

TECHNICAL REVIEW OF GEOTHERMAL POTENTIAL OF NGOZI AND SONGWE GEOTHERMAL PROSPECTS, TANZANIA

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1. INTRODUCTION

This paper presents the executive summary of the recently-completed geothermal resource assessment report for the Ngozi volcano and Songwe hot springs geothermal prospects in southwest Tanzania (Alexander et al., 2016). This report was prepared for the United Nations Environment Programme (UNEP). As part of their initiative to promote geothermal resource development and utilization in East Africa, UNEP has implemented the GEF-funded African Rift Geothermal Development Facility Project (ARGeo). One of ARGeo's primary components is to provide technical and financial assistance for surface exploration studies for the ARGeo member countries (Burundi, Eritrea, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, and Uganda).

In 2015, the recently-formed Tanzanian Geothermal Development Company (TGDC) submitted a request for technical assistance to UNEP for surface exploration studies at the Ngozi and Songwe geothermal prospects (TANESCO, 2015). TGDC requested in its proposal provision of scientific equipment and high level experts in areas of geology, geochemistry, and geophysics. UNEP chose this proposal as one of the projects for technical assistance for surface exploration studies.

The Geothermal Development Company of Kenya (GDC) was nominated to provide technical advice and equipment for the surface exploration studies at Ngozi. Three technical consultants were selected by UNEP to provide advisory services and hands on training: Kenneth B. (Keg) Alexander, geologist; William Cumming, geophysicist; and Luigi Marini, geochemist. This report was prepared by the UNEP technical consultants.

Preexisting and new geological, geochemical, and geophysical data have been compiled and evaluated to form separate, integrated resource conceptual models of Ngozi and Songwe. The conceptual models illustrate the various components of a geothermal system: heat source, reservoir, cap rock, temperature distribution, and fluid pathways. Alternative conceptual models representative of the uncertainty in the data and interpretation are used for exploration well targeting and resource capacity assessment.

2. NGOZI

The active Ngozi volcano is part of the Rungwe Volcanic Province (RVP) located at the Mbeya triple rift intersection of the Western and Eastern Branches of the East African Rift System (EARS). The primary geothermal features are thermal water discharges (up to 89 °C) on the bottom of the Ngozi crater lake that are modeled as having come from a 232 ± 13 °C geothermal reservoir. The origin of the warm springs 8-12 km W and 12-14 km NW of Ngozi is ambiguous but they clearly do not emanate from the reservoir. It is more likely that meteoric water is conductively warmed by the geothermal system, either by a concealed outflow from it, or by a separate upflow.

The MT-TEM resistivity data detect a pattern of low to moderate resistivity over a resistive zone that is consistent with clay-bearing, impermeable volcanic and sedimentary rocks surrounding Ngozi that directly overlie high resistivity impermeable metamorphic basement rocks, consistent with the

geochemistry and hydrology that all point to a Ngozi geothermal system that pierces the metamorphic rocks and is sealed off from its surroundings. Because of the inaccessibility of the caldera area, the MT could neither support nor reject a hypothesis of a conventional low resistivity smectite cap over the likely upflow area. The closest adjacent stations detect a very thick 10 to 50-ohm zone that likely corresponds to impermeable volcanic rocks overlying the low permeability very resistive metamorphic rocks. A <7 ohm-m, gently dipping, 500-m thick zone is interpreted as clay-rich sediments that extend north, south, and west of Ngozi, aligned along structures. At a distance of about 2 km from the Ngozi caldera these sediments are truncated, probably by a combination of lack of deposition around the raised volcanic edifice, disruption by volcanic eruptions, and structural offset (generally but not always down-dip toward the volcano).

Although the MT lacks direct evidence for a smectite clay cap over an upflow, it is permissive of a cap in the gap between stations near the caldera and a <7 ohm-m zone that stretches to the west of the caldera above the water table is interpreted as alteration over a likely boiling or gassy zone near the water table between the caldera and the warm springs 8 to 12 km west of Ngozi. This shallow alteration is consistent with heat loss from the caldera area toward the springs but, to be consistent with geochemical indications that the springs are conductively-heated meteoric water, the proposed optimistic model assumes that a deep, convecting reservoir extends up to 2 km west of the caldera rim, where it conductively heats adjacent low permeability rock that, in turn, heats meteoric water at the water table.

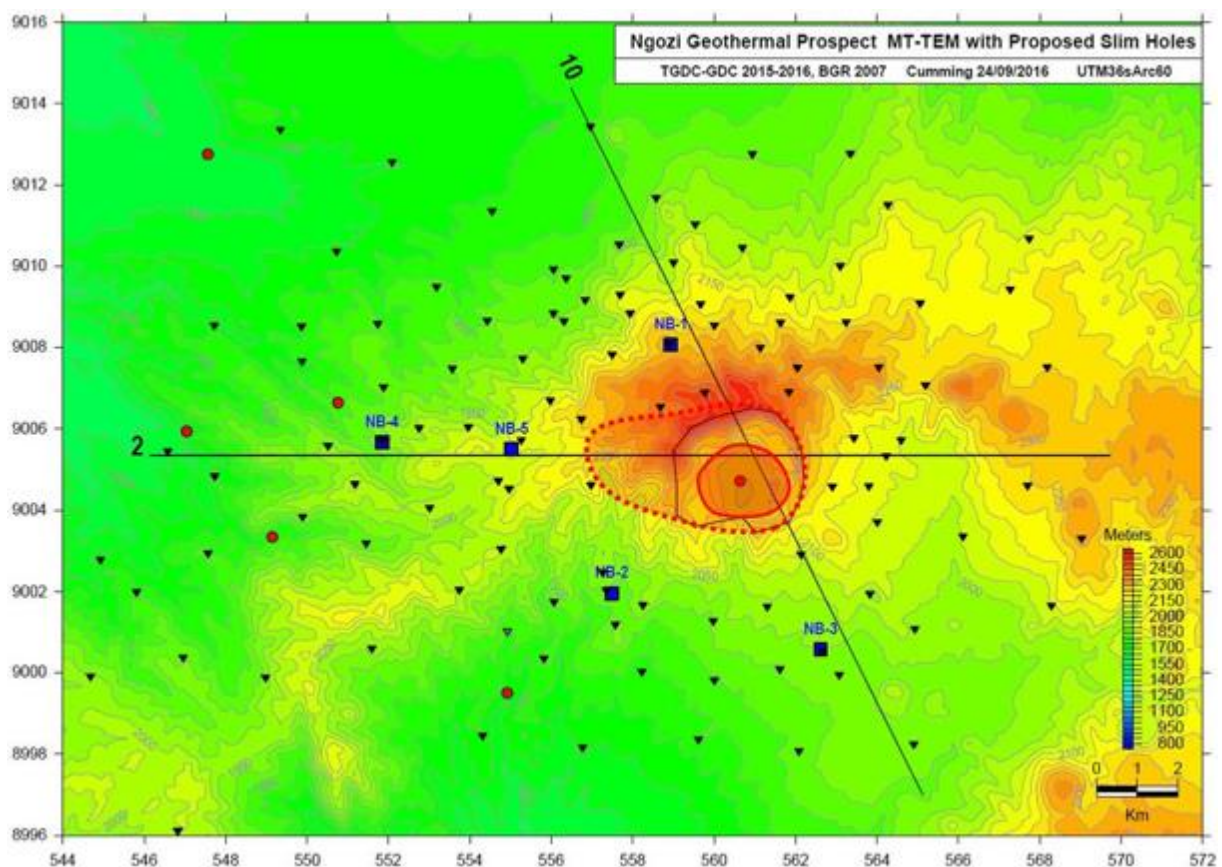


Figure 1. Map of the topography of Ngozi volcano and vicinity. The dashed red outline of the 12 km² P10 reservoir area roughly corresponds to the clay alteration zone that appears to thin near Ngozi, consistent with upflow or high temperature outflow (albeit with no exit for a deep chloride outflow). The P50 (solid red line) roughly corresponds to the 2.9 km² crater lake. The 0.6 km² P90 area is not shown but is centered on the springs in the lake (small red circle). Black triangles are locations of MT-TEM measurement points. Blue squares are proposed slim hole locations. Red circles to the W and NW of Ngozi are warm springs. Schematic geological cross section of Profile line 10 is shown in Figure 2 and the resistivity cross-section along the resource strike in Profile line 2 is shown in Figures 3 through 5.

Because the MT survey does not extend over the very rugged upper flanks of the Ngozi caldera area, it does not directly define a clay cap over the inferred upflow zone but, together with the geochemistry, it is consistent with a roughly elliptical reservoir that extends about 2 km to the west of the perimeter of the Ngozi caldera at a 10% level of confidence, the 12 km² P10 area in Figure 1.

The integrated conceptual model, based on the interpretation of available geological, geochemical, and geophysical data, suggests that the geothermal resource at Ngozi is likely supported by a relatively small, deep upflow of geothermal fluids rising directly beneath the Ngozi crater lake. In the preferred conceptual model (the P90, meaning an estimated 90% probability), the base of the altered volcanic rocks overlies the basement metamorphic rocks, except at an upflow corresponding to the vent of the volcano. In the median model, P50, the resource is assumed to underlie the structural base of the caldera, in an area close to the size of the lake. The P10 is the most pessimistic case at a 10% level of confidence (aside from a model in which no productive resource exists). This is confined to the basement and overlying volcanics that were disrupted by the intrusive neck of the volcano (Figure 1).

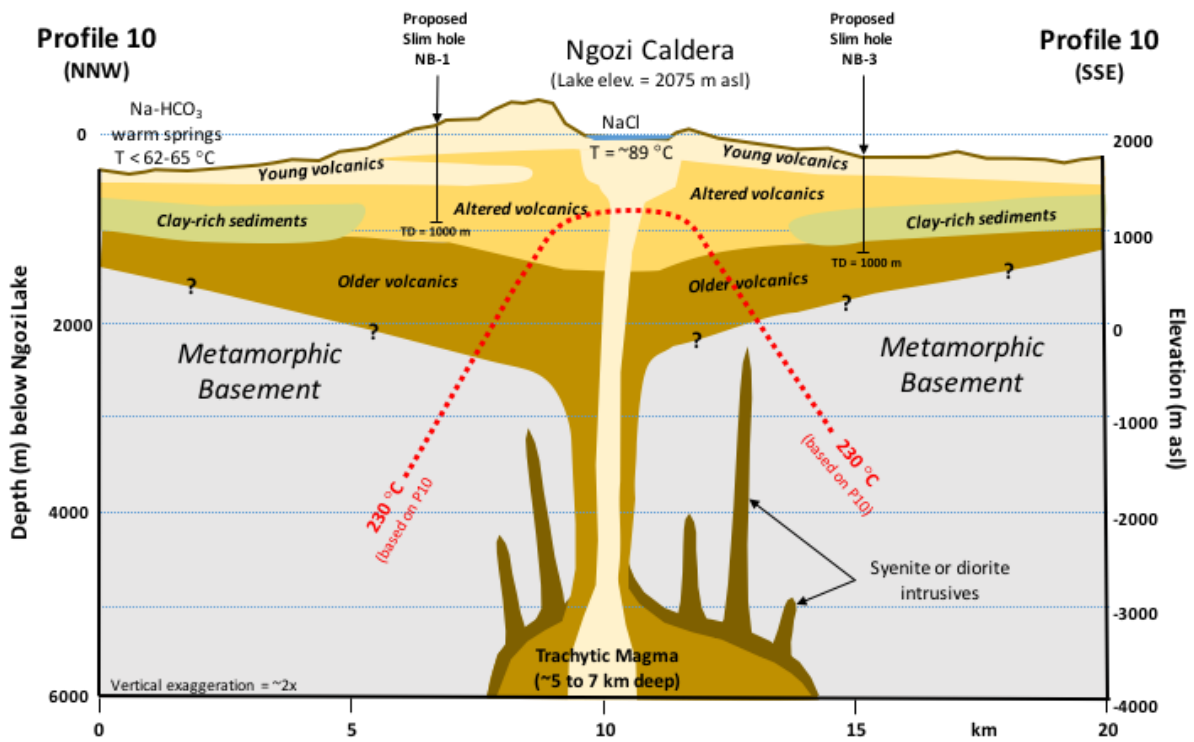


Figure 2. Schematic geological conceptual model for Ngozi volcano. NNW-SSE cross-section through Ngozi. Location of Profile 10 shown in Figure 1. Depth to basement uncertain. Proposed slim hole depths of 1000 m are speculative for illustration purposes.

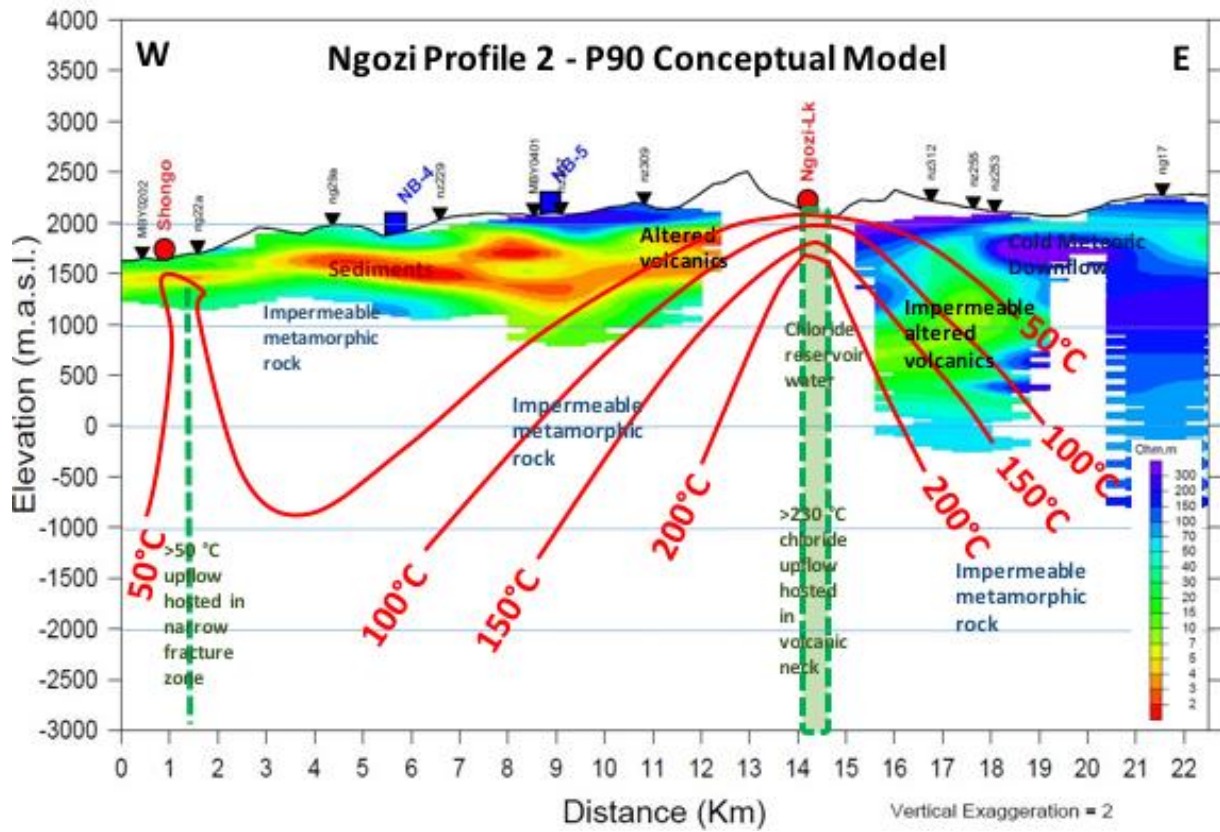


Figure 3: P90 conceptual model for Ngozi volcano. W-E cross-section through Ngozi along Profile 2 (Figure 1)

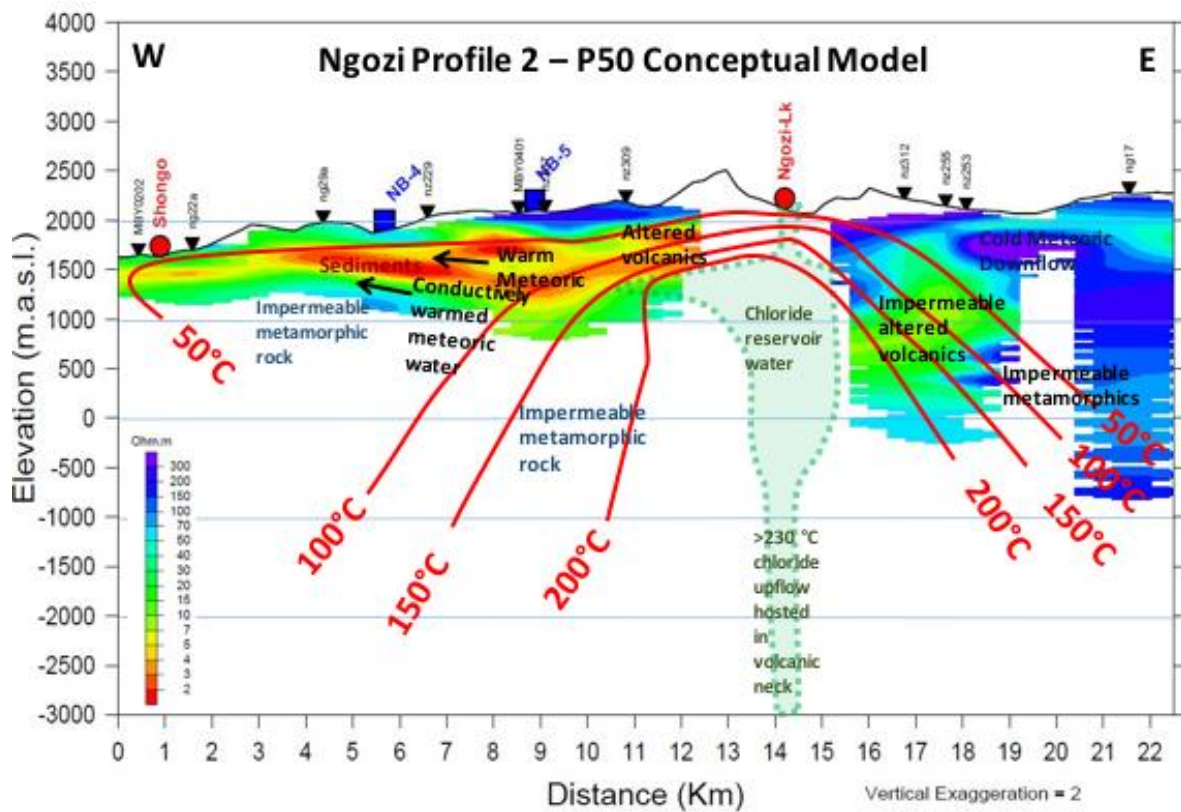


Figure 4: P50 conceptual model for Ngozi volcano. W-E cross-section through Ngozi along Profile 2 (Figure 1)

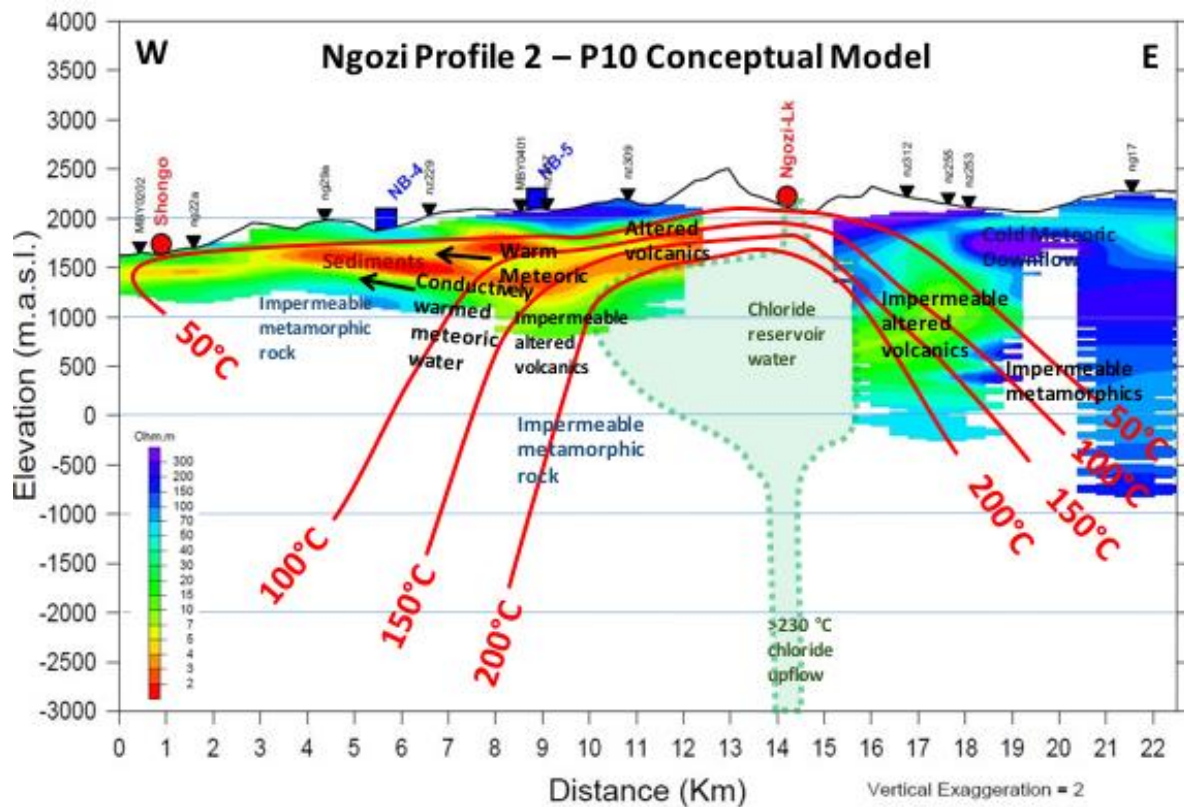


Figure 5: P10 conceptual model for Ngozi volcano. W-E cross-section through Ngozi along Profile 2 (Figure 1)

Heat Source

The heat source of the Ngozi geothermal system is likely a trachytic magma chamber, perhaps 5 to 7 km deep, which was replenished after the Ngozi Tuff eruption less than 1,000 years ago (Figure 2). Because of access limitations near the caldera, reliably resolving magma at >5 km at Ngozi would be difficult unless it extends several km outside the perimeter of the caldera, but such a large magma body at <7 km is inconsistent with the geochemistry and heat loss.

Geothermal Reservoir

The Ngozi geothermal reservoir is likely hosted in three formations: (1) the most recent intrusive neck of the volcano with brittle high temperature alteration; (2) comparatively old volcanic rocks that are expected to have greater potential than the metamorphic basement rocks for sustaining relatively high, distributed fracture permeability, except where altered to low temperature smectite clay that is imaged as 10 to 50 ohm-m by the MT (which is below all of the adjacent MT stations but not necessarily in the gap at the caldera), and (3) intrusive rocks (syenite and diorite), that are related to deep dykes and old, crystallized magma chambers and may have significant permeability if fractured. The minimum depth of the Ngozi geothermal reservoir is 520 ± 140 m below the lake water surface. Although the maximum depth to 230 °C could be several km, such models would be non-commercial and probably non-productive (and so affecting the probability of success but not the resource capacity range at 230 °C). To be commercial, a reservoir would have to be shallower, although specifics would depend on a reservoir engineering assessment beyond the scope of this study.

Cap Rock

The cap rock of the Ngozi geothermal system is comprised of volcanic rocks that have been hydrothermally altered at temperatures less than 200 °C so that they contain smectite clay that makes them impermeable and also low resistivity. Over the area of the currently interpreted upflow within the caldera, the ruggedness of the topography and the lake precluded the acquisition of MT and so no conventional low resistivity cap has been imaged, but the gap in the MT coverage is permissive of

such a cap existing. In the area surrounding the interpreted Ngozi reservoir, the MT images a lateral clay cap or barrier to flow in two distinct zones.

A <7 ohm-m (and generally <3 ohm-m) very low resistivity zone is found as shallow as 100 m depth and as deep as 1200 m to the north, west, and south of Ngozi in a generally flat lying layer that is likely to consist of smectite-bearing lake deposits that conform to regional NW structures that controlled their deposition. Based on the geometry of the warm springs, the sediments probably act as a cap that confines outflow of conductively heated meteoric water and possibly cooled and density-stratified outflow of chloride reservoir water. The chloride water is not a target for a slim hole well because it is necessarily low temperature (otherwise it would buoyantly reach the surface) and information from the well is unlikely to affect the assessment of the geothermometry in the lake in a manner that would decisively affect well targeting.

A 10 to 50 ohm-m, moderate resistivity zone extending to depths as great as 2000 m surrounds the Ngozi volcano and likely corresponds to volcanic rocks with mixed-smectite-illite clay alteration that would also act as a permeability barrier. Because the Proterozoic basement rock near Ngozi is very likely to be impermeable except where pierced by Ngozi volcanic conduit, if the smectite-bearing volcanics directly overlie the Proterozoic in the area surrounding Ngozi, this would effectively isolate the hydrology of the Ngozi crater lake and any underlying geothermal reservoir. This is consistent with the lack of chloride detected in surrounding hot springs, but does not preclude minor chloride leakage.

Reservoir Liquid

The deep geothermal reservoir beneath Ngozi has an estimated temperature of 232 ± 13 °C, TDS of $15,800 \pm 2300$ mg/kg (Na-Cl composition), and a P_{CO_2} of 15 ± 4 bar. The geothermal reservoir is recharged by both meteoric waters (70-50% approximately) and primary magmatic waters (30-50% approximately).

Upflow and Outflow

The main outflow of the Ngozi geothermal system is represented by the hot waters entering the Ngozi crater lake from below, with temperatures of up to 89 °C and a flow rate of 44 ± 7 L/s. This corresponds to a maximum natural heat discharge of 16 ± 3 MW (thermal). The neutral chloride upflow into the Ngozi crater lake is able to overcome the pressure of the lake surface at 2074 m asl, which is much higher elevation than the aquifers surrounding the volcano associated with warm springs at 1100 to 1830 m asl. This requires that any reservoir under the volcano have a pressure that could support the upflow into the Ngozi crater lake and yet be sufficiently isolated by an impermeable shell so that it does not have a chloride outflow into surrounding aquifers at a rate high enough to be detected. In fact, no chloride water consistent with outflow from a reservoir beneath the lake has been detected in surrounding springs and rivers, even to the south, where outflows would be expected based on the drainage pattern.

Two areas of warm springs are found near Ngozi: (1) to the NW of Ngozi, at 12-14 km from the caldera rim, where the cap is truncated and (2) to the W of Ngozi, at 8-12 km from the caldera rim, where the cap is some hundred meters thick. The chemistry of these warm springs indicates that they are conductively heated, either by direct conduction from a reservoir or by concealed lateral outflows of chloride water from the Ngozi geothermal reservoir, although other explanations are conceivable. In any case, because no significant chloride reservoir outflow is detected, any such leakage cannot be at a high enough temperature, or high enough rate to support production near the hot springs. However, a potentially productive outflow may extend west of the perimeter of the upflow beneath the Ngozi caldera, as shown in Figure 1.

Next action: Slim-hole Drilling

It is not practical to target the potential geothermal reservoir directly beneath the Ngozi caldera because the steep topography makes the vicinity of the crater lake inaccessible to conventional drilling rigs. Based on the difficulty of access, the closest plausible drilling location to the caldera

would require a borehole deviation of >1500 m and probably >2000 m to reach the P50 outline. A specific target is not resolved by the available MT. The geochemistry is inconsistent with an interpretation of >230 °C temperature correlated with permeability below the shallow MT low resistivity zone west of the caldera. It is conceivable that a directional well with 1500-m deviation could reach the interpreted optimistic P10 resource outline. Although a slim hole would not directly test the P10 zone, if it was much lower cost than a production well, it could reduce the risk-weighted cost of the production well. If it encountered a temperature pattern consistent with the proposed P10 conceptual model, the directional well would be drilled, if not, drilling would be terminated. Therefore, we recommend that any initial geothermal drilling at Ngozi use low-cost slim hole rather than full-size exploration production wells, targeted at a location and depth that will detect the temperature pattern in the conductively-heated, impermeable clay zone surrounding the target area to increase confidence in the existence of a nearby reservoir.

Locations of five slim holes are suggested based on (1) the presence of existing dirt roads or tracks, (2) the proximity to the crater lake, (3) relatively low elevation, and (4) the distribution of locations around the Ngozi crater lake consistent with the conceptual model.

3. SONGWE

The Songwe prospect is defined by several hot springs associated with travertine deposition that has become massive over its 360,000-year duration. The springs and travertine are most likely supported by water and CO₂ upflow in fracture permeability developed where the bounding hinge fault on the SW margin of the Songwe basin intersects a prominent step-over fault (Figure 6). The 112 ±16 °C geothermometry of the hot springs is consistent with meteoric water circulation to depths of 1.5 to 2.6 km where the regional thermal gradient could supply adequate heat. Geothermal resources with similar temperature have supported small geothermal power plants in the western USA but, worldwide, they are more commonly developed for direct use of heat and tourism.

The Songwe River thermal area includes several hot springs that discharge water at a temperature of 55-80 °C (Figure 6). Although the Songwe hot springs had once been hypothesized to be an outflow from Ngozi volcano, 42 km to the ESE, more complete geological, hydrological, geochemical, and geophysical data and analyses demonstrate that this is very unlikely.

The location of the Songwe hot springs and the associated travertine deposition is hydrologically controlled by the location and water level of the Songwe River and the water elevation of Lake Rukwa to the NW. The Songwe River originates from the metamorphic basement rock of the Chumwa Range to the S and SW of Songwe springs. The river flows northward along the W side of Panda Hill before entering the Songwe hot springs area (Figure 6). Over the last 360,000 years, the locations of the Songwe and other nearby hot springs, have moved to the NW as water levels in Lake Rukwa and the Songwe River have dropped. The extensive travertine deposits also follow the migration of spring discharge points to the NW over the same period (Figure 6). The travertine deposition is related to the oversaturation of the fluid with calcite upon loss of CO₂ as the fluids reach the surface. The elevated flux of cold CO₂ is typical of this part of the East African Rift and related to deep crustal-mantellic processes, not shallow magmatism that might be associated with a volcanic geothermal system.

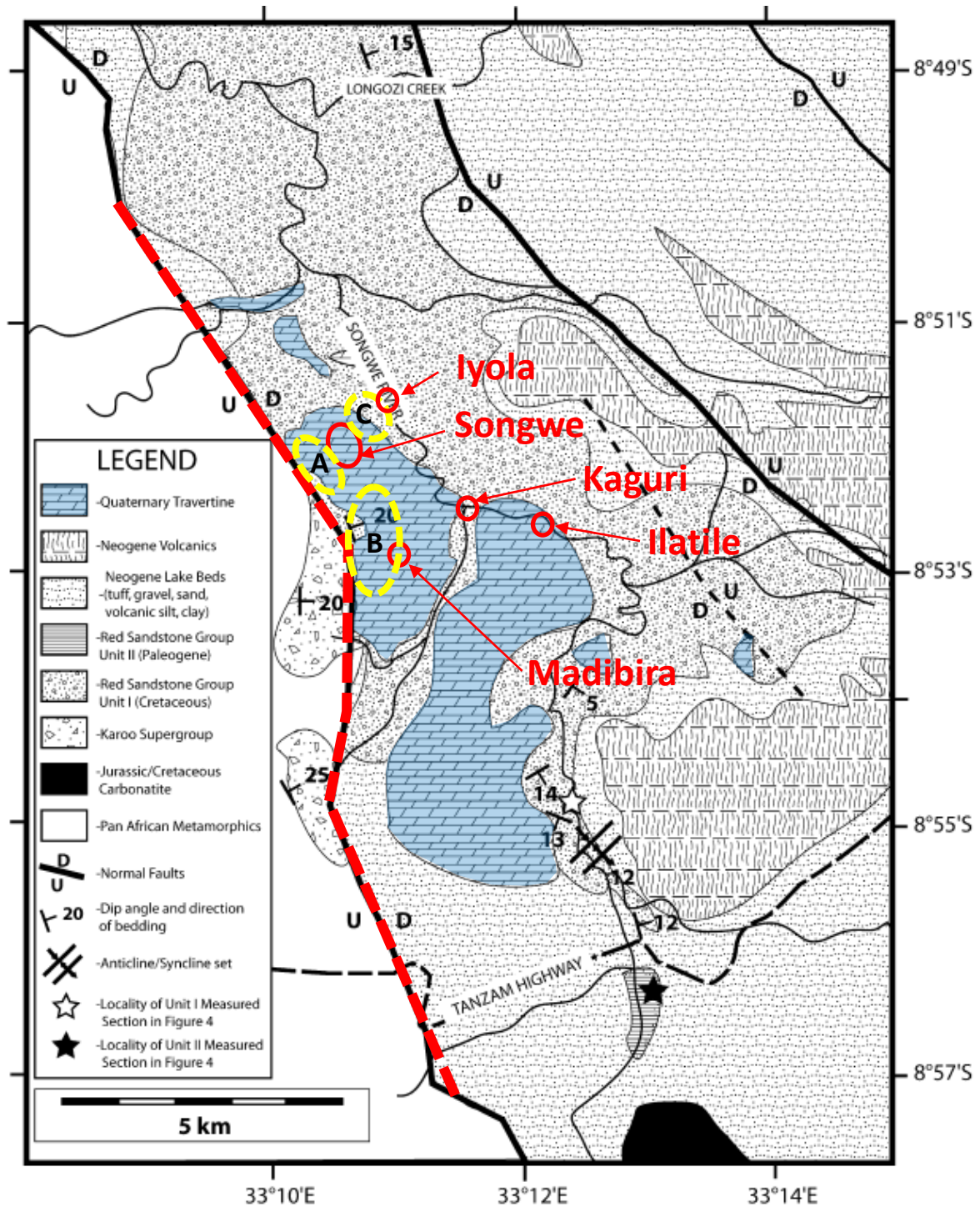


Figure 6. Location of Songwe River thermal area (hot springs in red) approximately 30 km W of Mbeya (and about 42 km WNW of Ngozi). SW Songwe basin fault with N-S step-over shown by dashed red line. Travertine deposits highlighted in blue. Areas in yellow circles are proposed locations for thermal gradient wells. Map adapted from Roberts et al. (2004) and references therein.

The Songwe geothermal conceptual model shown in Figure 7 is fault-hosted and, consequently, its development is chiefly governed by the structural framework and the water table, although the interaction of several additional processes control which specific conduits host flow at any given time. The precipitation of solids from hot water to form travertine is a dynamic process, changing at a geologically short time scale. When CO₂ is lost on exposure of the hot water to atmospheric pressure,

calcium carbonate precipitates, increasing the elevation and extent of the travertine. Cooling and organic action also affect travertine build-up. Water channels can become clogged by precipitation. Most of these changes occur at or near the surface but changes in pressure are communicated to greater depth. The differences in elevations of the various spring discharges (as much as 25-30 m) over a relatively small area imply that subsurface fluid paths are complex. As the travertine deposition migrates NW, areas that once hosted active hot spring flow and travertine deposition can experience influx of cold water and dissolution, enhancing pathways for cold water influx.

There are two alternative conceptual models for the fault-hosted system at Songwe. In the conceptual model for Alternative A, the ascending branch of the Songwe thermal circuit is controlled by both the SW basin fault of Songwe basin and the normal step-over fault of the Songwe basin fault, which determines conditions of high vertical permeability favoring the upflow of the thermal waters towards the surface (Figure 7).

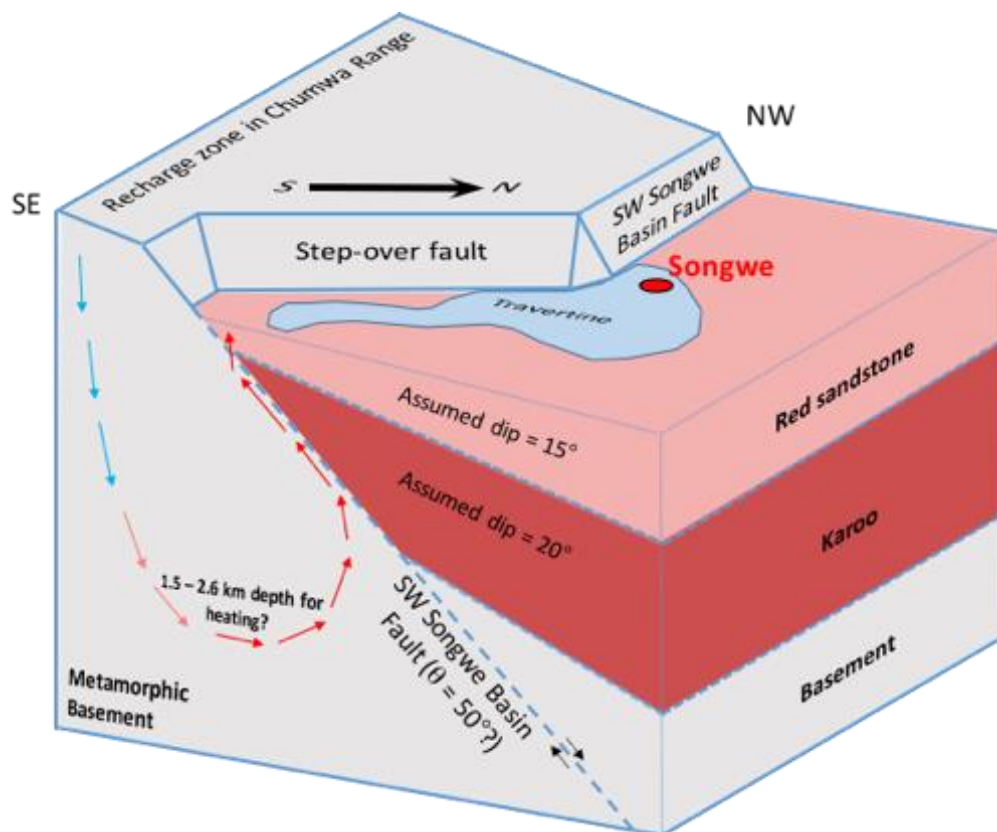


Figure 7. Schematic geological conceptual model for Songwe hot springs (Alternative A). Shallow lake bed sediments not shown for clarity.

The geometry of the basin margin and step-over fault intersection is detected in a general sense by the surface geology, MT, TEM, gravity, aeromagnetic, and ground magnetic surveys but none have the resolution required to characterize specific fluid pathways. Pathways could be better characterized by drilling small-diameter temperature gradient holes (TGHs) prior to targeting wells capable of commercial production.

The TGH wells would also resolve the Alternative B model that the upflow zone might be positioned to the NE of Songwe, in the half graben beneath the clay-rich sediments that the MT resolves as a low resistivity zone filling the half graben and dipping up to the SW, where they would divert the gas-rich

hot water to Songwe (Figure 8). Recent geological field surveys have identified hot springs at Iyola (Figure 6) located NE of the Songwe hot springs, which may indicate an upflow zone to the NE (Figure 8). However, the lack of reported gas leakage in the half graben and the longevity of the travertine deposition makes the model with the main upflow beneath the deeper recent sediments (Alternative B) less likely than an upflow at the structural intersection at the basin margin (Alternative A).

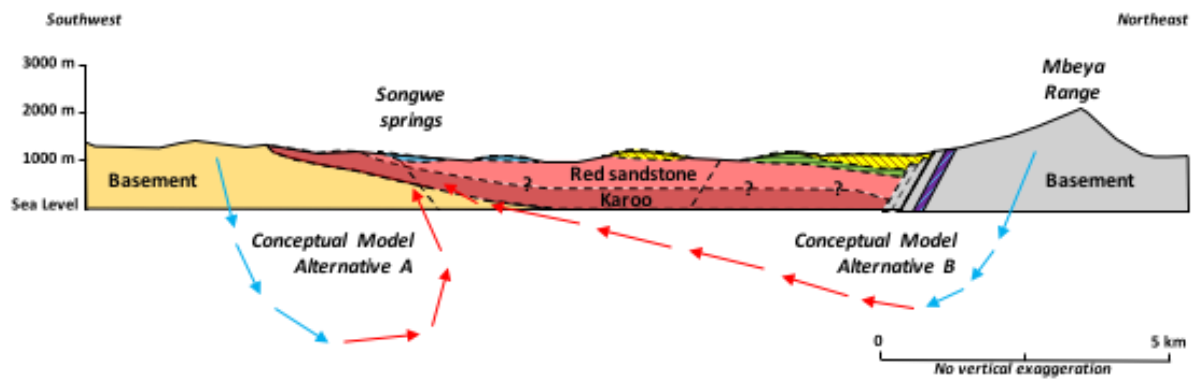


Figure 8. Schematic SW-NE cross section showing alternative conceptual models for Songwe hot springs.

The descending branch of the Songwe thermal circuit likely occurs mainly in the fractured metamorphic rocks of the Chumwa Range to the S with possible input from the SSE where the Panda Hill carbonatites occur. Due to the absence of a magmatic heat source, the descending meteoric waters are heated by conductive heat transfer. This implies that they have to descend to depths where rock temperature is high enough. The maximum depth to which the meteoric water descends is constrained by the geothermometric temperature of the hot springs (112 ± 16 °C) and the geothermal gradient, likely to be within the range of 40-50 °C/km, implying a circulation depth of 1.5 to 2.6 km. Based on long term simulation models run of numerous analogous developed systems at these depths, permeability is likely high enough to allow the transit of the water through the fractured rocks and low enough to permit efficient rock-to-water heat transfer.

The outflows of the Songwe geothermal system are represented by the hot springs of Songwe spring itself, Iyola, Rambo-Ilatile, Madibira, and Kaguri (Figure 6). Their total natural discharge is between 50 and 75 kg/s, corresponding to a total heat transfer on the order of 7-10 MW thermal (MWt), assuming a median outlet temperature of 60 °C. Based on rules of thumb for estimating MW electrical (MWe) from MWt and allowing for reduced efficiency at lower temperature, this would suggest a minimum potential power capacity of about 0.5 MWe. All of the hot springs have similar chemistry suggesting that mixing with shallow groundwater is negligible. Their chemical composition is Na-HCO₃, with average TDS of 3271 ± 115 mg/kg. The high P_{CO2} values and the chemical composition of the Songwe hot spring waters indicate very likely occurrence of calcite precipitation upon CO₂ loss, in agreement with the extensive travertine deposition. Mitigation of calcite scaling will probably be needed during any type of commercial exploitation of the Songwe geothermal system.

Next action: Drilling of Temperature Gradient Holes (TGHs)

As summarized above, potential targets at Songwe are ambiguous because the dip of the most important structures and formations are not well constrained, the fluid pathways through the shallow travertine is likely to be complex, and there is some ambiguity in the general conceptual model. Drilling of 5-6 shallow (100 m to several hundred m) wells (general locations shown on Figure 6) to measure formations, structures, and the temperature gradient near the Songwe hot springs is expected to establish, at relatively low cost, the overall structure, formation dip, and the general location of the upflow and outflow zones.

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