leaves) or to avoid wastage of rotten fruits (e.g. bananas). The presented rural electrification concept will be applied in several sites at the Mbaka and Livingstone faults if on-going exploration will show promising results.

The paper gives an overview on previously existing data and the new findings for geothermal development at Mbaka and possibly also Livingstone faults.

1. INTRODUCTION

It is long known that Tanzania has a significant yet untapped geothermal potential (McNitt 1982). Recently, the Ministry of Energy and Minerals recognized that there is potential for enhancing the power supply security and covering the rising power demand in the country (Mwihava et al. 2004).

Geothermal Power Tanzania Limited (GPT) is a company based in Dar es Salaam with shareholders from Mauritius (Aspac Mining Limited), Germany (GeoThermal Engineering GmbH), the Tanzanian Government's National Development Corporation, a local Tanzanian company - Interstate Mining and Minerals Ltd and investors from Australia and Singapore. GPT plans to develop geothermal projects in Tanzania. Five prospecting licenses were granted by the Tanzanian Ministry of Energy and Minerals to GPT in the last quarter of 2011 in Mbeya area in southwestern Tanzania. Together with other conventional and renewable sources of energy, GPT plans to power the entire Mbeya energy region. The main reasons for choosing Mbeya area is the availability of natural resources and the good infrastructural framework.

New exploration activity by Mbaka exploration team started with site visits in January 2012 mainly for purposes of identifying sites for drilling of deep temperature gradient wells in the well-known northern part of Mbeya area. This was followed by a more extensive field survey in May 2012 focusing on identification of "new" i.e. so far not sampled hot springs and flow-rate measurements in the less well studied southern part of Mbeya area. A third survey (mainly sampling campaign) took place in July/August during the dry season in the southern part of Mbeya area for purposes of receiving least diluted fluids and least atmospherically contaminated gas samples.

This area with low-temperature geothermal resources is suitable for rural electrification.

2. RURAL ELECTRIFICATION AND DIRECT USE

The project area is located within a rural area except for Tukuyu city with ca. 50,000 inhabitants. Connecting more village residents to electricity (rural electrification) would mainly serve the demand for cost-effective lighting of rooms using bulbs. The driving force for the rural electrification process is the fact expensive kerosene for fueling lamps becomes unnecessary (Figure 1). This would e.g. allow pupils to more time to learn and do homework in the evening and reduce eye and respiratory system health problems. Additional electricity demand exists for powering radios (currently with small non-rechargeable dry-cell batteries) and charging mobile phones.

The major barrier to the use of electricity among the poor village residents is the comparably high connection costs per household. However, schemes with pre-financing of connection costs can make those initial costs affordable.

Furthermore the project will create short- term jobs for construction workers (road, drilling site, plant) and long-term jobs e.g. for local guards and technical personnel working in the power plants.

All measures together will enhance the overall economic growth in the region.

It is expected that geothermal electricity generation will be higher than the demand of surrounding rural households alone. Therefore, agroindustry i.e. tea companies and small scale industry including hotels in Tukuyu with relative constant and comparably high demand are the second target group for electricity and heat sales. Additionally, a diesel powered coal mine near the border of Malawi will also be included in the market assessment. Finally, a cross-border 33 kV transmission line would allow for export of excess power to the nearby Malawi (interconnection between Kyela, Tanzania to Karonga, Malawi).

Currently, the projected power demand is being estimated and compared with the expected geothermal power generation for solid planning of the rural electrification project.

Figure 42: Kerosene lamps offered in shops of villages in the project area (January 2012).

In parallel, concepts for direct heat use are under development. Waste heat from the power plant could be used for: (i) sustainable drying of tea leaves within an area of major tea plantations in an effort to reduce the CO_2 footprint of the tea companies, (ii) drying of cocoa seeds under constant conditions (especially in the rainy season when drying with the help of sunshine is not reliable) to enhance the quality of the produced cocoa oil (Figure 2) and (iii) drying of bananas to reduce wastage resulting from rotting i.e. promoting banana chips production. So far only a small amount of rotten bananas is used as ferment in local honey breweries (Figure 3). The same fruit drying installations could be used for e.g. mangos which cannot be completely consumed by local villagers or sold on the market during the time of over-production (Figure 4).

Figure 2: Cocoa seeds drying during the rainy season (January 2012) with the help of sunshine under non-reliable conditions (background left) and one of several small scale cocoa oil production sites in the foreground.

Figure 3: Honey brewery using rotten bananas as ferment (January 2012). Left: ongoing fermentation process; Right: final product.

Figure 4: Ripe mangos being consumed by local villagers or sold on the market. Both measures are not sufficient for mitigating overproduction (January 2012).

Additionally, the temperature of the produced thermal water would allow for effective cooling via absorption chillers (combined heat, cooling and power plant) and this would prevent the rapid degradation process of locally consumed perishable foodstuffs. All measures would be beneficial for the economic growth in the region.

3. GEOSCIENTIFIC ASSESSMENT

In this chapter the geoscientific data is presented for characterizing the low-temperature geothermal system. A preliminary assessment (geology and geochemistry) of the entire Mbeya area is given in Delvaux et al. (2010) and Kraml et al. (2010).

3.1 Geology

The project area is situated at the triple junction of Rukwa, Usangu, and Karonga rift basins which form a part of the western branch of the East African rift system (Figure 5). The rift-rift-rift triple junction is characterized by prominent alkaline young-Quaternary volcanism (Rungwe volcanic complex). The Rungwe volcanic complex consists of three major eruption centers, namely Ngozi, Rungwe (2960m a.s.l.) and Kiejo volcanoes. The last eruption of Kiejo volcano occurred in historic times and was dated by reconstructing the family tree of a local villager at about 1800 A.D. (Harkin 1955).

3.1.1 Tectonic Framework

The northernmost sub-basin of the Nyasa rift - the Karonga basin - is an asymmetrical down-to-the-east half-graben, which is characterized by the prominent NW-SE trending Livingstone border fault and the parallel major intra-basin Mbaka fault (both seismically active). Especially in the latter of the two, deep-reaching structures are highly permeable allowing for ascent of hot water from the floor of the ca. 5km deep rift basin. Several hot springs emanate along the Mbaka fault (Figure 5).

The springs and carbon dioxide (CO_2) emanations are located mainly at the crossing of the SW dipping and NW-SE trending Mbaka fault with sub-vertical faults of the youngest NNE-SSW Usangu trend and the older ENE-WSW basement trend (Delvaux et al. 2008; Figure 6).

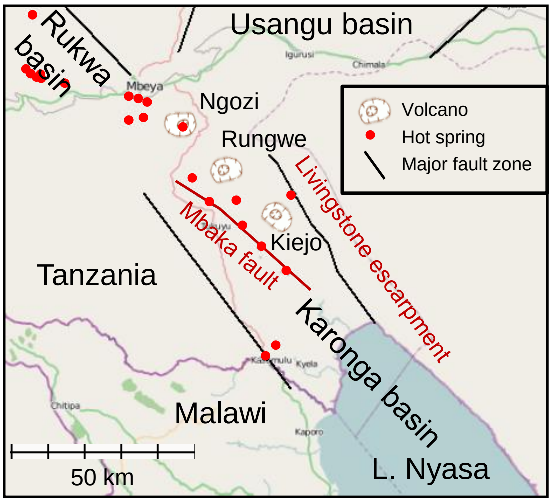

Figure 5: Simplified geological framework conditions in the project area.

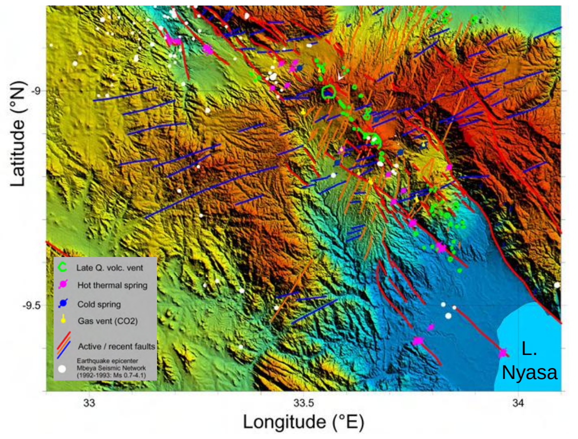

Figure 6: Mapped lineaments (blue: basement trend, red: main rift trend, orange: Usangu trend), hot springs (pink), cold springs (blue), gas vents (yellow), volcanic vents (green) and earthquake epicenters (white dots). (Delvaux et al. 2010)

During Cenozoic rifting, the Rungwe area was uplifted and denudation processes exposed the Precambrian basement at the earth surface in Tertiary times (van der Beek et al. 1998).

The first Cenozoic rifting episode took place from Late Miocene to Late Pliocene and is characterized by normal faulting (NW-SE main rift trend). The subsequent rifting period started in Middle Pleistocene with changed kinematic regime. This Neotectonic period (which continues until today) is characterized by a dextral strike-slip reactivation of the NW-trending rift faults (Delvaux et al. 1992, Mortimer et al. 2007). For a detailed recent assessment of the complex actual stress field in the study area see Delvaux & Barth (2010).

<u>3.1.2 Rock Types (Basement and Volcanic/Sedimentary Infill)</u>

The Precambrian basement is exposed on the footwall of the Mbaka and Livingstone faults. The basement consists mainly of Ubendian gneiss, but also migmatite, quartzite and subordinate granulite and metabasite occur.

The Ubendian gneiss is unconformably overlain by coal bearing Karoo sediments (mainly Permian) which are exposed at the western side of Karonga basin in the area of the Kiwira coal mine (Songwe-Kiwira Karoo basin; Damblon et al. 1998).

Karoo conglomerates are unconformably overlain by the so-called "dinosaur beds" which mainly consist of red sand- and siltstones. The thickness near Mbaka fault is not exactly known. Further to the west a thickness of nearly 600m is documented for those deposits (Ebinger et al. 1989, 1993a). The stratigraphic context had been under debate for a long time until Damblon et al. 1998 and Roberts et al. 2004 pinned down the stratigraphic relations (lower unit = Cretaceous; upper unit = Paleogene).

The "dinosaur beds" are unconformably overlain by the basal unit (thin muddy sandstone) of a volcano-sedimentary sequence. This basal Late Miocene unit marks the start of the Cenozoic rifting period.

The entire volcano-sedimentary sequence has a thickness of >200m as documented in the western part of Karonga basin (Ebinger et al. 1989, 1993a). However, in the central part of Mbaka fault the exact thickness of this sequence is not known.

Table 1: Stratigraphic column of the hanging wall of Mbaka fault as expected at Kilambo geothermal prospect (Ebinger et al. 1989, 1993a, Fontijn et al. 2011).

<u>Recent top soil</u>
<u>Holocene Rungwe pumice</u> 4 ka (≤1m to ≤30cm depending on distance to eruption center)
• Older "basalt" dated at 2.3 Ma at the top of the section
• Ugali tuff (phonolitic ignimbrite) near the top (caps Chiwondo beds)
• East of Mbaka fault: Masukulu phonolites and phonolitic tuff dated at 5.5 Ma possibly occur also W of Mbaka fault
• Older "basalts" dated at 6.3 Ma
• 200m-thick fluvio-lacustrine sequence of cross-bedded conglomerates, sandstones, black mudstones, water-deposited ash and tuffs, and phonolitic ignimbrite
• Lacustrine calcite-cemented sandstones and/or conglomerates with reworked Karoo and phonolite clasts overly the Songwe tuff
• Songwe tuff dated 8.6 Ma at the base of the >200m thick section (conformably over basal unit)
• basal thin muddy sandstone
<u>Cretaceous/Paleogene "dinosaur beds"</u> (mainly red sand- and siltstones) <600m
<u>Permian Karoo Supergroup</u> (conglomerates, coal bearing fine grained sediments)
<u>Precambrian basement</u> (mainly Ubendian gneiss, migmatites, quartzites)

The expected stratigraphic succession at the hanging wall of Mbaka fault is presented in Table 1 including the detailed stratigraphy of the Late Miocene to Late Pliocene sequence. On the footwall of Mbaka fault, the young volcanic eruption products of Rungwe volcanic complex are directly overlying the Precambrian basement. The major rock types of the mafic alkali-basaltic lavas are nephelinites (at Kiejo), basanites (at Tukuyu), alkali basalts (at Rungwe) and picrites (at Kiejo). Differentiated rocks include phonolites and trachytes also in the form of pumice, the latter having formed during highly explosive (up to plinian) eruptions.

The volcanic activity can be divided into three phases based on field relations (Harkin 1960) and on age determinations (Ebinger et al. 1989, 1993a; Ivanov et al. 1999): (i) Late Miocene - 9.2-5.4 Ma, (ii) Late Pliocene to Early Pleistocene - 3-1.6 Ma, (iii) Mid-Pleistocene to Recent - since 0.6 Ma. The first two phases correspond to the Older Extrusives and the third phase to the Younger Extrusives, as defined by Harkin (1960. See Fontijn et al. 2012 for a detailed recent volcanological review of the study area).

At the high-priority site Kilambo, alkali-basaltic lavas (2.3 Ma) and trachytic to phonolitic tephra layers form the uppermost part of the stratigraphic succession except for a thin cover with 4 ka Rungwe pumice (Figure 7) and the top soil (Table 1). Directly at the adjacent escarpment of Mbaka fault a young alkali-basaltic lava flow of Kiejo volcano is exposed in a quarry for mining of road construction material. The young lava flow has taken the same valley as the straight river both following in a newly postulated fault perpendicular to Mbaka fault (Usangu trend).

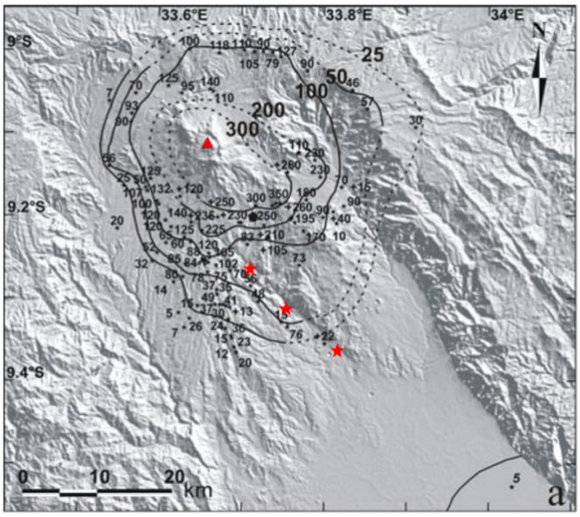

Figure 7: Isopach map [values in cm] for the 4 ka trachytic Rungwe pumice (from Fontijn et al. 2011; modified). The red triangle marks Rungwe crater and the three red stars mark the major geothermal systems at Mbaka fault.

The coincidence of abundant maars aligned parallel to the southern part of Mbaka fault and along perpendicular magma feeding directions of Kiejo (see Figure 20 below) suggest that the pathways of descending surface waters and ascending magma injections are both fault-controlled.

3.2 Geochemistry

In this section a short overview is given on the chemical and isotopic composition of fluids, gases and travertines. For a more extended discussion (except for newly sampled warm spring at Livingstone fault) see Kraml et al. (2010).

3.2.1 Fluid and Gas Chemistry

Major element geochemistry (Figure 8) indicates that the sampled Na-HCO_3(-Cl) fluids of the Mbaka hot springs as well as warm spring at Livingstone fault are "peripheral waters" with a high amount of admixed (near-) surface water. Therefore, also in the Na-K-Mg diagram (Figure 9), all fluids are plotting in the immature or partly equilibrated field. That excludes a geothermometric assessment for Livingstone sample. However, for Mbaka and western Karonga fluids, reservoir temperatures of >160°C can be deduced based on mixing of an equilibrated hydrothermal fluid with (near-) surface waters. These findings are in agreement with earlier studies (e.g. Hochstein et al. 2000, Branchu et al. 2005, Delalande et al. 2011).

First geochemical modeling (Mnjokava 2007 and Kraml & Hehn unpublished) of Kilambo hot spring water implies a mixture of hot ascending reservoir fluid with cold near-surface water in mixing ratios of about 1:5. Total dissolved solids of the modeled reservoir fluid are expected to be around 20 g/l and the fluid is oversaturated in some silicate minerals and silica (see also modeling results of Delalande et al. 2011 for Ilwalilo hot springs [named Mbaka in the present paper and in Kraml et al. 2008, 2010] located at Mbaka fault NW of Kilambo circulation system).

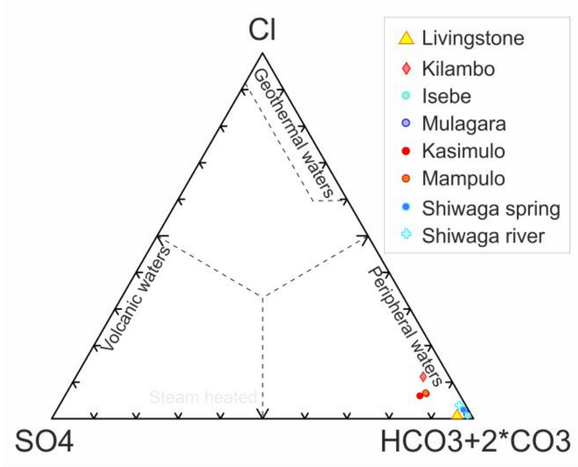

Figure 8: Cl-SO4-Alkalinity diagram indicating a high proportion of (near-) surface water of hot springs and especially of newly sampled warm spring at Livingstone fault.

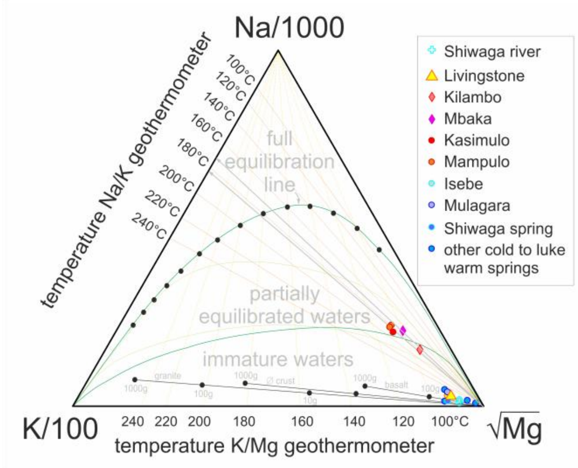

Figure 9: Na-K-Mg diagram showing mixing relations of a deep equilibrated fluid with (near-) surface waters.

Trace element geochemistry of the fluids including Rare Earth Elements (REE) was first applied in the study area by Kraml et al. (2008). The REE pattern (Figure 10) shows a characteristic positive Eu anomaly only in the case of hot spring waters indicating plagioclase alteration during the interaction of hot fluid with the reservoir rock (gneiss).

The river water is characterized by LREE enrichment, flat HREE patterns and the ubiquitous negative Eu anomaly as well as higher REE concentrations which is typical of upper continental crust and clastic sediments (McLennan 1989). The same pattern and very high concentrations are characteristic of highly differentiated alkaline pumice deposits from Rungwe volcanic complex as analyzed in a <1000 year old distal ash layer intercalated in sediments of northern Lake Nyasa (Williams et al. 1993).

Alkali basaltic rocks occurring in the area (i.e. alkali basalts, nepelinites, basanites) show steep patterns from La through Tb and slightly decreasing HREE pattern (Furman 1995).

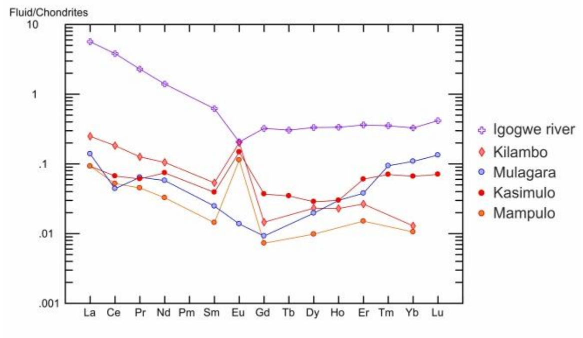

Figure 10: REE pattern of Karonga hot springs compared to a river and a cold spring in the study area (normalized with values of Sun & McDonough 1989) (see text).

The cold spring - Mulagara - (Figure 10), which emanates from the southern flank of Rungwe volcano, shows a similar REE concentration range to the hot springs but no Eu anomaly and a rising HREE pattern. Most cold springs in highly elevated areas at Rungwe and Kiejo volcano represent perched groundwater aquifers.

Fluid evolution (see extended discussion in Kraml et al. 2010) is characterized by fault-controlled descending meteoric surface waters (gravity driven), enriched by ascending volcanic CO_2. The high CO_2 flux in the recharge area is documented by commercial shallow CO_2 wells (0.5bar) drilled for the production of sparkling soft-drinks. Major species gas analyses of the free gas phase indicate that the gas composition in the hot springs can be explained by simple two component mixtures i.e. volcanic CO_2 and atmospheric gas (Figure 11).

The CO_2-rich water causes silicate hydrolysis of the crystalline rocks i.e. alkali-basaltic cover and gneisses of metamorphic basement (non-equilibrium conditions with excess SiO_2 and HCO_3^-). The fluid tends to equilibrate in the deep reservoir within Precambrian gneisses (as supported by a crustal He and Sr component; see below). Ascending hot fluid (buoyancy driven) partly re-equilibrates at lower temperatures (110 to 120°C) on the way to the surface (as indicated by fast equilibrating silica and K/Mg geothermometers), degasses at relative shallow level (calcium carbonate precipitation) and mixes with shallow groundwater (non-equilibrium). The CO_2 in the shallow groundwater is also overwhelmingly of volcanic and not atmospheric origin excluding CO_2 used as tracer for mixing processes (see section 3.2.2).

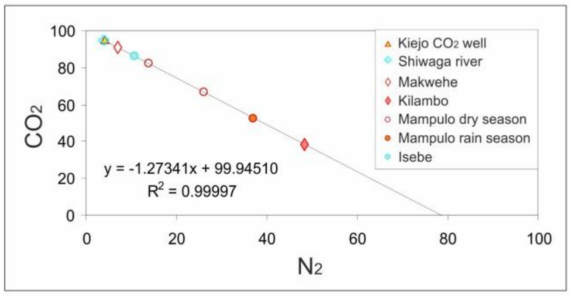

Figure 11: Mixing of volcanic and atmospheric gas. The fraction of atmospheric gas depends on the admixed fraction of air-saturated (near-) surface water (Kraml et al. 2010).

3.2.2 Gas Isotopic Composition

Gas samples of bubbling hot and cold springs were also analyzed for their carbon isotopic composition of CO_2. The measured values are characteristic for volcanic CO_2 (Kraml et al. 2010). Also the ^{14}C activity values of TDIC and CO_2 gas indicate a "dead" carbon input, without any significant contamination by atmospheric carbon (see Delalande et al. 2011 for extended discussion).

Additionally, helium isotopic compositions of the free gas phase were analyzed. Water sample was taken which may have been atmospherically contaminated during sampling procedure, only in case of Kilambo (as noted in the field book and in Kraml et al. 2008). The results are presented in Figure 12.

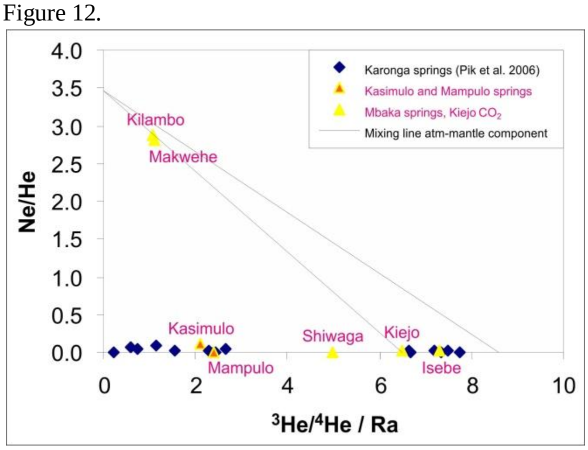

Figure 12: Normalized Helium isotopic composition vs. Ne/He ratio (data were taken from Pik et al. 2006 and Kraml et al. 2008).

The helium isotopic composition of most samples can be explained by a mixture of a mantle and a crustal components pointing to a long residence time in the Precambrian basement. Only the water sample from Kilambo hot spring and a nearby sample of gas bubbles taken from a river near Makwehe hot spring, showed a mixing relation between the Kiejo mantle component and the atmosphere. However, comparable data from Kilambo springs analyzed by Pik et al. 2006 did not show atmospheric mixing trend. Therefore, new helium samples will be taken for purposes of clarifying this important issue.

3.2.3 Travertine Isotopic Composition

Travertine of Kilambo hot spring consisting of calcite (as determined by XRD analyses) was analyzed for its stable isotope composition of Strontium, Oxygen and Carbon.

Using the $\delta^{18}O$ values of the fluid, the $\delta^{13}C$ value of the CO_2 in the gas phase and the fractionation factors of O'Neil et al. (1969) and Deines et al. (1974) for the systems $\delta^{18}O$ $CaCO_3$-H_2O and $\delta^{13}C$ $CaCO_3$-CO_2 respectively for calculating the paleo-fluid temperatures, the values are close to the present hot spring temperature (54°C and 53°C compared to the measured 56°C).

A systematic study of fossil occurrences of Kilambo travertine (U/Th dating and stable isotopes) would be necessary to reconstruct the geothermal activity in space and time.

The strontium isotopic composition of Kilambo travertine indicates a more intensive fluid/rock interaction with the Precambrian gneiss than the Songwe fluids (and related travertines; Figure 13). The latter belong to the separate geothermal system of Ngozi volcano further to the north. In accordance with high crustal helium components (which is yet to be confirmed for Kilambo) and the pronounced positive Eu anomaly in the REE pattern, independent constraints could be put on the type of the reservoir rock.

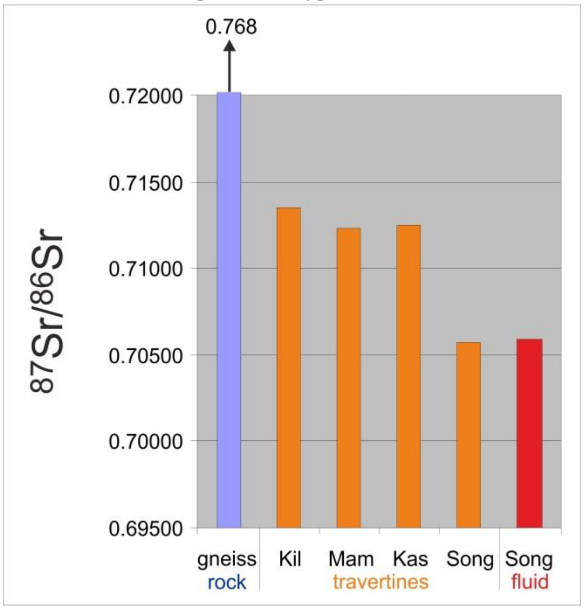

Figure 13: Sr-isotopic composition of basement rocks (Ubendian gneiss), travertines and Songwe hot spring water (for explanation see text).

3.3 Climate and Hydrology

In this section, a short summary of climatic and hydrologic conditions of the study area is described below.

3.3.1 Climate

The ratio of potential evapotranspiration to precipitation (index of dryness) in the target region of Mbaka and Livingstone fault including the recharge areas is 0.6 indicating humid conditions (catchment 1.11, Figure 14). The humid climate assures a comparably high recharge maintaining the water pressure in the deep reservoir.

The overall hydraulic gradient in the drainage basin is directed to the SSE (Gibert et al. 2002).

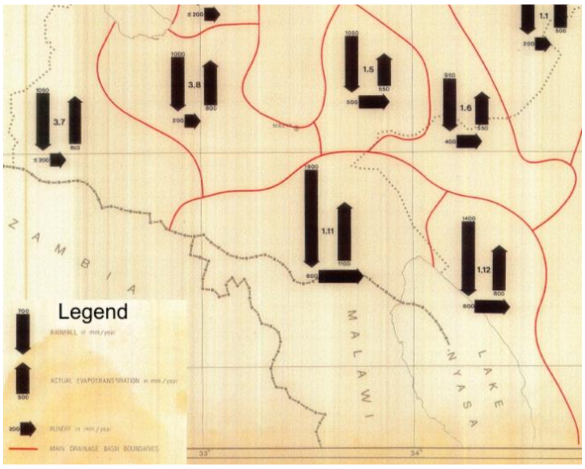

Figure 14: Mean annual potential evaporation, precipitation and runoff in study area situated within drainage basin 1.11 (CCKK 1982).

3.3.2 Hydrology and Isotope Hydrology

Kilambo hot springs are characterized by a combined flow rate of 20-40 l/s (Hochstein et al. 2000) and partly artesian outflow (Figure 15 a,b). The temperature of the hot springs and their artesian pressure (if any) vary with time and season. This observation supports the model with final admixture of a local groundwater component.

Figure 15a: Gas-rich hot spring in Kilambo area with slightly artesian outflow (water temperature of 61.1°C on 14th of May 2012). The flow rate was measured at slightly above 1 l/s with a 28°V-notch weir.

Figure 15b: Spouting spring in Kilambo area with slightly artesian outflow (water temperature of 55.3°C on 14th of May 2012). Flow rate estimated at significantly above 1 l/s.

The working area is surrounded by highlands of significant elevation (Figure 16).

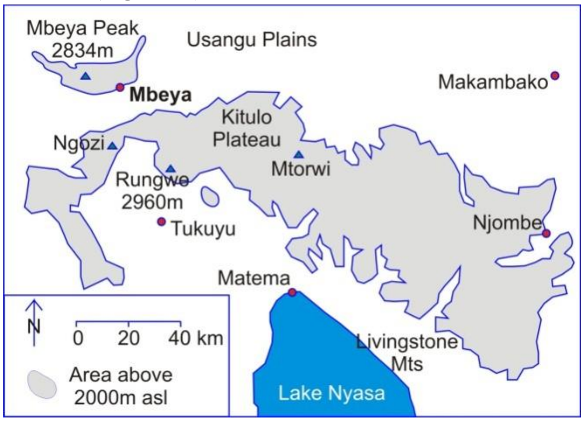

Figure 16: Highlands around working area situated SE of Tukuyu.

The highlands are characterized by a depleted oxygen and hydrogen isotopic composition (altitude effect) and lakes like Lake Nyasa in the lowland show an additionally enriched signature due to their free water surface (=> evaporation) (Figure 17).

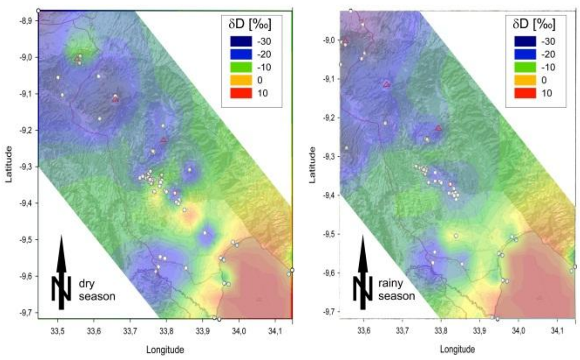

Figure 17: Areal distribution of δD values in the working area during dry and rainy season (data from Delalande et al. 2005 to 2011, Branchu et al. 2005 and Kraml et al. 2008). Artifacts from the interpolation algorithm could be avoided at Lake Nyasa where data points with the same value were added (location not shown)

Since Kilambo fluids are characterized by depleted isotopic compositions the recharge area must include the highland of Kiejo volcano in the north. Kiejo water samples taken from two rivers at 1625m and 491m a.s.l. and from one cold spring located at ca. 920m a.s.l. are slightly more depleted than Kilambo hot spring fluids (Figure 18) which emanate in ca. 600m a.s.l.. Most depleted fluid samples are from two rivers originating near Rungwe summit and one spring located near the summit of Rungwe volcano.

Shanzira cold spring (2500m a.s.l.) near the summit of Rungwe shows a slight oxygen isotope shift to the left of the Meteoric Water Lines (both local and global) which can be explained by isotope exchange with volcanic CO_2. This exchange reaction is not restricted to subsurface waters and also appears at rivers (e.g. Shiwaga: >2‰ oxygen isotope shift; Figure 18 and Delalande et al. 2011) where the river crosses a fault characterized by a massive CO_2-degassing (see also section 3.5).

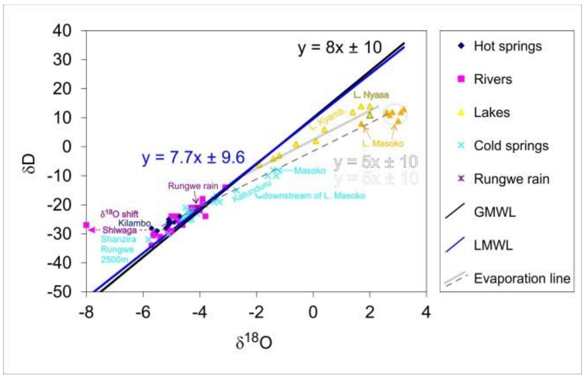

Figure 18: δD vs. δ18O diagram for fluids sampled in the study area (dry season). Data are taken from the extensive work of Delalande 2005 to 2011 as well as from Branchu et al. 2005 and Kraml et al. 2008 (for explanation see text).

The high amount of CO_2 involved in the evolution of the hot spring fluids also leads to a significant shift in isotopic composition to the left of the Meteoric Water Lines (H_2O-CO_2 exchange effect up to >7‰!; see Delalande et al. 2011) masking the equilibrium achieved in the deep reservoir during oxygen isotope exchange with the gneiss (where water/rock interaction at high temperature took place causing a less pronounced shift to the right). The higher shift to the left of the MWLs in case of more saline hotter fluids could be attributable to the flushing with volcanic CO_2 once the fluid meets the highly permeable Mbaka fault in depth. The exchange reaction between water and CO_2 is very fast even in the vapor phase (Delalande et al. 2011). Waters ascending fast in highest permeable "CO_2-lifted" zones show only negligible admixture of surface (river) water containing atmospheric CO_2. The river water infiltrates only in little quantities at Mbaka fault from the earth surface (with H- and O-isotopic mean composition of rain in Rungwe area in 900m elevation) and/or groundwater with evaporation signature (like Katunduru-Masoko cold spring trend) meets the uprising fluid. The lower the amount of admixed river water and the lower the evaporation signature (of only locally occurring groundwater at Masoko maar-lake) the more is the left shifted composition preserved compared to stronger diluted fluids.

3.4 Conceptual Models

Hochstein (2000) presented the first conceptual model for the Kilambo hot spring, i.e. outflow of a concealed (possibly high-temperature) reservoir further upstream (i.e. in 18km distance). As inferred from the location of the reservoir, he suggested the only known place with silica sinter (described by Harkin 1960) in the entire Mbaka region.

Branchu et al. (2005) interpreted the Kilambo and two other hot springs (Mampulo & Kasimulo) at the western rim of the Karonga basin as basinal brines rising from the deepest part of Karonga basin from about 5km depth and diluted with meteoric water. Those authors suggested a magmatic heat source as the driving force and explained the elevated heat flow measured at the bottom of northern Lake-Nyasa with values at the western part of up to 80-90mW/m^2. The magmatic heat source is responsible for a fault related localized hydrothermal discharge at the lake floor and its extension on land is represented by Kasimulo hot springs. Along the lake axis the heat flow with values of 50-60mW/m^2 is still slightly higher than the mean value for the African continent (49.8 mW/m^2). There, at least sub-lacustrine gas emanations in 4m water depth were observed near the mouth of Kiwira river; Kyela lineament in Figure 6).

In this paper we interpret the three separated major hot spring areas at Mbaka fault as follows (Figure 19): In the higher elevated areas of Kiejo and Rungwe volcano meteoric water infiltrates and the fluid is heated up on the way down taking up volcanic CO_2 (high flux in the Rungwe and Kiejo area). The hot fluids are mainly guided along active sub-vertical faults of the Usangu trend and along faults of the Basement trend to Mbaka fault (rift basin trend) in the SW of the recharge area. The hot fluids rise at the deep entry point at Mbaka fault leading to surface manifestations in the form of hot springs along the fault trace (dilution by descending river water at Mbaka fault and shallow ground water).

The fossil silica sinter on the basement gneiss at the northernmost geothermal system could be explained by additional magmatic heat released e.g. during the most prominent Holocene eruption of Rungwe volcano (4 ka) due to the recent replenishment of the magma chamber leading to excess conductive heat. For the southernmost high priority Kilambo prospect, a conclusive conceptual model has to include the magmatic heat from Kiejo volcanic system in the evolution of the fluids (Figure 20).

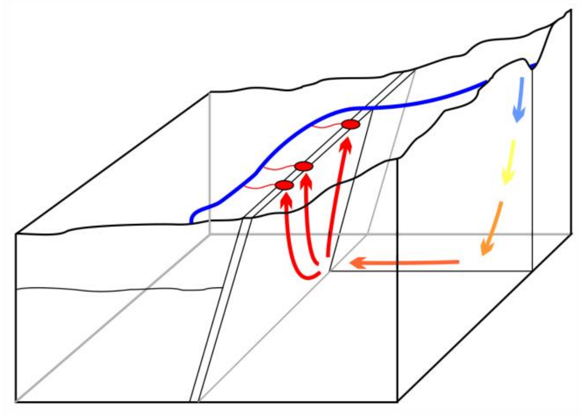

Figure 19: Schematic sketch of fault-hosted Kilambo geothermal circulation system (not to scale). The Kilambo hot springs are aligned along Mbaka fault and the main recharge area with infiltration of surface water (indicated by blue to orange arrows) is located just outside of the block model to the right. The additional volcanic heat source (recent dike intrusions of Kiejo volcano) is not shown for clarity.

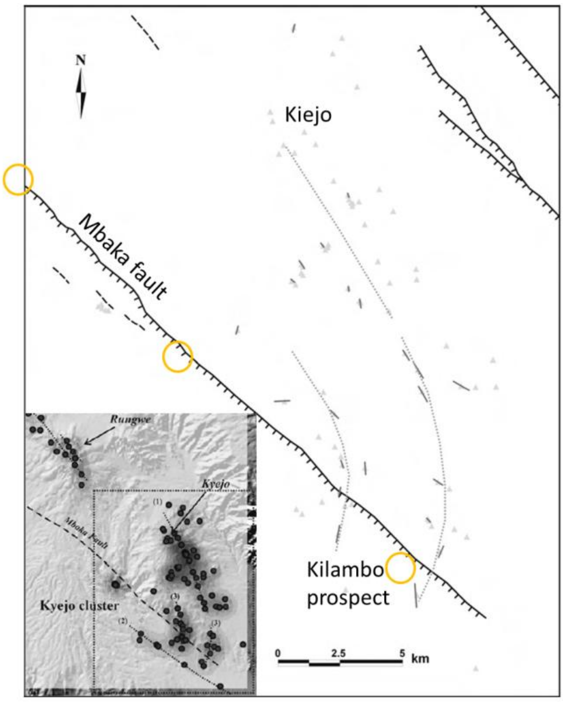

Figure 20: Dotted grey lines suggest magma feeding directions of Kiejo volcano based on vent alignments, and vent elongation directions (Fontijn et al. 2010, modified)

3.5 Preliminary Hazard Assessment

Natural hazards are mainly due to inter-related seismicity, volcanic activity, CO_2 degassing and landslides in case of steep volcanic topography with thick unconsolidated pumice deposits, being typical for Rungwe volcano.

Since three zones of seismicity meet within the working area, the activity rate of major earthquakes (= annual number above the lower bound magnitude of 4.5) gives the best case values of 1 earthquake every 2.4 years with a magnitude of up to 7.1, most likely 1 earthquake every 1.4 years with a magnitude of up to 7.3 and in the worst case 3 earthquakes per year with a magnitude of up to 7.8 (Midzi et al. 1999; see also Langston et al. 1998).

Landslides could easily be triggered by seismicicity or volcanic activity in Rungwe area but also by liquefaction of pumice deposits after heavy rain falls (Bucher 1980).

A continuous volcanic risk is based on CO_2 emanations especially along active faults, causing human victims like at site Shiwaga river located NW of Rungwe volcano.

In addition to explosive eruptions, debris avalanche deposits of a major sector collapse of Rungwe volcano masks the trace of the northern prolongation of Mbaka fault at the earth's surface (Fontijn et al. 2010). Alkali-basaltic lava flows like the 8km long only 200 years old Sarabwe flow from Kiejo volcano (Harkin 1955) have to be taken into account for planning the geothermal installations.

Dike-like magma injections of Kiejo volcano, which is characterized by dominantly alkali-basaltic effusive activity, are expected at Mbaka fault near the Kilambo prospect (Figure 20).

Only Iramba maar-lake nearest to Mbaka fault, less than 2.5km SE of Kilambo hot spring and located at the end of the major magma feeding system of Kiejo, shows a contribution of deep hot fluid (Delalande et al. 2008b). The calculated hydrothermal input corresponds to 3-4 l/s of Kilambo spring water. Other maar lakes aligned parallel to Mbaka fault further in the foreland (Figure 20) may reflect former injections of Kiejo's magma feeding system. In that respect the not investigated Lake Ikapu 2km west of Kilambo hot spring will be included in the subsequent investigations to fully understand the entire Kilambo circulation system.

In the future one could learn from a continuous monitoring of hot spring temperature, spouting height, electrical conductivity in combination with chlorine measurements how pronounced the seasonal effect is for using the remaining signal for hazard assessment.

3.6 Preliminary Drilling Concept and Plan

The preliminary drilling concept aims to tap the hot rising fluid below the mixing zone with local groundwater and above the entry point in depth. Up to three additional production wells are possible at Kilambo site to enhance the yield in case of a low flow rate. After successful drilling of the production well(s), a reinjection well will be drilled downstream (= in SE direction) to a depth shallower than the production well i.e. within the upper part of the mixing zone of groundwater with hot fluid.

Based on the expected stratigraphy in the hanging wall of Mbaka fault the preliminary drilling plan for the first more than 600m deep wildcat slim hole using an Atlas Copco CS14 rig is as follows:
A conductor pipe (e.g. in the first 5 meters) with well head for lateral outflow of drilling mud and thermal water (diameter PQ) will be set into the ground to provide the initial stable structural foundation for the borehole. For the first few hundred meters (i.e. the thickness of basaltic lavas and tuffs) drilling with HQ diameter using standard wire-line drilling equipment is planned. The depth drilled with HQ diameter will be 1.5m into the red sandstone for stable placement of the NW casing. The next several hundred meters (= mainly sandstones and intercalated mudstones) down to the target (= gneiss) drilling with NQ standard wire-line equipment is envisaged. After logging, testing and sampling the drilling rig will be removed and the exploration well will be available for later long-term production tests and for monitoring while drilling the full-size production well some 10 meters aside with a bigger rig. At the very end of the project once the observation well is no longer neede the well will be cemented (a few hundred meters) down to the casing shoe of the NW casing, to leave the it in an environmentally safe condition.

4. CONCLUSIONS

The Mbaka fault bears a few low-temperature fault-hosted deep-circulating geothermal systems, fed by perpendicular faults on the foot wall with deep fluid which may additionally be heated by Rungwe magma chamber in the northern part and (less sustainably) by recent Kiejo dike intrusions in the southern area.

Infiltrating surface waters diluting the ascending hot fluids are provided mainly from rivers which are erosionally cut into the hanging wall along the perpendicular faults as well as directly at the Mbaka fault itself.

The preliminary drilling concept aims at tapping the hot rising fluid below the mixing zone with local groundwater and above the entry point in depth. The reinjection well will be located downstream (= in SE direction) and in shallower depth than the production well.

After successful drilling, a wellhead generator will be installed for rural electrification and direct use of the waste heat (mainly drying of tea leaves and banana chips production).

A significant benefit for the rapidly growing Mbeya area is expected from serving the energy needs of the region – it will result in an enhanced economic growth in the entire region including the rural areas.

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