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# Dimensionality and Directionality Analysis of MT Data to Image Geothermal Systems in Kiejo-Mbaka Geothermal Field, South-West Tanzania

Tumbu L, Mizunaga H,

lucas.tumbu98@gmail.com

mizunaga@mine.kyushu-u.ac.jp

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**ABSTRACT**

The Kiejo-Mbaka geothermal field is located close to the eastern margin of the Karonga rift basin and is part of the Rungwe Volcanic Province (RVP), where the East African Rift System (EARS) splits up into its Western and Eastern branches in southern Tanzania. The area is characterised by an Intrusive Precambrian gneiss metamorphic basement complex (**MIT**), that either sub-crops or outcrops along the NW-trending and SW-dipping Mbaka fault. Kilambo hot springs manifest and flow just along the Mbaka fault, the highest Swift-skew, phase-sensitive skew and ellipticity were observed in the Mbaka ridge area, where these parameters indicated strong 3-D characters starting from frequencies of about 1 Hz at relatively greater depth, which indicates the necessity for 3-D inversion in order to know the deeper part of the study area. Greater variability in the induction arrows direction and module are well evinced. YX-Phases are out of quadrant greater than (90 deg) and apparent resistivity curves for the TM-modes are greater than that of TE-modes for many of the MT stations lying on the Mbaka ridge area, as an implication of high resistivity zones beneath the Mbaka ridge regions, with a strike directions probably close to x-axis. On the other hand, the reason for the latter may be a possible current channelling that is strongly within the ridge area, owing to topographic effects. The lowest Swift-skew, phase-sensitive skew, ellipticity and shortest induction arrow lengths are on the Mbaka river plain, west to south-west of the Mbaka fault, and on the eastern plateau of the Mbaka escarpment, indicating 1D/2D characters for short period ranges at relatively shallow depth, therefore, 1-D/2-D inversion may probably represent the shallow portion of the study area.

## 1. INTRODUCTION

Resistivity is an important physical parameter to image the subsurface and to resolve ambiguities in structures of a geothermal system thereby identifying the depth and geometry. In high-enthalpy geothermal system like the Kiejo-Mbaka geothermal field, the resistivity distribution highly depends on the hydrothermal alteration (Ussher et al., 2000; Munoz, 2014). Tanzania Geothermal Development Company limited (TGDC), conducted resistivity imaging using MT method at Kiejo-Mbaka geothermal field. The studies were aimed to image and investigate on how the conductivity distributions of the subsurface varies with depth, the studies were conducted from September to October, 2016.

In this study, dimensionality and directionality analysis in Kiejo-Mbaka geothermal field are presented prior to 1-D, 2-D and 3-D inversions and modelling, which is a commonly well-known approach in MT community. MT data from 76 MT sites were used over a frequency range of 0.0001-1,000 Hz to image the subsurface conductivity distribution at Kiejo-Mbaka geothermal field.

The ultimate goal for this paper was to assess the dimensionality and geoelectrical strike of the study area prior to inversions and modelling. This included also detection for the effects of near-surface inhomogeneities, caused by galvanic distortions, such as static shifts and correcting it. The analysis will in particular help to remove the distortions which resulted from near-surface inhomogeneities within the surveyed area, however statics shift is not the scope of the paper and will not be discussed here. The paper will focus mainly on dimensionality and directionality analysis of the MT dataset.

## 2. KIEJO-MBAKA GEOTHERMAL AREA

The geophysical survey area was designed to cover the Kiejo-Mbaka geothermal area, located close to the eastern margin of the Karonga Rift Basin about 90 km SE of the town of Mbeya as shown in (Figure 1).

The Kiejo-Mbaka area is part of the Rungwe Volcanic Province of the Western rift branch of the East African Rift System. The basaltic and volcaniclastic sequence from the Rungwe Volcanic Province covers an accommodation zones between three asymmetric basins (Figure 1). The Songwe basin, the Usangu basin, and the Karonga basin. The Songwe Basin is a rift valley linking the Rukwa depression to the Rungwe Volcanic Province (Delvaux et al., 2013).

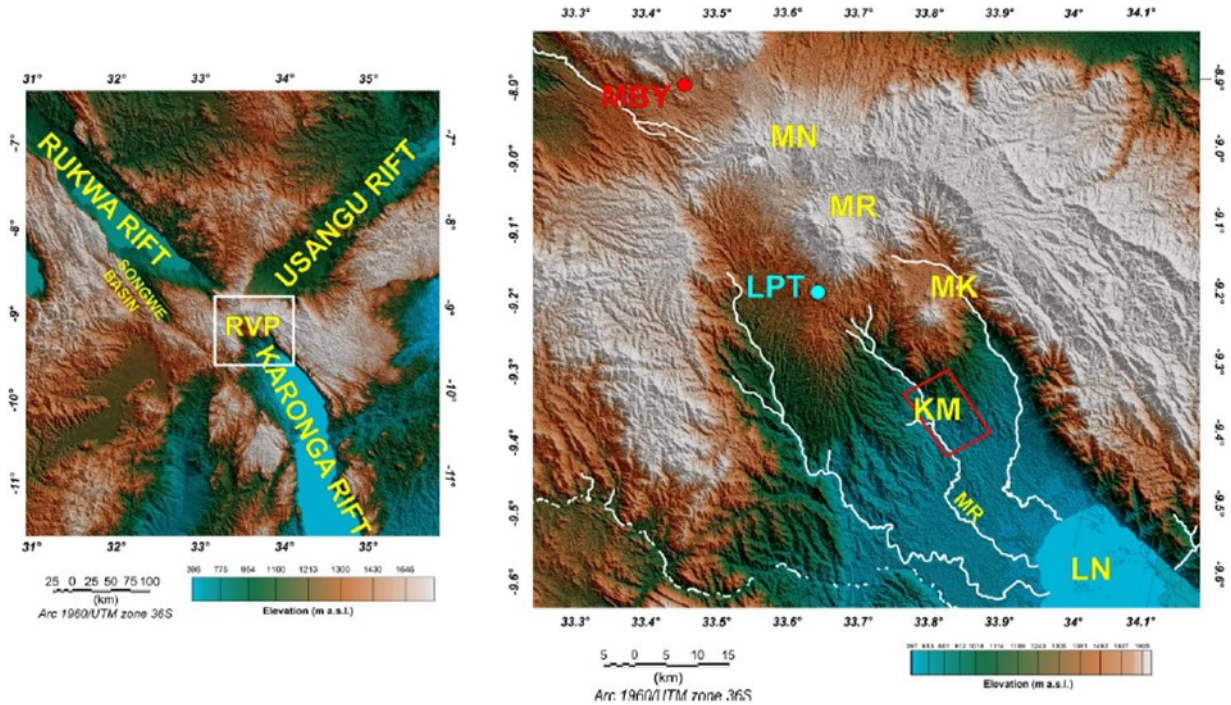



**Figure 1: Location of the Kiejo-Mbaka survey area in the Karonga Rift. KM: Kiejo-Mbaka area (marked by a red rectangle); RVP: Rungwe Volcanic Province; MK: Mount Kiejo; MR: Mount Rungwe; MN: Mount Ngozi; MR: Mbaka River. LN: Lake Nyasa. Town of Mbeya is marked by MBY (red circle). The MT reference site (Lupoto) is labelled "LPT". Main rivers are marked by white lines, ELC and TGDC (2016).**

## 3. MT DIMENSIONALITY AND DIRECTIONALITY ANALYSIS

Prior to 1-D, 2-D or 3-D inversion, it is necessary to identify a preferred geoelectrical strike. This is accomplished based on known local or regional geology or by performing some sort of dimensionality analysis on the dataset.

Dimensionality and directionality behaviour across the survey area have evinced four different station groups with relatively homogeneous characteristics. The analysis for dimensionality for all the approaches discussed under this study have shown similarities and resolved the subsurface conductivity structures at Kiejo-Mbaka geothermal area to be most reliable for 3-D interpretation to know the deep structure for the study area.

This section shows the results of the dimensionality analysis and the EM strike directions of the conductivity distributions around the MT sites based on different approaches. The analysis based mainly upon parameters derived from the impedance phase, tipper and secondarily from its amplitude, the locations for the surveyed MT sites are as shown in (Figure 2).

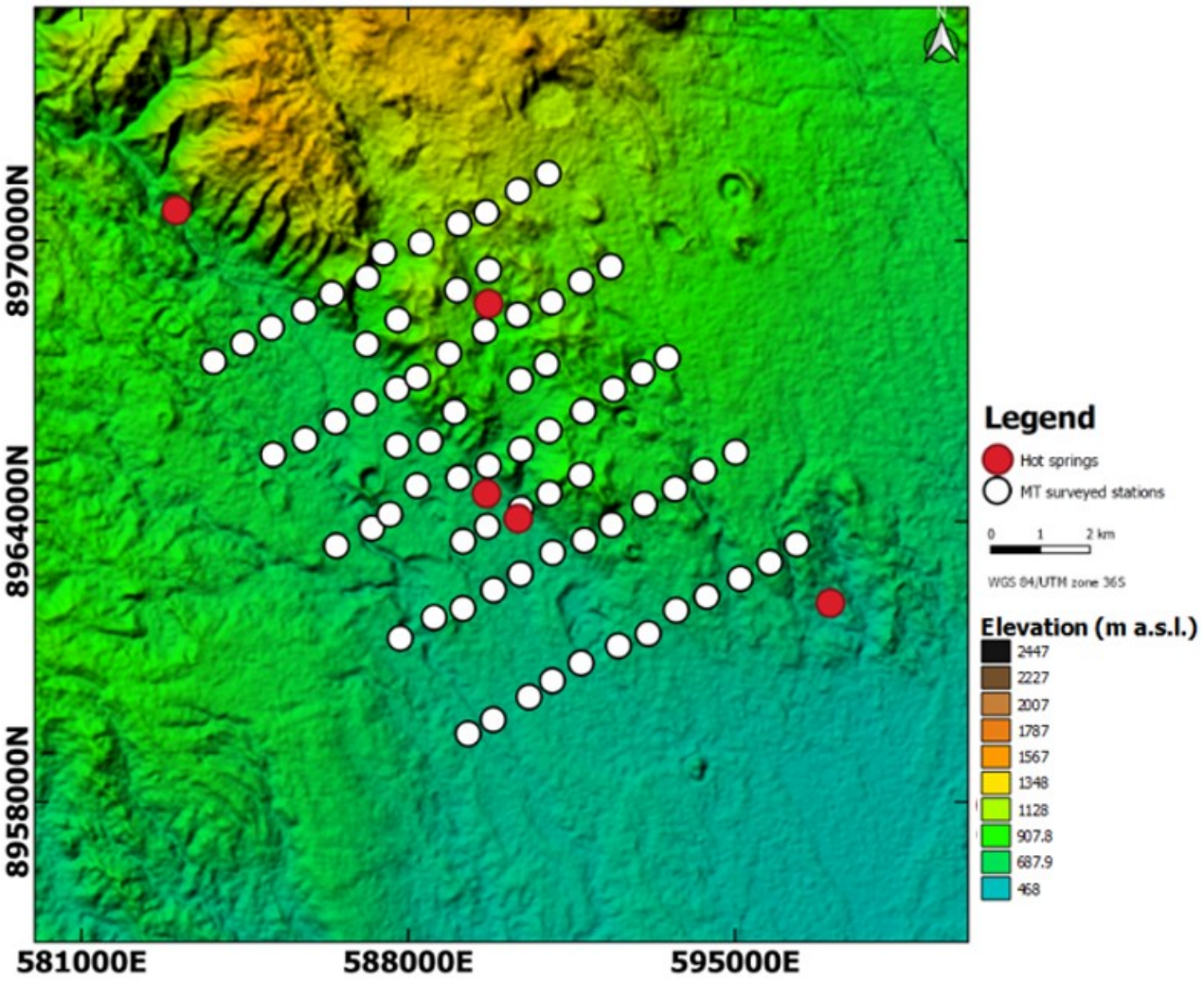



**Figure 2: Locations of the MT stations, marked by white circles. The hot springs are shown by red circles for reference.**

With regard to the dimensionality of the geological environment, the impedance tensor elements change, as summarized in Table 1 below:

| | Dimensionality | | |
|---|---|---|---|
| | 1-D | 2-D | 3-D |
| **tensor components** | $Z_{xx} = Z_{yy} = 0$<br>$Z_{xy} = -Z_{yx}$ | $Z_{xx} = -Z_{yy}$<br>$Z_{xy} \neq -Z_{yx}$ | $Z_{xx} \neq -Z_{yy} \neq Z_{xy} \neq Z_{yx}$ |
| **impedance tensor $Z$** | $\begin{pmatrix} 0 & Z_n \\ -Z_n & 0 \end{pmatrix}$ | $\begin{pmatrix} 0 & Z_{\parallel} \\ Z_{\perp} & 0 \end{pmatrix}$ | $\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$ |

**Table 1: Dimensionality of the impedance tensor**

Upon computing suitable parameters embedding the relationships between the **Z** components, and in particular between the diagonal and the principal (off-diagonal components), one may estimate the dimensionality of the resistivity structure around a given MT site.

MT dataset are to be analyzed with care on their dimensionality and directionality before further modelling, not all datasets are necessarily complying to 1-D, 2-D or 3-D inversion and modelling. Traditionally, MT data analysis has used the methods (Swift, 1967) to determine the geoelectrical strike directions and dimensionality of the data. One value, called "**skew**," can be used as a quick check for dimensionality. The result of analysis found that the skew values were below 0.2 for short periods which indicates

that the data were either 1-D or 2-D and the skew values were mostly greater than 0.2 for longer periods which implied that the data were 2-D or 3-D (Ranganayaki, 1984).

To check the dimensionality of MT dataset, phase tensor analysis (Caldwell et al., 2004), Swift-skew (Swift, 1967), Bahr's phase sensitive-skew and ellipticity were used altogether. The results indicate structures at relatively deeper depths showing 3-D character, which is an implication for 3-D inversion to image subsurface structures at Kiejo-Mbaka geothermal field and will be more reliable to know the deep structures for the research area.

### 3.1 Phase tensor analysis

Caldwell et al., 2004 first introduced the phase tensor analysis approach. The phase tensor Φ is defined as the ratio of the real (***X***) and imaginary (***Y***) parts of the complex impedance tensor, ***Z***.

Given the complex impedance tensor

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \quad (1)$$

In the Kiejo-Mbaka geothermal field, phase tensor maps at different frequencies revealed the dimensionality of the MT data with the shape of the phase tensor being circular and with a small skew value at 350 Hz and 100 Hz showing a 1-D character as shown in (Figure 4).

The phase tensor is elliptical and has a relatively small skew angle at near 1 Hz, indicating 2-D structures (Figure 5). The phase tensor analysis reveals three-dimensionality below 1 Hz, as deeper structures characterized by a high skew angles as indicated at 0.002 and 0.005 Hz in (Figure 6). In general, characterization of the site based on phase tensor analysis shows 1-D and 2-D dimensionality at relatively shallow depth, while 3-D structure is detectable at relatively low frequencies below 1 Hz at deeper depths characterized by high skew angles. Table 2, below characterizes the phase tensor elements in case of 1-D, 2-D and 3-D structures.

| Case | φ (phase tensor) | Skew angle | Color |
|---|---|---|---|
| 1-D | circular | Low (-3,3) | Yellow |
| 2-D | elliptical | Low (-3,3) | Yellow |
| 3-D | elliptical | High | Blue & Red |

**Table 2: Phase Tensor (PT) elements**

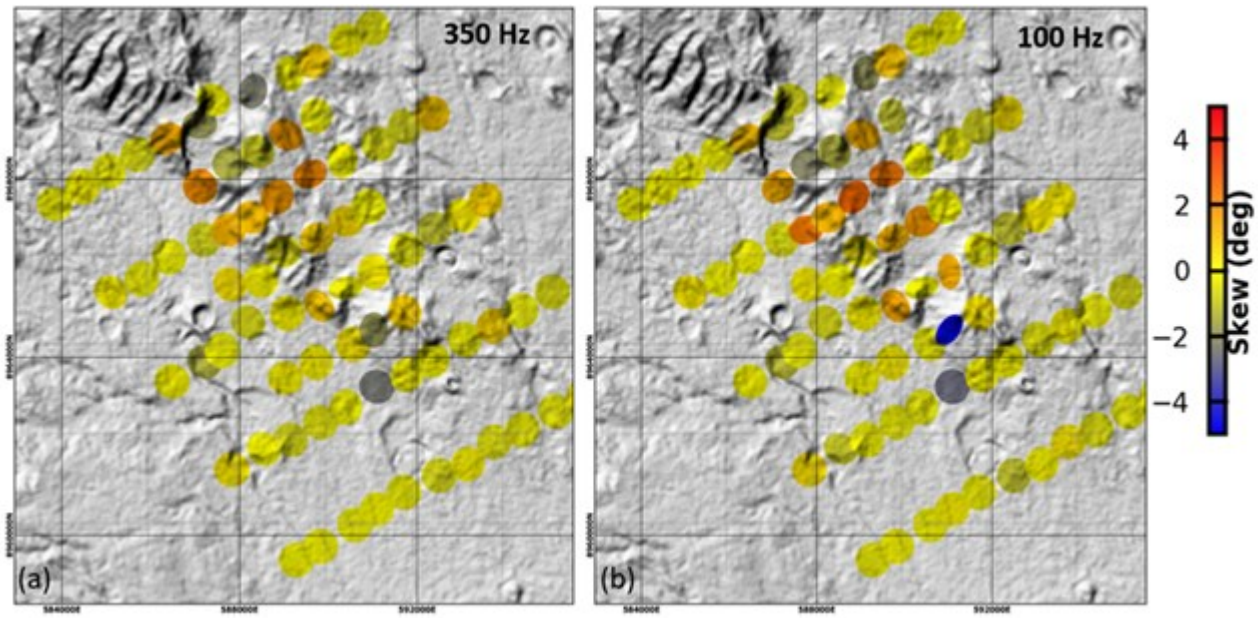



**Figure 4: Phase tensor map at 350 Hz and at 100 Hz.**

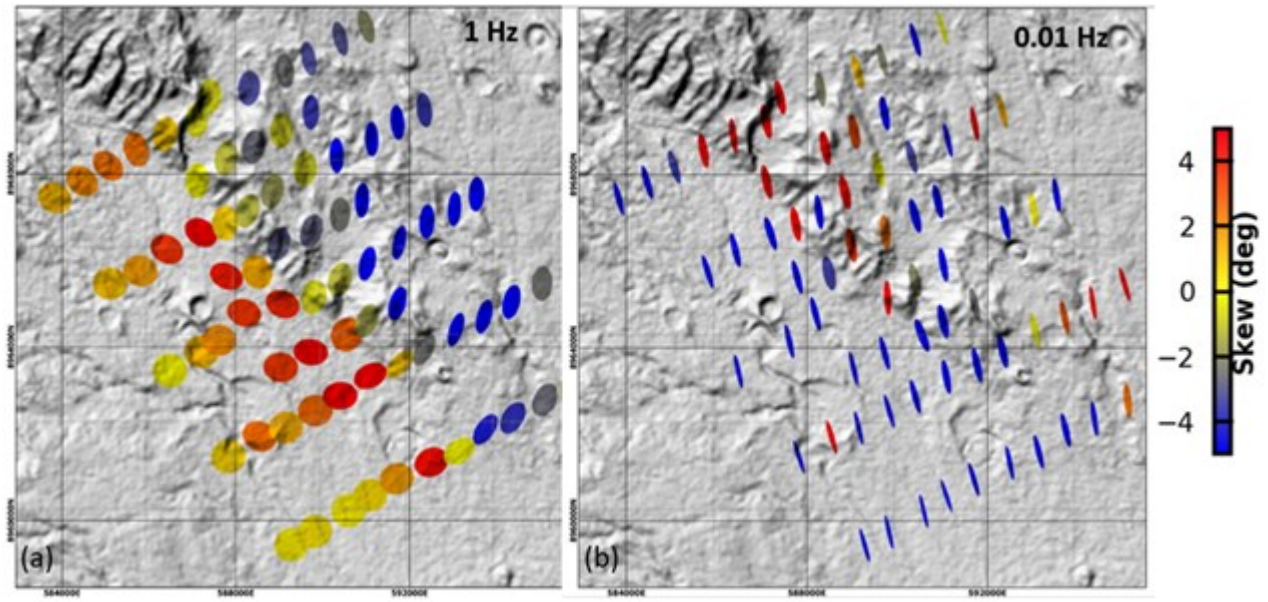



**Figure 5: Phase tensor map at 1 Hz and at 0.01 Hz**

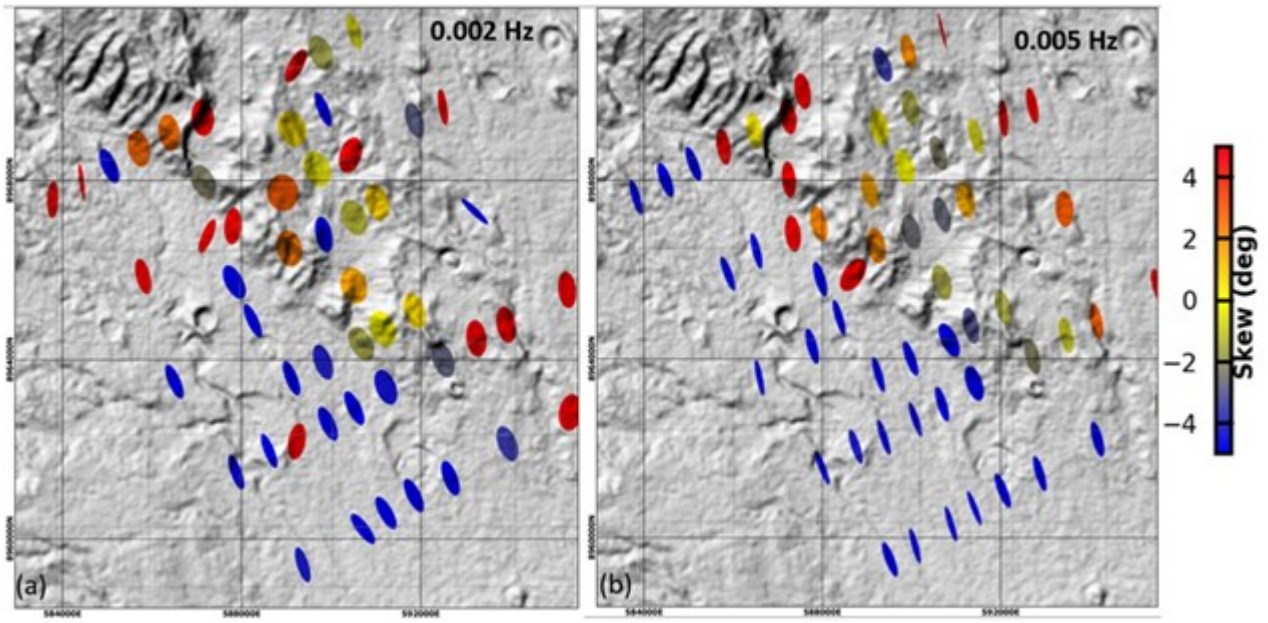



**Figure 6: Phase tensor map at 0.002 and at 0.005 Hz.**

### 3.2 Swift-skew, ellipticity and the phase-sensitive skew

Skew is the index of the EM coupling between the measured electric and magnetic field variations in the same direction. There is no coupling for the case of a 1-D structure and when measurements are made parallel and perpendicular to the strike of a 2-D structure, but there is always coupling over a 3-D structure except at a point of radial symmetry (Swift, 1967). Thus, for 1-D and 2-D structures, Swift-skew should be zero. This is rarely the case in practice as a result of the ever present noise in the field data.

Swift-skew (Swift, 1967) and ellipticity (Word, 1970) are being used to indicate whether response at a given site is 3-D. Skew is defined as the ratio of the magnitude of the sum of the impedance tensor for the diagonal elements and the differences of the impedance tensor for the anti-diagonal elements, and can be used as a measure of 3-D dimensionality.

$$Swift - skew\ (\kappa) = \frac{|Z_{xx} + Z_{yy}|}{|Z_{xy} - Z_{yx}|} \tag{2}$$

The Swift-skew and the ellipticity will become zero for 1-D and 2-D character for noise free data only and will have higher values above zero for 3-D in the presence of 3-D effects or structures (Vozoff, 1991). For Kiejo-Mbaka data

sets, a Swift-skew value of 0.3, phase-sensitive skew value of 0.3 and ellipticity below 0.1 were considered as threshold values, values below these threshold value, were considered zero as an indication for 1-D and 2-D situation. Ellipticity is a dimensionality parameter, defined as ratio of the impedance tensor similar to the skew, but varies with rotation.

$$\lambda(\theta) = \frac{Z_{xx}(\theta) - Z_{yy}(\theta)}{Z_{xy}(\theta) + Z_{yx}(\theta)} \tag{3}$$

Most of the stations at Kiejo-Mbaka geothermal field detected 3-D structures on ridges and at relatively low frequencies below 1 Hz that correspond to structures at deeper depths, indicating high Swift-skew and ellipticity. The Swift-skew, ellipticity, phase-sensitive skew for some of the selected sites are close to zero below the threshold values at high frequencies showing 1-D and 2-D characters at relatively shallow depth. The Swift-skew, ellipticity and phase-sensitive skew are all together plotted for selected MT stations, M01, M21, M23, and M40 as shown in Figure 7 and Figure 8 while, dimensionality maps using Swift-skew are shown in Figure 9. A plot of the Swift-skew, ellipticity and phase-sensitive skew for all surveyed 76 MT stations for the study area, revealed the same results as shown in Figure 10.

The three-dimensionality indicators that are the Swift-skew, ellipticity and phase-sensitive skew matched with the phase tensor analysis in Figure 4-6 as shown on phase tensor maps at 350, 100, 1, 0.01, 0.002 and 0.005 Hz. The indication of a 1-D and 2-D characters at relatively high frequencies and 3-D character at low frequencies on ridges and at deeper depths is an implication for a need of a 3-D inversion, that could be more reliable for defining a geothermal system at Kiejo-Mbaka geothermal area.

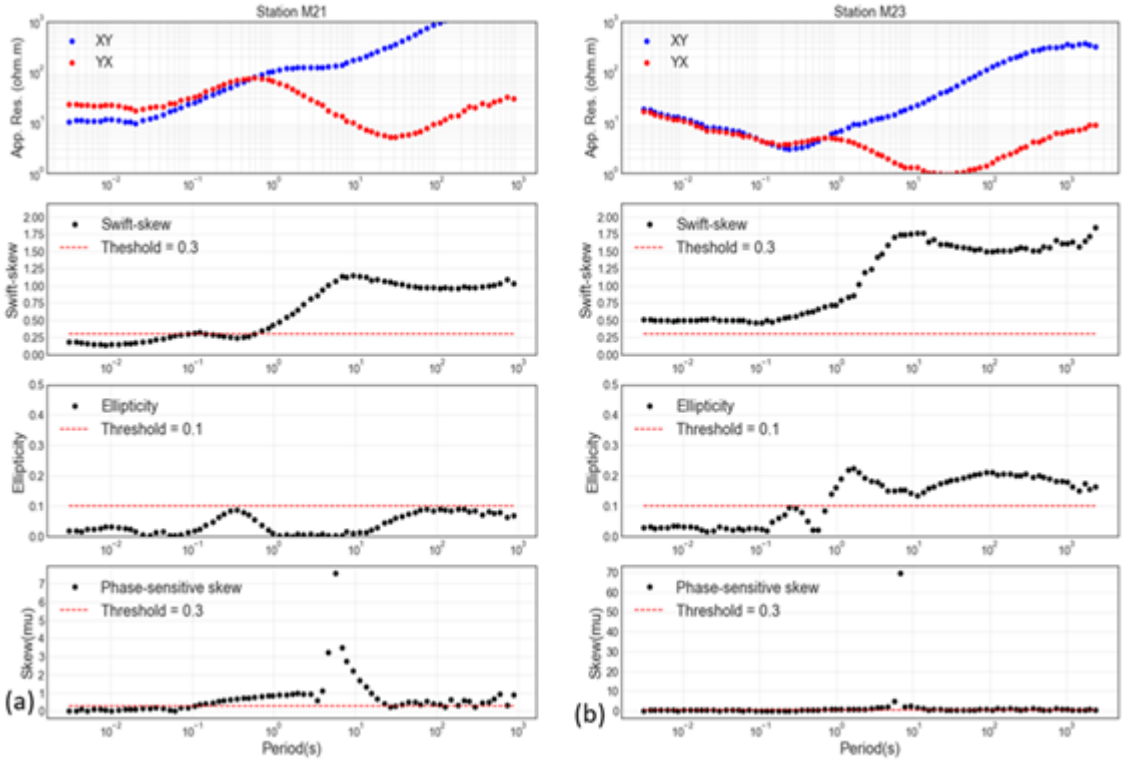



**Figure 7: The Swift-skew, ellipticity and phase-sensitive skew with the corresponding apparent resistivity curve for station M21 and M23.**

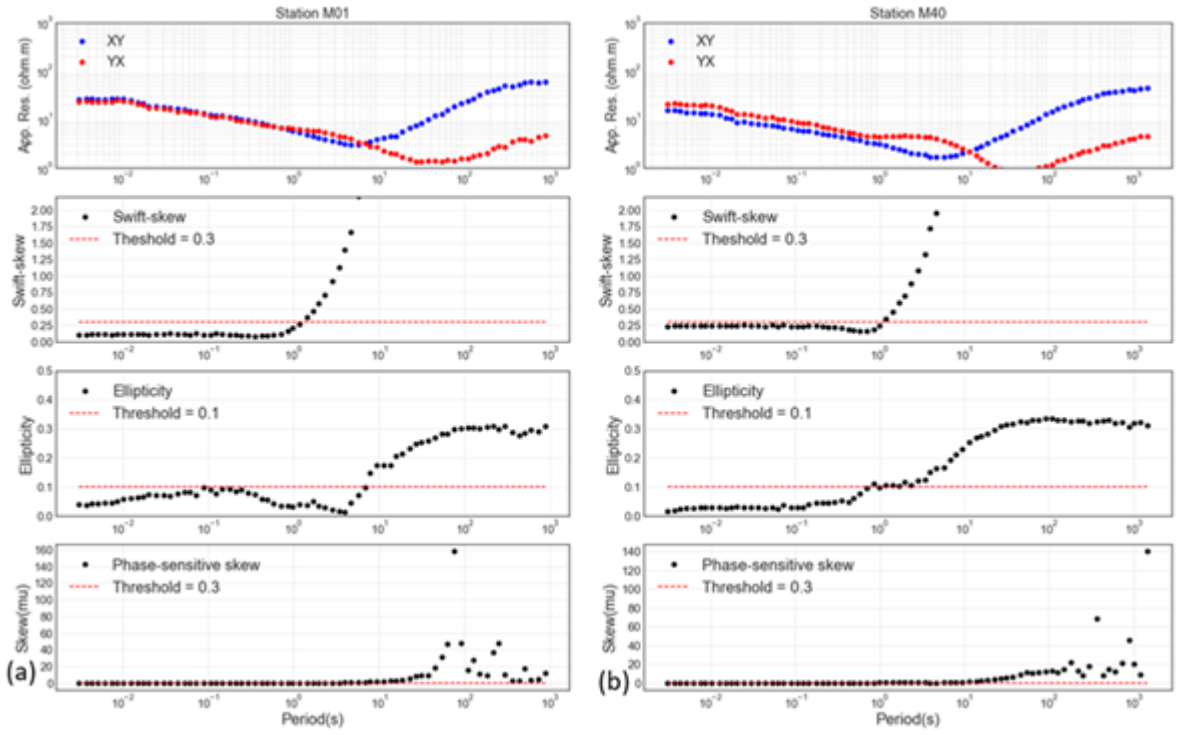



**FIGURE 8: The Swift-skew, ellipticity and phase-sensitive skew with the corresponding apparent resistivity curve for station M01 and M40.**

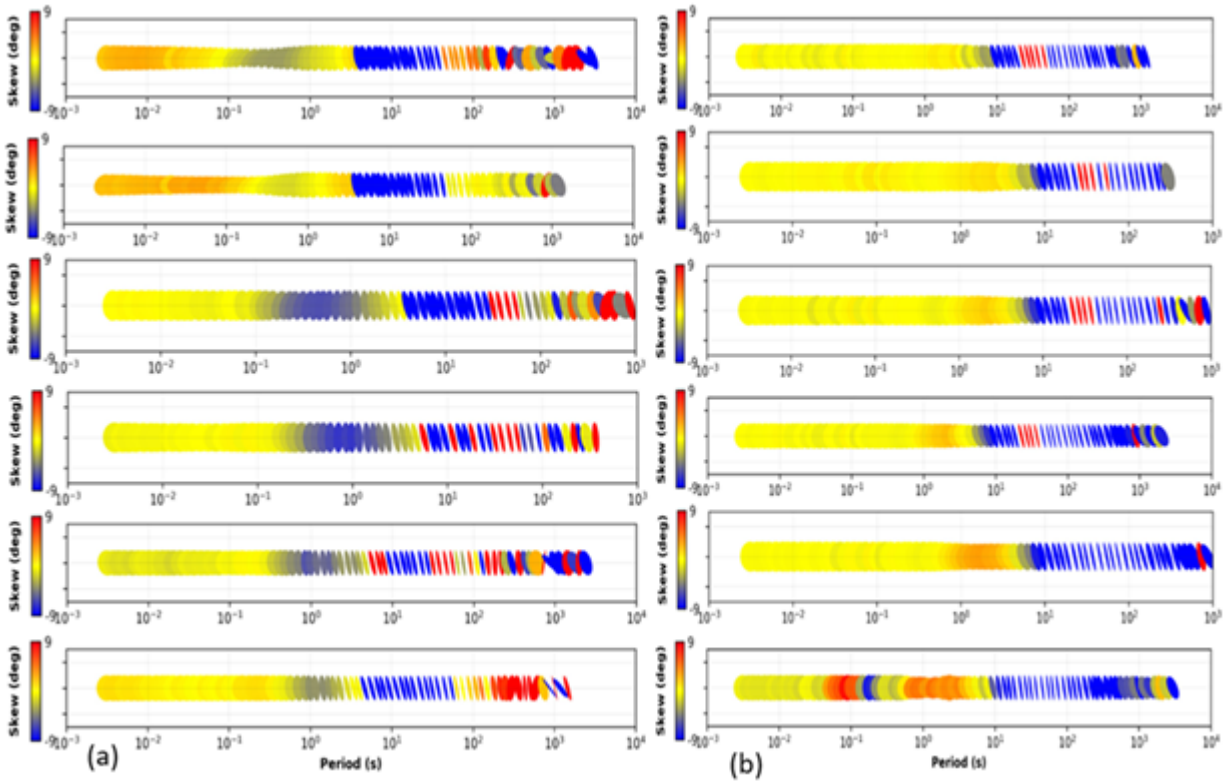



**Figure 9: (a) Dimensionality maps using Swift-skew in Kiejo-Mbaka geothermal field 6 stations along the profile line KML1 on ridges as shown in Figure 2. The strong 3-D effects are well observed below 100 Hz northern part of the surveyed area. (b) Dimensionality maps using Swift-skew in Kiejo-Mbaka geothermal field 6 stations along the profile line namely, KML8 on river plains. The strong 3-D effects are well observed below 1 Hz southern part of the survey area.**

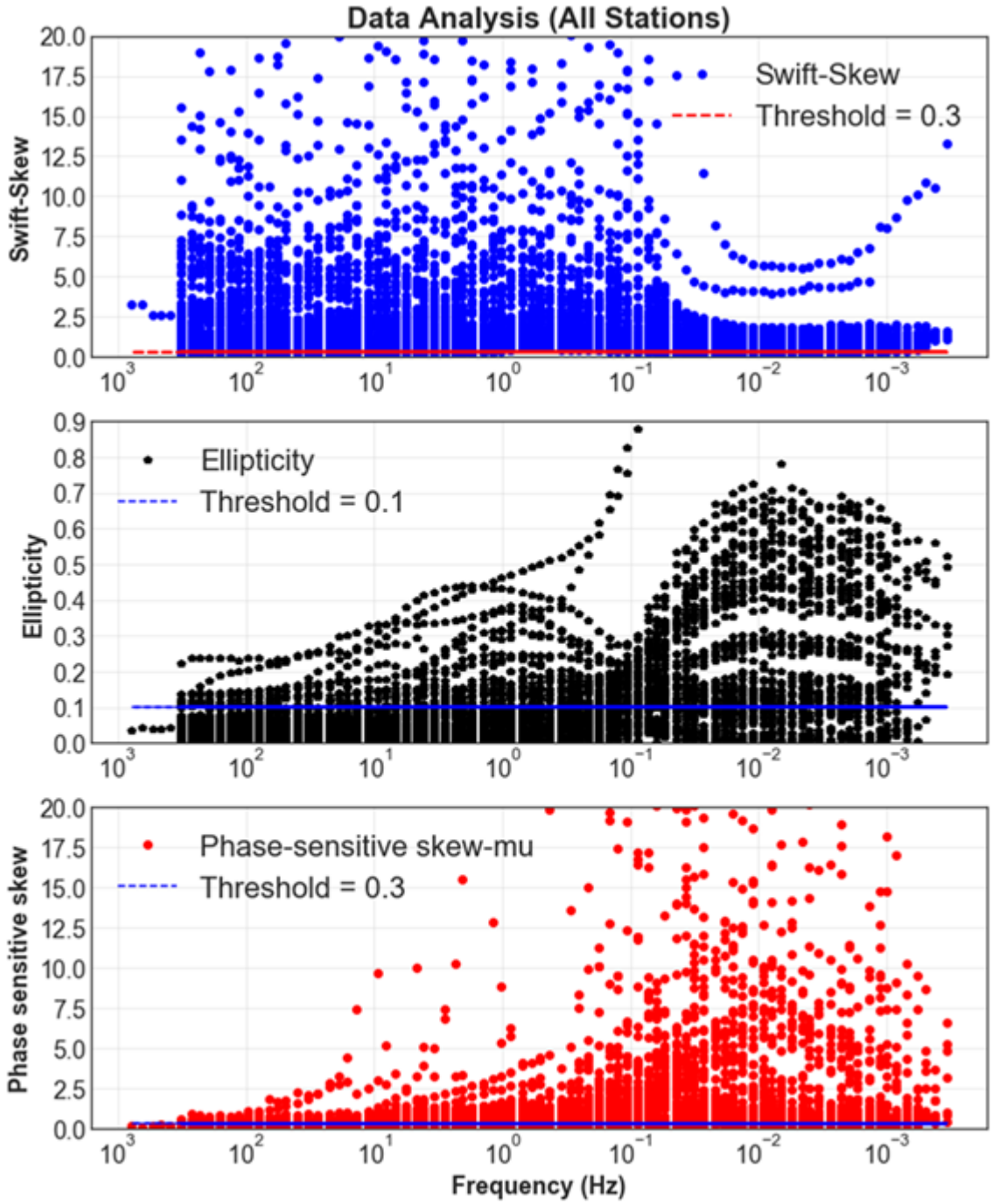



**Figure 10: The Swift-skew, ellipticity and phase-sensitive skew for all surveyed 76 MT stations in the study area.**

### 3.3 MT geoelectric strike analysis

The impedance tensor can provide diverse information about EM strike directions among others. The geoelectric strike analysis for MT data serves for determination of the strike of dominant 2-D geo-electrical structure even though the noise and local distortion may be challenging. Normally, the strike angle is the least stable parameter which can be resolved from MT data (Jones and Groom 1993). The direction in which the conductivity of a 2-D structure does not vary is termed as the strike direction (principle conductivity axis). The angle between the principle conductivity axis and the x-axis is called the angle of strike. The axis parallel and perpendicular to the strike are the principle (preferred directions).

#### 3.3.1 Rose diagrams

Distribution of the regional EM strike direction (degree from N, positive clockwise) was estimated, as shown by the plots of rose diagrams and the regional EM strike over frequency range 1 - 0.001 Hz in Figure 11 and Figure 12. The strike analysis for the MT dataset, illustrated a rotation angle of about 170º for the data before applying the 2-D inversion. At short periods, scatters are observed reflecting a contribution from shallow-local structures. The NW-SE related trend lineaments are corresponding to the Mbaka fault, whilst, the NNW-SSE related trend lineaments correspond to lineaments visible from topography. In general, the

regional EM strike may be assumed as WSW-ENE trend for long periods ranges, and is perpendicular to the Mbaka fault, where stable azimuths are observed within this period range.

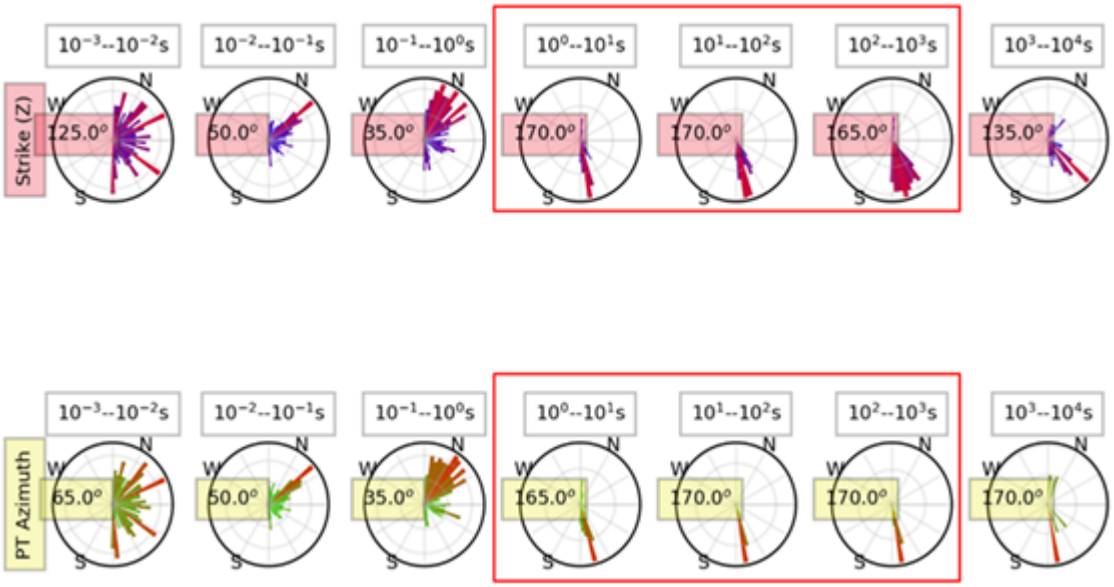



**Figure 11: Rose diagrams of the strike angle for the MT data over frequency range 1 - 0.001 Hz, indicating the (long-period) strike (Z) and Phase tensor azimuth (PT).**

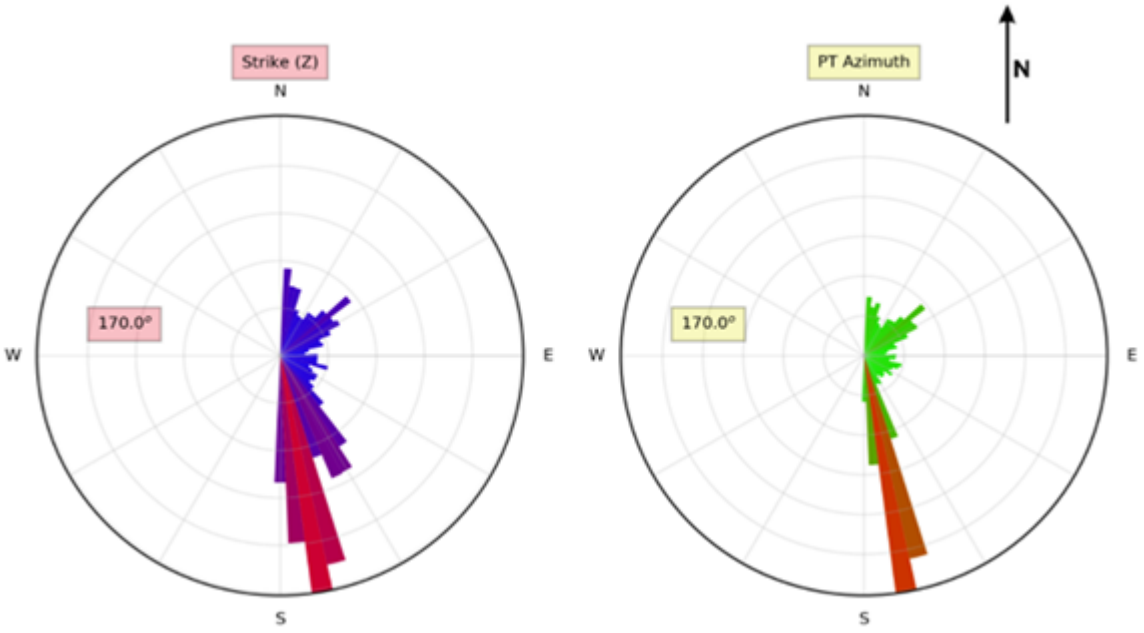



**Figure 12: Rose diagrams of the strike angle for the MT data over frequency range 1 - 0.001 Hz, indicating the (long-period) strike (Z) and Phase tensor azimuth. Stable azimuth below 1 Hz, up to 0.001 Hz are observed, this frequency range can then be used to reliably estimate the regional strike.**

## 4. CONCLUSION

Prior to a decision of 1-D, 2-D or 3-D inversion or modelling, it is important to identify a preferred geoelectrical strike. This is accomplished based on known local or regional geology of a particular area, or by performing some sort of dimensionality analysis on the dataset. The dimensionality analysis for all the approaches discussed in this paper, are similar and indicated the need for 3-D inversion, in order to resolve the deeper parts for the study area.

The study area was observed to have severe 3D effects, therefore, 1-D/2-D inversion may not reliably represent the true subsurface conductivity distributions, especially for the deeper part within the prospect.

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