Resistivity Structure of the Paka Geothermal Prospect in Kenya

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Keywords

Geothermal, Magnetotellurics (MT), Transient Electromagnetics (TEM), Paka

ABSTRACT

Geothermal energy sources are formed by heat stored in rocks at depth. In regions with high heat flow, like at volcanically active plate margins, high total thermodynamic energy is accumulated in high-enthalpy resources. Unaltered volcanic rocks generally have high resistivity which can be changed by hydrothermal activity. Hydrothermal fluids tend to reduce the resistivity of rocks by altering the rocks or by increasing salinity. Initial regional exploration for geothermal resources in Kenya indicated that the Quaternary volcanic complexes of the Kenya rift valley provided the most promising prospects for geothermal exploration. Consequently, detailed exploration for geothermal power has been concentrated around volcanic centres within the rift valley. Studies show that these centres have positive indications of geothermal resource that can be commercially exploited. The geothermal potential of the area is associated with these magma chambers that constitute the heat sources. Magnetotelluric (MT) data show that the heat sources are shallow beneath the volcanic centres. This paper concentrates on the geophysical work that has been carried out in the Paka Geothermal prospect using MT. Paka is a relatively small shield volcano located just to the north of Korosi volcanic complex. Volcanic activity commenced by 390 ka (Trachyte's) and continued to within 10 ka (basalts).

Data collected using magnetotellurics is used to determine the resistivity distribution within the earth to depths of many kilometers which is then interpreted in terms of lithology. The contrast in resistivities provides an excellent tool for identifying geothermal targets. So magnetotellurics is the standard method for mapping the alteration cap and via 3D inversion the underlying reservoir.

1.0 Introduction

Geophysics is a discipline of earth sciences that studies earth by quantitative observation of its physical properties. Geophysical exploration techniques are employed during surface exploration to identify structures that could be possible conduits for geothermal fluids, presence of heat sources and outline drilling areas where exploration wells can be sited. The commonest geophysical method employed in exploration for geothermal energy is the electrical conductivity technique. In the transient electromagnetic (TEM) method, an electrical current is injected into the ground, and its decay and the magnetic field created are measured, from which the resistance of the underground rocks is determined. The TEM method, in ideal conditions, can investigate down to 1 km. For deeper studies, the magnetotelluric (MT) technique is preferred, in which fluctuations of the earth's natural electrical and magnetic currents are used. Due to the presence of hot rocks and saline hot waters, geothermal areas tend to have low resistivities. The gravity and magnetic methods assist in identifying heat sources. Microseismic as well as magnetic investigations assist in identifying structures such as faults.

Paka volcano is located at the Northern rift in Kenya. Geophysical surveys comprising of Magnetotellulics (MT) and Transient Electromagnetic (TEM) methods were employed from 1st February, 2010 to 15th February, 2010. The objective was to carry out an infill survey to establish the extent of a geothermal resource in this area and to site wells for exploratory drilling.

2.0 Previous Work

2.1 Seismology

Since the early 1970s, both passive and active source seismic investigations have been carried out in order to understand the formation and structure of the Kenyan part of the East African rift valley (Achauer, 1992; Achauer, 1994; Hamilton et al.,1973; Henry, 1987; Henry, *et al.*, 1990; Keller, *et al.,* 1994; Keller, 1994; Slack, *et al.,* 1994; Jane Tongue, *et al.,* 1992; Tongue, *et al.,* 1994; Fairhead and Stuart, 1982). Some of these results have been applied in the search for geothermal energy in Kenya. The United States Geological Survey carried out seismic studies at Lake Bogoria area in 1972 and located earthquakes of magnitude 2 or less that were restricted mainly within the fields along fault zones (Hamilton and Muffler, 1972). The resulting time-distance plots indicated the Lake Bogoria area is underlain by a three-layer volcanic sequence of about 3.5 km thick. This sequence is in turn underlain by a layer with a P-wave velocity of 6.3 km/s. Their interpreted model shows a structure with velocities higher than the average upper crustal velocities within the rift.

In 1986/87 a micro-earthquake network was set up in the Lake Bogoria region in an area of about 25 km diameter in the Molo graben, NdoIoita graben and Kamaachj horst comprising of 15 recording stations. Results from the survey appeared to suggest that most of the activity was associated with larger, older faults of the rift flanks rather than younger grid faults cross-cutting the rift. The earthquake depth distribution showed that most activities occurred above a depth of 12 km, and no 'normal' activity takes place below 15 km, implying a deep brittle-ductile transition zone (Figure 1).

During the KRISP Project, the University of Leicester carried out micro-seismic monitoring at Lake Bogoria geothermal prospect (Young *et al.,* 1991). Results from here, too, indicated that seismicity is confined to faulted zones.

2.2 Gravity and Ground Magnetics

The Bouguer gravity data used in this review have been obtained from two sources. The main source was the University of Texas at El Paso's (UTEP) database. It is comprised of over 60,000 stations from East Africa, and a subset for the central Kenya rift was extracted from it. The second source consisted of reports from workers and thesis of students for this part of the rift (Fairhead, 1976; Simiyu and Keller, 1997; Swain, 1992; Swain, *et al.,* 1994; Swain *et al.,* 1981; Swain and Khan, 1978). These data have been reduced to Bouguer values using a density of 2.67 g/cm^3 and adjusted to a common IGSN71 gravity datum.

Analysis of this (Figure 2) data shows a large positive anomaly, located in the central part of the area (between Lake Baringo and Emoruangikokolak volcanic centre) running in a N-S direction. This could be related to the axial high anomaly that could be a heat source for a possible geothermal system. However the data is too sparse to give a detailed picture of localised anomalies.

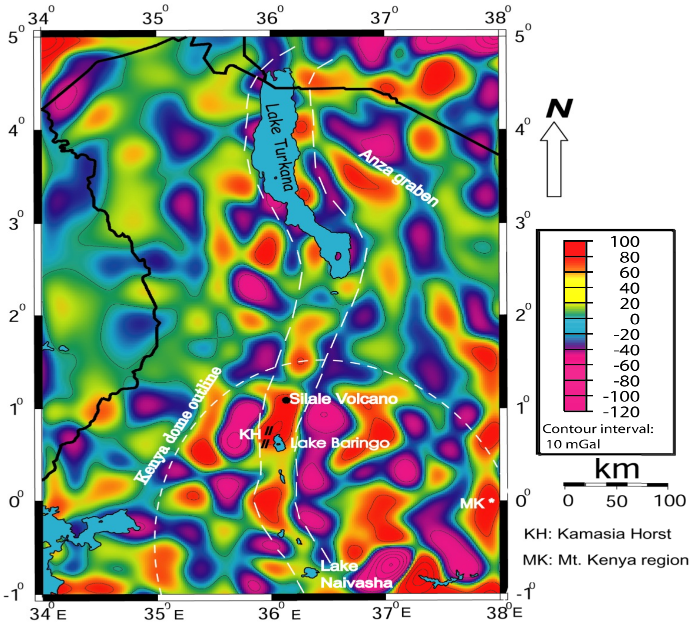

Figure 1. Band-pass filtered gravity map of the northern part of the Kenya rift. Wavelengths passed 30-150 km. After Mariita, 2003.

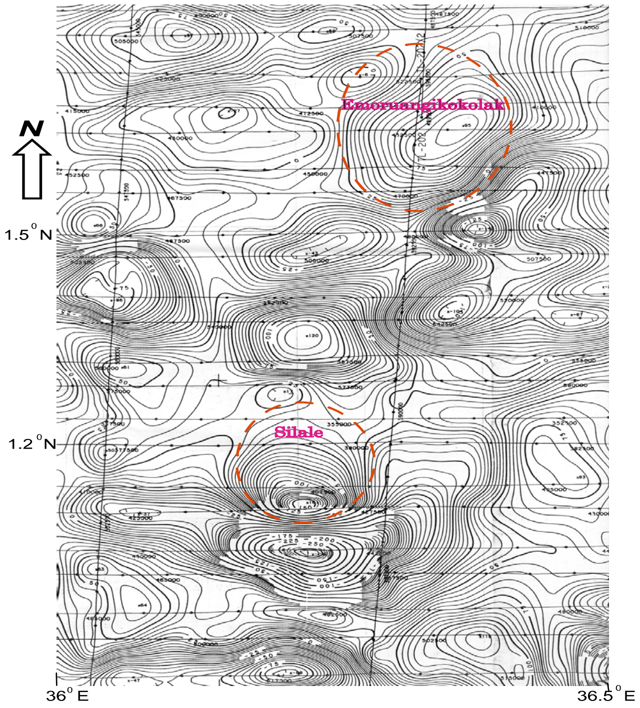

Figure 2. Aeromagnetic residual field intensity contour map for areas around Korosi-Chepchuk, Paka, Silale and Emoruangikokolak volcanic centres. Regional field correction used IGRF 1985 and updated to 1987. (Modified from NOCK, 1987).

In 1987 the Ministry of Energy, on behalf of the National Oil Corporation of Kenya, contracted CGG to carry out an aeromagnetic survey along the Rift Valley (NOCK, 1987). The data was collected at a terrain clearance of 2996 masl. Various data reduction techniques were applied to these, producing different contour maps. In this review, we have evaluated the residual anomalies after reduction to pole, since qualitative information can be derived from such maps to provide clues as to the geology and structure of a broad region from an assessment of the shapes and trends of the anomalies. The area is marked by a series of high-amplitude magnetic anomalies. The wavelengths of these anomalies are less than 2.5 km, their amplitudes showing broad peaks reaching several hundred gammas and their shapes are either isometric or oval. This magnetic field is very typical of what is observed over basic volcanics, i.e. basalts. The positive anomalies coincide closely with known Quaternary volcanoes. Conspicuous examples that were noted were positive anomalies coinciding with the Korosi, paka, Silale, Emoruangikokolak and The Barrier volcanoes. Figure 2-2 highlights these features corresponding to these volcanic centres. These high magnetic makers would suggest massive basalts in the subsurface (if not exposed), whereas the overlying terrain would have negligible susceptibility compared to that of basalt. The highest magnetic signal was recorded at the south-eastern slopes of Korosi, around Komolion.

2.3 Resistivity

2.3.1 Transient Electromagnetic (TEM)

TEM soundings were carried out in Paka prospect area spread using Central Loop TEM Array. In all the soundings, a 300m x

300m transmitter wire loop was used. A half-duty square wave current was transmitted at frequencies of 16 and 4 Hz. Logarithmically spaced sampling gates were used with 16 Hz having 25 gates starting at 36.14µsec to 12.18msec; 4 Hz had 31 sampling gates starting at 36.14µsec to 48.42msec At each repetition rate, several repeated transients were stacked and were later transferred to a Personal Computer for processing.

Raw data files were read and downloaded from the GDP-16 receiver by using TEM SHRED (a Zonge Geophysics program) and the TEM-AVG (also a Zonge Geophysics program) was used to calculate averages and standard deviations of repeated transient voltage measurements and late time apparent resistivity as a function of time. WingLink (Geosystem) interpretation program was used to perform 1-D inversion on the data. A total of 55 TEM soundings were carried out bringing the total to 73 soundings (Figure 3).

2.3.2 Magnetotellurics (MT)

MT soundings were carried in Paka prospect a 5-channel MT data acquisition systems (MTU-5A, from Phoenix Geophysics-Canada), with each sounding taking an average period of 17 hours.

SSMT2000 software (provided by Phoenix Geophysics-Canada), was used in producing Fourier transforms from the raw time-series data. The program, MTU-Editor was then used to write the MT data files to Electronic data interchange (EDI) format for use with the WinGLink geophysical interpretation software to perform 1-D inversion.

EM data (averaged stacks from GDP-16, TEM raw data) collected on same locations as the MT sites were also exported to WinGLink program, where their 1-D models were used for static shift corrections on the MT data. A total of 92 MT soundings were carried out bringing the total to 107 soundings (Figure 4).

3.0 Results of MT and TEM Survey

Interpretation of the resistivity structure of Paka prospect was done by the construction of contour planar maps. Examination of the iso-resistivity maps above and below sea-level and by resistivity cross-sections across major geological structures. The MT method suffers a static shift problem, which was resolved by applying the central-loop TEM method along with MT to resolve the resistivity in the uppermost kilometre by joint inversion. The equivalent MT model of phase and resistivity generated from TEM data was used to correct for static shifts in the MT data. In most cases the TEM model fitted the TE mode of the MT data very well.

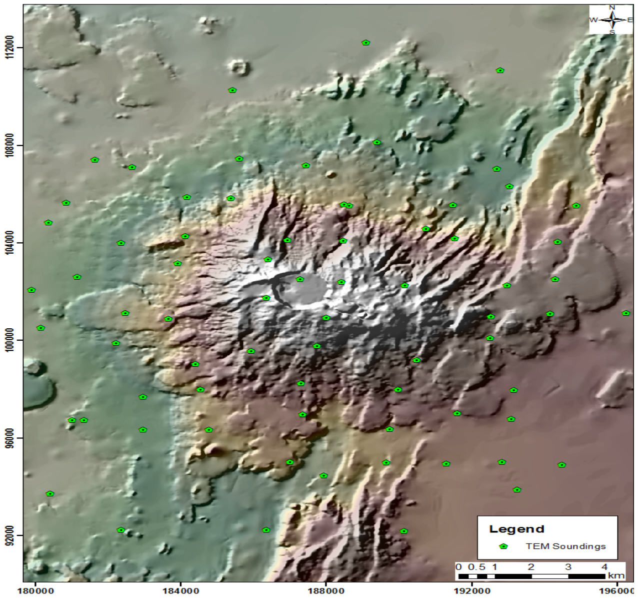

Figure 3. Current MT locations map.

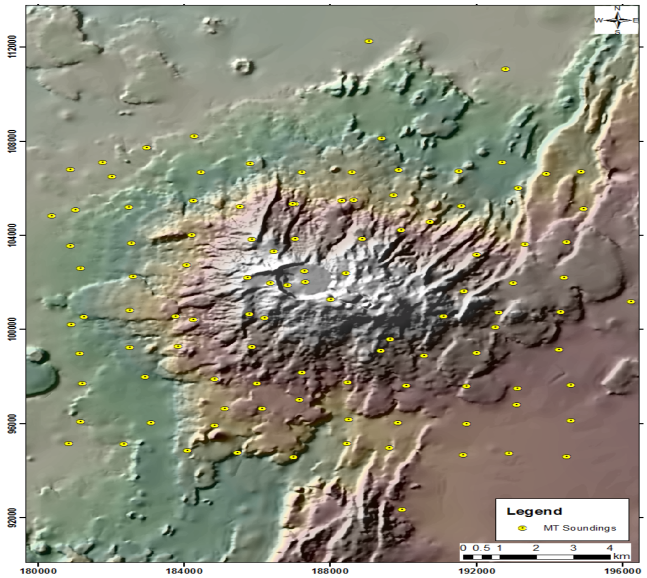

Figure 4. Current TEM locations map.

Iso-resistivity Maps

Resistivity at 1000 masl

Resistivity distribution at 1000 masl shows a low resistivity anomaly of 3 ohm.m on the south western and eastern part of the plot at shallow depth which is as a result of conductive clay minerals near the surface (Figure 5). The fairly high-resistivity values alighning along Nagoreti fault and towards Kaiyomot areas is due to unaltered formations near the surface.

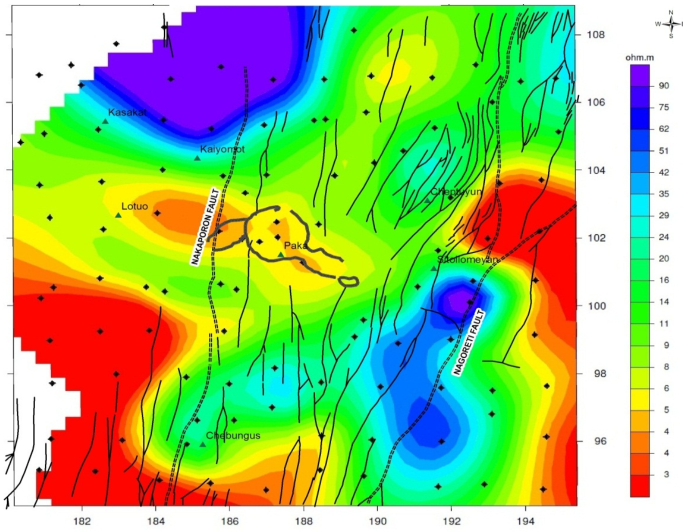

Figure 5. Resistivity at 1000 masl.

Resistivity at 500 masl

At 500 masl (Figure 6) a high resistivity anomaly (34 ohm.m) aligns itself in the direction of major structures NNE and it is as a result of un-altered formations at about 500 meters below surface and on the eastern part of the plot a low resistivity anomaly persists due to conductive clays though it is not well constrained further east due to scarcity of data.

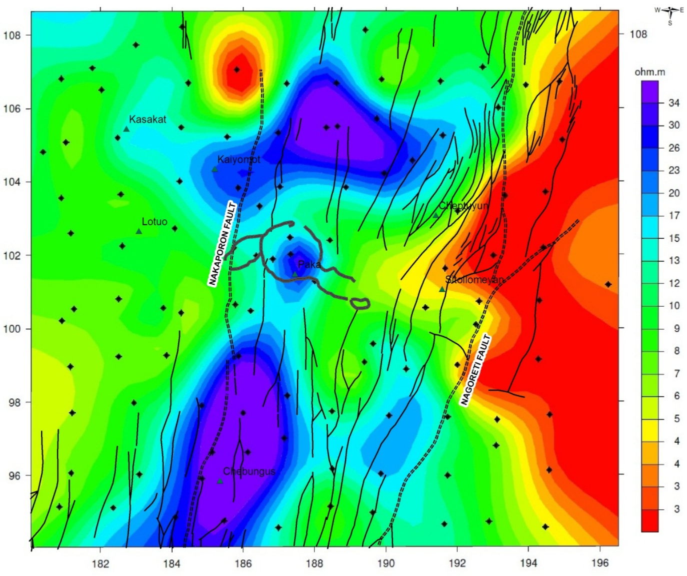

Figure 6. Resistivity at 500 masl.

Resistivity at Sea Level

At sea level (Figure 7) hydrothermal alteration sets in on the Western part of the prospect area as a result of low temperature hydrothermal clay minerals such as smectite and illites and also on the North eastern parts which connects to the southern flanks of the Silali prospect to the North though the data is not enough to clearly define it Northwards. On the central part of the plot a resistivity anomaly of less than 49 ohm.m is evident and this can be interpreted as the reservoir zone for this prospect area and is characterised by high temperature alteration minerals such as chlorites and epidotes.

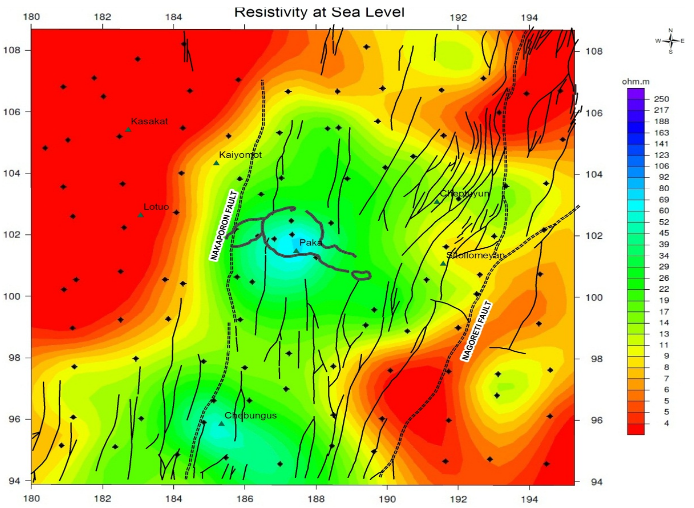

Figure 7. Resistivity at Sea Level.

Resistivity at -1000 mbsl

A high resistivity anomaly (Figure 8) aligns itself towards NNE and is a vapour system hosted under the caldera and runs southwards towards Chepungus. The low resistivity on the eastern side is due to hydrothermal alteration and around Lotuo a resistivity of 28 ohm.m is seen extending towards Kaiyomot and is characterised by high-temperature alteration minerals such as chlorites and epidotes, and it can probably interpreted as a fracture zone.

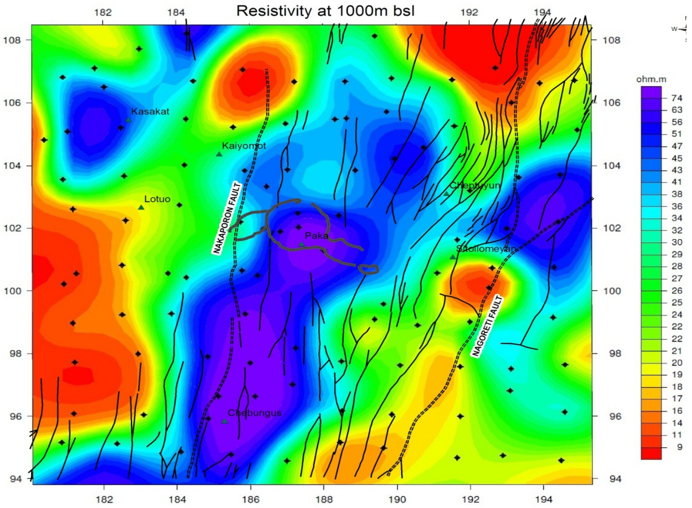

Figure 8. Resistivity at 1000 mbsl.

Resistivity at -2000 mbsl

A deep conductor appears around Lotuo area and is hosted where there is a discontinuity with the vapour system below the caldera (Figure 9). There is a discontinuity of intermediate resistivity values bordering the conductor and the vapour system which aligns in the direction of the major structures.

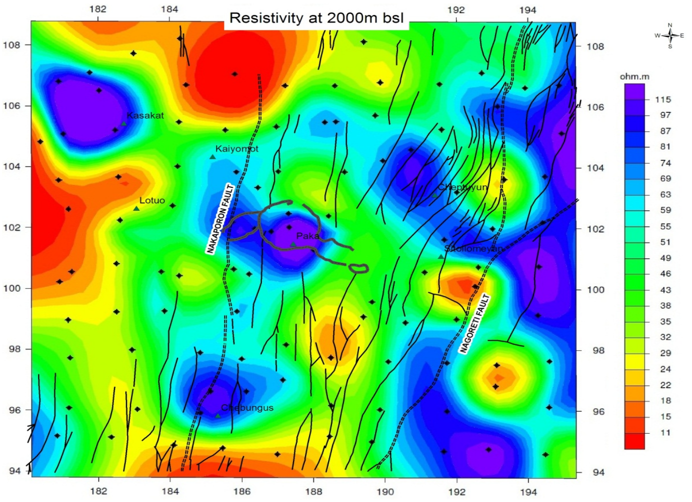

Figure 9. Resistivity at 2000 mbsl.

Resistivity at -3000 mbsl

The vapour-dominated system becomes more pronounced on the central part of the prospect and aligns in the direction of the major structures (Figure 10). This is probably a dry-steam zone while on the western part the deep conductor is extending in the south western part and associates with two-phase characteristics. The deep conductor occurs between a buried fault zone which is postulated to be a zone of circulation for hydrothemal fluids and high fracture porosity, hence the low-resistivity anomaly.

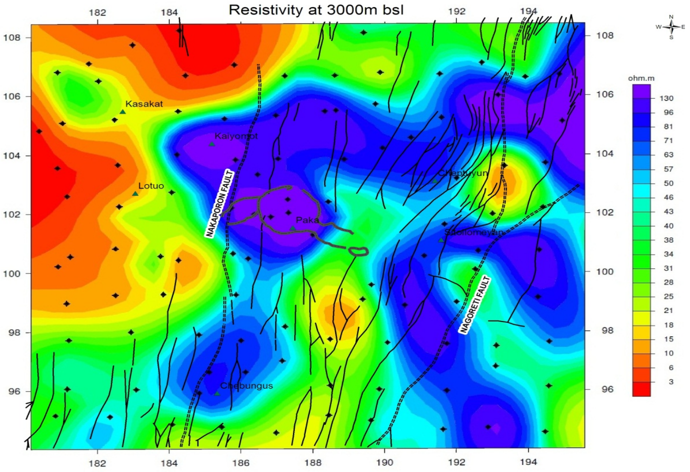

Figure 10. Resistivity at 3000 mbsl.

Resistivity at -4000 mbsl

A similar resistivity structure as in the previous plot is seen (Figure 11) with the deep conductor becoming more aligned on the western part of the plot and the vapour-dominated system aligned along the fault lines and towards the eastern part of the plot.

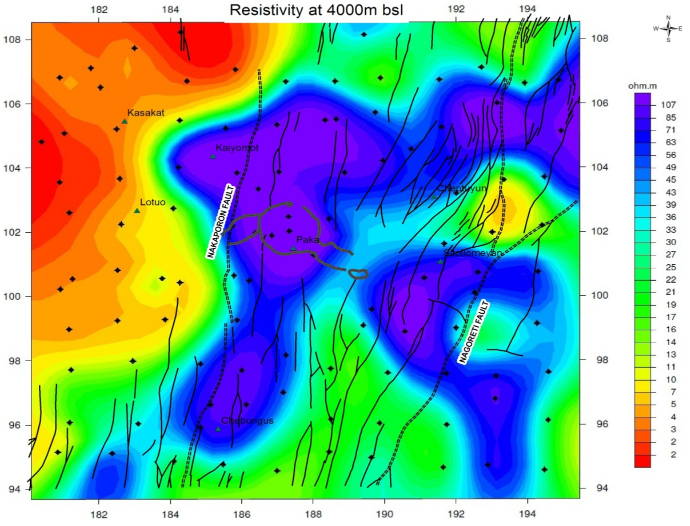

Figure 11. Resistivity at 4000 mbsl.

Resistivity at -5000 mbsl

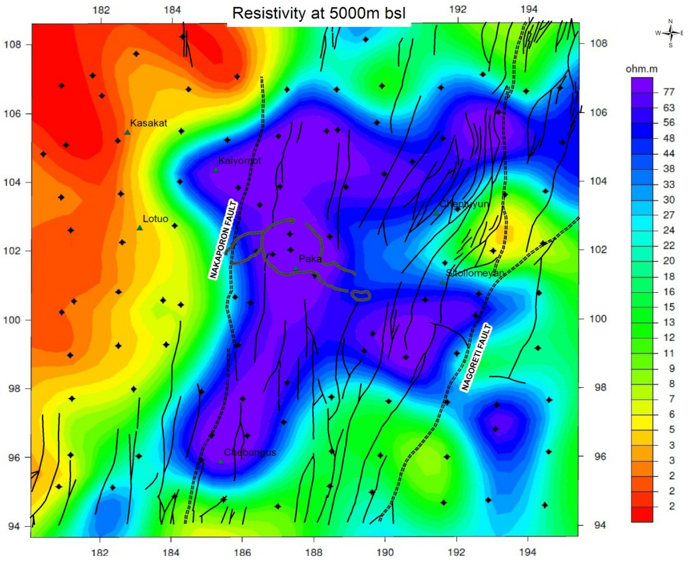

Figure 12. Resistivity at 5000 mbsl.

The conductor is clearly defined on the western part and the fault lines form a boundary from which it is evident that the two systems are structurally controlled and there is an indication of a deep magmatic body below (Figure 12).

Cross-Sections

Cross-Section along N-S

This section cuts through the western part of the prospect in a North- South direction, and it clearly defines a conductor in this prospect from a depth of 2km below sea level, which is 3km below the surface (Figure 13). Towards the southern part there is a clear boundary from the central part which is the probable fracture zone separating the deep conductor from the vapour system. The alteration zone is clearly mapped at about 1km below sea level.

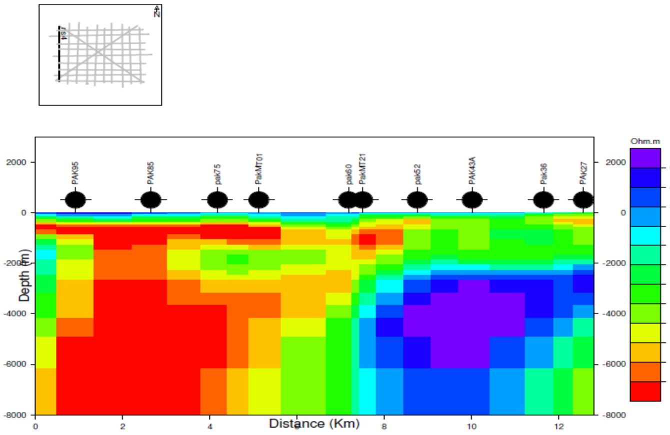

Figure 13. 2D Resistivity Cross-Section along N-S.

Cross-Section along E-W

This section cuts through the central part of the prospect in an East-West direction (Figure 14), and it clearly shows that the deep conductor and the vapour system is structurally controlled and hence exibits a two-phase characteristic at depth.

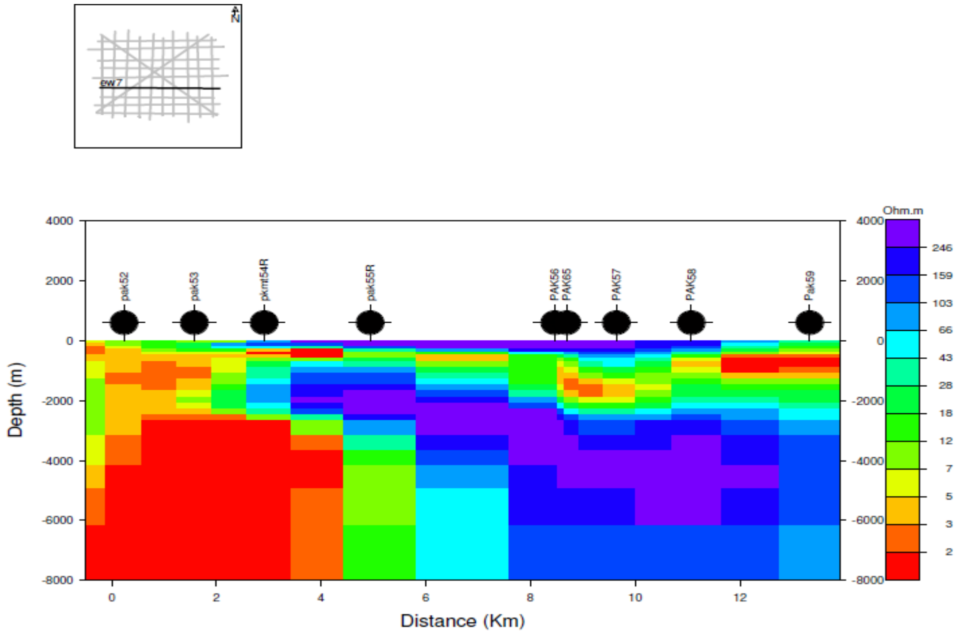

Figure 14. 2D Resistivity cross-section along E-W.

Conclusion

- Paka hosts a very high-temperature geothermal system about 3km below the surface and it is associated with a hot magmatic body below.
- It is a vapour-dominated system as seen from the inversion results.
- Exploratory wells should be drilled to prove the resource.

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