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Mapping of Mesozoic Sediments below Deccan trap using Magnetotelluric Method.

*Surajit Gorain**(sgorain@gmail.com), *Puja Prakash, Dr. Prabhakar Thakur*
Hindustan Petroleum Corporation Limited

Summary

Magnetotelluric (MT) data can be particularly useful for delineating potential hydrocarbon traps (sediments which are conducting) below volcanic (which are resistive) which give rise to multiple reflection and scattering of seismic energy. The diffusive signal propagation used in MT can be an advantage in a region of intense heterogeneity while seismic signals will be scattered, the MT signals diffuse and give a reliable estimate of the physical property of the medium.

Response curves have been generated in absence and presence of local heterogeneities for 2-D earth. The electrically anisotropic sediment is sandwiched between the isotropic/anisotropic trap and isotropic basement. The apparent resistivity and phase data show a consistent phase splitting in the absence of local heterogeneity. Whereas in the presence of conducting local heterogeneity the consistent trend is shown only by the phase data. The apparent resistivity data does not show a consistent trend due to galvanic distortion. Thus, the models can be described only by considering phase tensor. The splitting increases with the anisotropy ratio (maximum resistivity/minimum resistivity) where as it is practically independent of the anisotropy angle.

Introduction

A major part of the estimated global reserves of hydrocarbons occurs in sediments overlain by thick basaltic sequences which makes imaging structures in the basalt-covered older sediments a key exploration challenge in many frontier areas with thick Mesozoic sediments overlain by thick basalt of the Deccan Trap (Satpal et al., 2006). However, it is virtually unexplored because of the limitations of conventional P-wave seismic in imaging the structures in the sub-basalt sedimentary sequences and the intrabasalt features.

The Deccan trap covers about 500,000 sq Km of the region in India covering part of Gujarat, Maharashtra and Madhya Pradesh. It is believed that the Deccan trap is formed due to volcanic eruption, which took place about 65 Ma years ago during upper Cretaceous-Eocene. The traps are made up principally of basic volcanic rocks of basaltic magma and lie flat as horizontal sheets. The Mesozoic sediments, which overlie the basement, beneath the Deccan Trap are

made up of shale, chert, impure limestone, pyroclastic materials etc. ranging in thickness from 0.5-2 km. shows the location map of the Deccan trap.

But unfortunately the conventional seismic is not applicable in mapping the sediment below the Deccan trap due to the presence of immense local heterogeneity. In such situation the seismic waves are reflected from the trap itself and virtually there is no transmission to the sediments below the trap (Figure 1.1). Thus, no information is available about the sediments.

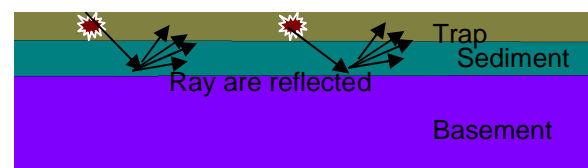


Figure 1.1 Diagram showing reflection from trap



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The sediments could be mapped using Deep Seismic Sounding (DSS) but DSS has lot of limitations. MT sounding cannot be used to detect oil or gas (which have resistivity exceeding 10^5 ohm-m) directly, but can help to delineate geological structures that can form hydrocarbon traps (Simpson and Bahr, 2006). Singh et al. (1984) has shown that the DT is electrically 3 layers. The top layer Trap is of resistivity ~ 100 ohm-m and the underlying sediment is conducting having resistivity of about ~ 20 - 50 ohm-m, which overlies the resistive (~ 5000 OHM-M) basement (Figure 1.2). Thus, the conductive sediments is sandwiched between resistive layers (Trap and Basement). Following, skin depth [Skin depth ≈ 500 (ρ/f)^{0.5}], the relatively basement helps in penetrating the waves to the sediments and thus providing information about the interested sediments.

Trap	100 Ohm-m
20 -50 ohm-m	Sediment
Basement	5000 ohm-m

Figure 1.2– Conductive structure of Deccan trap

In the present work different electrically isotropic and anisotropic 2-D models have been considered to map the sediments using MT method both in the presence and absence of local heterogeneities.

Theory and/or Method

MT is a passive exploration technique that utilizes a broad spectrum of naturally occurring geomagnetic variations as a power source for electromagnetic induction in the earth. In MT the fluctuations in the natural electric, E , and magnetic, fields is measured from that the electrical impedance (Z) is calculated $Z=E/H$ which is the function of frequency (ω). The apparent resistivity and phase is then calculated from the observed impedance.

The trap as well as the sediments is electrical anisotropy. Anisotropy is a state in which a physical characteristic varies in value along axes in different directions - a physical measurement made in one direction differs from the measurement made in another direction. Thus, in electrical anisotropy the electrical property is dependent on the direction.

Considering Figure 1.3 the left hand side shows both isotropic as well as anisotropic medium. In isotropic medium $\sigma_1 = \sigma_2$ where as in anisotropic medium $\sigma_2 = 3\sigma_1$. Note the directions of current density (J) and electrical field (E) in both the situation. The direction is parallel in the isotropic case where as it is not parallel in anisotropic situation.

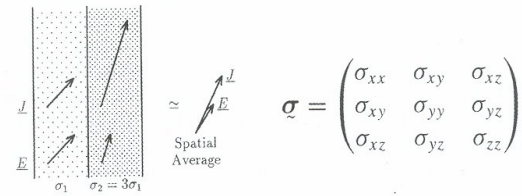


Figure 1.3: Representation of electrical anisotropy in earth materials

Again **Induction Vector or Tipper** is define as the ratio of the vertical component to the horizontal component of magnetic field i.e. $[H_z/H_x]$

The project aims in mapping the sediments (both isotropic as well as anisotropic) below isotropic and anisotropic traps.

- A. In this respect various response curves have been generated for different situations pertinent in the Deccan trap, viz., the traps and the sediments could be isotropic and or anisotropic 2-D.

Response curves over a 2D earth:

As the phase splitting depends mainly on the thickness of the layers and on the anisotropic ratio so for 2-D the following models are selected.

In the first sets of models the following parameter are taken-

Lithology	Nature	Thickness	Anisotropic ratio	Strike direction
Trap (100 ohm-m)	Isotropic	1 km and 2 km		
Sediment (20 ohm-m)	Anisotropic	0.5 km, 1 km and 2 km	1:1.5	30°
Basement (5000 ohm-m)	Isotropic	Infinitely extend		

In the second sets following models are analyzed-

Lithology	Nature	Thickness	Anisotropic ratio	Strike direction
Trap(100 ohm-m)	Anisotropic	1 km and 2 km	1:1.5	30°
Sediment(20 ohm-m)	Isotropic	0.5 km, 1 km and 2 km		
Basement(5000 ohm-m)	Isotropic	Infinitely extend		

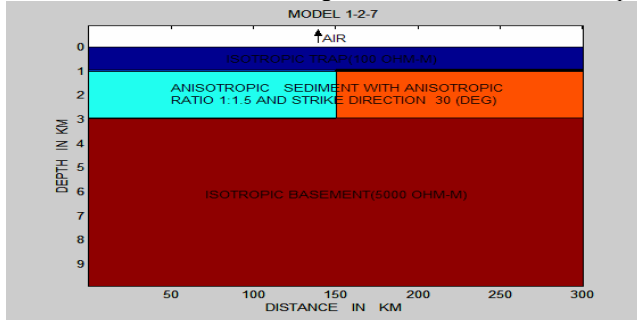


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In the third case the following models are analyzed-

Lithology	Nature	Thickness	Anisotropic ratio	Strike direction
Trap (100 ohm-m)	Anisotropic	1 km and 2 km	1:1.5	30°
Sediment (20 ohm-m)	Anisotropic	0.5 km, 1 km and 2 km	1:1.5	30°
Basement (5000 ohm-m)	Isotropic	Infinitely extend		

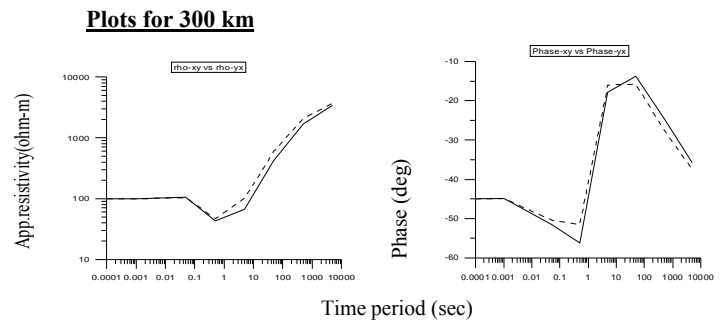
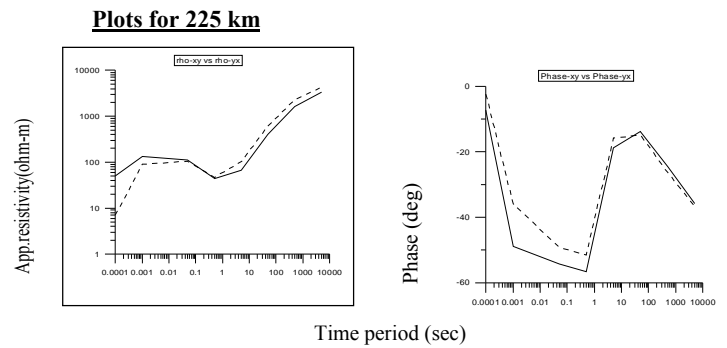
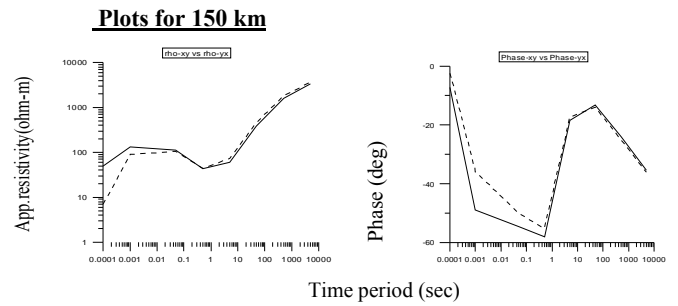
Out of these models the following model is selected as an example-



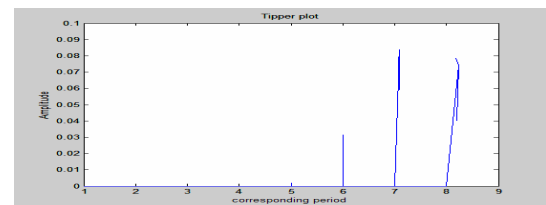
As shown in the model the profile is taken as 300 km long. The apparent resistivity and Phase variation with frequency is plot at 75 km interval.

The plots of apparent resistivity phase and Tipper plot for zero km-

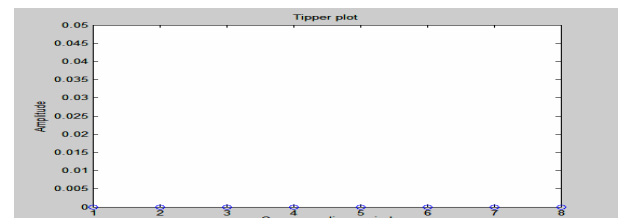
Plots for zero km



Tipper for 75 km



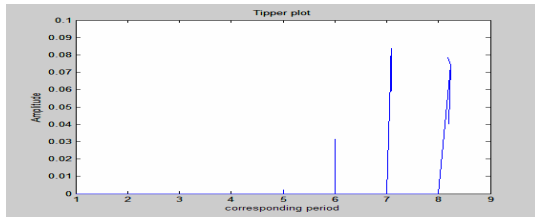
Tipper for zero km



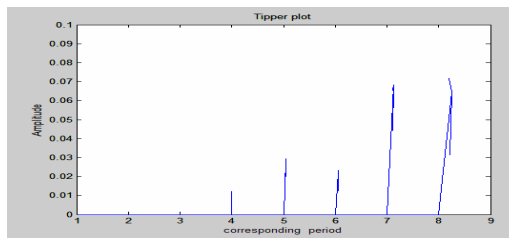


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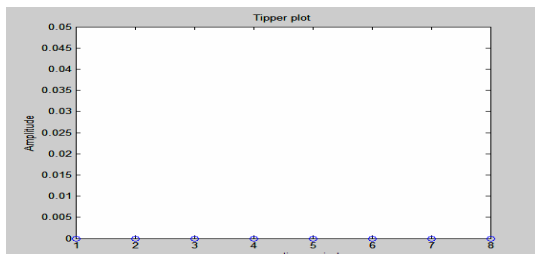
Tipper for 150 km



Tipper for 225 km



Tipper for 300 km

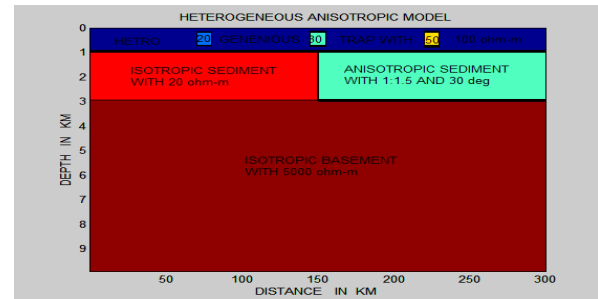


Results and Discussion

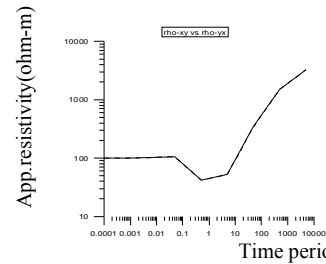
Here only the xy and yx components are shown because for 2-D case Zxy and Zyx have some value but the diagonal components are zero. For 0 km no splitting is seen because the assumed model is isotropic. The 75km plot shows splitting despite the fact that the model is isotropic because of the effect of anisotropy on the later half of the model. As expected the plots for 150 km and 225 km shows splitting depicting anisotropic character. The plot over 300 km cannot be considered to be reliable as it is at the edge of the model. The induction vector plot shows negligible magnitude and does not vary with the direction despite the fact that the model is two-dimensional in nature. Thus analyzing either the apparent resistivity or phase plots is

sufficient for interpreting anisotropic model along with induction vector. Here also the phase splitting increases with the increase in anisotropy factor (maximum resistivity/ minimum resistivity).

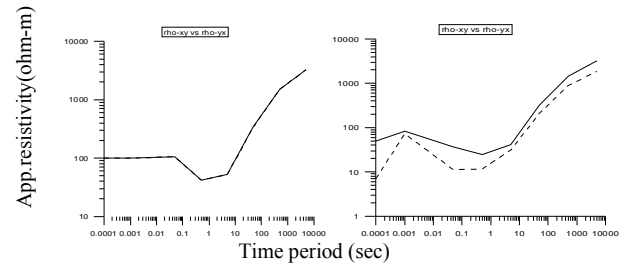
In general the traps have local conducting heterogeneities. Thus, in subsequent figure a vertical contact model for the sediments with left portion as isotropic and the right half as anisotropic with presence of local conducting heterogeneity in isotropic trap have been considered. As in earlier case the profile length is 300 km, data has been analysed at every 5 km interval and the plots for 0km, 75 km, 225 km and 300 km have been shown.



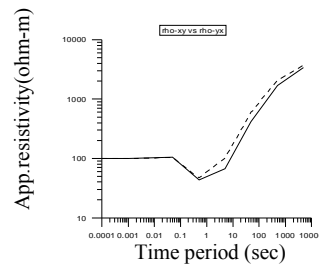
ρ_A plot for zero km



ρ_A plot for 75 km



ρ_A plot for 300 km



As concluded earlier that the anisotropy could be indicated either by the splitting of apparent resistivity or phase and



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Where \mathbf{E} is the observed electric field vector, \mathbf{E}_S is the scattered or secondary electric field produced by the action of the regional field on the conductive heterogeneity and ω is the angular frequency. Assuming that the inductive effect are negligible and that \mathbf{E}_R does not vary significantly over the lateral extent of the conductive heterogeneity and the scattered field \mathbf{E}_S is to a good approximation linearly proportional to regional electric field \mathbf{E}_R .
Due to the presence of the local conductor heterogeneity, $\mathbf{E}(\omega)$ gets distorted due to the fact that \mathbf{E}_R get distorted i.e.

$$\mathbf{E}(\omega) = D\mathbf{E}_R(\omega) \quad (2)$$

Where D is the 2×2 distortion matrix i.e., the observed electric field is a linear superposition of the regional field a scattered electric field (\mathbf{E}_S).

Though, the observe electric field gets distortion but not the observe magnetic field vector ($\mathbf{H}(\omega)$),

$$\mathbf{H}(\omega) = \mathbf{H}_R(\omega)$$

Where, \mathbf{H}_R is the regional magnetic field vector
Cantwell et al. (2004) defined the observed phase tensor as:

$$\Phi = \mathbf{X}^{-1} \mathbf{Y} = (\mathbf{D}\mathbf{X}_R)^{-1} (\mathbf{D}\mathbf{Y}_R) = \mathbf{D}^{-1} \mathbf{X}_R^{-1} \mathbf{D} \mathbf{Y}_R = \mathbf{X}_R^{-1} \mathbf{Y} = \Phi_R$$

Where Φ_R represent the regional phase tensor.

Thus, the phase tensor analysis shows that the phase data is not distorted by the presence of local conducting heterogeneity unlike apparent resistivity data.

The above model is now being analysed using phase data only. Now depending upon the "The Phase Tensor Analysis" the plots of the phase are as follows.

induction vector, here only the apparent resistivity is being analysed. Figures indicates that there is no consistent apparent resistivity splitting and it becomes difficult to conclude on the anisotropy by studying the apparent resistivity splitting. This happens because the apparent resistivity plots are distorted in the presence of local heterogeneity.

Phase Tensor

In the presence of local conducting heterogeneity in the Decan trap causes local distortion of the amplitudes of the electric field causing impedance magnitudes to be enhanced or diminished by real scaling factors but not the phase of the field. The obtained impedance tensor thereby would be distorted and any interpretation based on the same would be geologically absurd. As the phase is not distorted at all the interpretation based on the phase tensor analysis give more accurate and precise results.

The impedance can be expresses as $Z=X+iY$ where X is the real component and Y is the imaginary component of impedance. We know the phase is define as $\Phi=X^{-1} Y$, so Phase tensor Φ can be written as the following matrix:

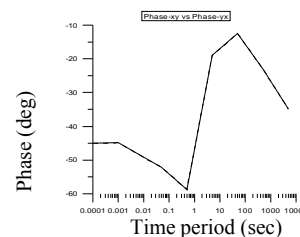
$$\Phi = \begin{pmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{pmatrix} = \{1/\det(x)\} \begin{pmatrix} X_{22}Y_{11}-X_{12}Y_{21} & X_{22}Y_{12}-X_{12}Y_{22} \\ X_{11}Y_{21}-X_{21}Y_{11} & X_{11}Y_{22}-X_{21}Y_{12} \end{pmatrix}$$

$$\text{Where, } \det(x) = X_{11}X_{22} - X_{21}X_{12}$$

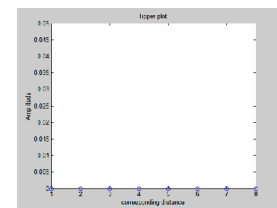
The accumulations of space charge along the boundaries of shallow inhomogeneity give rise to galvanic distortion. The major contribution comes from the surfacial bodies, which lies within the skin depth at the higher frequency. This effect shifts the apparent resistivity curves by a constant magnitude for all the frequencies. The distortion produced by localized conductivity heterogeneity on the regional electric field vector (\mathbf{E}_R) can be represented by the equation (1)

$$\mathbf{E}(\omega) = \mathbf{E}_R(\omega) + \mathbf{E}_S(\omega) \quad (1)$$

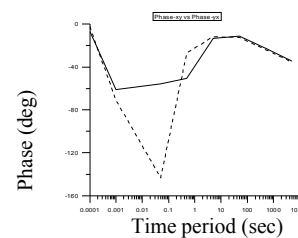
Phase plot for zero km



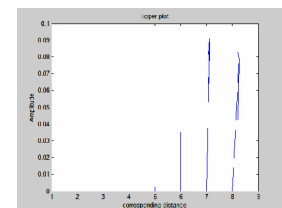
Tipper for zero km



Phase plot for 75 km



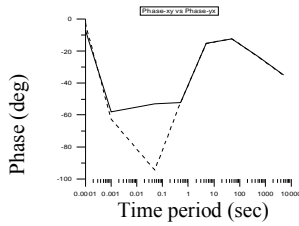
Tipper for 75 km



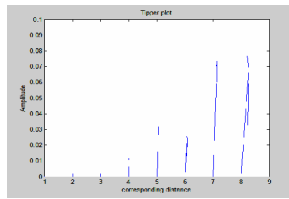


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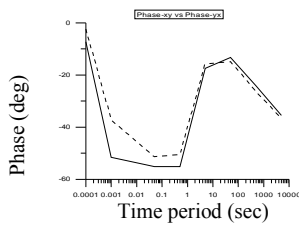
Phase plot for 150km



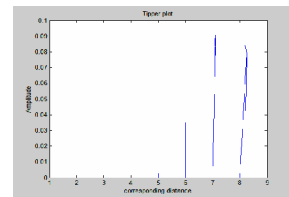
Tipper for 150 km



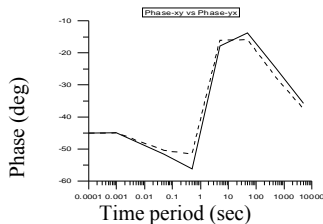
Phase plot for 225km



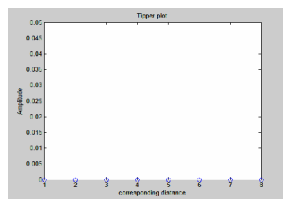
Tipper for 225 km



Phase plot for 300km



Tipper for 300 km



The plots show that there is a consistent phase splitting and is not affected by the presence of local conducting heterogeneities. The induction vector plot shows a negligible value.

Conclusion

Model response has been generated for anisotropic sediments in the presence of both isotropic and anisotropic traps. The model considered here were both 1-D as well as 2-D. The affect of anisotropic ratio, anisotropic strike direction and thickness of both trap and sediments have been analysed. The effect of presence of local conducting heterogeneities in the isotropic trap has also been analysed for a 2-D vertical contact model overlying anisotropic sediments.

The important conclusions are

- In the absence of local conducting heterogeneity the anisotropy indicators are either consistent

splitting of apparent resistivity data or phase data and induction vector.

- The splitting increases with the anisotropic ratio.
- The anisotropic strike direction does not show much dependence on the splitting.
- The thickness shows some dependence on the splitting.
- In the presence of local conducting heterogeneity the apparent resistivity data does not show consistent splitting because of the fact these get influenced to a great extent by surface anomalies and galvanic distortions.
- However, the phase data show consisting trend because the phase of the electric field does not get distorted.
- Induction vector generated by lateral conductivity gradient.
- The splitting is associated with negligible induction vector.
- Lateral structure is very unlikely to generate a very large splitting in impedance phase at a single site with no associated Hz.
- If the splitting observed two polarizations of phases where causes the lateral gradients the amount of phase splitting should change with distance from the lateral structural responsible.
- The negligible amount of induction vector and consistent phase splitting is generated by anisotropy rather than by lateral structure.

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