Multidimensional Resistivity Imaging Using Magnetotelluric Data and its Geological Interpretation in Kiejo-Mbaka Geothermal Field, South-West Tanzania

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ABSTRACT

In this paper, the comparison results of 2-D and 3-D MT inversions are presented. A total number of 76 MT soundings acquired using broadband magnetotelluric (BBMT) were inverted. The static shift effects of the MT datasets were corrected using spatial median filter techniques. Dimensionality and directionality analysis were performed prior to inversion, and depicted above 1 Hz lowest Swift-skew, ellipticities and phase sensitive-skew on the Mbaka flood plain. For low frequencies below 1 Hz, higher Swift-skews, ellipticities and phase sensitive-skews are observed in the ridge area. This suggests that the resistivity distribution within the research area presents three-dimensional properties, even beneath the sedimentary basin. This is the reason, why 3-D MT inversion was preferred. The comparison between 2-D and 3-D MT inversions results, with geological interpretation particularly, hydrothermal temperature alteration zones and structural lineaments are performed to reconstruct the subsurface resistivity distribution within the study area. The inversion calculations produced the resistivity models with a resistive central body surrounded by conductive anomalies. The resistive body inclines toward both SE and NW. It is delimited by two conductive zones; one SW-dipping with a high-angle, another NE-dipping and less inclined. The former is associated with the Mbaka fault, whereas the latter has a direction correlating to the Livingstone border fault system.

1. Introduction

The magnetotelluric (MT) method has been improved since its initiation in the 1950s with regard to both methodology and data analysis. The MT method is the main branch of electromagnetic (EM) exploration, introduced by Tikhonov (1950) and Cagniard (1953). Up to date, the MT technique is still the most powerful method for investigating the deeper subsurface structure and for delineating the resistivity boundaries within the area of interest. In this study, the apparent resistivity is inverted to the actual subsurface resistivity structure by applying 2-D and 3-D inversions. The geological information supports the final
The combination of geophysical and geological methods has been successful in exploration of geothermal resources in different fields.

The modern computing systems, like the use of data space such as the Nonlinear Conjugate Gradient (NLCG) for the modular electromagnetic (ModEM) have made 3-D modelling and inversion of MT data achievable, and it is now becoming common and useful for detailed subsurface investigations. In recent years, 3-D MT inversion has become the most popular techniques among EM induction methods, especially in volcanic-settings with medium-high enthalpy geothermal systems like the Kiejo-Mbaka geothermal area.

2. Geological Setting for The Study Area

The Kiejo-Mbaka geothermal prospect, which is part of the western branch of the East Africa Rift System (EARS) covers an area of approximately 1,500 km². It is located within the Rungwe Volcanic Province (RVP) as shown in Figure 1. The RVP is situated at the triple junction formed by the Rukwa rift (developed along the Ubendian belt) with NW-SE strike, Usangu basin (developed along the Usagaran belt) with NE-SW strike and Karonga rift (also known as Malawi rift) with N-S strike basins (Figure 2). The northernmost sector of the Karonga basin maintains the NW-SE direction of the Rukwa basin, being delimited to the NE by the NW-SE-trending Livingstone master border fault, which is therefore called Livingstone sub-basin.

![Figure 1: Major geological elements of the study area (after Kraml et al., 2012).](image-url)
2.1 Structural Setting

The structural setting of the study area has been reconstructed through a combination of the observations made in the course of the geological survey and the results of the remote sensing study (ELC and TGDC, 2016). The dominant structures in the area are the NW-SE followed by the less dominant structures trending N-S and minor structures with E-W trend Figure 3. The prominent NW-SE major structures in the area are the main Livingstone fault, Mbaka fault and the Kisyelo faults. The hot springs are located along the Mbaka fault.
Figure 2: Location of RVP (Mbeya Triple Junction) regarding the basement and the rift structure, on the background of colour-coded SRTM DEM (after Delvaux et al., 2010). The study area is shown by black square.
3. Data and Methods

3.1 Two-Dimensional Inversion

In a 2-D earth, the coordinate axes are rotated until one of them is along strike, e.g. \( y \) is along the strike and \( x \) is perpendicular to the strike. As a result of complicated geological environments which is often encountered in geothermal fields, 2-D interpretation has limitations and needs several assumptions, therefore it is failed to produce realistic models in this study. This situation illustrates the limitations of the 2-D MT interpretation in geothermal exploration (Uchinda and Sasaki, 2006).

This study considered the Occam inversion scheme by Constable et al. (1987), deGroot Hedlin and Constable (1993), and Uchida (1993) by seeking the “smoothest”, or “minimum norm” model subject to an appropriate fit to the data within a reasonable tolerance. Occam’s 2-D inversion is based on the minimization of the following object function:

\[
U = \|\partial_y m\|^2 + \|\partial_x m\|^2 + \mu^{-1} \{W \|d - F(m)\|^2 - X^2\},
\]
where the expression $\| \partial_y \mathbf{m} \|^2 + \| \partial_z \mathbf{m} \|^2$ is a norm of the model roughness, $\mu$ is the Lagrange multiplier, the third term in the equation represent the data misfit, $W$ is $M \times M$ diagonal weighting matrix, $\mathbf{d}$ represents the observation vector, and $F(\mathbf{m})$ stands for the forward model response. Figure 4, shows the TE and TM pseudo sections. Whereas Figure 5, demonstrates the cross sections derived from 2-D MT inversion and well elaborated in the discussion section.

Figure 4: Top: TE and TM resistivity pseudo sections showing the differences between data and the models with residuals approximately zero, as an indication of a reasonable fit. Bottom: is a transition curve of R.M.S error with the iterations.
Figure 5: Three SW-NE trending profiles along KML1, KML3 and KML5. The Mbaka fault is marked by red arrows; Lufundo manifestation is indicated by red square, and Kilambo hot spring is shown by red circle.
3.2 Three-Dimensional Inversion

For 3-D inversion we used the ModEM software (Kelbert et al., 2014), with additions for parallel computing described by Meqbel (2009). ModEM is based on a finite difference (FD) approach to solve Maxwell’s equations on a staggered grid. The 3-D inversion is performed by minimization of the following object function.

\[ \Phi = (f(m) - d)^T C_d^{-1} (f(m) - d) + \lambda (m - m_0)^T C_m^{-1} (m - m_0), \]  

(2)

where \( f(m) \) is the FD nonlinear forward operator that maps the model vector \( m \) from the model space into the data vector \( d \) in the data space, \( m \) is the conductivity model, \( m_0 \) is the priori conductivity model, \( d \) is the observed data vector, \( C_d \) is the data covariance matrix, \( C_m \) is the model covariance matrix, and \( \lambda \) is a trade-off parameter between data fit and regularization.

For the 3-D inversion results in this study, the function \( \Phi \) has been minimized by the non-linear conjugate gradient (NLCG) scheme (e.g. Rodi and Mackie, 2001; Kelbert et al., 2014).

The model grid used for 3-D inversion consists of 37 x 38 x 60 cells in x, y, and z directions (84,360 cells in total) as shown in Figure 6. In the central portion of the model in which the vertical direction with 60 layers were used, the dimensions of the boundary blocks increased with a factor of 2 in both x and y directions while the z direction increased by factor of 1. The thickness of the first layer was set to 10 m and the subsequent layers increase by a factor of 2, the horizontal cell size is 450 m and a misfit of about (3 R.M.S) was achieved after the inversion runs. The apparent resistivity sounding curves and phase responses for the observed versus calculated responses for MT stations (M13 and M16) are shown in Figure 7.
Figure 6: 3-D grid for inversion, where the central part of the horizontal grid is used. (a) Site locations are marked by blue dots. (b) In the vertical (z) direction, the grid consists of 60 layers and then the grid spacing augments logarithmically with depth, a detailed view of the central part of the grid, up to a depth of about 8,000 m. (c) Topography has been taken into account by model discretization and the vertical spacing also increases logarithmically above the topography surface.
4. Results and Discussion

4.1 Comparison Results Between 2-D and 3-D MT Inversion

This section compares and contrasts between the inversion results for 2-D resistivity models reconstructed using Occam scheme, from 3-D resistivity models reconstructed using ModEM program from the impedance tensor $Z$. Here, WSW-ENE trending profile lines (KML1, KML3 and KML5) in Figure 9 are discussed. During the process of interpretation, structural lineaments were observed with four structural trends as shown in Figure 8. The trends were observed to be related to; Mbaka fault trend N130-140°, Livingstone fault trend N120°, Usangu rift related trend N030-040° and Nyasa lake rift trend (N-S).
Figure 8: 3-D volume rendering of resistivity distribution with topography in Kiejo-Mbaka geothermal field recovered from 3-D MT inversion using ModEM programs. Structural lineaments are indicated by gray plane surfaces. Geothermal surface manifestations are shown by red spheres. MT stations are represented by black squares. Major and minor faults are superimposed on 3-D volume rendering of resistivity distribution for reference.

Figure 9: Location map for the vertical slices of the 2-D and 3-D resistivity models which is used in interpretation of 2-D and 3-D inversion results. Black squares mark the MT sites. Red spheres indicate the geothermal surface manifestations. The Mbaka fault is shown by white dashed line, whereas profile lines are indicated by white lines.
4.1.1 Resistivity Cross sections and Depth Slice Maps

The general subsurface structure that can be identified are similar in both 2-D and 3-D inversion results, however the 3-D inversion results enabled better resolution in understanding the geometry of such features at greater depth, as noticed in resistivity cross sections as shown in Figure 10.

The subsurface structure has relatively better resolution at greater depth as compared to 2-D results, bearing in mind that the area of research is strongly affected by 3-D effect, therefore 3-D inversion results may represent the realistic subsurface structures than 1-D/2-D. The resultant resistivity distributions are displayed by mean of horizontal resistivity slice maps in Figure 11. Furthermore, it is clear that, the lithology in the area is mainly dominated by the outcrop of Precambrian metamorphic intrusive basement complex (MIC) and the Livingstone gneiss (LIV gneiss). Therefore, several anomalous resistivity zones can be identified. This leads to inferring that resistivity distribution probably is not directly related to its lithology.

The 2-D and 3-D resistivity models, and the resistivity depth slice maps are characterized by general features named, a resistive central body \((R)\) related to MIC, surrounded by conductive anomalies \((C1, C2, \text{ and } C3)\) probably correlative to low-temperature hydrothermal alterations.
Figure 10: The corresponding WSW-ENE resistivity cross-sections from 2-D (left) and 3-D (right) inversions along profiles KML1 (top row), KML3 (central row), and KML5 (last row). The location of Mbaka fault is marked by red arrows, Kilambo hot springs are indicated by red circles and Lufundo manifestation is indicated by red squares.
Figure 11: Horizontal resistivity maps for the (Z) using 100 Ωm homogeneous half-space as initial model. MT stations are marked by black squares. The fault planes are estimated where resistivity contrast exist. Western side delimited by the Mbaka fault and the northeastern side delimited by the Livingstone border fault and has SE dippings. The Mbaka and Kisyelo faults are clearly obtained at around -500 m a.s.l.

From figures 10 and 11, the main features that can be inferred from the cross sections and from the resistivity depth slice maps in both 2-D and 3-D resistivity models are similar in general, and being characterized as follows:

a. The sections are characterized by a central resistive body indicated as "R" corresponding with the outcrop of Precambrian metamorphic intrusive complex basement (MIC) and Livingstone gneiss (LIV gneiss).

b. Conductive anomaly C1 is a thick beneath the rift plain westward of the Mbaka fault; this layer shows locally very low resistivity values (<1 Ωm). It could be related to a low-temperature alteration zone in the MIC or LIV metamorphic rocks.

c. Conductive anomaly C2 is thin and shallow with minimum resistivity between 2-5 Ωm, it could be related to a shallow low-temperature alteration zone in the MIC basement. This anomaly could be associated with the Lufundo manifestations.

d. Conductive anomaly C3 is deeper positioned further toward eastern side with resistivity approximately 10 Ωm. It could be related to a low-temperature alteration zone in the MIC or LIV metamorphic rocks.

e. Conductive anomaly C4 is relatively resistive zone with resistivity approximately 50 Ωm. It could represent a high-temperature alteration zone.
Discontinuities $D_1$ and $D_2$ have been pinpointed by following iso-resistivity surfaces of 100 $\Omega$m. The discontinuity $D_1$, is correlated to the Mbaka fault and marks a border between the conductive layer in the plain ($C_1$) and the resistive rift shoulder ($R$) constituted by MIC and LIV metamorphic rocks. The discontinuity $D_2$, marks a border between the resistive rift shoulder ($R$) and the conductive zones toward eastern side constituted by $C_2$ and $C_3$.

The ‘big’ resistivity discontinuities ($D_3$) toward SW and NE directions in both 2-D and 3-D resistivity models might be interpreted as a boundary between the undifferentiated sedimentary complex and the MIC in the SW and NE directions. These structures could be interpreted as impermeable faults, and might play a great role in controlling the circulations of hot fluids in a geothermal reservoir.

4.1.2 Conceptual Model of Geothermal Systems at Kiejo-Mbaka

The conceptual model is demonstrated mainly on 3-D MT inversion results in Figure 12(a). The conductive anomaly in question mark (?) below the MIC, probably could be interpreted as partial melts at deeper depth in the MIC. With reference to previous studies (ELC and TGDC, 2017), Kiejo-Mbaka geothermal system was inferred as a fault-controlled system. Moreover, the extensional domains (fault-controlled) systems, sometimes can co-exist with magmatic intrusions. Therefore, it is difficult to distinguish between the two systems. Henceforth, follow-up is required to understand the conductive anomaly in question mark (?) whether it is an artifact of inversion or a meaningful structure. Sensitivity studies could solve the uncertainties and its resolution of the obtained resistivity models caused by inherent ill-posed problem of non-uniqueness from a linear and a non-linear point of view which is not part of this work. From the conceptual model illustrated in Figure 12(a) in this study, two reservoirs $R_1$ and $R_2$ were interpreted, and two slim holes are proposed to access $R_1$. A vertical slim hole that targeting a reservoir $R_1$ at a depth of 1,500 m, and a directional well targeting the intersection of $R_1$ and the Mbaka fault. In the same figure another reservoir $R_2$ might be located towards NE direction and accessible through drilling a vertical slim hole.
Figure 12(a): Conceptual model of geothermal systems based on 3-D MT inversion. Geothermal surface manifestations are indicated by red dots. MF: means Mbaka fault; the trace of the Mbaka fault is shown by vertical red arrow.

Figure 12(b): Detailed schematic diagram illustrating a conceptual model of geothermal systems at Kiejo-Mbaka. The cartoon shows the co-existence of both heat source and fault controlled system. Notice that the cartoon is not to scale.
5. Conclusions

Although the non-uniqueness in inverse problem of MT sounding data is well known, the inversion usually requires a preferred model to represent and interpret the data. It is most desirable to avoid under and/or over parameterization. With regardless of inversion schemes, if the data errors have been well estimated with zero mean, the model will mostly rely to a large degree by depending upon the data errors as well as the data themselves. Therefore, every effort in the field is required to correct estimation of errors. 2-D and 3-D MT inversions are in good agreement each other with the main features which were named, a resistive central body (R) correlative to outcrop of Precambrian metamorphic intrusive basement complex (MIC), surrounded by conductive anomalies (C1, C2, C3 and C4). The resistivity models, were able to isolate the two discontinuities (D1 and D2). The boundaries of the discontinuities to western and northeastern side were clearly indicated, D1 which is caused by the Mbaka fault to western side and D2 caused by the Living stone border fault in the northeastern side of the study area. The Precambrian basement (MIC) either outcrops or sub crops between the two fault planes.

REFERENCES


