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Geothermal Characterization of Selected Volcanic Systems in Kenya from Resistivity and Gravity

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ABSTRACT

An extensive geophysical survey comprising over 400 MT and 515 gravity stations covering Korosi, Paka and Silali volcanoes in the northern Kenya are reviewed in order to construct 1D resistivity inversion models correlated with mapped geological structures in the vicinity of the volcanoes and with previous gravity studies. The resistivity pattern imaged by EM methods conducted over a geothermal reservoir from the surface down typically includes near-surface unaltered rocks (>100 Ωm) underlain by low resistivity smectite-zeolite alteration (<10 Ωm in andesite, rhyolite, basalt and sedimentary rocks and <20 Ωm in trachyte and phonolite rocks), that are, in turn, underlain by a more resistive zone (>10 Ωm) that is ambiguous but may correspond to the high-temperature chlorite/illite-epidote alteration associated with a productive geothermal reservoir, and possibly further underlain by deeper low resistivity associated with partial melt.

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 a 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 2D 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 fissure swarm goes straight NE but both gravity and resistivity maps a feature west of the currently active fissure zone. This suggests that the rift has recently moved eastwards. Correlation of resistivity and alteration minerals from recently drilled wells suggest a zone with higher permeability and a temperature of about 240 °C.

1.0 INTRODUCTION

Three volcanic systems in the northern sector of the Kenyan rift system have been extensively studied using resistivity and gravity methods. The survey comprised of over 700 MT and 515 gravity stations covering Korosi, Paka and Silali volcanoes, aimed at assessing the occurrence of geothermal resources. The change in physical properties caused by hydrothermal alteration can be detected by various geophysical methods including a variety of resistivity methods as well as passive seismic, magnetic and gravity surveys. Resistivity methods, particularly magnetotelluric (MT) and transient electromagnetic (TEM)methods have played dominant role in imaging the geometry of geothermal reservoirs (Rosenkjaer et al., 2015; Ussher et al., 2000; Árnason et al., 2010).

Gravity survey was done to complement resistivity studies in order to further constrain the geologic setting of the potential geothermal resources. The analysis of the gravity data in this study includes assessing density within the elevation range of the gravity stations to compute Bouguer gravity, estimating regional and residual gravity, reviewing of gravity maps with respect to geology and producing models of subsurface density variation that are consistent with the resistivity structure revealed by the MT/TEM survey (Lichoro et al., 2017).

1.1 Korosi Geothermal prospect

The Korosi geothermal project area is located immediate north of lake Baringo. The volcano is bisected by a fracture network of NNE-trending faults which steps progressively eastwards across the volcanic complex between the two major bounding faults within which numerous geothermal surface manifestations occur. Most manifestations are closely associated with NNE faults within a zone of generally intense fracturing to the east of the main boundary fault running along the western margin of the Korosi volcano. Surface temperatures in excess of 95 °C have been recorded in the area.

1.2 Paka Geothermal prospect

Paka geothermal prospect is located about 20 km north of Lake Baringo, and is the geothermal prospect with the most surface thermal manifestations. Paka is dominated by a zone of intense normal faulting and fissuring both on the eastern and north-eastern flanks (Dunkley et al., 1993). Geothermal manifestations are extensive at Paka comprising fumaroles, altered and steaming ground at up to 97 °C, mainly at the Paka summit craters and on the northern flank. Recent drilling at the volcano has discovered geothermal reservoir with bottom hole temperature above 240 °C.

1.3 Silali Geothermal prospect

Silali geothermal prospect is located about 50 km north of Lake Baringo. The main geothermal manifestations around Silali caldera consist of surface alteration and steaming ground, hot springs, and fumaroles (Fig. 1). The hottest and most extensive manifestations

occur in the eastern half of the caldera floor where areas of surface alteration and fumaroles are aligned to the NNE fissure zone with recorded temperature up to 96.8 °C. Gas chemical indicators from these fumaroles encouraged Development Company to explore the geothermal potential of these areas.

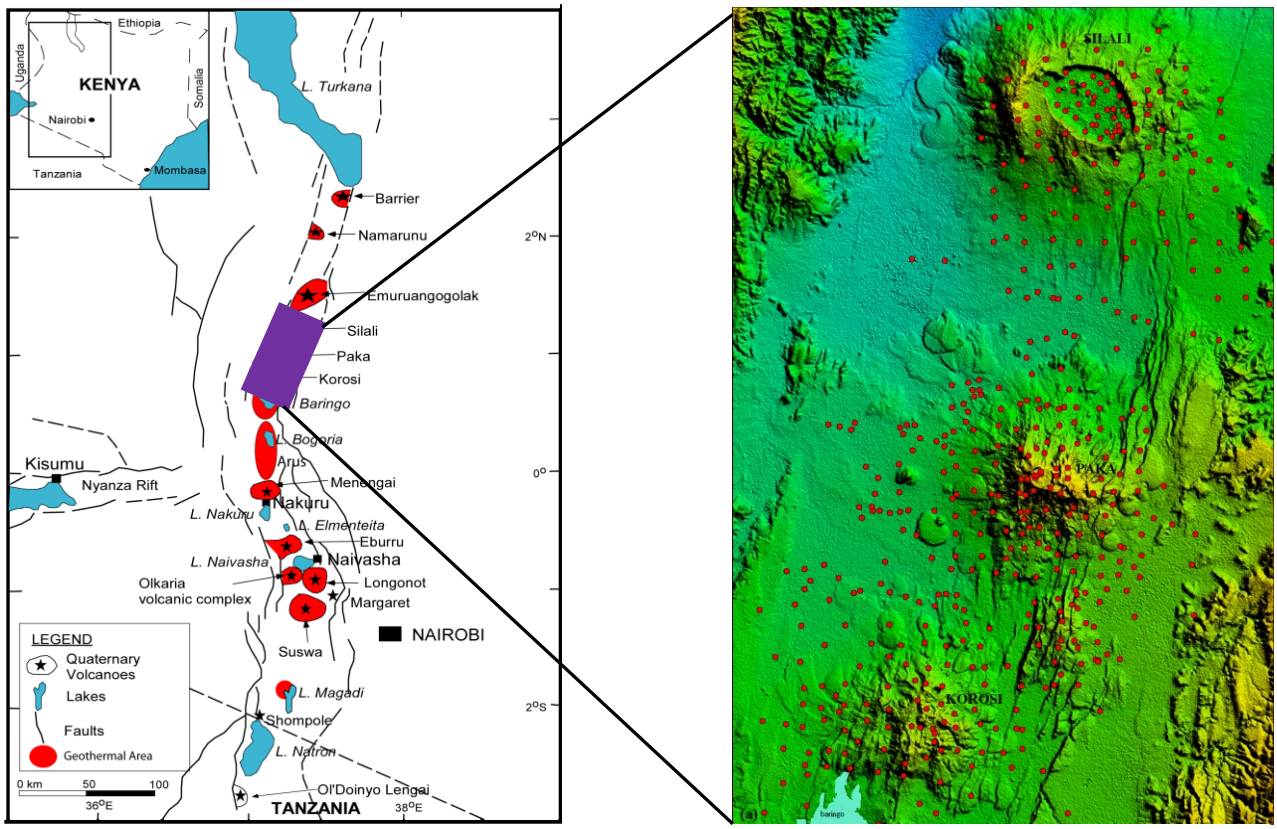


Figure 1: (a) Location map of the area of study showing the (b) Digital elevation map showing MT station locations at Korosi, Paka & Silali.

2.0 EXPLORATION DATA INTERPRETATION

Resistivity and gravity data were collected and processed by Geothermal development company in the Korosi-Paka-Silali prospects. Results from both data sets showed fairly consistent structures that were also in agreement with mapped geological structures. Preliminary interpretations of the processed images suggested that areas between Paka and Silali volcano have a structural pattern that is offset eastwards from the older rift zone corresponding to high resistivity, high density in the subsurface.

We have drawn representative gravity profiles (Fig. 2) across the study area in NW-SE directions across the volcanoes to detect density variations within the volcanoes and their flanks. The figure shows residual gravity profiles (drawn in red) and the regional anomalies (drawn in dotted blue line) superimposed with the left axis representing the residual anomalies and right axis representing the regional trend. The regional anomalies vary smoothly along the profiles, reflecting deeper density variations.

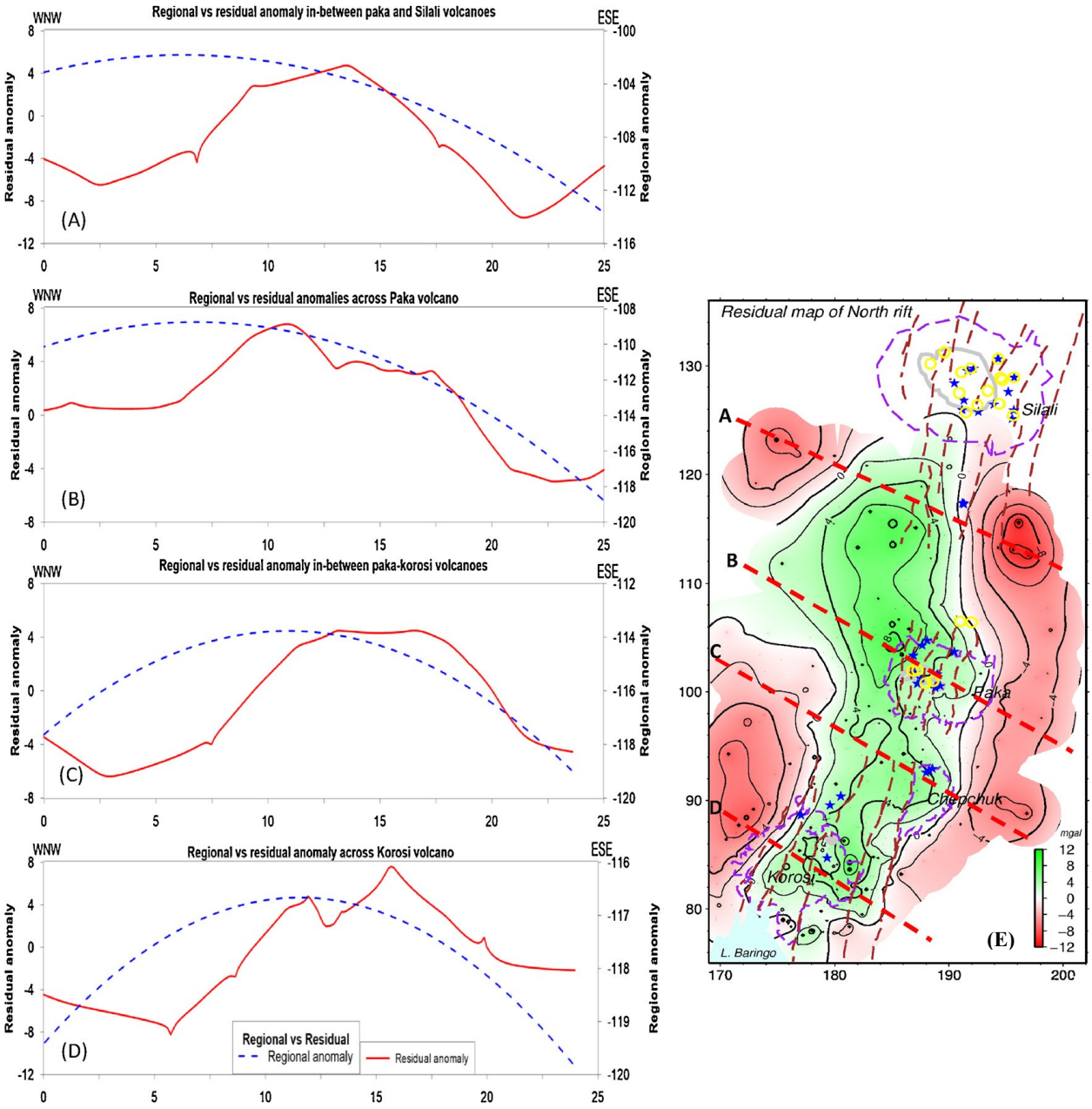


Figure 2: Residual gravity anomalies (red) and regional field (blue). Profile locations are shown as dashed lines on the inset map; y-axis is in mGal and x-axis is distance in km.

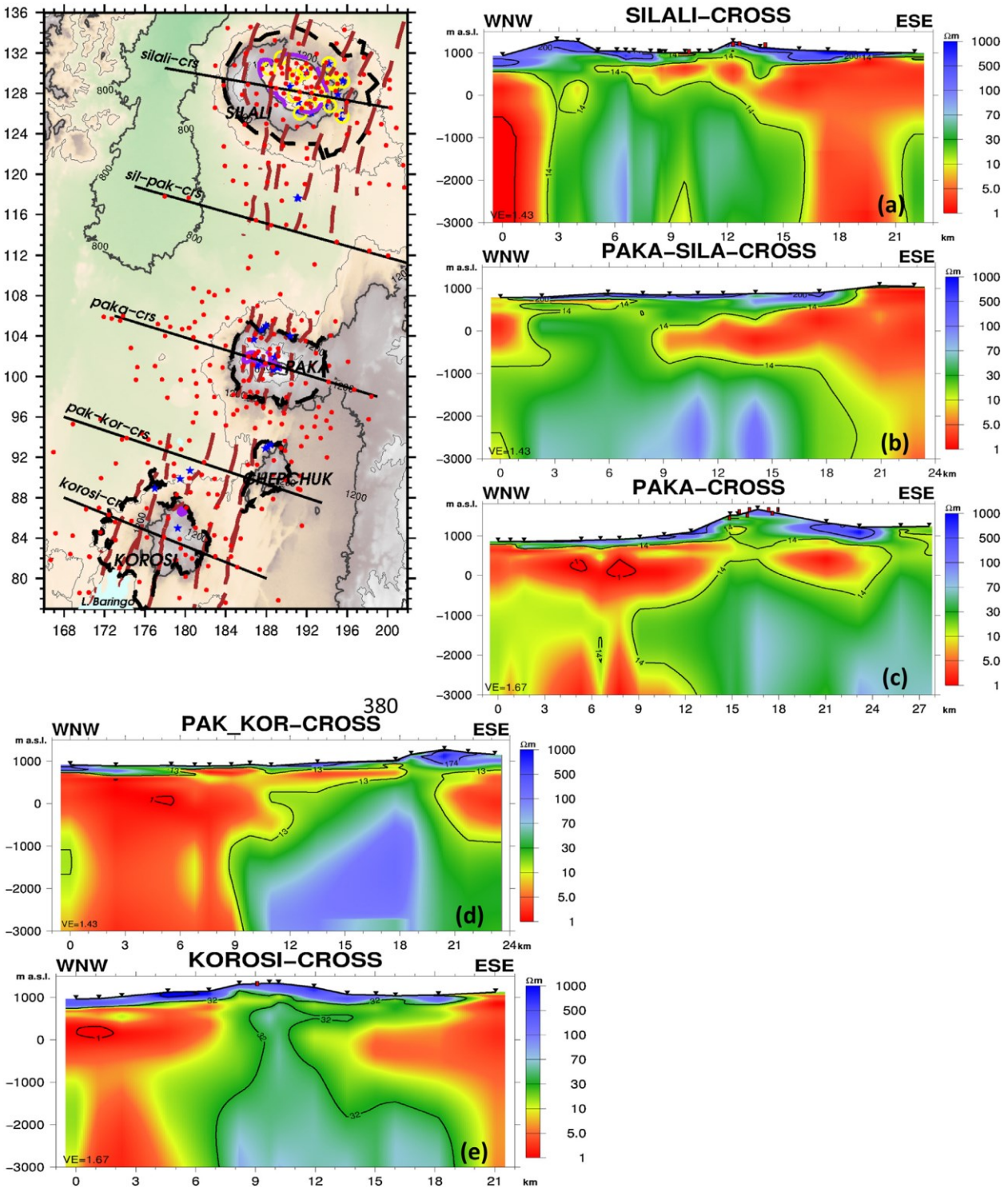


Figure 3: Resistivity cross-sections across Korosi, Paka and Silali based on 1D joint inversion of MT and TEM data: From top; (a) across Silali; (c) between Paka and Silali; (c)Paka; (d) Chepchuk and (e) Korosi volcanoes as shown on the location map to the left. Inverted triangles are MT stations and Red symbols on cross-sections are fumaroles. Volcanoes are shown in broken black lines and craters in purple. Blue stars and yellow rings: geothermal surface manifestations.

Similarly, we drew resistivity cross-sections in WNW-ESE direction to show resistivity variations between the summit area and the flanks of the volcanoes (Fig. 3). All the profiles show very prominent thick conductors on either side of the volcanoes which has been interpreted as altered sediments and/or volcaniclastics deposited in the rift during past eruptions (Cumming, 2014; Lichoro, 2013). However, beneath the inferred volcaniclastics there appear vertically oriented resistivity contours below 1500 mbsl (Fig. 2) which we think could be caused by MT distortion due to lateral boundaries that are closer in distance than the depth of the feature. This distortion might limit model resolution at the base of the inferred volcaniclastics. In the summit areas the resistivity pattern is characterized by a thin resistive (>60 ohm-m) surficial layer underlain by a more conductive layer that is about 10 ohm-m at the Silali and Paka volcanoes and about 30 ohm-m at the Korosi volcano. The conductive layer is generally thinner in the summit areas where it is likely to correspond to low temperature hydrothermal smectite clay alteration and thicker adjacent to the volcanoes where it is

interpreted as volcanic sediments and weathered ash with high smectite clay content. A higher resistivity zone is detected below the conductive clay layer on all of the MT profiles. The value of the higher resistivity below the conductor is more ambiguous, both because of inherent limitations to MT (Chave and Jones, 2012) and local data quality issues (Cumming, 2014). However, the elevation of the transition from lower to higher resistivity at the base of the conductor is typically reliably resolved using 1D inversions of the MT invariant or TE-mode in geothermal settings, except near lateral discontinuities in the conductor (Dipippo, 2016) and this has been an important diagnostic in geothermal exploration. A local apex in this transition is sometimes correlated with the top of a high temperature geothermal reservoir (Anderson et al., 2000), although such features are ambiguous since they can also be correlated with warm buoyant outflows from a geothermal reservoir, shallow smectite clay overlying the resistive illite clay (phyllic) cap of a deeper geothermal reservoir, or relict alteration over an old reservoir that has cooled (Cumming, 2016).

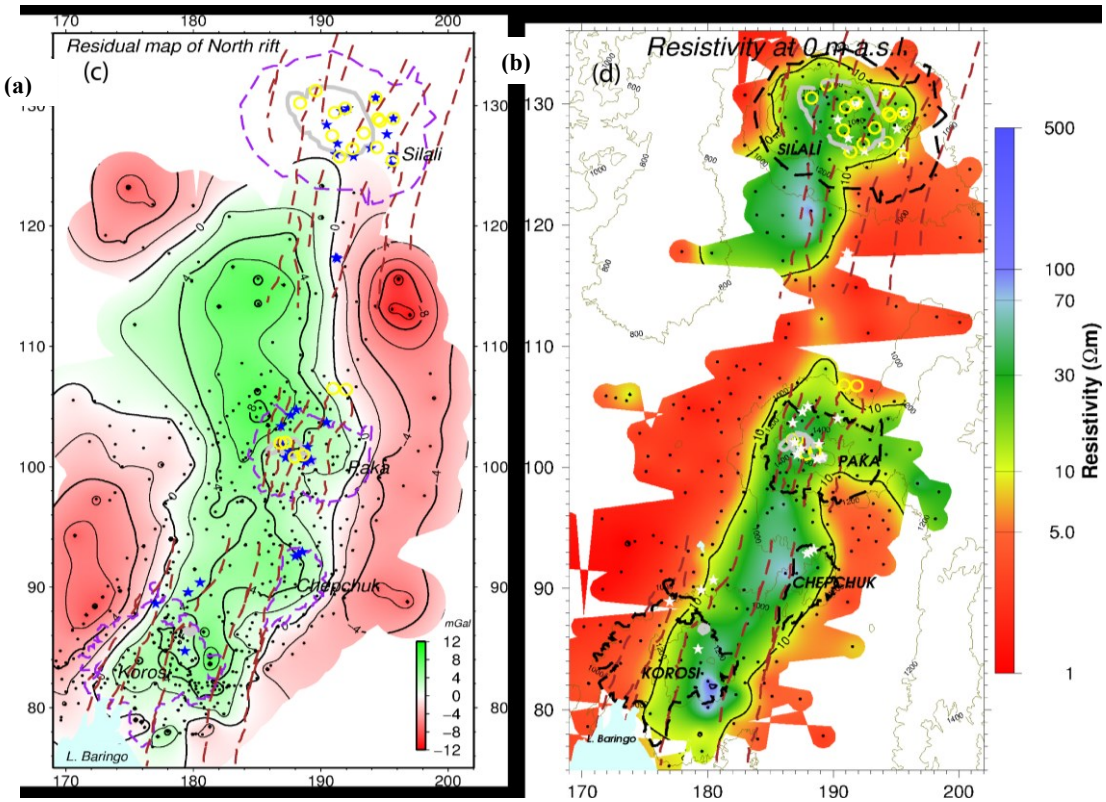


Figure 4: Gravity and resistivity maps for study area, showing (a) Residual gravity and (b) Resistivity at sea level. Stars and yellow rings are geothermal surface manifestations, purple and black dashed line outline the boundaries of the volcanoes, and brown dashed lines show fissure swarm. Coordinates are in UTM in km zone 37 (WGS84).

3.0 CORRELATION OF GRAVITY ANOMALIES AND RESISTIVITY STRUCTURE

The overall results shown in our gravity residual map (Fig. 4a) are in fair agreement with observations from resistivity study (Fig. 4b). 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 the (green) high resistivity trend is interrupted by a (red) conductor but the green gravity high is continuous, albeit with a shift to the west of the axis of the gravity low. This inconsistency could be due to thick, compacted high temperature altered low porosity tuffs with high density but low resistivity. On the flanks of the volcanoes, where low resistivity was imaged, low gravity reveals low densities, which have been interpreted as volcaniclastics/buried pyroclastic units. Surface geothermal manifestations like fumaroles are mainly located at the margin of the high gravity, potentially controlled by faults and those occurring at the summit of Paka caldera are within a more local zone of relatively low gravity.

Similarly, the gravity results (Fig. 4a) are in fair agreement with the westward offset in high gravity in the Silali sector north of Paka volcano seen in the resistivity (Fig. 4b) 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 (based on younger eruption centers) 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.

4.0 CORRELATION OF SURFACE GEOPHYSICS DATA WITH DOWN DATA FROM PAKA WELLS

Two resistivity cross sections are displayed together with the available alteration data from nearby wells are projected onto the sections. The NW-SE section on Figure 5 crosses the central part of the Paka volcano. There is an indication of the low resistivity zone above the high resistivity core at depth of about sea level. The section shows the up doming of the high resistivity core where well PW-01 is projected onto the section. The data from the well show that the alteration corresponds well with the resistivity. There is an indication of the low resistivity zone at depth within the high resistivity core towards the SE of the profile. The well encountered temperatures of >240 °C at the reservoir depth. The low resistivity embedded in the high resistivity core about 20km on profile may suggest a zone with higher permeability and or probable higher temperature.

Section N-S on Figure 6 crosses through the two wells and crosses the main surface manifestations at the Paka caldera. The low resistivity cap covers almost the entire section getting pronounced on both east and west. Alteration data from wells PW-01 and PW-02 are projected on to the cross section. Well PW-01 goes through the prominent low resistivity anomaly that closes off the main up doming on the central section of the geothermal field. Well PW-02 appears to be on the edge of the low resistivity cap beyond which resistivity increases northwards. This corresponds fairly well with the alteration data from the wells.

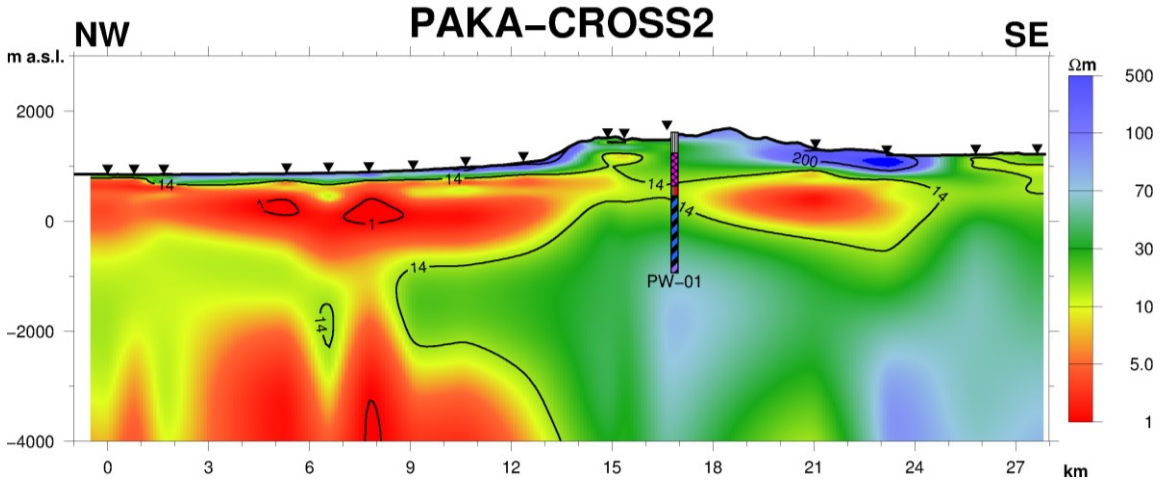


Figure 5: Resistivity cross section NW-SE and alteration data from well PW-01

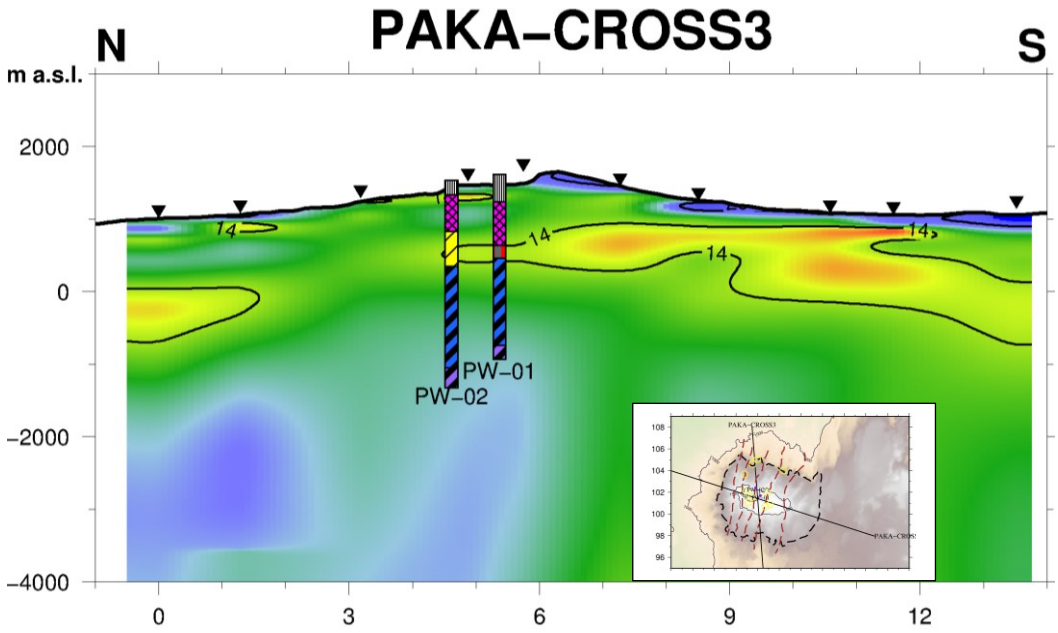


Figure 6: Resistivity cross section N-S and alteration data from well PW-01 and PW-02. Inset map shows the locations of the sections

4.0 DISCUSSION

The residual gravity anomaly map of the Korosi-Paka-Silali region reveals a coherent pattern with gravity varying over a range of about 20 mGal (Fig. 4a). It delineates a clear NNE-SSW positive gravity anomaly extending through the inner rift segments. The gravity processing and modelling illustrate how the overall gravity trend correlates with the mapped fissures of the axis of the rift. Comparison with a previous MT resistivity study (Lichoro et al., 2017), shows a strong correspondence between the gravity high along the rift axis and eastwards shallowing of high resistivity from depths of about 2 km to 1 km, correlated with the volcanic centers and the zone of intense faulting and fracturing within the inner rift. Correlation between MT resistivity and gravity show a good match between low resistivity and low gravity, especially on the flanks of the volcanoes, attributed to greater thicknesses of low density, high clay pyroclastics and sediments. Also, a shallow layer below the Paka caldera follows the same pattern, where the conductive clay layer corresponds to a density of 2.2 g/cm3. Elsewhere surficial fracture zones within the rift are characterized by higher resistivity lavas and probably propylitic alteration (Frolova et al., 2010) at depth of about 2 km corresponding to >2.6 g/cm3 density. These have significant implications for the geothermal potential within this part of the volcanic rift zone. A low resistivity

cap underlain by a high resistivity core reflects the temperature dependent alteration of the rocks. Correlation of resistivity and dominant alteration shows that the base of the conductive cap denotes temperature of about 240°C.

5.0 CONCLUSION

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 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. The correlated resistivity and alteration minerals from drilled wells suggest a zone with higher permeability and a temperature of about 240 °C. This is actually confirmed by the drilling of well PW-01 at Paka volcano. 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.

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