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Surface Exploration of a Viable Geothermal Resource in Mbeya area, SW Tanzania. Part I: Geology of the Ngozi – Songwe Geothermal System

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ABSTRACT

Geothermal surface exploration in SW Tanzania in the frame of the GEOTHERM programme in 2006-2009 allowed to evidence and characterizes the Ngozi – Songwe geothermal system in the area of Mbeya, as part of the Rungwe Volcanic Province. This paper presents the geological and sismotectonic aspects of the geothermal system, including the distribution of seismic epicentres, Quaternary volcanic vents, and thermal springs (hot/cold) and gas vents (CO2). The geothermal system is closely related to the Ngozi volcanic system and is associated to large travertine deposits, that started to be active at least 36 Ka ago U-Th dating on Songwe Travertine. The Late Quaternary stress field and related deformation define the structural architecture of the volcanic system and exert a strong influence on the thermal waters which are circulating trough the active fault network. The strong altitude gradient drives efficient and distant transfer of the fluids from the Ngozi volcano recharge area, trough the geothermal reservoir located between the Ngozi crater and Mbeya town, towards the discharge areas in the Songwe valley.

1. INTRODUCTION – GEOTHERM IN TANZANIA

Geothermal surface exploration in Mbeya area of Tanzania was carried out between 2006 and 2009 within the framework of GEOTHERM technical cooperation programme. GEOTHERM programme is implemented by the Federal Institute for Geosciences and Natural Resources (BGR, Hanover, Germany) on behalf of the Federal Ministry for Economic Cooperation and Development (BMZ, Bonn, Germany). The Royal Museum for Central Africa collaborated with the GEOTHERM group for the geological background of the project.

Geological investigations for geothermal exploration in the Mbeya area included structural, volcanological, and travertine investigations applying the following methods: Structural investigations included mapping of lineaments (remote sensing using SRTM DEM 90 and geo-referenced aerial photographs), ground truthing of lineaments in the field with tracing of active faults via hot spring emanations, as well as measurement and inversion of fault slip data using TENSOR software. The results of the reconstructed past tectonic stress state were compared with the present-day stress inferred from published focal mechanisms of earthquakes. Volcanological investigations included chemical (XRF) and isotopic (TIMS) analyses of pumice from Ngozi volcano proposed for the first time as heat source for major surface manifestations (Songwe hot springs). Additionally, chemical, mineralogical (XRD, CEC) and isotopic analyses of xenoliths found in the pumice deposit of the caldera forming event as well as a bathymetric survey of the lake within the Ngozi caldera were done. Travertine investigations included chemical (XRF, μ-EDXRF), stable isotope (carbon, oxygen, strontium, neodymium), and mineralogical analyses as well as U/Th disequilibrium dating (TIMS). The results for Ngozi-Songwe geothermal system are:

(i) Most thermal springs are aligned along the major NW-SE rift trend that controlled the long-term development of the Rukwa and North-Malawi (Nyasa) rift basins. During the last 0.5 Ma, the local fault kinematics is dominated by NW-SE horizontal extension and NE-SW horizontal compression leading to a new network of conjugated strike-slip faults. Fluid flow is mainly controlled by fracture permeability along active faults.

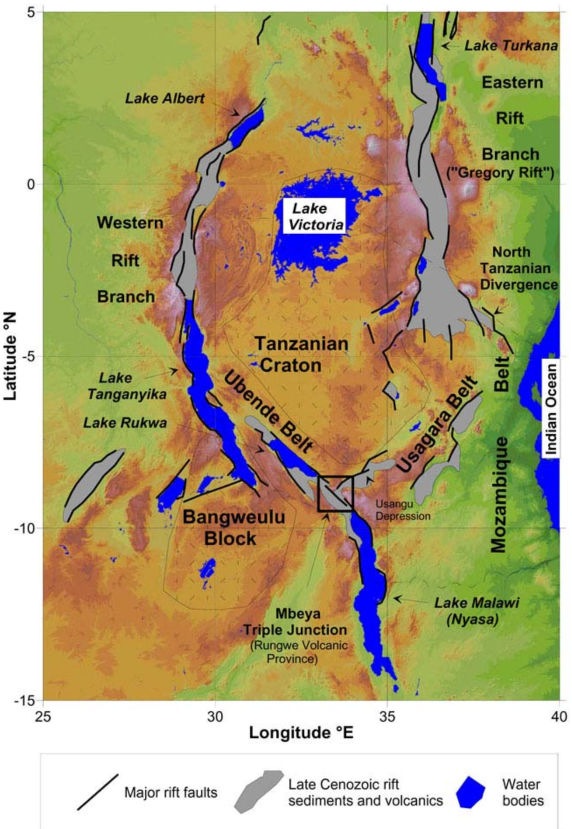

Figure 1: Location of the area regarding the Basement and the rift structure, on the background of colour-coded SRTM DEM.

(ii) A newly discovered volcanic cone below the surface of Ngozi Caldera Lake most likely represents the eruption centre from which eruptions took place after the major caldera forming event. The replenishment of the magma chamber more recent than 13ka suggests a viable heat source in the subsurface. The mineral assemblage of the analysed altered xenolith (Ubendian gneiss) can be explained by low-temperature alteration suggesting that the high-enthalpy reservoir not being located in the Precambrian basement.

(iii) Supporting evidence from Sr and Nd isotopic composition of fossil Songwe travertine characterised by close to mantle values was found. The lack of a significant crustal component implies that the major fluid-rock interaction occurs within volcanic rock pile on top of the Precambrian basement. Abundant xenoliths of Ubendian gneisses suggest a magma chamber situated within the Precambrian basement. The O and C isotopic composition indicates that the fossil travertine is of thermogene origin, documenting the longevity of the geothermal system. Together with e.g. U/Th dating of Songwe travertine evidence was found for a linkage of volcanic and geothermal activity as well as climate conditions in space and time.

The present paper defines the geological context of the Ngozi-Songwe geothermal system near Mbeya. It is based on a compilation of data largely acquired by the first author outside the frame of the GEOTHERM programme and supplemented by results from joint field investigation.

2. GEOSCIENTIFIC REVIEW OF THE FIELD AREA

2.1 Regional Geology

The simplified geology of Tanzania can be summarised as follows (Figure 1): Achaean rocks dominate in the central to northern parts of Tanzania that form the Tanzanian Achaean Craton. They are surrounded to the southwest by the Palaeoproterozoic Ubendian belt and to the southeast by the Palaeoproterozoic Usagaran belt. The latter has been largely overprinted by the Pan-African Mozambique belt during the Neoproterozoic along the eastern margin of the Tanzanian Craton. Related to different rifting episodes, the Achaean and Proterozoic rocks are covered partly by Permian (Karoo) to Quaternary sediments including Cenozoic volcanics (Delvaux 1991). The youngest sediments and volcanics are related to the active Cenozoic East African Rift System (EARS), which is divided into a western and eastern branch. In general, the EARS developed almost parallel to the Ubendian and Usagaran mobile belts and the two branches form a triple junction at Rungwe Volcanic Complex (Delvaux & Hanon 1993) in the Mbeya area (Fig. 1).

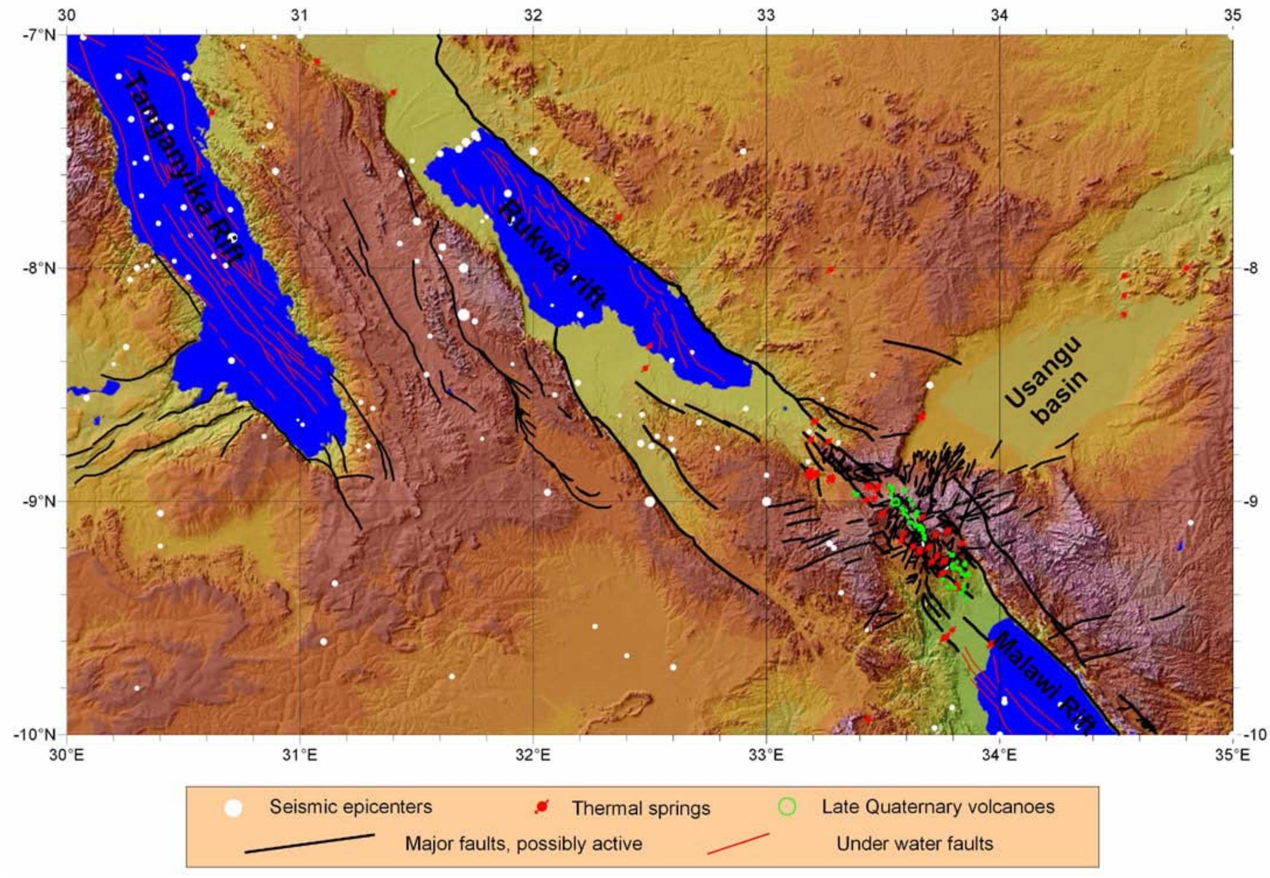

Figure 2: Neotectonic faults in the South Tanganyika – Rukwa – Nyasa region, with seismic epicenters, thermal springs and Quaternary volcanoes (after Fontijn et al., submitted) of the Rungwe Volcanic Province on the background of colour-coded SRTM DEM.

2.2 Tectonics, Volcanic and Seismic Activities

The fault pattern and kinematics of the neo-tectonically active East African Rift System in the working area was analysed e.g. by Delvaux et al. (1998; Figure 2) and the related distribution of earthquake epicentres and earthquake depth distribution in Mbeya region is intensively discussed in Delvaux & Hanon (1993).

The triple junction of the NW-SE trending South Rukwa and North Malawi Rift basins intersected by the NE-SW trending Usangu depression is covered by the Rungwe volcanics (e.g. Ebinger et al., 1989; Delvaux 1991, Delvaux & Hanon 1993). Rifting in the North Malawi Rift has undergone two successive phases (Delvaux et al. 1992), normal faulting (early phase) occurring during WSW–ENE extension and strike-slip motion (second phase) along a WNW/NW–ESE/SE direction. In the second phase, NW-SE oriented sub-basins were formed due to transtension while transpression led to localised uplifts.

The magmatic activity in Mbeya area started in Miocene times (Songwe Tuff: 8.60±0.04 Ma; Ebinger et al. 1989; 1993). The Late Quaternary record of explosive eruptions is well preserved in lake sediments (e.g. Massoko maar lake; Gibert et al. 2002). The last eruption of the recent volcano Kiejo in the Rungwe area occurred ca. 200 years ago (Harkin 1960).

In summary, the conditions for high-enthalpy resources are principally favourable in the Mbeya region due to the presence of active faults allowing fluid flow, young volcanic heat sources (which are sparse in other parts of the western branch of EARS) and the occurrence of surface manifestations (e.g. hot springs) indicating geothermal activity in the subsurface.

2.3. Lithological Units

In relation to Cenozoic, rifting the Rungwe area was uplifted and denudation processes exposed the Precambrian basement (mainly Ubendian gneisses) at the earth surface in Tertiary times (Van der Beek et al. 1998). The Rungwe volcanic rocks are directly overlying the basement in the central part of the area (e.g. at Ngozi and Rungwe volcano). According to Harkin (1960) the volcanic rocks are classified as older and younger extrusives. The older extrusives occur mainly in the area of Poroto Mountains. They are mainly composed of phonolites, trachytes, and basaltic lavas. The younger volcanic eruptions are centred at Kiejo (youngest eruption product is tephrite lava), Rungwe (mainly phonolitic trachytes as pyroclastics) and northern Poroto mountains (including e.g. Mpoli and Izumbwe melanephelinitic lavas and Ngozi pumice layers).

K/Ar and $^{40}Ar/^{39}Ar$ age determinations for the eruptive products are published e.g. by Ebinger et al. (1993) and youngest eruptions were dated by ^{14}C method (e.g. Gibert et al. 2002).

The basement of the rift towards Lake Rukwa is overlain by increasingly thickening sediments which are exposed in Songwe river valley (Damblon et al. 1998; Delvaux et al., 1998). The profile exposed in Songwe river gorge and the travertine quarry is shown in Figure 3.

The Karoo was mainly deposited during Permian and is exposed with ca. 180-300m thickness at the western escarpment on top of Precambrian basement gneisses. The Karoo conglomerates are overlain by the Red Sandstone Group (Dypvick et al., 1990) that has been recently shown to be composed of a lower (Cretaceous) unit and an upper (Paeogene) unit (Damblon et al. 1998; Roberts et al., 2004). The Cenozoic lake beds on top of the red sandstones are overlain in the eastern part of the gorge without unconformity by a basaltic lava flow (550 ka). The travertine of Songwe hot springs is younger than the basaltic lava and overlain by an about 11 ka old volcanic ash (Figure 3). At the sites of the Songwe hot springs recent travertine is deposited.

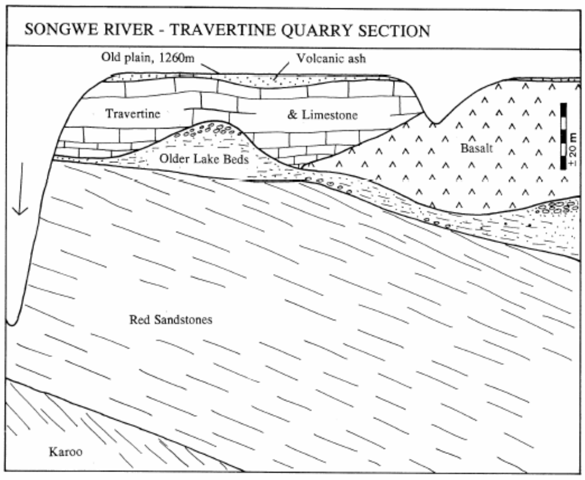

Figure 3: Stratigraphic succession in Songwe area including evidence from drill holes (from Delvaux et al. 1992)

The basement rock beneath the sediments consists of sheared garnet gneiss, and shattered zones within this gneiss probably provide channels along which the volcanic gasses rise (James 1967).

Additionally, it is important to note that there are a number of Pre-Cenozoic intrusive carbonatites in Mbeya (Figure 4) region namely the Neoproterozoic Musensi carbonatite and the Cretaceous Mbalizi, Songwe scarp and Panda Hill carbonatite (Brown, 1964; Pentelkov and Voronovskiy, 1979 and references herin; Pisarskii et al., 1998). The latter is located between Ngozi volcano and Songwe hot springs (Fawley and james, 1955; Fick and Van Der Heyde, 1959).

3. INVESTIGATIONS AND RESULTS

3.1. Geological Setting and Evolution

Geological investigations were done to trace geothermal fluid flow via surface manifestations in space and time (alteration zones, travertine deposits, active faults).

The area of investigation belongs to the Rungwe Volcanic Province near Mbeya which is located at the intersection between the western and eastern branches of the East African Rift System, forming a the triple junction between the South-Rukwa, North-Malawi (Nyasa) and Usangu rift basins. Its present-day architecture is the product of a long-term rift evolution into several successive stages. The Neotectonic period in that area represents the second – and still active stage of the Late Cenozoic rifting history, and is constrained by dated volcanics from the Rungwe massif, to have started 1.5 - 1 Ma ago. Tectonic investigations in the area show that fluid flow is controlled by fracture permeability mainly along active faults. Most thermal springs are aligned along the major NW-SE rift trend that controlled the long-term development of the Rukwa and North-Malawi (Nyasa) rift basins (Figure 4). During the last 0.5 Ma, the local fault kinematics is dominated by NW-SE horizontal extension and NE-SW horizontal compression leading to a new network of conjugated strike-slip faults.

3.2. Late Quaternary Architecture

A detailed investigation combining SRTM DEM90, referenced aerial photographs, topographical and geological maps and field observations allow to refine the knowledge of the tectonic architecture.

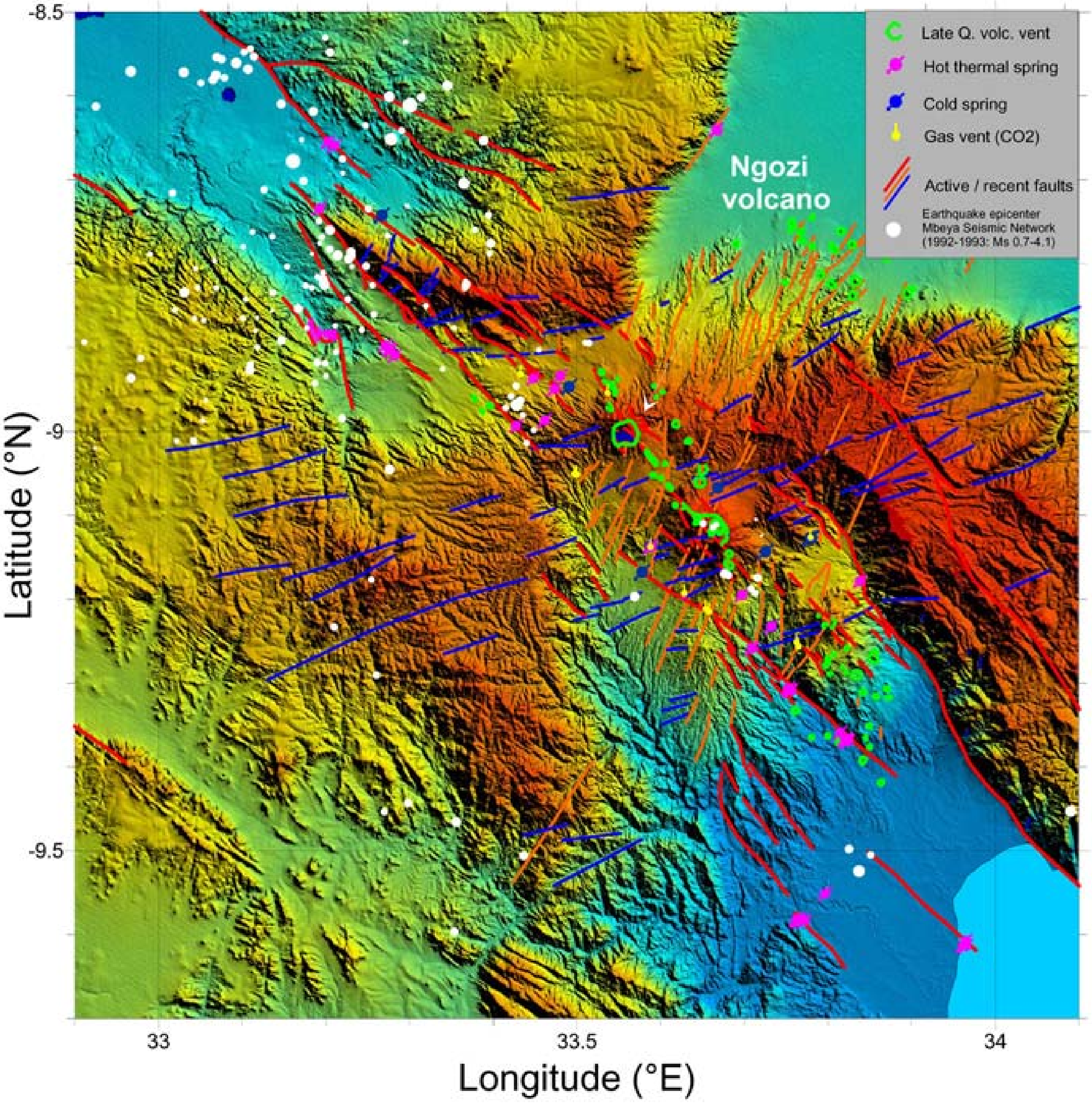

Figure 4: Evidence for recent tectonic activity: fault lines, earthquake epicentres (from Camelbeek and Iranga, 1996), recent volcanic vents (from Fontijn et al., submitted), and thermal springs differentiated as hot thermal (temperature above ambient, sometimes with CO2), cold meteoric springs, and CO2 vents with no water outflow.

The RVP is currently affected by a strike-slip to extensional type of tectonic stress regime with both horizontal ENE-WSW maximum compression and NNW-SSE minimum compression (extension) axes.

Deformation localises mainly along high-angle faults that cross-cut the whole volcanic massif and along which significant strike-slip to oblique-slip movements occur. These faults often reactivate older basement structures and/or normal fault systems within Late Quaternary rift sediments and volcanics.

They exert a strong control on the volcanic vent location and also on the discharge of many hydrothermal springs (hot springs up to 74 ° in temperature, CO_2 gas vents, or a combination of the two) and cold meteoric springs. Ar-Ar dating of recent volcanics and U-Th dating of the Songwe Travertine shows that the Ngozi geothermal system started to be active at least 360 Ka ago.

3.3. Tectonic Stress

A consistent pattern of Late Quaternary to Present-day stress field is shown by 3 different lines of evidence:

(1) the focal mechanism of the Mbeya 1994, Ms 4.5 earthquake;
(2) Geological fault-slip data in Late Quaternary sediments and volcanics;
(3) Focal mechanisms from minor earthquakes (Mbeya Seismic Network).

All show a strike-slip stress regime with N-S to NNW-SSE horizontal extension and E-W to ENE-WSW horizontal compression (Fig. 5).

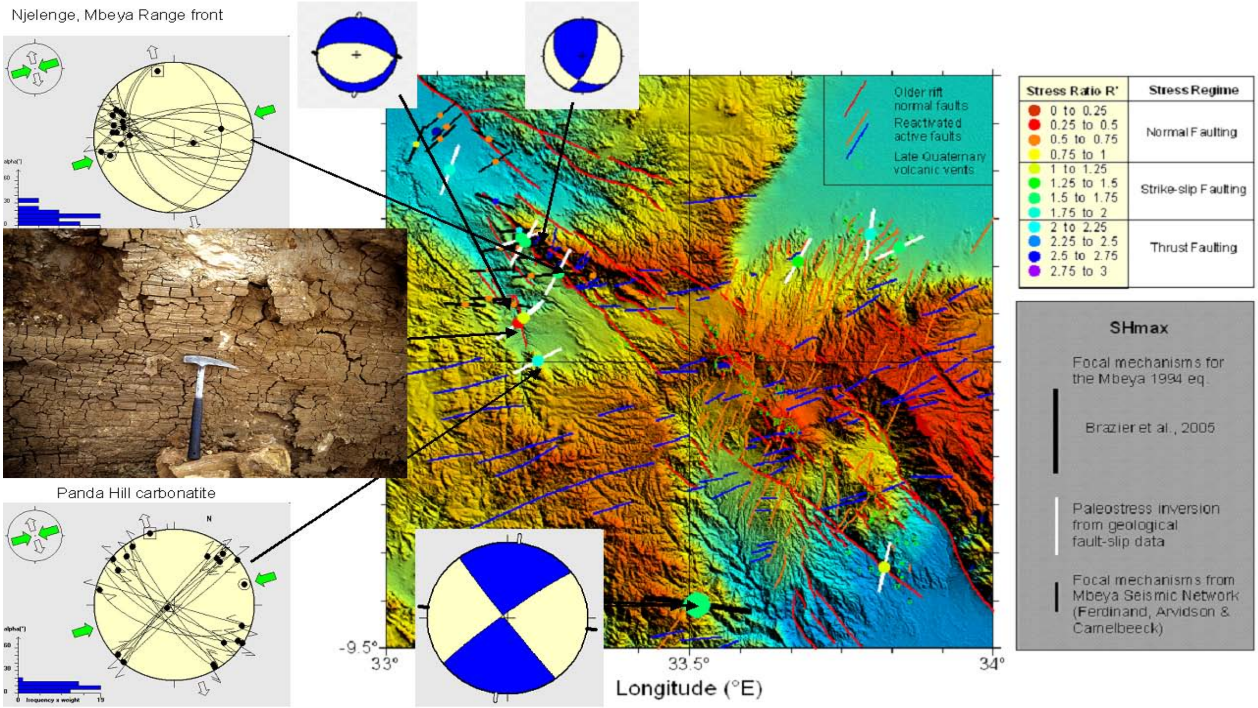

Figure 5: Tectonic stress in the Mbeya area, combining geological field data with earthquake focal mechanism data from Ferdinand and Arvidsson, (2002) and Brazier et al. (2005).

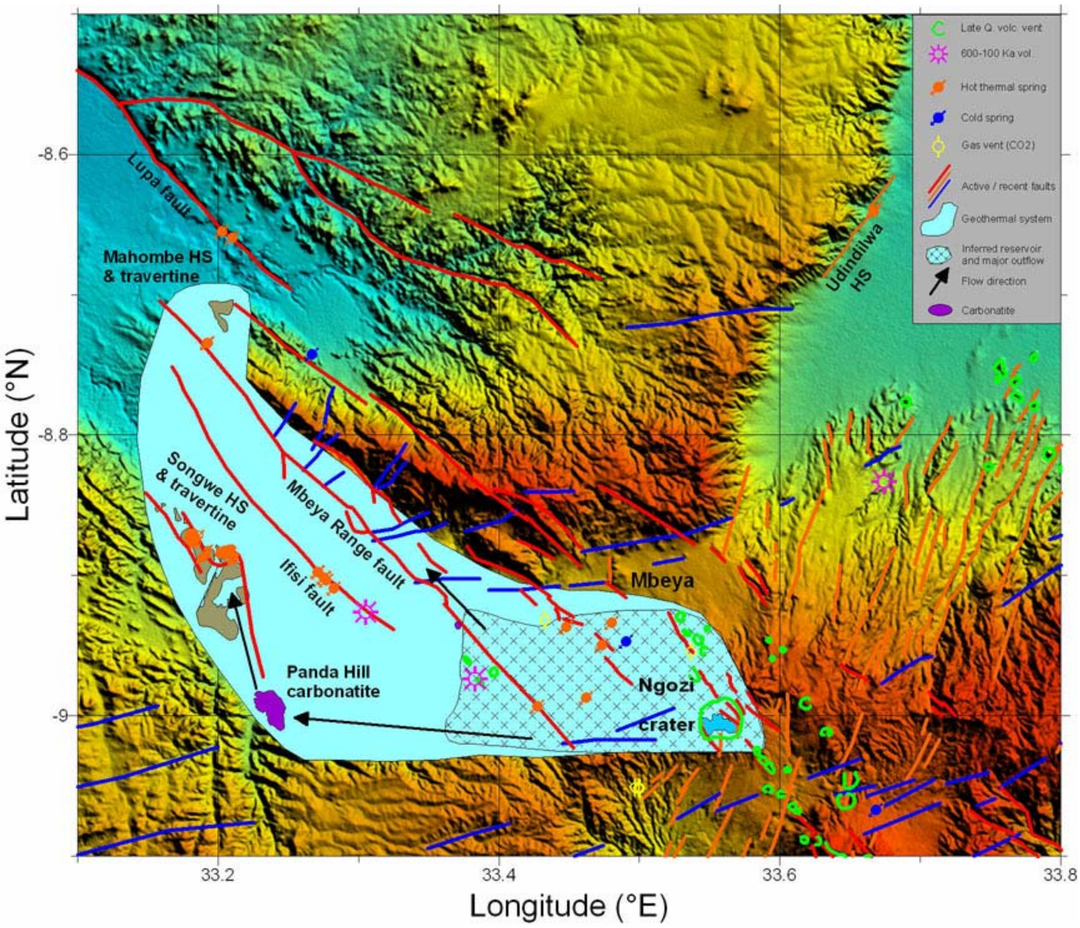

Figure 6: Map of the proposed Ngozi - Songwe Hydrothermal System.

3.4. Ngozi - Songwe Geothermal System

Geochemical investigation of the thermal waters and gas and the associated travertine deposits, together with a geophysical survey allows to propose a consistent geothermal model for the Ngozi-Songwe part of the Rungwe Volcanic Province (Fig. 6).

The Ngozi volcano forms the recharge area, the geothermal reservoir is located between the Ngozi crater and Mbeya town and the thermal waters are circulating trough the active fault network towards the discharge areas in the Songwe valley, following the natural slope gradient (Figs. 7, 8).

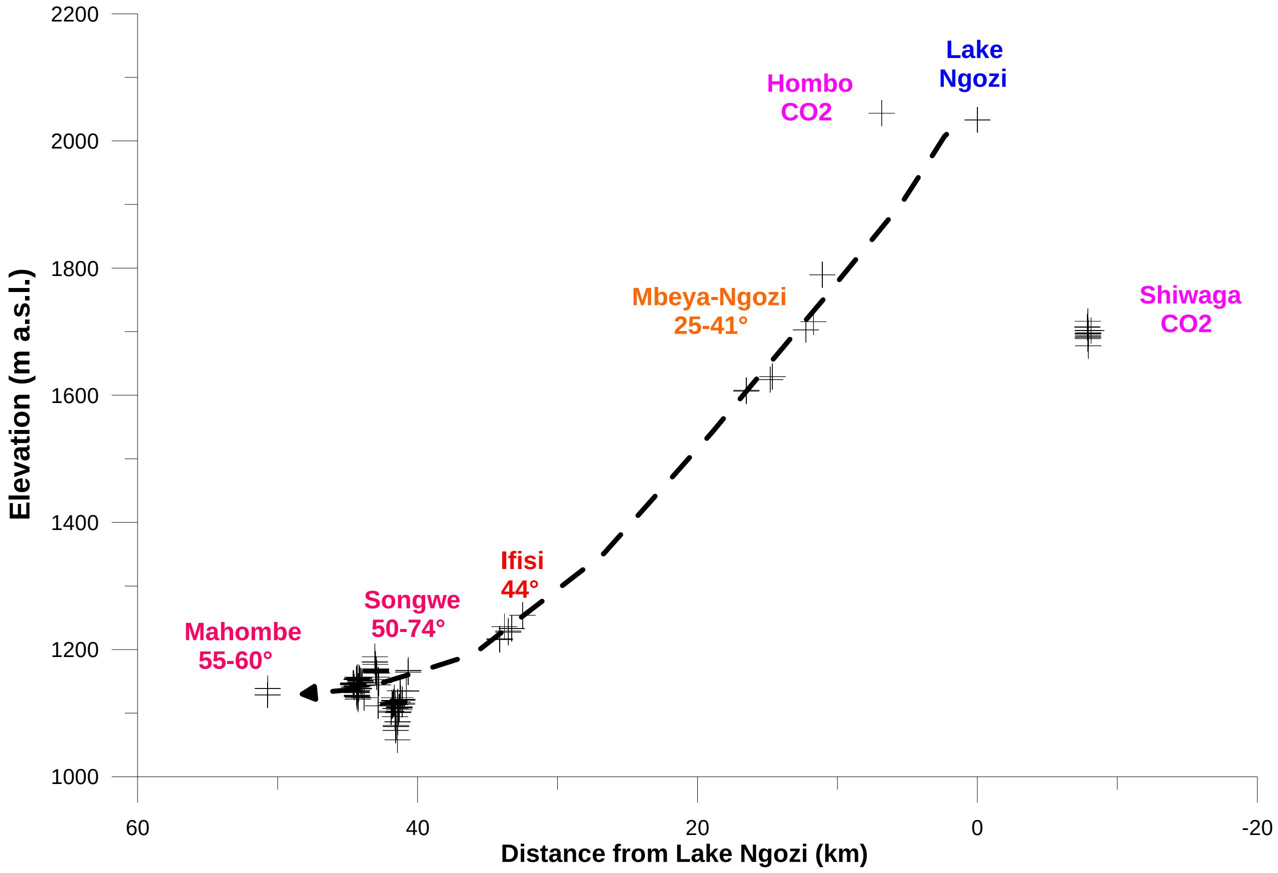

Figure 7: Distance – elevation plot of the thermal springs with their temperature, from the Ngozi volcano recharge area to the Songwe valley discharge.

Figure 8: Fault controlled fluid circulations. The thermal waters of the springs along the Ifisi rifer are emerging from a fault zone. The latter initially developed as a normal fault system (conjugated normal faults as seen here) and was reactivated as a steep strike-slip fault.

4. CONCLUSIONS

Surface exploration of the Mbeya area evidenced the Ngozi-Songwe hydrothermal system that appears to be related to its particular setting at the junction between the eastern and western branches of the East African Rift System. This system appear to be related to the Ngozi volcanic system, with heat from the underlying magma chamber, fault-controlled water circulation driven by the important altitude difference between the recharge area (the Ngozi volcano and the discharge area (the Songwe valley). The dating of associated recent volcanics and travertine deposits suggest that this hydrothermal system is active at least since 360 Ka ago.

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