UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme
Orkustofnun, Grensasvegi 9,
IS-108 Reykjavik, Iceland

40th Anniversary Workshop
April 26 2018

MAPPING GEOTHERMAL AND STRUCTURAL FEATURES OF THE NORTHERN KENYA RIFT WITH MT AND GRAVITY MEASUREMENTS

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ABSTRACT

A geophysical survey comprising over 400 MT and 515 gravity stations on the Korosi, Paka and Silali volcanoes in the northern Kenya rift was conducted to assess the occurrence of geothermal resources in the three major volcanic centers. A 1D joint inversion of MagnetoTelluric (MT) and co-located Transient ElectroMagnetic (TEM) has revealed a resistivity pattern consistent with the existence of several geothermal systems within the study area. Each geothermal system is characterized by a relatively resistive 100 ohm-m surficial layer overlying an ~10 ohm-m low resistivity zone interpreted as the hydrothermally altered clay cap of the system. The cap overlies a higher resistivity zone of about 60 ohm-m with a top at about 1000 m depth, interpreted as a potential high temperature alteration zone. The trend of moderate high resistivity at the depth of the potential reservoir corresponds to the zone of intense faulting and fracturing as imaged on the surface.

Gravity models are dominated by 10 to 15 km wide gravity high of 8 mGal amplitude striking NNE along the inner rift corresponding to high resistivity below 2 km depth. Gravity lows due to structures shallower than 2 km depth at the Paka and Korosi volcanoes have been interpreted as low density bodies within their edifices, likely to consist of either unaltered near-surface pyroclastics or deeper tuffs altered at 60 to 180 °C to hydrothermal smectite clay. MT resistivity models were used to further constrain the 2.5D gravity models. The high resistivity, low density near-surface rocks on the flanks are interpreted to represent unaltered pyroclastics above the water table, whereas low resistivity, low density bodies underneath the Paka and Korosi volcanos indicate low density tuffs, hydrothermally altered to hydrated smectite clay. The deeper high density zone below the volcanic inner rift is likely to be a combination of higher temperature, low porosity alteration associated with geothermal reservoirs and/or denser rocks related to intrusions.

Mapped fissure swarm agrees with both gravity and resistivity south of Paka volcano but northwards between Paka and Silali volcanoes there is inconsistency where the fissure swarm goes straight NE but both gravity and resistivity show a feature west of the currently active fissure zone. This suggests that the rift has recently moved eastwards.

1. INTRODUCTION

The Northern Volcanic Zone of Kenya extends from the Lake Bogoria in the south to Lake Turkana in the north. It consists of numerous volcanic centres aligned in the inner axis of the Kenya rift system. The area under study here includes three major volcanoes namely Korosi, Paka and Silali (KPS) that lie within the Northern Kenya rift segment. The segment is intersected by a 10 km-wide zone of intense faulting and fracturing that strike in NNE-SSW direction. The most recent volcanic activity in the area (Black Hills lava) occurred some few hundred years ago. Volcanic development in the Northern Kenya initiated with the formation of Quaternary volcanoes less than 1 Ma ago. KPS volcanoes are located in the inner trough of the rift where they form low-angle shield volcanoes composed predominantly of trachytic and basaltic lavas and pyroclastic deposits (MacDonald, 2003; Dunkley et al., 1993; Williams et al., 1984). The volcanoes at Korosi, Silali and Paka formed about 500 ka, 460 ka and 390 ka, respectively, with caldera collapse at Silali and Paka occurring at about 64 ka and 10 ka, respectively (Dunkley et al., 1993), and formation of several volcanic domes on all the three volcanoes. The area is believed to host high temperature geothermal activity connected to recent magma intrusions.

The KPS sector was chosen for this study since it is the next frontier for geothermal exploration in Kenya after earlier studies had indicated possible geothermal potential. Preliminary studies at several volcanoes along the rift had presented thick low resistivity on the flanks, which needed additional study to understand the cause, hence the need to study a larger section of the volcanic rift zone.

Geothermal exploration in this region began in the 1990s but was intensified in 2010 after the formation of the Geothermal Development Company (GDC). This was supported by earlier results that hinted at possible geothermal resource. Numerous hot springs, altered surfaces and fumaroles within this sector of Kenya rift have created interest for geothermal exploration and exploitation. As part of this study about 400 magnetotelluric (MT) and 515 gravity data points have been collected to assess the occurrence of geothermal resources in the major volcanic centers.

Resistivity methods (MT & TEM) have become useful techniques for imaging geothermal reservoirs, especially when combined with other datasets, e.g., seismic or gravity. MT uses naturally occurring electromagnetic (EM) fields over the Earth's surface that originate from regional and worldwide thunderstorm activity and from interaction of the solar wind with the Earth's magnetosphere. The relationship between electric (E) and magnetic (H) fields on the earth surface depend on the subsurface distribution of electrical resistivity which is a reflection of properties and distribution of fluids. The EM field is frequency dependent such that high frequencies are sensitive to shallow depths while lower frequencies penetrate to greater depths, and are inverted for subsurface electrical properties (Vozoff, 1991). Gravity method, on the other hand, describes subsurface geological structures based on variations of the gravity field due to the difference in density between the rocks. This way the method can be used to determine the lateral position of the rocks and hence infer permeability or lack of it in the subsurface.

This paper demonstrates how resistivity together with gravity method, can be used to map structural and geothermal features. We correlate the two methods to show consistency with already known geological formations and highlight their effectiveness in recovering subsurface structures that are not discernible from surface geological mapping. When the two methods are interpreted together with surface manifestations we can characterize permeability inferred from geophysics.

2. RESISTIVITY AND GRAVITY SURVEY

2.1 MT and TEM data acquisition and processing

The MT and TEM surveys carried out in the Korosi-Paka-Silali area were designed to image resistivity from the near-surface to several kilometres depth in order to detect the characteristic resistivity patterns associated with occurrence of geothermal resources in the context of the geophysics of the major volcanic centres. A total of over 400 MT and TEM soundings have been acquired in field campaigns between 2005 and 2014 in the entire study area (see Figure 1). The MT data were acquired with Phoenix MTU-5A 24-bit recording systems using porous pot electrodes and three induction coils providing a frequency range of 0.001–320 Hz. Telluric dipole lengths of either 70 or 100 m were used depending on terrain limitations.

The MT time series were processed using the programs SSMT2000 and MTeditor (Phoenix Geophysics, 2005), based on the robust approach described by Egbert and Booker, (1986), to produce cross-power estimates and generate EDI files. TEM data were collected using a Zonge GDP-32 data logger and a transmitter with current loop sizes ranging between 100 × 100 and 300 × 300 m^2 and a receiver coil with an effective area of 10,000 m^2. The measured TEM data was processed using the TemxZ program (Árnason, 2006) which provided editing, selection, averaging and error estimation tools to calculate late time apparent resistivity as a function of time.

The program TEMTD (Árnason, 2006) was used to compute joint MT-TEM 1D Occam inversions of the TEM simultaneously with the MT determinant resistivity and phase. These joint 1D Occam inversions were interpolated to generate the resistivity maps and cross-sections.

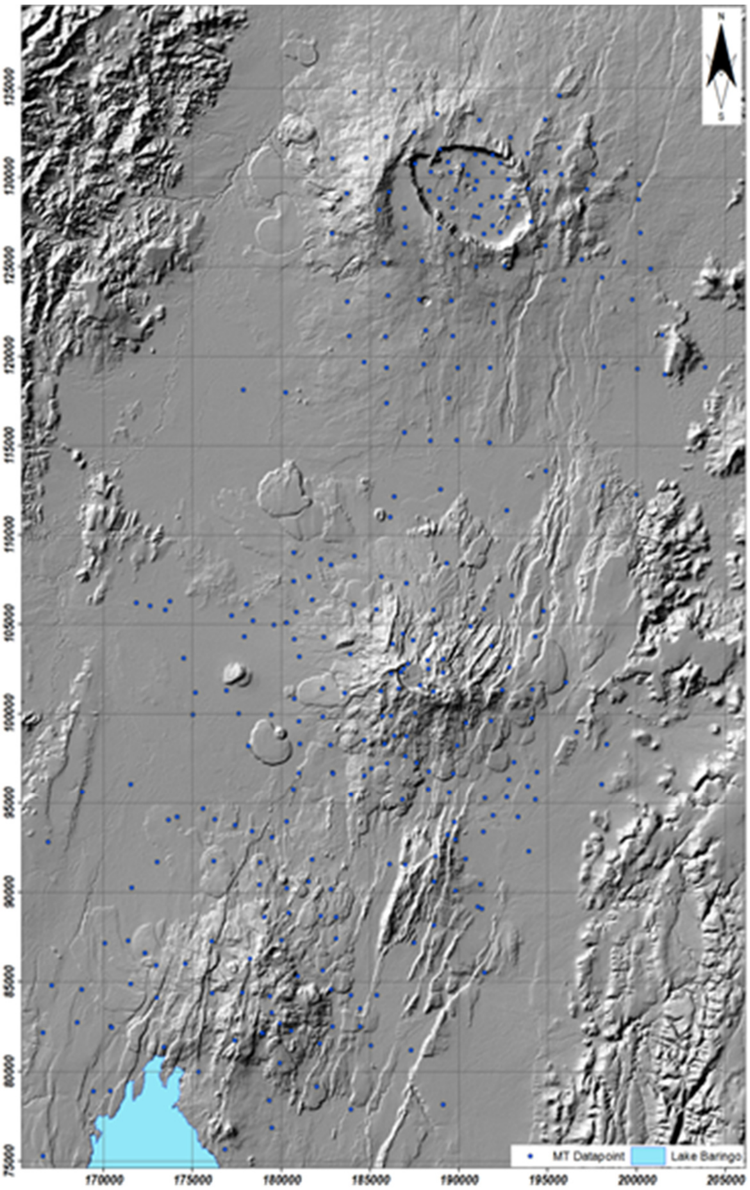

FIGURE 1: Location of map for both MT and gravity (blue dots) across the three main volcanic centres, Korosi, Paka and Silali

2.2 Gravity survey and processing

The gravity survey covers the same area as resistivity (Figure 1). A total of 515 gravity stations were measured by Geothermal Development Company (GDC) between 2014 and 2017. The gravity station spacing ranges from 200 to 500 m subject to topographical access limitations in the volcanic areas of greatest interest.

Gravity data were measured using a Scintrex CG-5 gravimeter (0.001 mGal resolution) with between 3 to 5 readings taken at every station. A gravity base station (Lat: 0.602038, Lon: 36.003956, Elev.: 1036.7 m, g: 977668.989 mGal) was established by GDC at the junction of the Kampi Samaki and the Marigat-Loruk road. Readings were tied to this base station with reoccupation at the start of each loop in the morning and again about 8 to 12 hours later after the day's readings. Elevation and location measurement was achieved through post-processing of data collected by Trimble GeoXT DGPS instrumentation with nominal precision of less than 0.05 m in x, y and less than 0.10 m for z, respectively, implying a gravity uncertainty related to elevation of less than 0.02 mGal. The Scintrex CG-5 has an in-built tide and drift correction, which ensures that deviations are less than 0.030 mGal in a 12 hour loop.

The corrected relative data from drift correction were then converted into absolute gravity data (Gobs) before it was reduced to complete Bouguer anomaly. Several corrections were applied to the data including; latitude correction, free air correction, Bouguer correction, and terrain correction. The reduction processes is achieved by the following equation:

$$CBA = Gobs - Gn + 0.3086h - 0.04193\rho h + TC$$

where CBA is complete Bouguer anomaly, Gobs is station absolute gravity, Gn is latitude correction, and TC is terrain correction. Bouguer density was determined by using Parasnis technique yielding Bouguer density value as 2.19 g/cm^3. This density value was used in Bouguer and terrain correction calculations. Terrain correction was done using elevation data acquired from ASTER DEM.

Trend Surface Analysis method was applied to Bouguer anomaly to separate regional and residual anomalies. Then residual anomaly data were used to develop 2.5-D forward model.

3. INTEGRATED INTERPRETATION OF RESISTIVITY AND GRAVITY

Gravity has been modelled along profiles perpendicular to the strike of the rift similar to those used in resistivity interpretations (Lichoro et al., 2017) to derive a geological model consistent with the MT resistivity cross-sections and gravity constraints on density. The purpose of this comparison is to further constrain resistivity structure of the area, particularly with respect to the variations detected in the alignment of the rift axis. Although the interpretation of gravity data alone is relatively ambiguous, 2.5D density models that are constrained by MT resistivity cross-sections, geological mapping and measured densities of rocks from other volcanoes in the rift have reduced the model ambiguity and have provided an improved understanding of this rift segment and its sub-surface structures.

The overall results shown in our gravity residual map (Figure 2c) agree fairly well with observations from resistivity study (Figure 2d) reported by Lichoro et al., (2017). Specifically, the high resistivity in the rift axis correlates with the high gravity in the same area. However, in the area between Paka and Silali volcanoes there is a break in high resistivity (shown by a conductor) but gravity high is continuous. This might be due to limited number of gravity readings in the area, but also resistivity may be exaggerating the discontinuity. On the flanks, where low resistivity was imaged, gravity reveals low densities, which have been interpreted as volcanoclastics/buried pyroclastic units. It is also observable that surface manifestations are mainly located at the margin of the high gravity, controlled by faults and those occurring at the summit of Paka caldera are within a more local zone of relatively low gravity and low resistivity.

Similarly, the gravity results (Figure 2c) are in a fair agreement with the westward offset in high gravity in the Silali sector north of Paka volcano seen in the resistivity (Figure 2d) which has been interpreted as a possible buried structural step-over in the rift alignment between Paka and Silali volcanoes. Both studies suggest that Silali volcano lies west of the currently active rift zone, which has gradually moved eastwards to align with the Paka volcanic axis (Lichoro et al., 2017). This is also consistent with the lack of geothermal activity on the western caldera sector in Silali. Further studies are necessary to establish whether this offset could be related to presence of a transform.

The low density on the flanks is consistent with the high porosity in the thick volcanoclastic sediments. Beneath the inner rift volcanic zone, where surface manifestations are prevalent, the

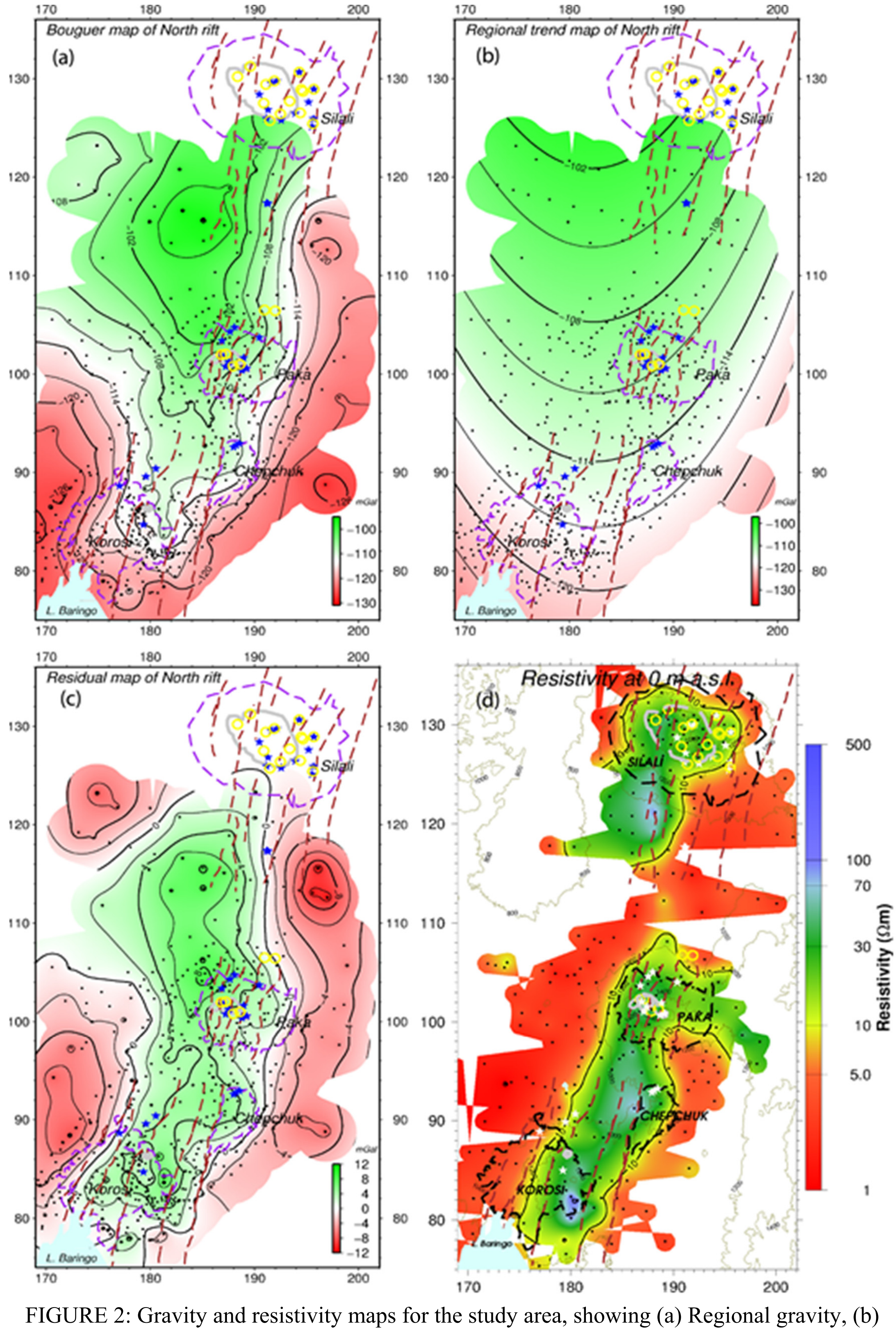

FIGURE 2: Gravity and resistivity maps for the study area, showing (a) Regional gravity, (b) Bouguer gravity, (c) Residual gravity, and (d) Resistivity at sea level. Stars and yellow rings are surface manifestations, purple and black dashed lines outline the boundaries of the volcanoes, and brown dashed lines show faults. Coordinates are in UTM in km (WGS84)

surface layer is of high resistivity underlain by low resistivity clay cap and a third highly resistive layer: The combined gravity effect of this layering presents generally as high density on the profiles except for minor zones at the summit area of Paka and Korosi volcanoes. The 2.5D density modelling (Figures 3 and 4) has confirmed these minor low density zones to be at shallow depth corresponding to low resistivity up-doming at the base of the clay cap. The correlation of high resistivity and gravity high might signify the location of the shallow transition to high rank alteration below the volcanic centres or uplift in the Precambrian crystalline rocks along the rift axis. In the conventional resistivity interpretation, higher resistivity beneath a clay cap is interpreted as geothermal reservoirs with high temperature clays like chlorite-illite dominating.

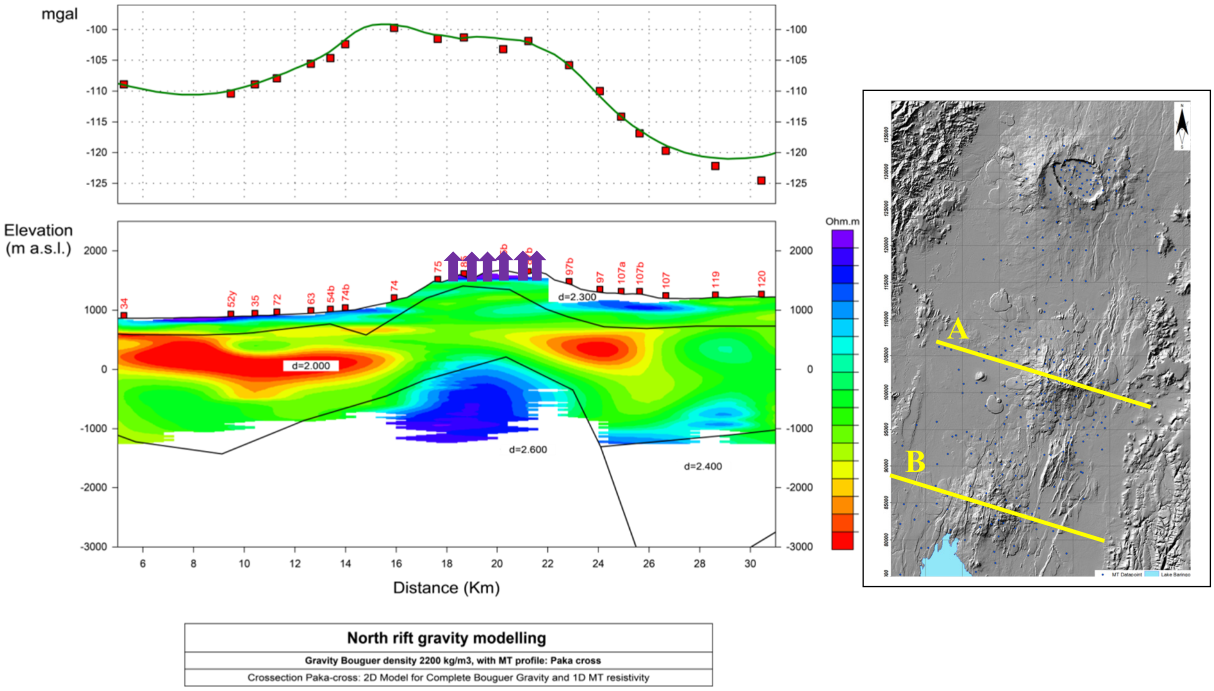

FIGURE 3: 2.5D density model for profile A across Paka volcano overlaid on MT resistivity to match gravity profile. Red squares are measured gravity points, green curve is the modelled gravity and the purple arrows are fumaroles. Black lines on MT cross-section mark boundaries of density bodies. Numbers give densities in g/cm3. Vertical exaggeration 2.33.

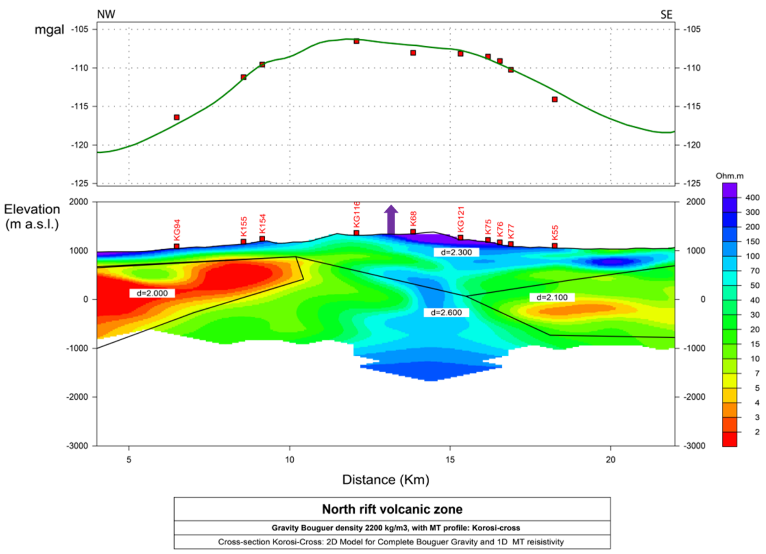

FIGURE 4: 2.5D density model for profile B across Korosi volcano overlaid on MT resistivity to match gravity profile. Red squares are measured gravity points, green curve is the modelled gravity and the purple arrows are fumaroles. Black lines on MT cross-section mark boundaries of density bodies. Numbers give densities in g/cm^3. Vertical exaggeration 2.0.

4. CONCLUSIONS

The joint gravity and MT resistivity interpretations along cross-sections show that a high resistivity and high gravity zone becomes shallower along the eruption axis of the rift and at the volcanoes. This has been interpreted as lava, dike intrusives and higher temperature alteration, possibly associated with a geothermal reservoir. The zone of low resistivity and low gravity on the flanks of the volcanoes and fissure eruption zones supports the conclusion that a thick zone of volcanclastics flanks these zones. The surface manifestations are mainly located at the margin of the high gravity, controlled by faults and those occurring at the summit of Paka caldera are within a more local zone of relatively low gravity.

This study shows that if resistivity and gravity are interpreted together, the independent constraints provided by resistivity pattern can improve confidence in the gravity models, particularly where they are supported by geology and petrophysical data. Results are in accord with a more regional study where the gravity high correlates with diking / fissure eruption flanked by sediments / pyroclastics. The mapped fissure swarm agrees with both gravity and resistivity south of Paka volcano but northwards between Paka and Silali volcanoes there is inconsistency where fissure swarm trends NE but both gravity and resistivity maps trend west of the currently active fissure zone. The more westerly trend is not discernible from surface geological mapping and has been interpreted as a buried fissure eruption west of the current fissure trend. Further gravity data acquisition north of Paka volcano would better constrain the evolution of the segmentation in this part of the rift and the apparent rift offset that may have existed in the past between Paka and Silali volcanoes.

ACKNOWLEDGEMENTS

The author greatly acknowledges the Geothermal Development Company (GDC) for permission to publish data for this paper and funding the data collection. UNU-GTP is acknowledged for the PhD scholarship and facilitating this research.

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