Qualitative Analysis of Audio Magnetotelluric (AMT) Data using Phase Tensors: A case study from Dhanjori Basin, Singhbhum Craton, India

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Keywords

Audio Magnetotelluric, Phase Tensor, Induction Vectors, Dhanjori Basin, Singhbhum Craton, Greenstone Belt

Summary

Dhanjori Basin, a part of Singhbhum Craton, Eastern India shows characteristics of the Greenstone belt and is a great source of sulphide mineralization in the area. AMT survey was conducted to infer the metallogeny of the area. Regional MT response is distorted by the presence of near surface intrusive bodies, but phase remains unaffected. Thus, Phase tensor approach has been utilized to identify the near surface conductive bodies and to have an idea about the regional dimensionality of the area.

Introduction

Paleoproterozoic Dhanjori formation is an important member of the Singhbhum craton (SBC) in eastern India (Saha, 1994).

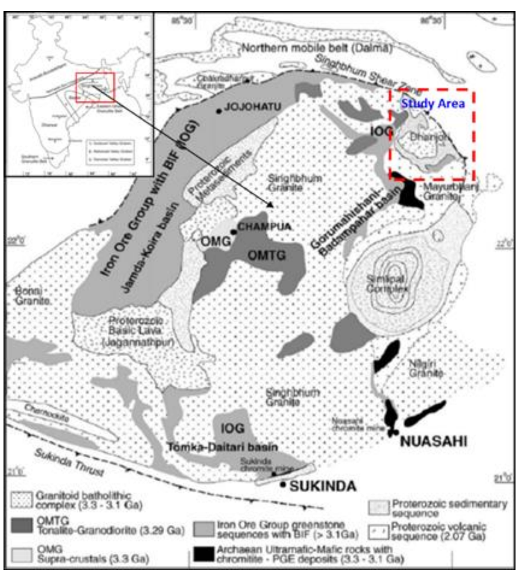


Figure 1: Geological map of the Singhbhum craton (modified after Saha, 1994) showing the study area by dashed square.

The formation shows features of the greenstone belt and is a great source of sulphide mineralization in the area, which were later remobilized and dumped along the Singhbhum Shear Zone (SSZ) as an epigenetic deposit. Das et al. (2008) predicted the vast possibility of the gold mineralization within the sulphide zones, which has made the region very lucrative as a common interest of researchers. Many works have been found supporting the evidences of gold mineralization within the Dhanjori Metavolcanics. Gold mineralization in Dhanjori basin is mainly associated with the quartz-pebble-conglomerates (QPC) mineralization which is supported by different Geological studies and the geochemical results (Haque and Dutta, 1996). Maurya et al. (2015) indicated the existence of volcanogenic massive sulphide body in North Singhbhum Mobile Belt across the Dalma volcanics through the Remote Reference (RR) Magnetotelluric (MT) soundings. The results of Electrical surveys also suggest different geological features viz. massive sulphide, QPC/quartz vein with distributed sulphide-gold, greenstone schist and dolerite dike/Proterozoic gabbro anorthosite mass across the Paleoproterozoic metavolcanics in Dhanjori Basin. Our study area also covers Dhanjori Basin, a part of Singhbhum-Orissa Craton (SOC), which is an important member of the Indian Shield (Figure 1).

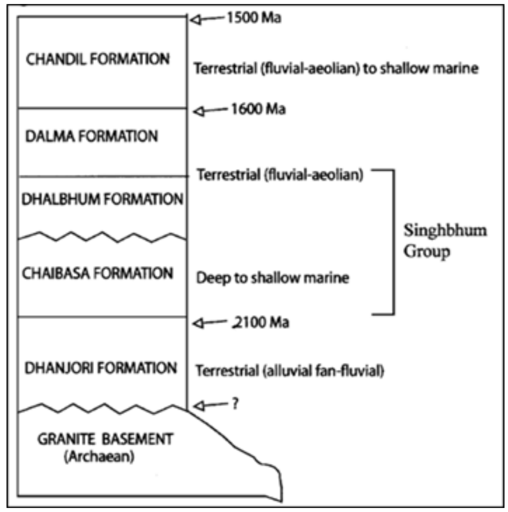
The phase tensor approach has become an important aid for analysis of the MT data (Caldwell et al., 2004). Although the amplitude of the observed electric field gets distorted by the presence of near surface resistivity heterogeneities, the phase relationship between the electric and horizontal components of the magnetic field remains undistorted. Phase doesn't get affected by the galvanic distortion. Regional phase response will be the same as it would be in the absence of any such conductivity heterogeneity. The fact motivated us to work with phase tensors, which give direct measure of the regional dimensionality unaffected by any type of distortion. Inference about the mineralogical potential of the area is not in scope of our current study.

Geological Setting

Indian shield is of Precambrian era (3.6-2.6 Ga). Part of it is characterized by Archaean nucleus of Singhbhum Granite (SG) batholithic complex and ancient supracrustal enclosed by several extended and arcuate Proterozoic belts. Gupta et al.,1985 considered Dhanjori as a part of Singhbhum Super Group of Proterozoic age. Dhanjori Group of volcano-sedimentary succession overlies unconformably over the Singhbhum Granite and are also overlain by Chaibasa and Dhalbhum formations constituting the Singhbhum Group. Both are again separated by another unconformity. Dhanjori Formation is made up of siliciclastic sedimentary rocks with intrusions of mafic to ultramafic (sometimes felsic) volcanic or volcaniclastic rocks which are metamorphosed into greenschist facies. The formation comprises of two members: Lower and Upper. Both the members have many similarities in terms of facies character, but significant differences still exist. Lower member contains phyllites, quartzites and thin streaks of conglomerate whereas the upper member is made up of volcanic and volcaniclastic rocks along with some quartzites and phyllites (Mazumder and Sarkar, 2004). The volcanic rocks of the Dhanjori mostly restricted to the Upper Member of the formation (Singh, 1998).

Stratigraphic succession of the Singhbhum crustal province. is shown in Table 1. Dhanjori basin is a part of one of the Greenstone Belts in Eastern India. Greenstone belts are the zones of mafic to ultramafic volcanic sequences with associated sedimentary rocks that has been metamorphosed later. They mostly occur within the Archaean and Proterozoic cratons between granite and gneiss rocks (De Wit et al., 1997). These zones act as the source for ore deposits of different economic minerals like gold, silver, copper, zinc, etc.

Table 1: Proterozoic stratigraphic succession of the Singhbhum crustal province (after Mazumder, 2005).



Theory

Galvanic distortion is one of the major issues in the field of MT data modelling and interpretation. A major breakthrough in distortion analysis was accomplished by Caldwell et al. (2004) through introduction of the phase tensor. Phase of a complex number is defined by the ratio of it's real and imaginary parts, which can be represented in the form generalized to a complex matrix or tensor. Hence, we define the phase tensor by the relation as

$$\emptyset = X^{-1}Y = \begin{pmatrix} \emptyset_{11} & \emptyset_{12} \\ \emptyset_{21} & \emptyset_{22} \end{pmatrix}$$

Where X and Y are the real and imaginary parts of the complex impedance tensor Z, which is the ratio of the electric and magnetic vector fields measured at the earth surface. Graphically, phase tensor can be represented by an ellipse, with axes equal to the magnitudes of the minimum and maximum values of the diagonal phase tensor elements, φ_{min} and φ_{max} (Figure 2).

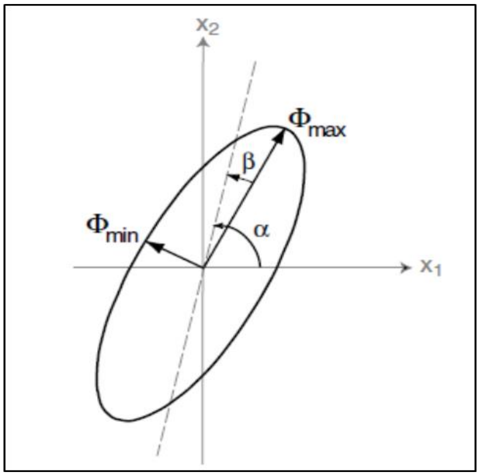


Figure 2: Graphical representation of the Phase Tensor (Caldwell et al., 2004).

We can define skew angle as a measure of asymmetry of the tensor as

$$\beta = \frac{1}{2} tan^{-1}\left(\frac{\emptyset_{12} - \emptyset_{21}}{\emptyset_{11} + \emptyset_{22}}\right)$$

Ellipticity (λ) is another property of the phase tensor which is used to measure the dimensionality of the data.

Induction arrows are graphical representations of the real part of the vertical magnetic field transfer function or tipper vector (K), defined by the equation $H_z = -K \cdot H_y$, where H_z is the vertical component of the total magnetic field and H_y is the horizontal component of the total magnetic field. Real part of the tipper vector points towards the region of highest conductance, when there is lateral variations in conductivity (Parkinson, 1959).

All these parameters e.g. φ_{max}, φ_{min}, β, λ etc. are coordinate invariants i.e. their values are independent of any co-ordinate system.

Methodology

The dimensionality analysis has been performed by analysing phase tensors (PT), impedance skew (β), ellipticity (λ), Minimum and Maximum phase (φ_{min} and φ_{max}) and induction vectors. Theoretically, for 1D structures, $\lambda=\beta=0$ and for 2D, $\lambda\neq0$ while $\beta=0$. In case of 3D structures, non-zero values are obtained both for λ and β. Directionality analysis has been performed through the analysis of strike and phase tensor azimuth. Threshold values of $\lambda = 0.11$ and $\beta = \pm 3°$ have been considered in the analysis. These values also have been used by Maurya et al. (2015) in the nearby Dalma volcanic region of the Singhbhum Craton providing a satisfactory result.

Results

Eighteen AMT soundings were acquired in the frequency range of 1 kHz to 10 Hz for a profile length of nearly 20 km crossing all major lithologies of the Dhanjori Group. The data were processed using extra-hybrid robust processing algorithms by Shalivahan, Sinharay and Bhattacharya (2006). MT profile encompasses four different geological domains- 1. Dhanjori volcanics (station DH-01 to DH-06$^{/}$), 2. Quartzite–Conglomerate–Pelites of Dhanjori Group (stations DH-07 and DH-07$^{/}$), 3. Kolhan Group (sites DH-08 and DH-08$^{/}$) and 4. Proterozoic Gabbro–Anorthosite–Ultramafics of Dhanjori formation (sites DH-09, DH-09$^{/}$ and DH-10) (Figure 3).

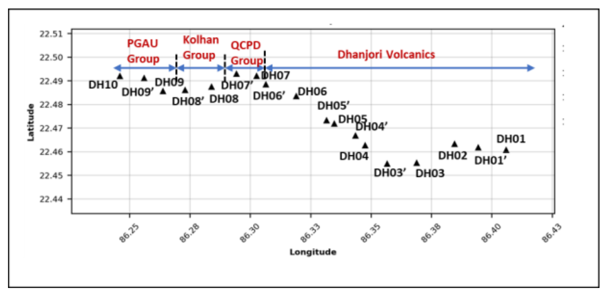


Figure 3: Station Locations over different geological formations of Dhanjori.

Phase Tensor ellipse plots were generated using MTpy, an open-source software package (Kirkby et al., 2019).

The plots are shown at three different frequencies. Other than very few sites (DH 01$^{/}$, DH08, DH09$^{/}$, DH10 at 5000 Hz; DH04, DH05$^{/}$, DH08, DH08$^{/}$ at 500Hz ; DH03, DH05, DH07, DH08 at 50Hz) all other sites show very high values of skewness ($|\beta|>3^{o}$) indicating the presence of 3D near surface bodies (Figure 4). Direction of induction arrows are laterally varying at each sites, indicating the possible presence 3D conductive structures. Strength of the induction arrows are very high for few sites at shallow (DH02, DH03$^{/}$, DH07$^{/}$), intermediate (DH02, DH05, DH07$^{/}$) and deeper (DH05, DH07$^{/}$, DH08$^{/}$) levels, specifying highly conductive zones around those sites. Direction of the induction arrows are also not following any particular trend laterally as well as over the full period range which indicates the presence of 3D regional structure. High value of β also supports the fact. Lateral variations in the directions of the real part of induction arrows also signifies change in conductivity structure over different geological units of Dhanjori corresponding to different mineralogical composition.

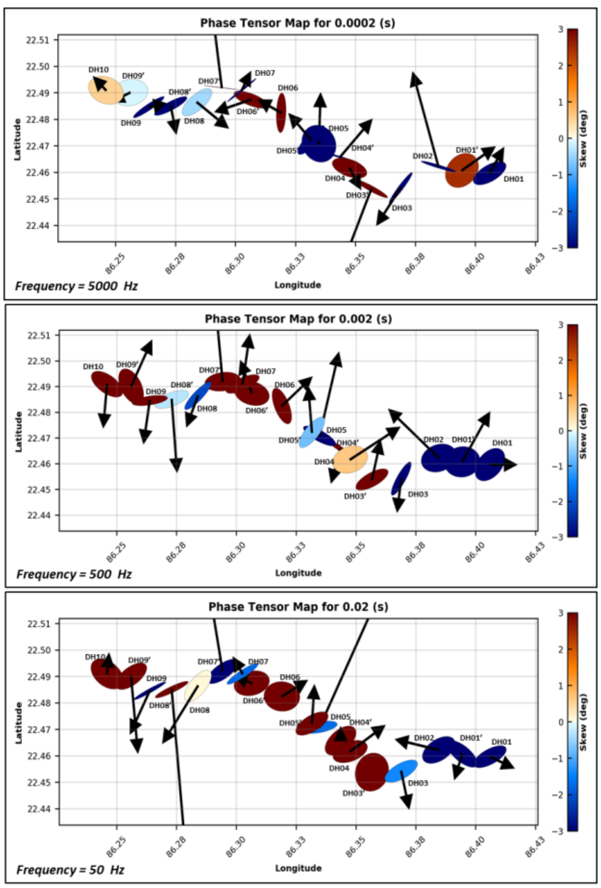


Figure 4: Phase tensor ellipse and induction vector plots over different stations of Dhanjori.

A cross section of PT ellipses is shown along the AMT profile in Figure 5. Colour scale represents the skew angle β. The ellipses are plotted in a way that the horizontal axis corresponds to east-west orientation. Segmented lines in the cross section enclose the ellipses with |β|>3°. 3D near surface anomalies are observed around 10^{-4} sec and also between 10^{-3} to 10^{-1} sec along all the geological units of Dhanjori, giving indication of the three dimensionalities in the area. Direction of the principal axes of the ellipses are changing over the period of time, which gives hints of 3D regional structure. Lateral changes in the principal axes direction are also observed indicating lateral variation in conductivity structure.

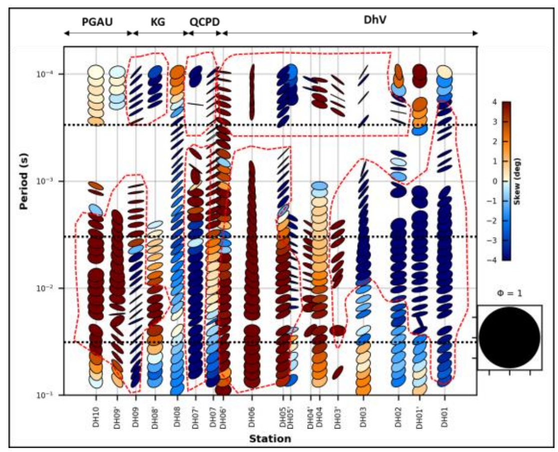


Figure 5: Cross Section of phase tensor ellipses along the profile.

The Maximum phase (φ_{max}) and Minimum phase (φ_{min}) as well as the difference between the two give another evidence of dimensionality. φ_{max} and φ_{min} will have equal values in case of 1D representing a circle. φ_{max} will show higher values in comparison to φ_{min} as we gradually progress from 2D to 3D. Higher the difference between the two, data supposed to be 3D. Maximum phase is showing very high value for most of the stations (>20^{o}) over all the periods while Minimum phase values are mostly (<20^{o}), indicating three dimensionality in the regional response (Figure 6 , Figure 7).

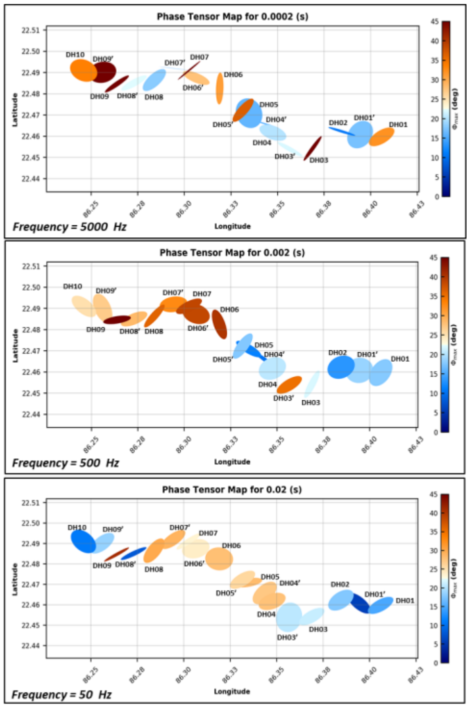


Figure 6: Phase tensor ellipse plot with Maximum phase.

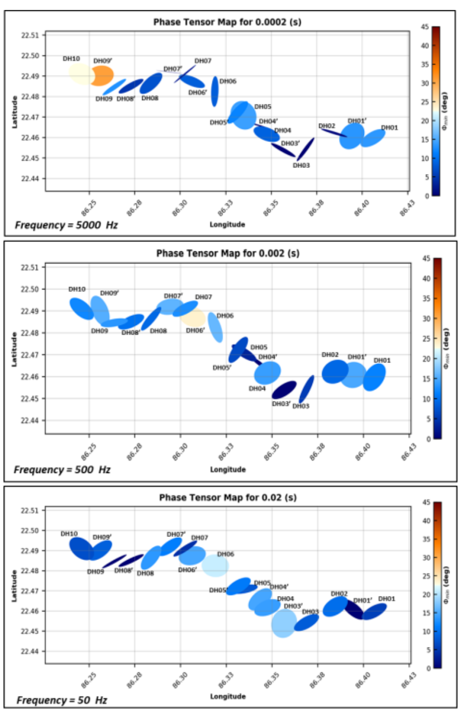


Figure 7: Phase tensor ellipse plot with Minimum phase.

Figure 8 shows phase tensor plot with Ellipticity. Almost all the stations are having λ values more than 0.11 (except DH05 at 5000 Hz and DH03/ at 50 Hz). It is clearly understood that the regional response is mainly three dimensional.

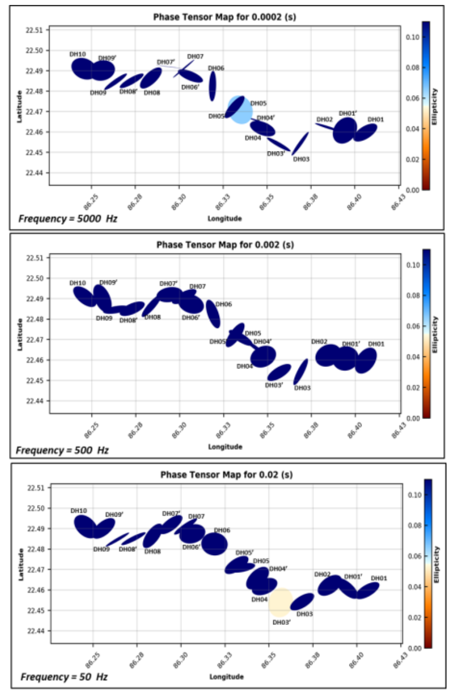


Figure 8: Phase Tensor ellipse plot with ellipticity.

For the analysis of directionality, strike and phase tensor azimuth has been plotted through rose diagram (Figure 9).

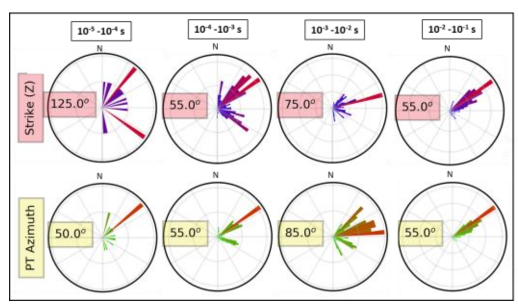


Figure 9: Rose diagrams showing strike and phase tensor azimuth direction over different period ranges.

The Z strike plots at periods shorter than 10^{-3} second show significant scattering which indicate greater galvanic distortions at shallower depths. At the same range of periods, in contrary, PT azimuths are much consistent proving that PT azimuth is less affected by near surface anomalies. However, no definite regional strike direction has been observed in the study area, as both strike and PT azimuth are showing diverse values over the period ranges. Observations also indicate regional dimensionality as 3D, specially in the intermediate period from 10^{-3} to 10^{-2} seconds.

Conclusions

Plots of phase tensor ellipses indicate the lateral changes in the regional conductivity structure at different depths. Results clearly show that PT azimuths are not affected by the presence of near-surface anomalous intrusive bodies where as such effects are prominent in Z strikes. Thus, the observations through PT maps are indicating the deeper regional response unaffected by Galvanic distortion. Analysis of dimensionality through several parameters related to phase tensor show variations of conductivity in the study area laterally as well as vertically. The PT azimuth variation also indicates the regional response to be 3D in the area. Lateral changes in the direction of induction vectors as well as PT principal axes suggest the change in the conductivity structure spread over different geological units of Dhanjori.

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