Journal of African Earth Sciences 101 (2015) 274–281

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Electrical conductivity of mantle in the North Central region of Nigeria

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ARTICLE INFO

Article history:
Received 18 March 2014
Received in revised form 22 September 2014
Accepted 5 October 2014
Available online 14 October 2014

Keywords:
Electrical conductivity profile
North Central region of Nigeria
Quiet-day ionospheric current
Mantle
Spherical harmonic analysis
Transfer function

ABSTRACT

The mantle electrical conductivity profile of the North Central region of Nigeria was determined using the quiet day ionospheric current variations (Sq). The employed magnetic averaged hourly data were obtained from Magnetic Data Acquisition System (MAGDAS) ground based observatories at two Nigerian stations located at Ilorin (8°30′N, 4°33′E) and Abuja (8°59′N, 7°23′E) for the year 2009 and 2010. The magnetometer data from Pankshin (9°20′N, 9°27′E) and Katsina-Ala (7°10′N, 9°17′E) for the same years were equally employed. The separation of both the internal and external field contributions to the Sq variations was successfully carried out employing spherical harmonic analysis (SHA). Transfer function was performed in computing the conductivity–depth profile for North Central region of Nigeria from the paired external and internal coefficients of the SHA. The conductivity value of approximately 0.039 S/m was estimated at a depth of 100 km which rose gradually to 0.087 S/m at 207 km depth and 0.142 S/m at 367 km (close to the base of upper mantle). Subsequently, the conductivity profile continued rising to a value of 0.144 S/m at 442 km, 0.164 S/m at 653 km and 0.174 S/m at 710 km. Finally, value of approximately 0.195 S/m at a depth of 881 km and 0.240 S/m at 1100 km depth were recorded at the lower mantle with no indication of leveling off. Some evidence of discontinuities near 100–214 km, 214–420 km, 420–640 km, 640–900 km and 900–1100 km were clearly obvious. The sharp increase in conductivity from about 100 km depth to 230 km was interpreted to correspond to the global seismic low velocity zone – the asthenosphere.

1. Introduction

Ionospheric current is that current flowing in the conducting layers of the earth's atmosphere (ionosphere). The ionized molecules in the ionosphere release swarms of electrons that form powerful electrical currents (Lowrie, 2007). These act as sources of external magnetic fields that are detected at the Earth's surface.

The quiet-day variation refers to the magnetic variation on some days that are free from magnetic disturbances. It comprises of the solar quiet daily variation Sq, which depends on solar time and the lunar daily variation *L*, which depends on lunar time. The lunar variations are usually very small and are overlain by other effects unlike the solar quiet variations that are large. During these quiet days, the variations show smooth trend and a definite pattern on daily basis. The variation is believed to be caused by electric current system flowing in the lower ionosphere. These current systems are believed to arise from fluctuating ionospheric winds, which blow the ionized air across the lines of force of the geomagnetic field thereby generating electric fields to drive the electric currents (Vestine, 1960).

The Sq variation could be applied in estimation of conductivity of the Earth. The depth to which the current penetrates depends on its period of variation and the conductivity profile of the Earth. At the Earth's surface, the measured field is a combination of both the external (source) and internal (induced) components from the current. The method depends on the possibility of separating the external and internal parts of the field using spherical harmonic analysis (SHA) and adopting a phase and amplitude relationships to estimate a weighted mean value of the conductivity down to the depth of penetration of the current. The penetration of an electromagnetic wave into the conducting Earth depends upon the wavelength of the source field and the conductivity profile of the area into which the wave travels.

The SHA provides a smoothed representation of the daily variation phenomenon. Schuster (1889) observed from his spherical harmonic analysis of the daily variations of the quiet magnetic field that the Earth does not behave as a uniformly conducting sphere, but the upper layers must conduct less than the inner layers. The first quantitative estimates of the deep Earth conductivity was performed by Chapman (1919), Chapman and Price (1930), and

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http://dx.doi.org/10.1016/j.jafrearsci.2014.10.002
1464-343X/

Chapman and Bartels (1940). From that time, improved mathematical techniques, data bases and the application of computers have constantly thrown more light into the understanding of the electrical properties of the inaccessible Earth structure (Campbell, 1989). The geomagnetic field variations recorded at the magnetic observatories facilitate determination of not only the changes in the electrical conductivity within the Earth as a function of depth, but also the external source current systems associated with them (Campbell, 1987, 2003).

Electromagnetic (EM) induction in the Earth by time-varying geomagnetic field variations at different frequencies facilitates looking into different layers of the Earth from surface up to upper mantle depths and beyond using electrical conductivity as a diagnostic parameter. For their ability to penetrate to greater depths, long period geomagnetic variations of periods of 1 day and above act as unique tools to probe the Earth's interior up to upper/lower mantle depths in the depth range of 200–1500 km (Chandrasekhar, 2011).

Electrical conductivity characterizes the composition and physical state of the Earth's interior. It is sensitive to temperature, pressure, partial melt, presence of volatiles, oxygen fugacity, iron content and mineral constitution of the rocks. Price (1970) reviewed the early studies of deep conductivity and discussed some of the special analytical difficulties such as the effect of highly conducting surface layers upon the computations. There had been reviews of the analysis techniques (Wait, 1982; Rokityansky, 1982; Campbell, 1987, 1989, 2003). Recently, some researchers had carried out research works on the determination of the mantle electrical conductivity using solar quiet day ionospheric current. These include the works of Campbell and Schiffmacher (1988), Arora et al. (1995), Campbell et al. (1998), Agha and Okeke (2007), Obiekezie and Okeke (2010), and Obiora et al. (2014).

In this work, we used separated external and internal field contributions from the quiet day field variations to profile the electrical conductivity of the mantle in the North Central region of Nigeria.

2. Sources of data

The Magnetic Data Acquisition System (MAGDAS) ground based geomagnetic observatory station was established in Ilorin (8°30′N, 4°33′E) by Space Environment Research Centre, Kyushu University, Fukuoka, Japan, in 2006. In 2009, another station was established at Abuja (9°40′N, 7°29′E). The magnetic averaged hourly data obtained from these two stations with the magnetometer data from Pankshin (9°20′N, 9°27′E) and Katsina-Ala (7°10′N, 9°17′E) for the years 2009 and 2010 were employed in this work. The four locations are in the North Central region of Nigeria. Fig. 1 is the Google Earth map of the geomagnetic location stations.

3. Method of analysis

Geomagnetic application of the SHA technique was originated by Gauss in 1838. Using the technique, Schuster (1889, 1902) proved that the larger part of Sq was due to current sources external to the Earth and that the smaller part could arise from induction within the conducting Earth. There are three important features of SHA that are of peculiar interest. First, the analysis requires regularly spaced measurements of the Earth's field over the entire surface analysis sphere. Next, the analysis fits a potential function representation of the fields with two rapidly converging series of associated Legendre polynomial waveforms which are truncated after a convenient number of terms. One of the series has terms with increasing powers of radial distance (going away from the Earth, the field would increase as if approaching an external current source). The other has increasing powers of reciprocal radial distance (going into the Earth, the field would increase as if approaching an internal source). For the Sq analysis, such series thereby represent a separation of the Earth's magnetic potential function into the composite external (ionospheric source) and internal (induced) contributions of the geomagnetic field. The process not only allows the construction of the ionospheric dynamo current system, but also the induced field gives information on the conductivity structure of the Earth (Campbell, 1989). The conductivity analysis method applied in this study has been described in great detail (Campbell, 1987, 1989, 2003; Campbell and Schiffmacher, 1987), hence it is not necessary repeating all the equations here.

The ionospheric Sq current system for a quiet day is assumed to be fixed in position with respect to the sun. In the daily passage of an observatory beneath this source current, a 360° longitude sample of the current behavior is obtained. Thus the 24-, 12-, 8-, and 6-h components of the daily field variations correspond to the $(360/m)°$ components of longitudinal field change where the "order" index m is equal to 1, 2, 3, or 4. Mirror technique using the slice method (Campbell, 1997) is applied in analyzing the Sq variations.

The series of polynomials used to fit the scalar potential function over the spherical Earth's surface are essentially a Fourier series of m harmonics along circles of given latitude and Legendre polynomials along great circles of given longitude. Fitting the associated Legendre functions involves a superposition of a number of terms whose amplitude coefficients need to be determined in a fashion similar to the Fourier series fitting with $m = 1, 2, 3, 4$. The p_n^m show $n - m + 1$ wave oscillations in 360°. Two computational restrictions are that n must be greater than or equal to m and that the Legendre series must be truncated at a particular value of n ($n = 12$ is used in this study).

The magnetic potential of the Sq field measured from the daily mean values at universal time T from both the external (source) current and the internal (induced) current can be expressed by;

$$V_n^m = C + a\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left\{\left(a_n^{me}\left(\frac{r}{a}\right)^n + a_n^{mi}\left(\frac{a}{r}\right)^{n+1}\right)\cos(m\phi) + \left(b_n^{me}\left(\frac{r}{a}\right)^n + b_n^{mi}\left(\frac{a}{r}\right)^{n+1}\right)\sin(m\phi)\right\}P_n^m(\theta) \quad (1)$$

where C, θ, a, r, and ϕ denote a constant of integration, the geomagnetic colatitude, the geocentric distance, the Earth's radius and local time of the observatory. a_n^{me} and a_n^{mi}, b_n^{me} and b_n^{mi} are Legendre polynomial coefficients, where e and i represent the external and internal values respectively.

In Sq analysis, $r \approx a$, (a = the Earth's radius, R), where

$$a_n^{me} + a_n^{mi} = a_n^m \quad \text{and} \quad b_n^{me} + b_n^{mi} = b_n^m \quad (2)$$

Hence, Eq. (1) could be written as

$$V_n^m(\theta, \phi) = R\sum_{n-1}^{\infty}\sum_{m=0}^{n}\left[a_n^m \cos(m\phi) + b_n^m \sin(m\phi)\right]P_n^m(\theta) \quad (3)$$

For application to deep-earth conductivity modeling, the field that is measured must come from source currents completely external to the earth and from source-induced currents arising within the earth.

Schmucker (1970) introduced the method of profiling the Earth's conductivity with a transfer function using the external and internal SHA coefficients at a given site. The depth to equivalent substitute conductors that produced the observed fields at the Earth's surface was deduced from transfer function. Campbell and Anderssen (1983) generalized the form of Schmuckers's transfer function C_n^m as follows:

$$C_n^m = z - ip \quad (4)$$