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Surface Exploration of a Viable Geothermal Resource in Mbeya Area, SW Tanzania. Part III: Geophysics

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ABSTRACT

Based on the geochemical results presented by Kraml et al. (this volume) the proposed high-temperature reservoir was traced by resistivity methods. To cover an exploration depth down to approximately 10 km a combination of the transient electromagnetic (TEM) and magnetotelluric (MT) methods have been applied.

2-dimensional resistivity models have been calculated and used for horizontal resistivity maps at several depth levels. The resulting resistivity structure may be interpreted as a high-temperature geothermal reservoir:

- high resistivity at shallow depth down to approximately 500 m,
- very low resistivity between 500 and 1000 m depth interpreted as clay cap fingering out laterally, and
- localized slightly increasing resistivities interpreted as advancement into the hottest part of the reservoir at about 2200 m depth below the surface.

At greater depth around 4000 m below surface the major NW-SE rift trend within the high-resistive Precambrian basement can be distinguished by its resistivity structure.

The interpretation of an intense alteration in the subsurface only to the W of Ngozi volcano deduced from MT and TEM measurements is supported by a prominent magnetic low with coinciding lateral extent, indicating demagnetization by alteration of the originally magnetic volcanic rocks forming the clay cap of the geothermal reservoir.

Deep exploration wells (about 2200 m) could be located according to the resistivity model derived. However, additional MT measurements are recommended to define the southward extension of the geothermal upflow zone more precisely. Additionally, deep temperature gradient wells reaching the top of the clay cap in about 500 m depth would further constrain the presented model and reduce resource related risk for the drilling of deep exploration wells.

1. INTRODUCTION

This paper is part of a series of three whereas two others deal with the geology (Delvaux et al., this volume) and geochemistry (Kraml et al., this volume) of the region. For detailed information on these topics, we refer the reader to these papers. The work reported in the mentioned papers on geochemistry and geophysics was completely conducted within the GEOTHERM Programme of BGR. This holds true also for part of the geological investigations (e.g. volcanological and travertine studies).

The area of investigation in the south-western part of Tanzania 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 (EARS), forming a triple junction (figure 1). Therefore the area is characterised by potential volcanic heat sources and fluid pathways along fractures of the EARS. Additionally, there is sufficient recharge from high elevated parts in the area for filling up the naturally lost fluid. The fluid and related thermal energy of 10 MW is lost mainly from Songwe hot springs which are indicating a substantial reservoir in the subsurface (Hochstein et al., 2000).

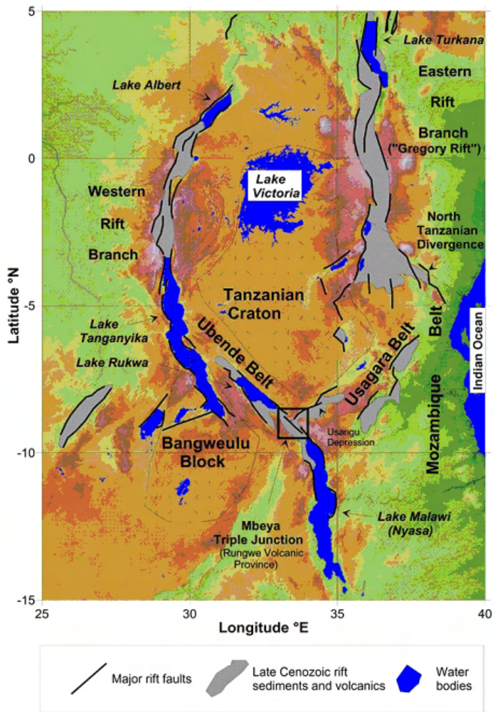

Figure 1: Simplified map of Tanzania and surroundings with major structural elements. The survey area near Mbeya is located in the depicted rectangle

Two main geothermal systems have been distinguished (Kraml et al., this volume): (i) Northern system (Songwe and other hot springs related to Ngozi volcano) and (ii)

Southern system (hot springs mainly related to recently active Kiejo volcano). The calculated reservoir temperature for the Northern system is above 200°C whereas the Southern system is significantly below 200°C. Therefore detailed exploration including geophysical surveys focused on the Northern system covering the area between Songwe hot springs and the Ngozi volcano.

2. GEOPHYSICAL INVESTIGATIONS

Geophysics in general and resistivity methods in particular are reckoned to be appropriate means to investigate high temperature geothermal systems when positive indications are found for a viable resource by geological and geochemical investigations.

The resistivity methods yield valuable additional information related to thermal alteration of the encountered host rocks and allow in suitable conditions estimates of lateral and depth extension of the geothermal resource as shown below.

2.1 Previous Geophysics

Previous existing geophysical data include e.g. low resolution airborne magnetic data, gravity and geoelectrics.

Previous geoelectrical soundings in the area of interest were carried out mainly for ground water investigations. In Mnzava et al. (2004) and DECON et al. (2005) geoelectrical soundings with penetration depths of a few tens of metres to approximately 150 m are discussed for geothermal prospecting for the first time in this area. They give an indication of the resistivity range to be expected in the area (3 to 100 Ohm*m). Unfortunately the achieved depth penetration is too shallow to delineate a geothermal resource. Prior to the GEOTHERM project no surveys with deep penetrating electromagnetic methods (e.g. TEM, MT) were conducted in the area for geothermal prospecting purposes.

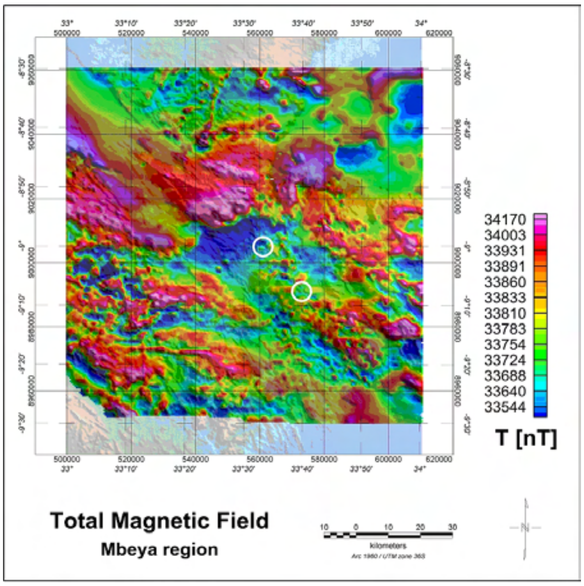

Figure 2: Airborne magnetic data from the Mbeya region underlain with SRTM data. Ngozi (NW) and Rungwe (SE) calderas are marked with white circles

Gravity data of the area permit a rough overview only and are not suitable for detailed investigation of the Ngozi volcano and its surroundings. The data coverage in the area of the Rungwe Volcanic Complex is mainly restricted to roads, except in the Usangu basin. Ebinger et al. (1993a,b) interpreted the gravity data in the area SE of Mbeya concluding that the pronounced gravity low which corresponds to the Quaternary-Recent eruptive centres of Rungwe and Ngozi volcano may reflect magma beneath those volcanoes at shallow crustal levels.

Marobhe (2005) and Mbede et al. (2006) interpreted aeromagnetic data mentioning a negative magnetic anomaly along NW/SE trending Mbaka fault and Rungwe volcano and a positive anomaly at Kiejo volcano SE of Rungwe among others. They concluded that “the non magnetic signature of Rungwe is best explained as being due to an underlying thermal anomaly that may have demagnetized the rocks”. However, the most prominent magnetic low appears only at Ngozi volcano (figure 2). The consequences of this observation are discussed in section 3 and 4.

2.2 Application of Resistivity Methods for Geothermal Investigations

Hydrothermal hot fluids tend to reduce the usually high resistivity of unaltered rocks for several reasons: by altering the rocks, by an increase in salinity and due to high temperature.

In high-temperature reservoirs with fluid temperatures above 200°C, the hydrothermal alteration plays the predominant role. Different alteration products occur, mainly depending on the temperature. At the top of a high-temperature geothermal system a zone with expandable clay minerals (smectites) and zeolites usually occurs. Its resistivity is generally lower (below 5 Ohm*m) than in overlying rocks affected by lower subsurface temperatures and is restricted to a temperature range from 100 to 180°C (figure 3). In the temperature range from 180 to about 240°C, the low temperature zeolites disappear and the smectite is partly transformed into less conductive non expandable clay minerals in a transition zone, the so-called mixed layered clay zone, associated with a slight increase of resistivity. Both zones form the so-called clay alteration cap, its low resistivity predominantly caused by the conductive smectite-zeolite zone.

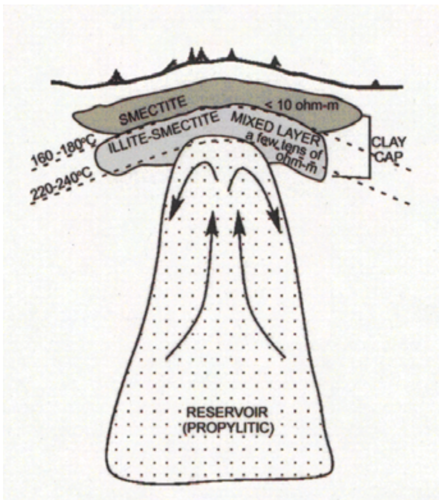

Figure 3: Geothermal resistivity model, modified after Johnston et al. (1992)

Below the clay cap a higher resistive core is to be found representing the geothermal reservoir. High-temperature alteration processes (>220-240°C) within the geothermal reservoir itself lead here again to an increase in the resistivity by forming pure illite (in acidic rocks) or chlorite (in basaltic rocks, Árnason et al. 2000) and epidote in this so-called propylitic alteration zone.

Higher resistivity occurs in the cooler nearly unaltered near-surface parts at temperatures below 70°C.

Sections both above and below the clay cap (the higher resistive core forming the reservoir below and the nearly unaltered volcanic rocks above) have higher resistivities, thus a localized succession of high-low-high resistivities with depth and a high resistive surrounding are somehow indicative for a geothermal high-temperature system (figure 3) and represent a possible drilling target. Clay-rich lake beds or layers of pyroclastic material (e.g. glassy pumice deposits) altered at low temperatures can be excluded by geological evidence and their different spatial appearance.

2.2.1 Transient Electromagnetics

The Transient Electromagnetic (TEM) method (for details see e.g. Nabighian and Macnae, 1991) uses transmitter and receiver coils with different sizes and configurations. The change of the primary field caused by an abrupt current shut-off in the transmitter coil induces eddy currents propagating into the ground, which are decaying with time and cause an induction effect in the receiver coil. The resulting decaying voltage curve in the receiver coil is recorded over a certain time window while the transmitter is off. Its amplitude and shape is indicative for the encountered resistivities. Depth related resistivities can be deduced from the time and amplitude by numerical inversion modelling.

A Protem57 system (Geonics, Canada) in the in-loop configuration was used. The size of the transmitter loop was 200 m by 200 m for most of the sites, feeding in a current of about 12 A. The investigation depth achievable with this configuration covers some tens of metres down to about 600 m, depending on the resistivity structure in the subsurface. For 1D-inversion modelling WinGLink software (Geosystem, Italy) has been used.

2.2.2 Magnetotellurics

The Magnetotelluric (MT) method (for details see e.g. Dobrin and Savit, 1988, Vozoff, 1991) utilises natural magnetic field variations caused by lightning discharges and currents in the ionosphere by solar wind interaction. The frequencies present in this natural variations range from tens of kHz to 0.001 Hz and lower. Therefore investigation depths in the kilometres range and deeper may be achieved with Magnetotellurics.

For data acquisition two full tensorial magnetotelluric stations (Metronix, Germany) have been used in a synchronized manner covering a frequency range from 10 kHz to 0.01 Hz (100s). The investigated depth covers 50 m to approximately 10 km. The overlap with the TEM of one decade eases joining both results and secures proper static shift correction of MT data, where necessary. Time series processing has been performed by the software Mapros (Metronix) whilst 2D inversion by the software WinGLink (Geosystem).

3. RESULTS OF TEM AND MT

The sounding locations shown in figure 4 have been arranged in profiles oriented NE-SW, i.e. roughly perpendicular to the strike direction of the Rukwa Rift structure. As already mentioned, all areas close to the Ngozi volcano are of utmost interest for deep penetrating electromagnetic methods. The strategy was to detect indications of a high-temperature reservoir which should have been formed far away from the outflow (Songwe hot springs) but close to the heat source (Ngozi volcano). The Ngozi volcano was proposed within the GEOTHERM programme for the first time as viable heat source for the Northern geothermal system in the Rungwe Volcanic Province near Mbeya town (Kraml et al., this volume).

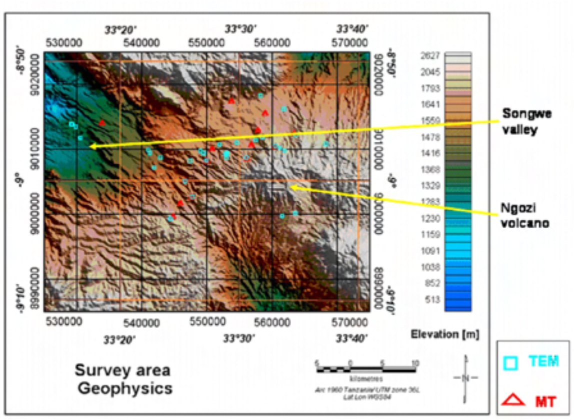

Figure 4: Locations of TEM (blue squares) and MT (red triangles) sites in the Mbeya region. Most sites are located north and west of Ngozi volcano. Basemap: SRTM data

All TEM resistivity curves within the entire survey area indicate lower resistivities at greater depths. The resistivity models at the Songwe valley reveal a low resistive layer at a depth of about 250 m, which might be due to sedimentary infill as deduced from geological evidence and horizontal appearance. At the sites located north and west of Ngozi volcano, the depth of the low resistive layer was determined by TEM from about 300-400 to 500-600 m below surface (figure 5).

The magnetotelluric results complement those of TEM and extend the depth of interpretation to about 7 km. The MT models show regions with resistivities as low as 4 Ohm*m. especially close to the NW flank of the Ngozi volcano. All 2D MT data were used as input for the resistivity maps for constant elevations in figure 6.

At shallow depths less than 400 m below surface resistivities close to the Ngozi are in the range of 20 Ohm*m. With increasing depth, resistivities decrease, reaching values below 10 Ohm*m at 1400 m depth (500 m a.s.l.). In Figure 6a the low resistive structure is fingering out in the direction of major flow gradients, thus indicating most probably high-temperature alteration. At a depth of about 1900 m (sea level, figure 6b) still smectite alteration is predominant. At about 2200 m (250 m b.s.l., figure 6c), resistivities increase again to values in the 15 Ohm*m range. According to the geothermal resistivity model presented in section 2.2 of this paper, this could be interpreted as the advancement into the so called *mixed layered clay zone* and further down into the reservoir itself. In Figure 6c the area of interest is encircled in black.

At greater depth of around 4000 m (figure 6d) a less pronounced resistivity anomaly appears within the Precambrian basement elongating in NW-SE direction, by this coinciding with the strike direction of the Rukwa rift.

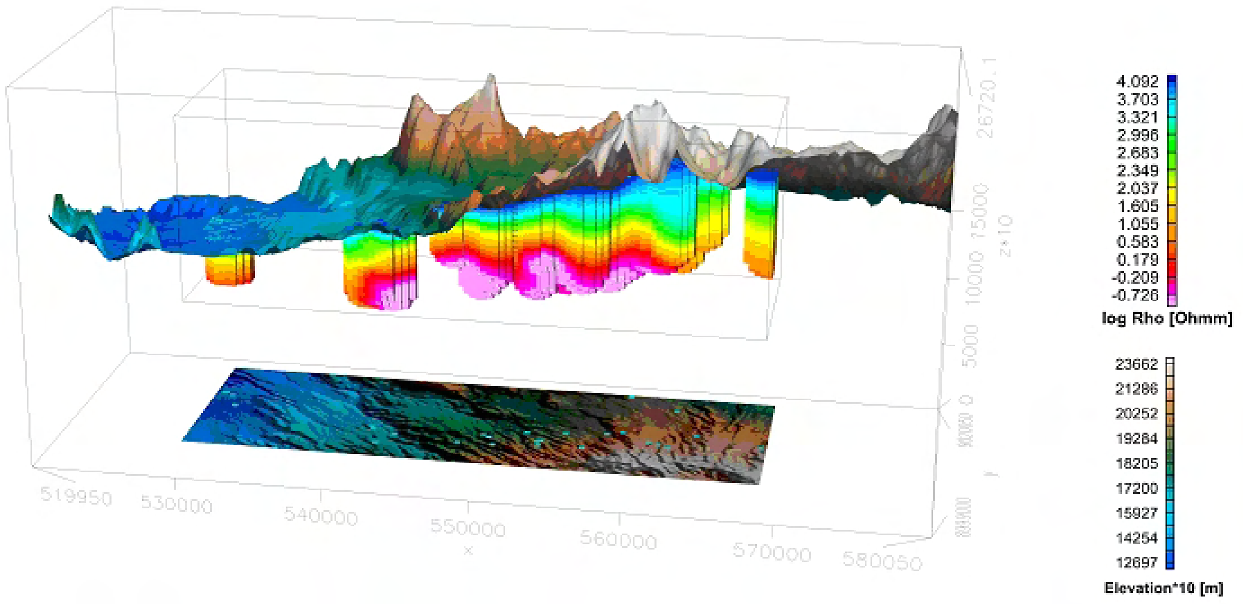

Figure 5: 3-dimensional voxel illustration of the TEM 1D inversion results in the northern part of the survey area, viewed towards NW. The relief on top is the surface topography in tenfold exaggeration. The 2D map at the bottom shows the topography with TEM sites marked as blue squares

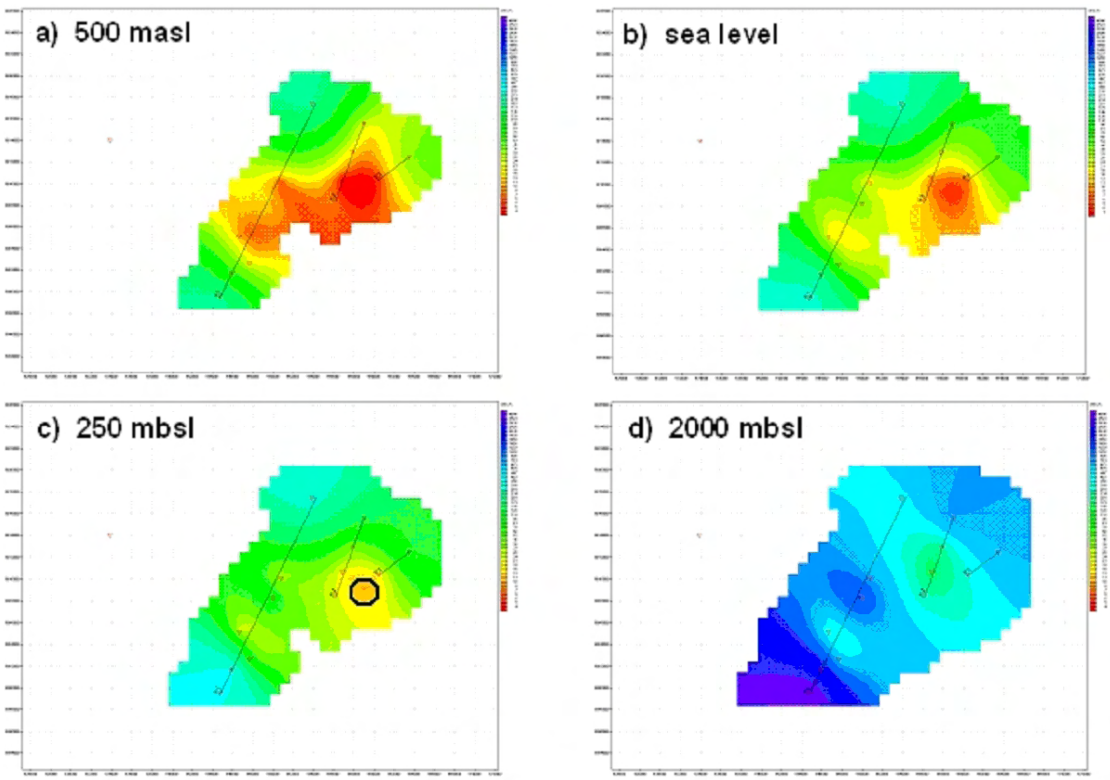

Figure 6: Resistivity maps based on 2D inversion results of MT. Constant elevations are given in meters above/below sea level (masl/mbsl). Area shown: 32 km S-N direction (8994000-9026000 UTM), 46 km W-E direction (526000-572000 UTM). Ngozi volcano at SE border of surveyed area. Songwe hot springs are further to the West (out of the map area). Resistivities are shown in a logarithmic scale between 4 Ohm*m (red) to 4096 Ohm*m (blue) a): Low resistive conducting zone (red) fingering out along major flow gradients. b): Extremely low resistivity (below 4 Ohm*m) possibly due to smectite alteration. c): Increase in resistivity indicating mixed layered clays and advance towards proposed reservoir, encircled in black. d): NW-SE trending resistivity anomaly along the Rukwa rift strike direction at greater depth within the Precambrian basement

CONCLUSIONS

Geophysical surveys in the investigated area of the Northern system included 2-dimensionally inverted magnetotelluric soundings (MT) and 1-dimensionally inverted transient electromagnetic soundings (TEM), yielding a resistivity structure of the subsurface down to approximately 7 kilometres depth.

The characteristic resistivity structure may be interpreted as a high-temperature geothermal reservoir: a) high resistivity from the surface down to approx. 400 m, b) very low resistivity between 400 and 1000 m predominantly around Ngozi volcano interpreted due to a dome shaped clay alteration zone related to geothermal activity, fingering out laterally and c) localized slightly increasing resistivities below the clay cap with interpreted hottest part of upflow zone reached in about 2200 m depth below the surface.

The interpretation of an intense alteration causing a low resistive zone in the subsurface to the W of Ngozi deduced from MT and TEM measurements is supported by a magnetic low in the same area (figure 2) indicating demagnetization by alteration of the magnetic iron oxides within the originally magnetic volcanic rocks.

From geological and geochemical evidence presented in Delvaux et al. and Kraml et al. (both this volume) and the geophysical data presented here, this allows for proposing a consistent conceptual model for the Ngozi-Songwe part of the Rungwe Volcanic Province.

The geothermal reservoir, which receives its recharge mainly from high elevated areas in the Poroto Mountains including Ngozi volcano, is located between the Ngozi crater and Mbeya town. The fluids are flowing through the faults of the major Rift trend (fracture permeability) towards the discharge areas mainly in the Songwe valley, following the natural hydraulic gradient (figure 7).

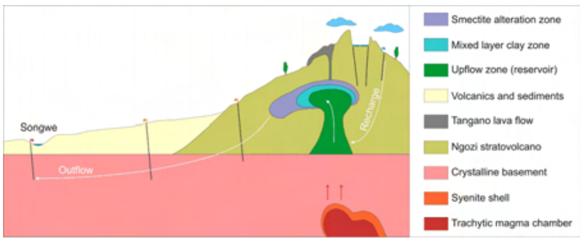

Figure 7: Schematic cross section through the Ngozi-Songwe geothermal system (not to scale)

Already on the basis of the presented conceptual model deep exploration wells could be sited for proving the proposed high-temperature reservoir. However, the suggestion of deep exploration wells should be based on additional MT measurements to more precisely define the southward extension of the geothermal system. Additionally deep temperature gradient wells below the groundwater level are recommended to reach the top of the clay cap in about 500 m depth to further constrain the presented model for the investigated Northern system.

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