International Journal of the Physical Sciences Vol. 5(6), pp. 637-641, June 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

Upper mantle electrical conductivity results from the dip equator latitudes of West African region

T. N. Obiekezie[1] and F. N. Okeke[2]*

[1]Department of Physics and Industrial Physics, Nnamdi Azikiwe University, Awka. Anambra State, Nigeria.
[2]Department of Physics and Astronomy, University of Nigeria, Nsukka, Enugu State, Nigeria.

Accepted 29 April, 2010

The very first study of the upper mantle electrical conductivity profile in the West African sub region using quiet day ionospheric currents has been carried out. The magnetometer data obtained from a chain of 10 geomagnetic stations installed in the African longitudes during the IEEY 1993 experiment were used. Spherical harmonic analysis (SHA) was used to separate the internal and external field contribution to the Sq variations. Transfer function was used to compute the conductivity–depth profile for West Africa from the paired external and internal coefficients of the SHA. We found a downward increase in conductivity that rose rapidly from 0.037 S/m at a depth of 100km to about 0.09 S/m at 205 km. This high conductivity region was found to correspond with the global seismic low velocity region-the asthenosphere.

Key words: Electrical conductivity, spherical harmonic analysis (SHA), ionospheric currents, upper mantle, West Africa.

INTRODUCTION

Solar quiet day (Sq) ionospheric currents are known to arise from thermal-tidal motions in the ionosphere and they induce a secondary current to flow in the conducting earth. The depth of penetration of this induced current depends on the characteristics of the source current and upon the distribution of electrically conducting materials in the earth. The field measured at the earth's surface is a complex mixture of the source and induced parts. Separating these currents into their component external (source) and internal (induced) parts using spherical harmonic analysis, the phase and amplitude relationships can be used to determine the conductivity within the earth.

The probing of the electrical depth structure of the earth has been achieved in the past using the Magnetotelluric (MT) and the geomagnetic deep sounding (GDS) methods. But recently it has been found that the solar quiet day ionospheric method could be used in probing the electrical depth structure of the earth. This was employed since it was discovered that the magnetotelluric (MT) and the geomagnetic deep sounding (GDS) methods are not only very cumbersome but they fail to resolve the conductivity–depth structure of the earth beyond 200 km from the crust.

The Sq method of determining the conductivity-depth profile of the upper mantle below the continents, started with the work of Chapman (1919). Chapman and Bartels (1940) made the first significant earth conductivity determinations with the separated external and internal fields. In 1970, Schumucker published the transfer equations necessary for obtaining conductivity versus depth profile from the separated external and internal SHA fields. A subsequent series of publications extended the Schumucker work with conductivity analysis of continental half sectors (Campbell and Anderseen, 1983; Campbell and Schiffmacher, 1985; 1988; Campbell, 1987; 1997; Arora et al., 1995; Campbell et al., 1998).

These works enumerated here were done in other regions of the world but not in Africa. Campbell and Schiffmacher (1988) attempted the determination of the conductivity-depth profile of the upper mantle for the seven continents of the world. But in Africa they determined for the Southern African region. Thus, no results had been obtained from the West African region. This was purely due to lack of observatories situated in

*Corresponding author. franciscaokeke@yahoo.com.

Abbreviation: SHA, Spherical harmonic analysis; **Sq,** solar quiet day.

the West African region. In 1992, the IEEY experiment was conducted and a line of ten Magnetotelluric stations were located in the West African sub region allowing to filling up this gap.

Vassal et al. (1998) used the data obtained during the IEEY experiment in the West African region and found that the dominant parts of both the electric and magnetic field diurnal regular variations are not related to the same ionospheric sources at the dip equator latitudes. They noted that the magnetotelluric and geomagnetic deep sounding methods of probing the conductivity of the upper mantle at dip equator latitudes could not yield any result. Okeke (2000) in her work pointed out that the new Sq model could yield favourable results if applied to other hemispheres.

Consequently, the Sq method is the only method that can be used in the dip equator latitudes of West African sub region. It has been found that this method has the ability to give reliable results up to the mantle transition zone where ordinarily the MT and GDS methods would not have given.

The purpose of this study is therefore, to use the solar quiet-day ionospheric current variations observed at a line of ten stations located in the dip equator latitudes of West African sub region to determine the conductivity-depth structure of the upper mantle of the region. This method is the most recent technique which has never been applied in the area under study and as such, this research is the first of its kind in the West African sub region, an innovative interesting study.

MAGNETIC DATA

In the framework of the French participation in the international equatorial electrojet year (IEEY), a chain of ten temporary magnetotelluric stations were installed between November 1992 and November 1994 along a 1200 km long meridian profile, between Lamto to Tombouctou (see Table 1 for station coordinates). These stations measured digitally the three components of the magnetic field and the two components of the telluric electric field and operated over a period of 20 months. Data from three permanent African magnetic observatories [Mbour (MBO), Bangui (BNG) and Tamanrasset, (TAM)] were also integrated into the electromagnetic data base (see Figure 1). The whole system of the ground magnetotelluric experiments (recorded minute values and computed hourly mean values) was maintained by ORSTOM (Institut Français de Recherche Scientifique pour le développement en coopération). The computed hourly values were employed in our analysis.

METHOD OF ANALYSIS

The analytical method involves the differential equations of Maxwell (1873) who showed that all the electromagnetic laws found in laboratory experiments (Faraday, Biot-Sarvat, etc) could be derived from a few compact mathematical expressions. For the situation in which an insignificant amount of current flows across the boundary between the earth and its atmosphere, Maxwell's differential equations were given a separable series solution in the spherical coordinates *r*, θ and φ by Gauss (1838) in his spherical harmonic analysis (SHA) of the Earth's main field. The separated radial solution allowed a division into parts that must be external and parts that must be internal to the earth. For these external and internal series, there are individual spherical harmonic analyses (SHA) polynomial (Legendre) terms, each having two indices, degree *n* and order *m*. The full field is then represented as paired (external and internal Legendre terms) elemental parts.

Gauss applied the SHA method to the global field observations and verified that most of the Earth's main field originated from internal sources. Schuster (1889, 1908), applied the Gauss SHA technique to show that the daily quiet-time geomagnetic field variations came mostly from sources of current external to the Earth. Details on this Gauss SHA technique can be seen in Campbell 1997. We analyzed the quiet fields with this SHA to separate the Sq ionospheric source currents from the induced currents within the Earth. Then, we applied Schumucker (1970), transfer equations necessary for obtaining conductivity versus depth profile from the separated external and internal SHA. Following the Schumucker (1970) transfer equation as given by Campbell (1997).

The depth to a conductive layer is given by;

$$d_n^m = z - p \text{ (Km)} \quad (1)$$

While the conductivity σ_n^m is given by;

$$\sigma_n^m = \frac{5.4x10^4}{m(\pi p)^2} \text{ Siemens/meter} \quad (2)$$

Where

$$Z = \frac{R}{n(n+1)}$$

$$\left\{ \frac{a_n^m\left[na_n^{me} - (n+1)a_n^{mi}\right] + b_n^m\left[nb_n^{me} - (n+1)b_n^{mi}\right]}{\left(a_n^m\right)^2 + \left(b_n^m\right)^2} \right\} \quad (4)$$

and

$$P = \frac{R}{n(n+1)}$$

$$\left\{ \frac{a_n^m\left[nb_n^{me} - (n+1)b_n^{mi}\right] - b_n^m\left[na_n^{me} - (n+1)a_n^{mi}\right]}{\left(a_n^m\right)^2 + \left(b_n^m\right)^2} \right\} \quad (5)$$

With

Table 1. Geographic positions of the magneto telluric stations operating during the IEEY West African experiment.

	Stations	Symbols of stations	Latitudes (°N)	Dip-latitudes (°N)	Distances (km) from dip-equator	Longitudes (°W)
1	Tombouctou	TOM	16.733	5.513	611.98	3.000
2	Mopti	MOP	14.508	3.288	365.00	4.087
3	San	SAN	13.237	2.017	223.91	4.879
4	Koutiala	KOU	12.356	1.136	126.11	5.448
5	Sikass	SIK	11.344	0.124	13.75	5.706
6	Nielle	NIE	10.203	-1.017	-112.85	5.636
7	Korhogo	KOR	9.336	-1.884	-209.17	5.427
8	Katiola	KAT	8.183	-3.037	-337.1	5.044
9	Tiebissou	TIE	7.218	-4.003	-444.48	5.241
10	Lamto	LAM	6.233	-4.988	-553.61	5.01

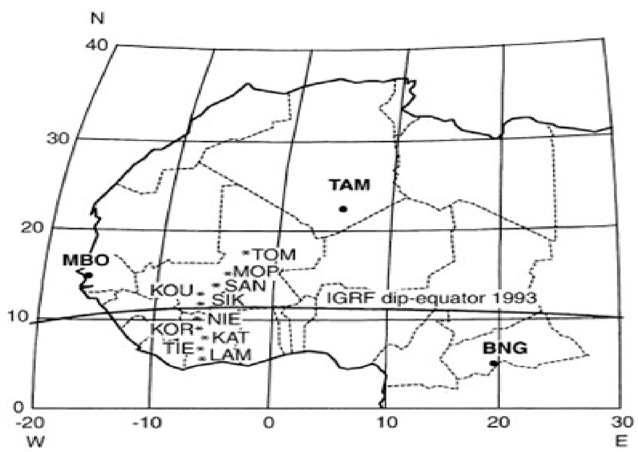

Figure. 1 The geographic location of the stations of the IEEY electromagnetic profile (*), three permanent African magnetic observatories (•). The Z = 0 line corresponds to the 1993 IGRF dip equator (Vassal et al., 1998).

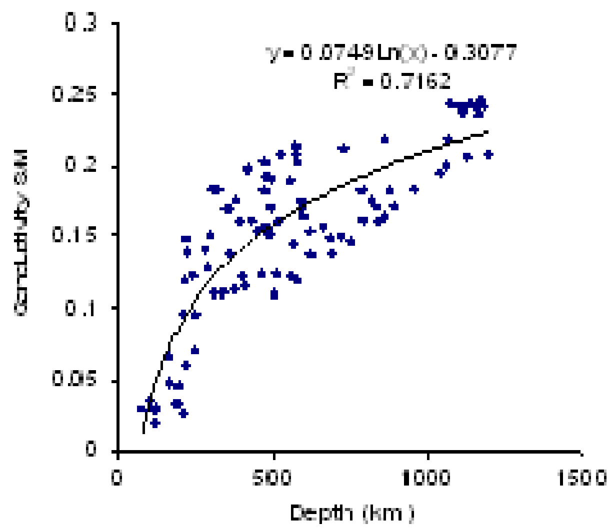

Figure 2. Conductivity-depth profile of the mantle based on the West African solar quite daily variation.

$$a_n^m = \left[a_n^{me} + a_n^{mi}\right]; b_n^m = \left[b_n^{me} + b_n^{mi}\right] \quad (6)$$

Where R is the earth radius in kilometers, a_n^{me} and b_n^{me} are the external cosine and sine coefficients and the a_n^{mi} and b_n^{mi} are the internal cosine and sine coefficients from the SHA of the Sq field.

Our analysis involves the selection of magnetically quiet-days selected from the five internationally quite days (IQDs) in each month for the year 1993. The Sq variation was determined followed by Fourier analysis of the three components of the field. Then, the polynomial fitting of the latitudinal variation of the station field Fourier components were computed, followed by the computation of the legendre polynomial coefficients. The SHA coefficients were computed to degree 12 and order four.

RESULTS

The electrical conductivity-depth profile of the upper mantle and transition zone based on the West African solar quiet-daily variation is seen in Figure 2. The small square is the conductivity-depth computation results while the solid line is the regression fitted values. The scatter observed in the conductivity–depth values could be as a result of variability of source current location, error from the SHA fitting, magnetic field contributions produced by other than quiet time field conditions (lunar, magnetospheric, etc) and error from field measurements. Despite the large scatter, the trend in the conductivity-depth profile is clearly supported (from the R^2 value). We see the conductivity profile rising rapidly from 0.037 S/m at a depth of 100 km to about 0.09 S/m at 205 km.The profile then rises steadily till it reaches 0.15 S/m at 476 km at the mantle transition zone, it continues to increase gradually until it got to 0.2 S/m at 880 km and 0.22 S/m at 1200 km at the lower mantle.

From the conductivity-depth profile the following deductions are drawn:

(1) That the Upper mantle can be viewed as a stack of inhomogeneous layers with a downward increase in conductivity which agrees with the global models, that indicated a steep rise in conductivity from 300 - 700 km. (Banks, 1969, 1972; Parker, 1971; Larsen, 1975; Campbell and Schiffmacher, 1988; Schultz and Larsen, 1990; Arora et al., 1995; Campbell et al., 1997).
(2) The rise in conductivity from about 0.037 S/m in 100 km to 0.09 S/m in 205 km correspond with the global seismic low velocity region, the asthenosphere (Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991).
(3) The global mantle seismic discontinuity at around 400 and 670 km depth could not be seen from the profile.

Our conductivity values are a little higher than the conductivity values obtained in the Australian Region by Campbell et al. (1997) and compares well with that obtained in the Himalayan region by Arora et al. (1995). Arora et al. (1995), found conductivity values of about 0.06 S/m from 50 to approximately 350 km and about 0.18 S/m at 500 km while Campbell et al. (1997) found conductivity values of about 0.045 S/m at 250 km and about 0.13 S/m at 470 km.

In the Southern African region, Campbell and Schiffmacher, (1988) found high conductivity values between about 150 and 350 km and a general increase thereafter; this is in agreement with the result of this work.

Oldenburg (1981) analysis of the upper oceanic asthenosphere and the inference of a high conductivity zone at about 200 km depth equally agree with our result. We could see correspondence existing between the high conductivity zone and the low velocity zone, this correspondence is in agreement with the global results of Tarits (1992) and the results of Agha and Okeke (2008).

Having compared our work with that obtained in other regions of the world, we therefore infer from our work; that below 400 km depth, the upper mantle under West Africa is highly conductive.

Conclusion

The application of the solar quiet day ionosphere current variations has enabled us to determine the conductivity depth structure of the upper mantle in the West African sub region. It is interesting to note that Vassal et al. (1998) employed magnetotelluric and geomagnetic deep sounding methods of probing the conductivity of the upper mantle using the same data sets employed in this present work but did not succeed in getting any result. On the other hand our technique has yielded results that are reasonable.

We found a downward increase in conductivity that rose rapidly from 0.037 S/m at a depth of 100 km to about 0.09 S/m at 205 km. The conductivity profile is found to be stepper at the upper mantle than at the transition zone. The seismic discontinuities at 400 and 670 km were not evident in the profile and the profile lies within the range of models determined from Australian, Himalayan and Southern African regions. We therefore conclude from our work that below 400 km depth, the upper mantle under West Africa is highly conductive.

ACKNOWLEDGMENTS

The IEEY experiment carried out in the African sector was possible because of the funds provided by: Ministère de la Coopération, Département de la Recherche et des Formations, ORSTOM, Département TOA (Terre Océan Atmosphère), CNET Centre Lannion, Ministère de la Recherche et de la Technologie, Centre National de la Recherche Scientifique, Département SDU (Sciencesde l'univers), CEA, Commissariat à 1Énergie Atomique the Université Paris-Sud; Abidjan University, Ivory Coast; Dakar University, Senegal. The efforts of the different individuals and groups who participated in the IEEY studies is greatly acknowledged.

REFERENCES

Agha SO, Okeke FN (2008). Upper mantle conductivity determination using quiet-day ionosphereic current, Nig. J. Phy. 20(1): 118-126.
Arora BR, Campbell WH, Schiffmacher ER (1995). Upper mantle electrical conductivity in the Himalayan region, J. Geomag. Geoelectr. 47: 653-665.
Banks RJ (1969). Geomagnetic variation and the electrical conductivity of the upper mantle. Geophys .J. R. Astr. Soc. 17: 457-487.
Banks RJ (1972). The overall conductivity distribution of the Earth. J. Geomagn. Geoelectr. Kyoto 24: 337-351
Campbell WH (1987). The upper mantle conductivity analysis method using observatory records of the geomagnetic field. Pure Appl. Geophy. 125: 427-457.
Campbell WH (1997). Introduction to geomagnetic fields, Cambridge University Press, New York p. 304.
Campbell WH, Anderssen RS (1983). Conductivity of the sub continental upper mantle: an analysis using quiet-day records of North America. J. Geomag. Geoelectr. 35: 367-382.
Campbell WH, Schifmacher ER (1985). quiet ionospheric currents of the northern hemisphere derived from quiet field records, J. Geophy. Res. 90: 6475-6486.
Campbell WH, Schiffmacher ER (1988). Upper mantle electrical conductivity for seven subcontinental regions of the earth, J. Geomag Geoelectr. 40: 1387-1406.
Campbell WH, Barton CE, Welsh W (1998). Quiet-day ionospheric currents and their application to upper mantle conductivity in Australia, Earth planets space 50: 347-360.
Chapman S (1919). The solar and lunar diurnal variation of the earth magnetism. Phil. Trans. Roy. Soc. London. A. 218: 1- 118.
Chapman S, Bartels J (1940). Geomagnetism, Oxford University Press p. 1049.
Dziewonski AM, Anderson DL (1981). Preliminary reference Earth model. Phys Earth Planet Inter. 25: 297-356.
Gauss CF (1838). Allgemeine Theories des Erdmagnetismus, in Resultate aus den Beobachtungen des magnetischen vereins im Yahr, edited by C. F. Gauss and W. Weber, translated from the German by E. Sabine and R. Taylor, 1841. Sci. Mem. Select. Trans. Foreign Acad. Learned Soc. Foreign J. 2: 184-251,
Kenneth DL, Engdahl (1991). Travel times for global earth quakes

location and phase identification ,Geophys. J. Int. 105: 429-465.

Larsen JC (1975). Low frequency (0.1 – 6.0 cpd) electromagnetic study of deep mantle electrical conductivity beneath Hawaiian islands, Geophys. J. R. Ast. Soc. p. 4.

Maxwell JC (1873). Treatise on Electricity and magnetism, Cambridge University Press, Cambridge p. 566.

Okeke FN (2000). Ionospheric Quiet-day currents and their effects on the interpretation of upper mantle conductivity. - A Review. Surveys in Geophysics 21: 487-498.

Oldenburg DW (1981). Conductivity structure of oceanic upper mantle beneath the pacific plate. Geophys. J.R. Astr. Soc. 65: 359-394.

Parker RL (1971). The inverse problem of electrical conductivity in the mantle, Geophys. J. Roy. Astr. Soc. 22: 121-138.

Schumucker U (1970). An introduction to induction anomalies, J. Geomag. Geoelectr. 22: 9-33.

Schuster A (1889). The diurnal variation of terrestrial magnetism, Phil trans. Lond. A, 180: 467-518.

Schuster A (1908). The diurnal variation of terrestrial magnetism, Phil Trans. Roy. Soc. London. Ser A. 280: 463-204.

Schultz A, Larsen J (1990). On the electrical conductivity of the midmantle. II Delineation of heterogeneity by application of external inverse solutions Geophys. J. Int, 101: 565-580.

Tarits P (1992). Electromagnetic studies of global geodynamic processes. 11th workshop on electromagnetic induction in the earth. Victoria University of Wellington 7: 1-7.21.

Vassal J, Menvielle M, Cohen Y, Dukhan M, Doumouya V, Boka K, Fambitakoye O (1998). A study of transient variations in the Earth's electromagnetic field at equatorial electrojet latitudes in western Africa (Mali and the Ivory Coast) Ann. Geophysicae 16: 677- 697.