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ELECTRICAL CONDUCTIVITY PROFILING OF THE EARTH'S INTERIOR USING MAGNETOTELLURIC METHODS: A REVIEW

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ABSTRACT

The electrical conductivity structure of the Earth's interior provides fundamental information about its composition, tectonic evolution, geothermal processes, and mineral resources. Among various geophysical techniques, the magnetotelluric (MT) method has emerged as one of the most reliable passive electromagnetic methods for investigating conductivity variations from shallow crustal regions to the upper mantle. The method utilizes naturally occurring geomagnetic micropulsations generated by interactions between the solar wind, magnetosphere, and ionosphere to estimate subsurface electrical conductivity. This review presents the theoretical foundations of magnetotelluric investigations, emphasizing the relationship between Earth's electric currents and geomagnetic field variations. Maxwell's equations governing electromagnetic induction are discussed together with the concepts of vertical conductivity profiling, skin depth, layered Earth models, and conductivity discontinuities. The influence of coastal effects and lateral conductivity contrasts on magnetic field variations is also reviewed. The paper highlights the importance of magnetotelluric techniques in crustal investigations, geothermal exploration, mineral prospecting, tectonic studies, and lithospheric characterization. Future developments involving three-dimensional inversion, integrated geophysical modelling, and computational advances are briefly discussed.

***KEYWORDS:** Magnetotellurics, Electrical Conductivity, Geomagnetic Micropulsations, Earth Currents, Maxwell's Equations, Skin Depth, Electromagnetic Induction, Geophysical Exploration.*

INTRODUCTION

Understanding the electrical conductivity distribution within the Earth is essential for interpreting its geological evolution and internal physical processes [1]. Variations in electrical conductivity are controlled by mineral composition, temperature, pressure, pore fluids, partial melting, and structural discontinuities. Consequently, conductivity measurements provide valuable constraints on crustal and mantle properties that cannot be obtained solely through seismic or gravity investigations.

Among the available geophysical exploration methods, the magnetotelluric (MT) technique has become one of the most powerful tools for imaging the Earth's electrical structure. Unlike active geophysical methods that require artificial energy sources, the MT method utilizes naturally occurring electromagnetic fields produced by interactions between the solar wind, magnetosphere, and ionosphere[2]. These naturally generated electromagnetic waves penetrate the Earth and induce electric currents whose characteristics depend on the conductivity distribution of subsurface materials. Analysis of the resulting electric and magnetic field variations enables researchers to infer conductivity variations over a broad range of depths. Geomagnetic micropulsations constitute an important source of natural electromagnetic energy within the frequency range commonly used in magnetotelluric investigations. These low- frequency oscillations continuously induce electrical currents inside the Earth, producing magnetotelluric fields that can be measured using electric field electrodes and magnetic induction coils[3]. The simultaneous observation of electric and magnetic field components forms the basis for estimating subsurface conductivity through electromagnetic theory. The theoretical framework of magnetotellurics is derived from Maxwell's equations. Under the assumption that conductivity varies predominantly with depth, these equations can be simplified to obtain analytical solutions for layered Earth models. Such models provide practical means for interpreting observed electromagnetic responses and estimating conductivity profiles beneath observation stations. The approach has become widely accepted because it provides reliable estimates of conductivity over depths ranging from a few hundred metres to several hundred kilometres. One of the major advantages of the MT method is its ability to investigate deep geological structures without drilling or excavation. Long-period electromagnetic waves possess greater penetration depths because of increased skin depth, allowing conductivity imaging of the lower crust and upper mantle[4]. Consequently, magnetotelluric investigations have become indispensable in tectonic research, geothermal exploration, mineral prospecting, volcanic monitoring, and studies of lithospheric evolution. Conductivity discontinuities represent another important consideration during magnetotelluric interpretation. Coastal boundaries, sedimentary basins, and tectonic faults introduce lateral conductivity contrasts that distort naturally occurring electromagnetic fields. These distortions influence the measured magnetic field components and must be considered during interpretation to obtain accurate conductivity models. The theoretical treatment of such discontinuities has significantly improved the interpretation of magnetotelluric observations in complex geological environments.

Over the past several decades, advances in instrumentation, digital signal processing, numerical modelling, and inversion algorithms have greatly enhanced the resolution and reliability of magnetotelluric investigations[5]. Modern three-dimensional inversion techniques enable detailed imaging of conductivity structures associated with tectonic boundaries, geothermal reservoirs, ore bodies, and deep crustal discontinuities. These developments have established magnetotellurics as one of the most important electromagnetic methods in modern geophysical exploration. The objective of this review is to present a comprehensive discussion of the theoretical principles governing magnetotelluric investigations, with particular emphasis on electrical conductivity profiling of the Earth's interior. The review summarizes the governing electromagnetic equations, conductivity profiling techniques, layered Earth models, skin depth concepts, and the influence of conductivity discontinuities while highlighting major applications in Earth sciences[6]. The discussion is based on the material presented in the uploaded chapter and related foundational literature.

RESULTS AND DISCUSION

Fundamental Theory of Magnetotellurics Magnetotellurics (MT) is a passive electromagnetic geophysical method that determines the electrical conductivity distribution within the Earth by utilizing naturally occurring variations in the Earth's electromagnetic field. The primary sources of these natural electromagnetic fields are ionospheric and magnetospheric current systems, which are driven by interactions between the solar wind and the Earth's magnetic field. These naturally varying fields induce secondary electric currents within the Earth, producing measurable electric and magnetic fields at the Earth's surface[7]. Their relationship provides direct information about the electrical conductivity of subsurface materials. Unlike controlled-source electromagnetic techniques, the MT method requires no artificial transmitter. Consequently, it is capable of probing conductivity structures over an exceptionally wide depth range, extending from a few hundred metres to several hundred kilometres depending upon the frequency of the natural electromagnetic source[8]. The basic objective of MT investigations is to establish a quantitative relationship between the horizontal electric field (E) and the horizontal magnetic field (H) measured simultaneously at the Earth's surface. This relationship, commonly expressed through impedance functions, forms the basis for estimating subsurface electrical conductivity. Electromagnetic Induction in the Earth Electromagnetic induction occurs whenever time-varying magnetic fields interact with

conducting materials. According to Faraday's law, changing magnetic fields induce electric fields, while the induced electric fields generate electrical currents whose magnitudes depend upon the electrical conductivity of the medium[9]. Within the Earth, induced currents are commonly referred to as telluric currents or Earth currents. These currents flow through conductive geological formations and generate secondary magnetic fields that modify the original geomagnetic field. Because different geological materials possess different electrical conductivities, the induced current distribution varies spatially[10]. Highly conductive formations permit stronger induced currents, whereas resistive rocks inhibit current flow. Consequently, measurements of the induced electromagnetic fields provide indirect information regarding subsurface lithology and geological structures.

Maxwell's Equations The theoretical foundation of magnetotellurics is based upon Maxwell's electromagnetic equations, which describe the interaction between electric fields, magnetic fields, and electric currents[11]. For harmonic electromagnetic fields, the governing equations are Gauss's Law for Electricity $\nabla \cdot D=\rho$ Where D represents electric displacement and ρ denotes electric charge density. Gauss's Law for Magnetism $\nabla \cdot B=0$ This equation indicates that magnetic monopoles do not exist and that magnetic field lines always form closed loops. Faraday's Law $\nabla \times E=-\partial B/\partial t$ This equation states that time-varying magnetic fields generate electric fields. Ampère-Maxwell Law $\nabla \times H=J+\partial D/\partial t$ Where, J is conduction current density and $\partial D/\partial t$ represents displacement current density. For magnetotelluric frequencies, displacement current is extremely small compared with conduction current and can usually be neglected. This approximation greatly simplifies the governing equations without significantly affecting accuracy.

Harmonic Electromagnetic Fields In MT theory, electromagnetic fields are generally assumed to vary sinusoidally with time, $ei\omega t$ where, ω denotes angular frequency. This assumption transforms the governing partial differential equations into ordinary differential equations that are considerably easier to solve analytically[12]. The Earth's conductivity is assumed to vary only with depth, $\sigma = \sigma(z)$ which converts the Earth into a one-dimensional layered conductor. Under these assumptions, Maxwell's equations reduce to differential equations describing electromagnetic wave propagation inside conductive media. Analytical solutions are obtained using the method of separation of variables, allowing electric and magnetic field components to be expressed as functions of both depth and horizontal position.

Layered Earth Model The layered Earth approximation assumes that each geological layer possesses uniform electrical conductivity while conductivity changes only at interfaces between layers. This assumption provides a reasonable approximation for many geological settings and greatly simplifies interpretation of magnetotelluric observations[13]. Typical layered models include: 1. Two-layer Earth model 2. Three-layer Earth model 3. Multi-layer conductivity models Each layer is characterized by 4. Electrical conductivity (σ) 5. Thickness (d) 6. Magnetic permeability (μ) 7. Dielectric permittivity (ε) Electromagnetic waves entering successive layers undergo attenuation and phase shifts depending upon these physical properties. By comparing measured responses with theoretical predictions, the conductivity and thickness of individual layers can be estimated.

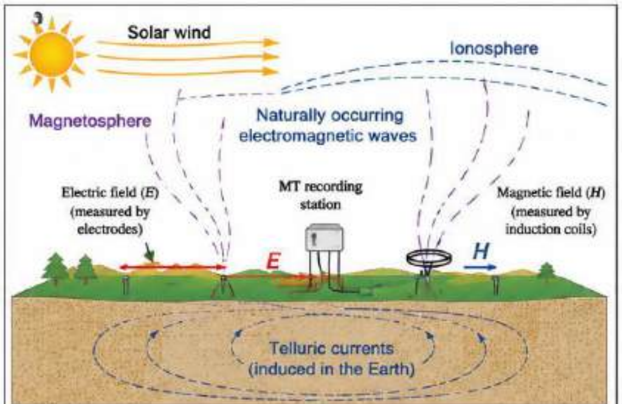

Fig. 1. Schematic diagram of the magnetotelluric (MT) method.

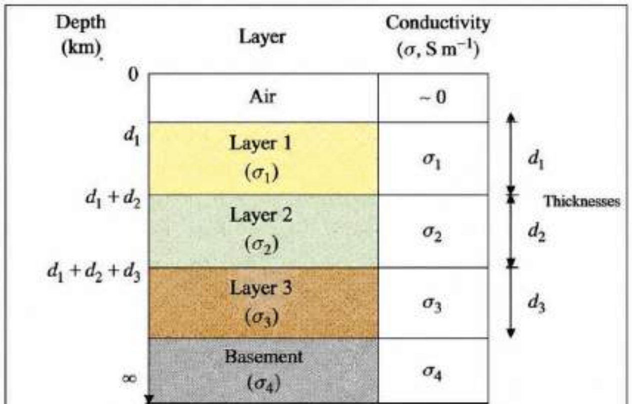

Fig. 2. One-dimensional layered Earth model used in MT interpretation.

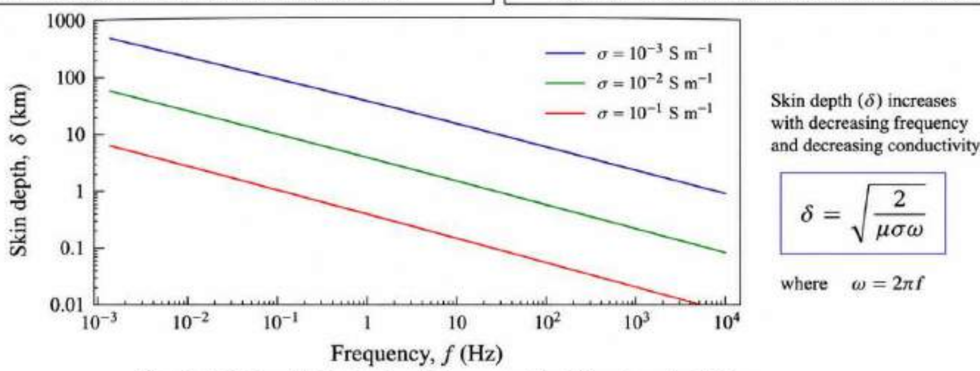

Fig. 3. Variation of skin depth with frequency for different conductivities.

Electromagnetic Wave Propagation Inside conductive media, electromagnetic waves undergo exponential attenuation. The attenuation constant depends upon 1. conductivity, 2. magnetic permeability, 3. frequency. Higher-frequency waves are absorbed rapidly and investigate only shallow regions, whereas lower-frequency waves penetrate deeper into the Earth[14]. This frequency dependence forms the basis of magnetotelluric depth sounding. The wave propagation constant is expressed as k=α+iβk where, α is the attenuation constant and β is the phase constant. The propagation constant increases with increasing conductivity, indicating that conductive rocks attenuate electromagnetic energy more rapidly than resistive rocks. Boundary Conditions At every interface separating two geological layers, electromagnetic boundary conditions must be satisfied[15]. The tangential components of both electric and magnetic fields remain continuous across the

interface, E1t=E2t These continuity conditions allow electromagnetic fields to be propagated from one layer to another, ultimately relating measured surface fields to conductivity variations at depth. This principle underpins magnetotelluric inversion methods[16]. Skin Depth and Electromagnetic Penetration Skin depth is one of the most important concepts in magnetotelluric investigations because it determines the maximum depth to which an electromagnetic wave can effectively penetrate a conducting medium. Electromagnetic energy decreases exponentially with depth due to electrical losses within the Earth[17]. Consequently, the amplitude of the electric and magnetic fields becomes progressively weaker as the wave propagates into conductive geological formations. The uploaded chapter explains that skin depth depends primarily on the electrical conductivity of the Earth and the angular frequency of the incident electromagnetic field. Higher frequencies are attenuated rapidly and therefore provide information about shallow subsurface layers, whereas lower frequencies penetrate much deeper and are suitable for investigating the lower crust and upper mantle[18]. This frequency dependence is the basis of magnetotelluric depth sounding. The chapter further notes that for a typical upper-Earth conductivity, skin depth increases substantially as frequency decreases[19]. It gives illustrative values showing penetration depths on the order of a few kilometres at higher frequencies and tens of kilometres at lower frequencies, emphasizing that very long-period variations are required for deep conductivity investigations. Vertical Conductivity Profiling Vertical conductivity profiling is one of the principal applications of the magnetotelluric method. According to the uploaded chapter, measurements of the tangential electric and magnetic field components at the Earth's surface can be related to subsurface conductivity through the theoretical framework derived from Maxwell's equations[20-23]. These relationships make it possible to estimate conductivity as a function of depth beneath an observation site. The chapter describes layered Earth models as convenient approximations for interpreting field observations[24]. In the simplest approach, the Earth is represented by an upper layer of constant conductivity overlying a basement of contrasting conductivity. The conductivity

profile is obtained by comparing observed electromagnetic responses with theoretical predictions generated for different layer thicknesses and conductivity values. A practical interpretation procedure summarized in the chapter consists of: 1. Observing a magnetotelluric variation with a well-defined frequency. 2. Calculating the experimental relationship between the measured electric and magnetic fields. 3. Assuming an initial conductivity for the upper layer. 4. Comparing experimental results with theoretical curves calculated for different layer thicknesses and parameter values. 5. Selecting the conductivity profile that provides the best agreement between theory and observation. Conductivity Discontinuities The uploaded chapter emphasizes that the assumption of horizontally uniform conductivity is often not valid in natural geological environments[25-30]. Coastlines, sedimentary basins, and other lateral conductivity contrasts introduce discontinuities that significantly influence measured magnetotelluric fields. In particular, the chapter discusses theoretical studies of coastline effects, noting that when the electric field is parallel to the coastline, the vertical magnetic field component may be substantially enhanced near the conductivity contrast[31-33]. These effects are most pronounced at relatively high micropulsation frequencies and can extend varying distances on the landward and seaward sides of the coastline. Such behaviour demonstrates the importance of accounting for lateral conductivity variations during interpretation of magnetotelluric observations. Applications of Magnetotelluric Conductivity Profiling Drawing on the discussion in the uploaded chapter, magnetotelluric conductivity profiling has several important applications in Earth science: 1. Investigation of the electrical conductivity structure of the crust and upper mantle. 2. Geological interpretation of layered conductivity models. 3. Determination of the depth and conductivity of subsurface layers through comparison of theoretical and observed electromagnetic responses. 4. Study of conductivity discontinuities associated with coastlines and other lateral geological contrasts. 5. Support for broader geophysical investigations through electromagnetic characterization of subsurface materials.

Table 1. Typical electrical conductivity of Earth materials

Material	**Electrical conductivity (S m^{-1})**	**Electrical resistivity (Ω m)**	**Remarks**
Dry granite	10^{-6}–10^{-4}	10^{4}–10^{6}	Highly resistive continental crust
Sandstone (dry)	10^{-5}–10^{-3}	10^{3}–10^{5}	Depends on porosity
Basalt	10^{-4}–10^{-2}	10^{2}–10^{4}	Moderate conductivity
Sedimentary rocks	10^{-3}–10^{-1}	10–10^{3}	Water content influences conductivity
Seawater	3–5	0.2–0.33	Highly conductive
Upper mantle	10^{-2}–10^{-1}	10–100	Temperature dependent

CONCLUSION

The magnetotelluric method as a theoretical framework for relating naturally occurring geomagnetic micropulsations to the electrical conductivity structure of the Earth's interior. Beginning with Maxwell's equations and the assumption of depth-dependent conductivity, it develops analytical relationships between surface electric and magnetic fields and subsurface conductivity distributions. Layered Earth models, skin-depth considerations, and treatment of conductivity discontinuities provide the basis for interpreting magnetotelluric observations. The chapter concludes that long-period electromagnetic variations are particularly valuable for investigating deep conductivity structures and that lateral conductivity contrasts, such as coastlines, should be considered during data interpretation.

REFERENCES

1. G. R. A. Ellis, "Geomagnetic micropulsations," Australian Journal of Physics, vol. 13, p. 625, 1960.

2. N. M. Brice, "An explanation of triggered very low frequency emissions," Journal of Geophysical Research, vol. 68, p. 4626, 1963.

3. M. Balser and C. A. Wagner, "Observations of Earth-ionosphere cavity resonances," Nature, vol. 188, p. 638, 1960.

4. A. J. Dessler, "The stability of the interface between the solar wind and the geomagnetic field," Journal of Geophysical Research, vol. 66, p. 3587, 1961.

5. H. Benioff, "Observations of geomagnetic fluctuations in the period range 0.3 to 120 seconds," Journal of Geophysical Research, vol. 65, p. 1413, 1960.

6. R. J. Slutz and J. R. Winkelman, "Shape of the magnetospheric boundary under solar wind pressure," Journal of

Geophysical Research, vol. 69, p. 4933, 1964.

7. W. K. Borthold, A. K. Harris, and H. J. Hope, “Correlated micropulsations at magnetic storm sudden commencements,” Journal of Geophysical Research, vol. 65, p. 613, 1960.

8. M. Casaverde, “Introduction to geomagnetism: the equatorial electrojet,” American Journal of Physics, vol. 29, p. 744, 1961.

9. T. Obayshi and J. A. Jacobs, “Geomagnetic micropulsations and the Earth’s outer atmosphere,” Geophysical Journal, vol. 1, p. 53, 1958.

10. S. Jain, “Electrical resistivity of the crust and upper mantle at Eskdalemuir, South Scotland,” Nature, vol. 203, p. 631, 1964.

11. Ellis, G.R.A., “Geomagnetic micropulsations”, Aust, J. Phys., vol. 13, p. 625 ; 1960.

12. Brice, N.M., “An explanation of triggered very low frequency emissions”, J.G.R. vol. 68, p. 4626; 1963.

13. Balser, M., and C. A. Wagner, “Observations of Earth-ionosphere cavity resonances”, Nature, vol. 188, p. 638; 1960.

14. Dessler, A.J., “The stability of the interface between the solar wind and the geomagnetic field”, J.G.R., vol. 66, p. 3587; 1961.

15. Benioff, H., “Observations of geomagnetic fluctuations in the period range 0.3 to 120 seconds”, J.G.R., vol. 65, p. 1413; 1960.

16. Slutz, R.J., and J.R. Winkelman, “Shape of the magnetospheric boundary under solar wind pressure”, J.G.R., vol. 69, p. 4933; 1964.

17. Borthold, W.K., Harris, A.K., and H.J. Hope, “Correlated micropulsations at magnetic storm sudden commencements”, J.G.R., vol. 65, p. 613, 1960a.

18. Casaverde, M., “Introduction to geomagnetism: the equatorial electrojet”, Am. Jour. Phys., vol. 29, p. 744; 1961.

19. Obayshi, T., and J.A. Jacobs, “Geomagnetic micropulsations and the Earth’s outer atmosphere”, Geophys. J., vol. 1, p. 53.; 1958.

20. Jain, Sudhir, “Electrical resistivity of the crust and upper mantle at Eskadalemuir, South Scotland”, Nature vol. 203, p. 631; 1964. 21. Jacobs, J.A., Rostoker, G., and t. Watanabe, “Worldwide propagation of impulsive