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Magnetotelluric Method: A Tool for Deep Crustal Study

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Summary

MT is a passive geophysical method, utilizing naturally occurring electromagnetic energy. The physical property of the subsurface measured is the electrical resistivity, familiar from the common electric logs. The measurement of time-varying electric and magnetic fields and the computation of apparent resistivity from these fields are precise, analytical steps and should be repeatable by any practitioner. The transition to depth from frequency is an interpretive step involving assumptions, the validity of which are case-dependent. The interpretation of geology based on vertical and lateral resistivity variations is, of course, an interpretive step. While not as inexpensive as gravity or magnetics, MT has been found by many operators to be a cost-effective way to enhance an exploration program. Typically, in the "pathfinder" role in overthrust exploration, MT is used first to determine if a prospective subthrust section is present, and then to define the extent of the subthrust section to place realistic limits on the amount of seismic data required. Then, as an exploration program matures, MT is used to augment seismic exploration as described above and by full integration with seismic data to obtain an MT-derived or constrained velocity model. MT survey has been conducted over the region of Narmada Son lineament, central India, Siwalik Himalayas, Iapetus Suture Zone in central Ireland, Central India and Kota-Kekri and from these studies, the geo-electric structure has been explored. Comparing with the gravity and seismic method, it is given a satisfied result. MT is the best tool for deep crustal study.

Introduction

Magnetotellurics (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. The amplitude, phase, and directional relationships between electric (E) and magnetic (H) fields on the surface depend on the distribution of electrical resistivity in the subsurface (Vozoff, 1991). Depending on signal frequency and resistivity of material being studied, the MT method can resolve geoelectric structure from depths of tens of meters to depths of tens of kilometers. Therefore, depth interpretation based on MT data is much more definitive than that based on gravity or magnetic data (Vozoff, 1972). In this paper, the theory and the methodology of determining electrical structure of subsurface using Magnetotelluric method have been focused and some of case studies have been discussed.

Theory

The electromagnetic methods can be broadly subdivided into two groups: (i) those using artificially generated signals and (ii) those using Earth's naturally existing field. MT relies on two sources, thunderstorm activity and solar wind interaction with magnetosphere, ionosphere of the earth. When solar wind encounters the Earth's magnetosphere, electrons and protons are deflected in opposite directions giving rise to an electrical current in the plasma and a magnetic-field effect. This interface moves back and forth erratically as energy of solar wind is arriving. Resulting magnetic effects that arise at the magnetopause are strongly modified by the time they penetrate the Earth's surface and are observed (Kaufman and Keller, 1981).

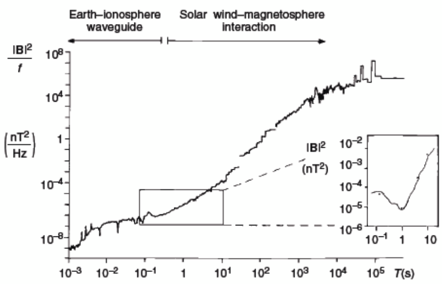

Figure 1. Power spectrum illustrating '1/f characteristics' of natural magnetic variations. Inset illustrates the reduced signal power in the dead-band.(Simpson et al., 2005)

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Maxwell's equations

The behavior of electromagnetic fields at any frequency is concisely described by Maxwell's equations, which for a polarisable, magnetisable medium may be expressed as:

$$\vec{\nabla} X \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} X \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

$$\vec{\nabla} . \vec{B} = 0$$

$$\vec{\nabla} . \vec{D} = \rho$$

- MT measures the orthogonal component of **E** (Induced) & **H** (Inducing) fields
- Components of field E_x, E_y, H_x, H_y, H_z

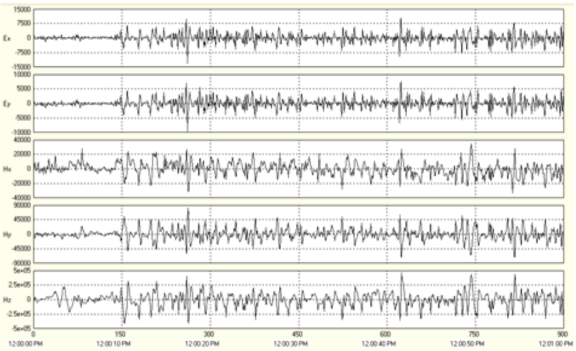


Figure 2. Time series MT data . Components of field Ex, Ey, Hx, Hy, Hz have been shown.

Skin Depth

The depth at which the amplitude of a plane EM wave will be attenuated to 1/e of its surface amplitude is called the skin depth, δ. Skin depth gives a relative measure of how deep the EM wave can penetrate into the Earth. Skin depth is related to resistivity as:

$$\delta = (\pi f \mu \sigma)^{-1/2} \cong 0.503 \sqrt{\frac{\rho}{f}} \text{ (km)},$$

Apparent resistivity

$$\rho_a(\omega) = \frac{1}{\omega \mu_0} \left| \frac{E_x(\omega)}{H_y(\omega)} \right|^2$$

If the Earth has a uniform resistivity, then the analysis above shows that ρa = ρ1 In general, the resistivity will not be constant with depth. In this case, the apparent resistivity can be considered as the average resistivity over a hemisphere with radius equal to the skin depth.

Phase

$$\Phi(\omega) = \tan^{-1}\left[Z_{xy}(\omega)\right] = \tan^{-1}\left[\frac{E_x(\omega)}{H_y(\omega)}\right]$$

The phase of Zxy (ω) is the phase angle between Ex (ω) and Hy (ω). For an electromagnetic wave travelling in free space Ex and Hy will be in phase with Φ (ω) = 0

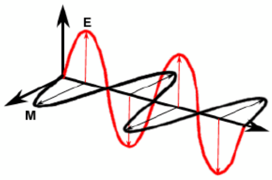


Figure 3. Phase diagram

For a half space, the phase is given by:

$$\Phi(\omega) = Z_{xy}(\omega) = \tan^{-1}\left[\frac{(1-i)}{\sqrt{2}} \sqrt{\frac{\omega \mu_0}{\sigma_1}}\right] = -\frac{\pi}{4}$$

This phase angle will be observed at all frequencies.

E- and B-polarization

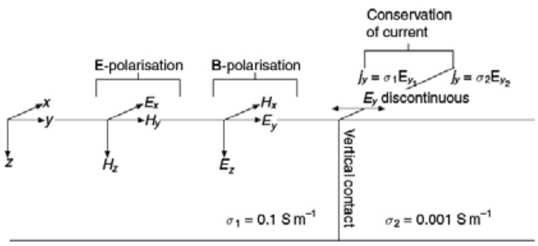


Figure 4. Simple 2-D model composed of quarter-spaces with different conductivities meeting at a vertical contact (planar boundary extending to infinity – i.e., striking – in the x direction). Conservation of current across the contact, where the conductivity changes from σ1to σ2, leads to the y-component of the electric field, Ey, being discontinuous. For this idealized 2-D case, electromagnetic fields can be decoupled into two independent modes: one incorporating electric fields parallel to strike with induced magnetic fields perpendicular to strike and in the vertical plane (E-polarization); the other incorporating magnetic fields parallel to strike with induced electric fields perpendicular to strike and in the vertical plane (B-polarization)(Simpson et al., 2005)

Impedance Tensor.

The impedance tensor relates electric-field measurements to magnetic-field measurements. Assuming a 1D earth, the impedance Z is given by:

$$Z_{xy} = \frac{E_x}{H_y} = \frac{\omega\mu}{k} = (1+i)\left(\frac{\omega\mu}{2\sigma}\right)^{1/2},$$

Methodology

How MT can measure the resistivity of the Earth?

Consider the transmitted EM signal just below the surface. We have shown that:

$$E_x^t(z,t) = E^t e^{-k_1 z} e^{-i\omega t}$$

and

$$H_y^t(z,t) = \frac{1}{i\omega\mu} E^t(-k_1) e^{-ik_1 z} e^{-i\omega t}$$

The impedance is defined as

$$Z_{xy}(\omega) = \frac{E_x(\omega)}{H_y(\omega)}$$

and it can be shown that it contains information about the conductivity of the Earth. Consider the value of impedance at z = 0 for the case of a uniform half space Earth.

$$Z_{xy}(\omega) = \frac{-i\omega\mu_0}{k_1} = \frac{-i\omega\mu_0}{\sqrt{-i\omega\mu_0\sigma_1}} = \frac{\sqrt{-i\omega\mu_0}}{\sqrt{\sigma_1}} = \sqrt{\frac{\omega\mu_0}{\sigma_1}}\sqrt{-i} = \frac{(1-i)}{\sqrt{2}}\sqrt{\frac{\omega\mu_0}{\sigma_1}}$$

Note that Zxy (ω) depends only the properties of the Earth, and not the air. The impedance is a complex number with magnitude:

$$\left|Z_{xy}(\omega)\right|^2 = \left|\frac{E_x(\omega)}{H_y(\omega)}\right|^2 = \frac{\omega\mu_0}{\sigma_1} \qquad \ldots\ldots(1)$$

Re-arranging (1) we can show that

$$\sigma_1 = \frac{\omega\mu_0}{\left|Z_{xy}\right|^2} = \frac{\omega\mu_0}{\left|\frac{E_x}{H_y}\right|^2}$$

This expression can also be written in terms of the resistivity of the Earth (ρ1) as:

$$\rho_1 = \frac{1}{\omega\mu_0}\left|Z_{xy}\right|^2 = \frac{1}{\omega\mu_0}\left|\frac{E_x}{H_y}\right|^2 \qquad (2)$$

Note that all terms on the right hand side of (2) can be measured, and this shows how surface measurements of electric and magnetic fields can be used to measure the resistivity of the Earth. It is important to consider which part of the Earth is being sampled in such a measurement. Since the EM fields attenuate in the Earth with a length scale of a skin depth (δ), this measurement samples a hemisphere around the observation site, radius δ.

Processing of MT data begins with conversion of time series segments into frequency domain fields by Fourier Transforms. Amplitude and phase characteristics as a function of frequency are expressed in real and imaginary parts. We measure a vector E field and a vector H field and relate them with an impedance tensor.

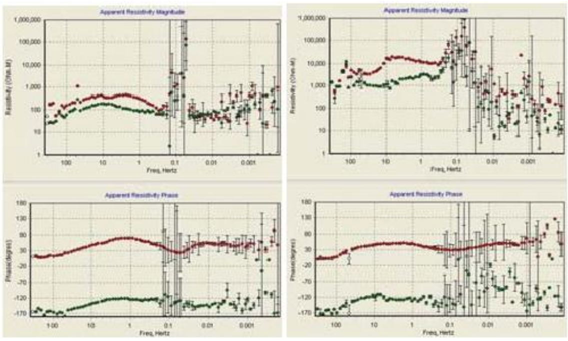
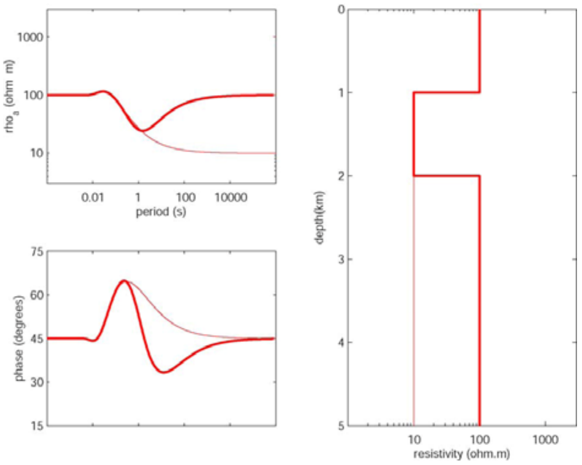


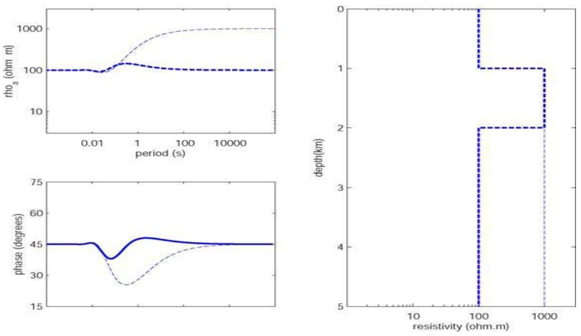
Figure 4. Apparent Resistivity and Phase response of MT data.

MT response of multiple layers

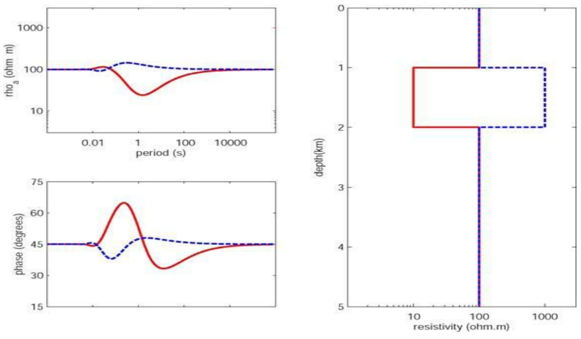
Case 1 : Conductive/resistive layer and half space



- At short periods (T < 0.01 s) apparent resistivity equals that of the upper layer (100 Ωm).
- Between periods of T = 0.01 and T = 0.1 s the apparent resistivity increases slightly. This is a resonance phenomenon that occurs when the skin depth is approximately equal to the thickness of the layer. It is rarely seen in field MT data. Note that this is also evident as slight decrease in phase.
- At period of T = 0.1 s the apparent resistivity starts to decrease rapidly as the conductive layer (10 Ωm) is detected by the EM signals.

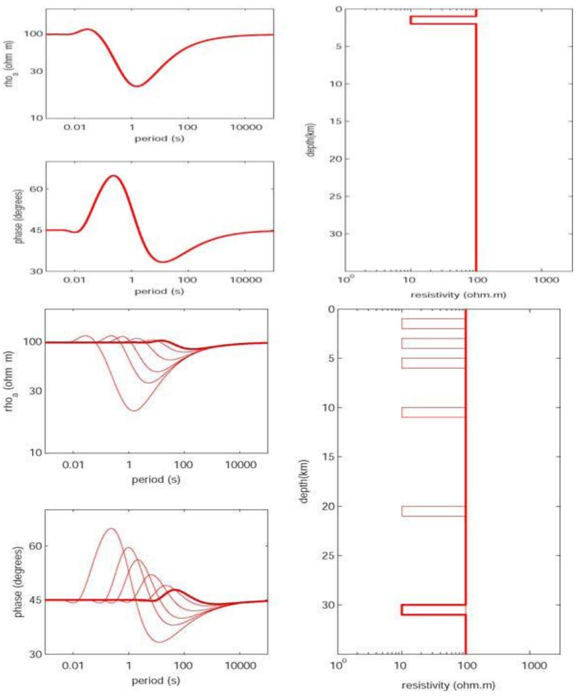


- This is identical to the previous example, except that the second layer is a resistor compared the first layer.
- Resonance phenomena is observed again, but in opposite sense.



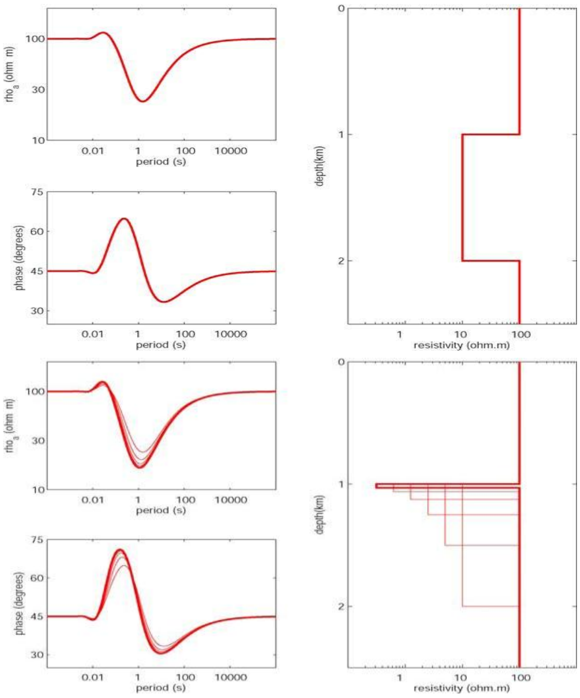
- Compare a second layer with resistivity contrast of 10 compared to the 1st and 3rd layers.
- Effect of second layer is observed at the same period in each case (T = 0.01 s) • Apparent resistivity at long period is same in each case (T ~ 10000 s)
- Model with conductive second layer has greater effect on apparent resistivity. This is because MT signals are strongly attenuated by the conductor and this makes a significant change at the surface, where the impedance is computed. In contrast, the EM signals travel through the resistive layer with minimal attenuation. Thus the resistive layer does not significantly change the surface impedance.

Case 2: Varying depth to a conductive layer



- As depth to the layer increases, the period at which it is detected increases. This is as expected from the skin-depth equation. Can you verify that the graphs above are correct for the 1 km thick layer that that resistivity = 100 Ωm
- The magnitude of the response decreases as the layer becomes deeper. This is because the apparent resistivity represents an average resistivity from the surface to the maximum depth of exploration.
- MT is good at determining the depth of a conductive layer. With typical quality field data, this can be determined within 10%

Case 3 : Layer of constant conductance



- Conductance of a layer is the product of conductivity and thickness
- Each model has a layer with conductance 100 Siemens. Thus to maintain constant conductance, as the layer becomes thinner, the conductivity increases
- Once the layer become thin (compared to it's depth), the MT curves for different combinations of thickness and conductivity cannot be distinguished.
- This is an example of non-uniqueness. MT cannot separately determine the thickness and resistivity of the layer. Only the conductance can be determined.

Examples

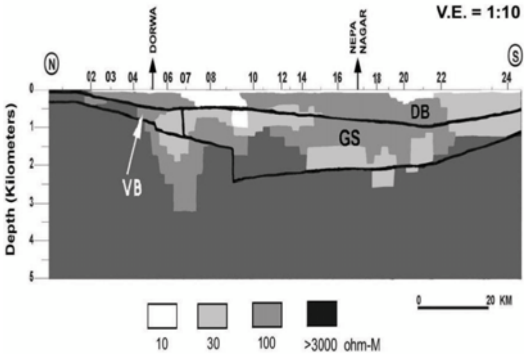


Figure 5. Geoelectric structure for the shallow section of Narmada Son lineament, central India (Rao et al,2004). The Deccan volcanics and sedimentary layers obtained from the DSS studies are overlain on the electric cross section for comparison sake. Here DB indicates the Deccan basalts, VB: Vindhyan and Bijawar sediments and GS:Gondwana sediments.

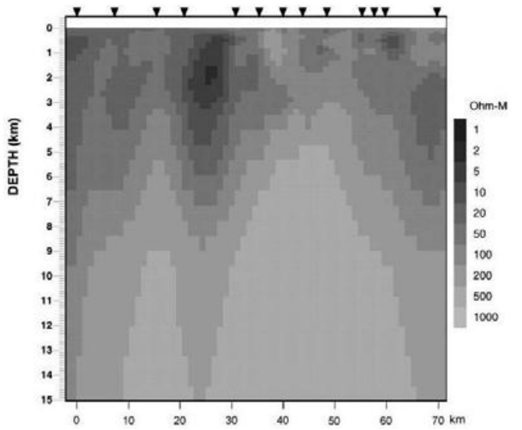


Figure 6.Shallow geoelectrical structure of Siwalik Himalayas using MT method.((Gokarn et al.,2002).

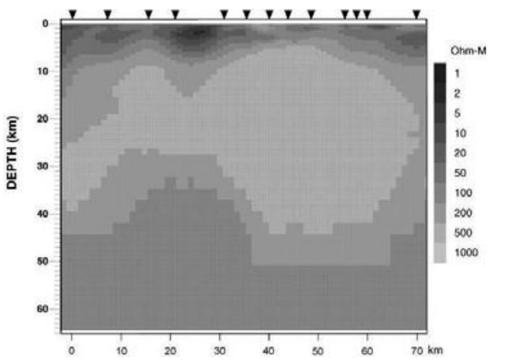


Figure 8. Deep geoelectrical structure of Siwalik Himalayas using MT method.((Gokarn et al.,2002).

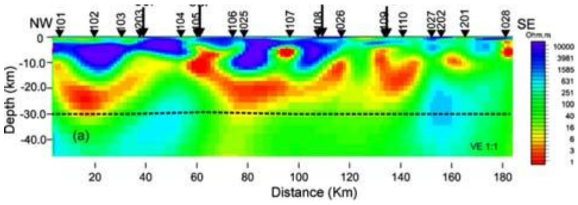


Figure 9. Geo-electric section across the Iapetus Suture Zone in central Ireland (Rao et al.,2007).

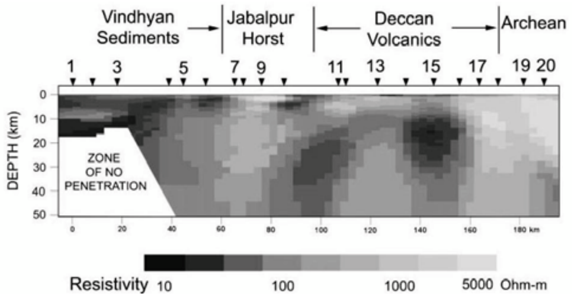


Figure10. Geoelectric cross-section of Central India using magnetotelluric data. (Gokarn et al.,2001).

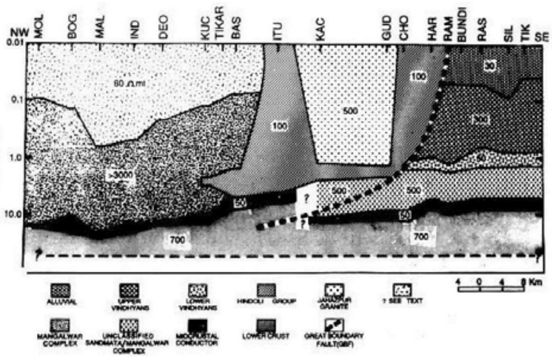


Figure 11. Geophysical Interpretation of Kota-Kekri profile inferred from the MT profile (Gokarn et al.,1995).

Correlation of MT method with other Geophysical Method

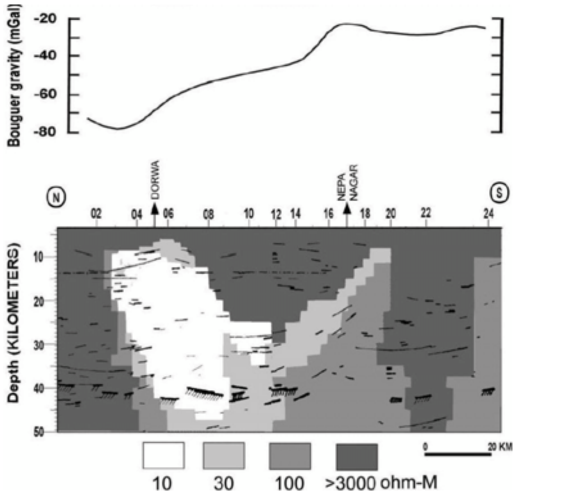


Figure 12. Deep geoelectric cross section of Narmada Son lineament, central India along with the crustal reflectivities obtained from the DSS studies The Bouguer gravity variation along the profile is shown on the top part (Rao et al.2004).

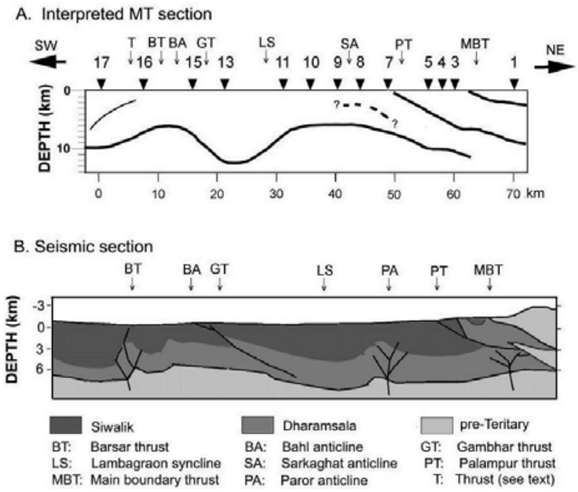


Figure 13.Tectonic interpretation of the Siwalik region (a) based on the MT results (Fig. 7) and (b) seismic studies of Raiverman et al. (1994). The major tectonic elements are marked on the top part of the diagrams. (Gokarn et al., 2002)

Conclusion

The MT method is a way of determining the electrical conductivity distribution of the subsurface from measurements of natural transient electric and magnetic fields on the surface.

The time variation of the earth's electric and magnetic fields at a site are recorded simultaneously over a wide range of frequencies.

MT method gives the insight to the earth's interior from the electromagnetic point of view.

It is however pertinent at this point to note that MT is not aimed at replacing any of the above techniques but should be viewed as a complimentary tool for the sub-structural investigation.

The depth penetration of the fields into the earth is inversely related to rock conductivity.

The thin but highly conductive layers are more clearly seen in the response functions because of their higher conductance.

The MT method yields conductive information from much greater depths than artificial-source induction.

The depth of penetration can be large as 100 km or more. Utilizing long periods in the range 10-100000s, the structure of the crust and upper mantle can be investigated.

B-Polarization resistivities tend to resolve lateral conductivity variations than E-Polarization resistivities.

The purpose of the data analysis is to extract reliable values of impedances, apparent resistivities, and the other earth response functions from the field records.

MT has better resolution than the gravity and magnetic method. It is inexpensive compared to the seismic techniques.

This technique has a low environment impact and needs a small crew.

Combining with other Geophysical methods, MT gives more accurate result.

From different studies it is accepted that MT is the best tool for deep crustal studies.

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