academicJournals

Vol. 8(42), pp. 1975-1982, 16 November, 2013
DOI: 10.5897/IJPS2013.4064
ISSN 1992 - 1950 © 2013 Academic Journals
http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Crustal and upper mantle electrical conductivity structure in north central Nigeria

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Accepted 14 November, 2013

Separated spherical harmonic analysis coefficients of the external and internal parts of the observed quiet-day geomagnetic field variations (Sq) for the North Central Nigeria were used to determine the conductivity profile to depths of about 873 km by Schmucker equivalent substitute conductor method. Within the crust, the conductivity increased from 0.027 S/m at a depth of 7.4 km to 0.074 S/m at 15.5 km and 0.098 S/m at 24 km depth. It suddenly rose to 0.181 S/m at 26.5 km and then decreased to 0.131 S/m at 37.1 km depth. The conductivity within the upper mantle rose gradually from 0.043 S/m at 60.4 km to 0.045 S/m at 100.7 km and reached 0.071 S/m at 220.6 km. It fluctuated from 0.092 S/m at 273.6 km to 0.105 S/m at 457.5 km and got to 0.118 S/m at 523.1 km. Finally, it reached 0.163 S/m at 601.9 km and 0.271 S/m at 727.3 km depth. There seemed to be some evidence of discontinuities near 71-165 km, 165-221 km, 221-405 km and 405-666 km. The region showed a roughly exponential increase of conductivity with depth. The profile gave evidence of a less steep increase in conductivity with depth to about 405 km and very steep increase in conductivity thereafter.

Key words: North Central Nigeria, crust, upper mantle, spherical harmonic analysis coefficient (SHA), geomagnetic field variation, quiet day, electrical conductivity-depth structure.

INTRODUCTION

The solar quiet daily field variations (Sq) provide a natural signal source with frequencies appropriate to upper mantle conductivity studies. Field variation measurements at the observatories are sensitive indicators of a number of physical changes that transpire between the sun and the Earth's surface. The principal cause of the geomagnetic quiet day field variations is the ionospheric dynamo current created when there is a force on the ionized region of the atmosphere in the presence of the Earth's main field. Selective characteristics of the collision frequencies of the ionized atmospheric particles make the E-region electrons near 100 km the most suitable current carriers (Campbell, 1987). A force on these electrons is created by the day-to-night thermotidal changes in the atmosphere as the sun rises and falls daily through the year and by some upper atmospheric winds of global scale.

The quiet condition ionospheric source currents induce secondary currents in the conducting Earth. The fields from the Sq system penetrate beneath the crustal levels to a depth dependent upon the effective wavelength of the source and the conducting properties of the deep Earth. At the surface observatories, a summation of the source and secondary fields are recorded. A Gaussian spherical harmonic analysis (SHA) method allows the separation of the source and induced fields representing their potential functions as two converging series of terms whose coefficients are indentified by order m and degree n indices. It is assumed that the ionospheric current system can be considered as fixed with respect to the sun as the earth rotates under the system. In this view, an observatory samples the field of this current through

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360° of longitude in 24 h. With this assumption, mathematical hemisphere has been established on whose surface the field variations are responding to an external vortex current source fixed in longitude and to a conducting Earth structure that is symmetric about the axis of the sphere (Campbell and Schiffmacher, 1988).

Determination of electrical conductivity as a function of depth helps to provide knowledge of physical state and chemical composition at different depths of the Earth's interior. Anomalies of electrical conductivity are very useful in identifying the zones of melting and dehydration. Hence, delineation of these zones is very important in understanding the mobile areas of the Earth's crust and upper mantle, where tectonic movements and regional metamorphism lead to distinct patterns of subsurface conductivity (Chandrasekhar, 2011). The study of the physics of the Earth's interior, particularly in terms of the variation of the electrical conductivity with depth is very essential.

The primary purpose of this study is to estimate the general conductivity profile of the crust-upper mantle portion of the Earth in the North Central Nigeria. The resulting conductivity profile will be compared with conductivity profiles of other researchers.

METHODOLOGY

Source of data

The average hourly geomagnetic data used in this study were obtained from geomagnetic stations established in parts of the region (Abuja; 9° 40'N, 7° 29'E and Ilorin; 8°30'N, 4°33'E) by magnetic data acquisition set (MAGDAS), Japan for the years 2008, 2009 and 2010.

Method of analysis

The spherical harmonic analysis coefficients are determined from the global distribution of Fourier coefficients. With the order m (values 1- 4) and degree n (values 1-12), the external cosine and sine coefficients are computed from (Campbell, 2003):

$$a_n^{me} = \frac{(n+1)a_n^m + c_n^m}{2n+1} \quad (1a)$$

$$b_n^{me} = \frac{(n+1)b_n^m + d_n^m}{2n+1} \quad (1b)$$

and the internal cosine and sine coefficients from

$$a_n^{mi} = \frac{na_n^m - c_n^m}{2n+1} \quad (1c)$$

$$b_n^{mi} = \frac{nb_n^m - d_n^m}{2n+1} \quad (1d)$$

a_n^m, b_n^m, c_n^m and d_n^m are called intermediate coefficients and they are computed from

$$a_n^m = \frac{2n+1}{4n(n+1)} \int_0^{180} \left[X_c^m \frac{dP_n^m}{d\theta} \sin(\theta) + Y_s^m m P_n^m \right] d\theta \quad (2a)$$

$$b_n^m = \frac{2n+1}{4n(n+1)} \int_0^{180} \left[X_s^m \frac{dP_n^m}{d\theta} \sin(\theta) - Y_c^m m P_n^m \right] d\theta \quad (2b)$$

$$c_n^m = \frac{2n+1}{4} \int_0^{180} Z_c^m P_n^m \sin(\theta) d\theta \quad (2c)$$

$$d_n^m = \frac{2n+1}{4} \int_0^{180} Z_s^m P_n^m \sin(\theta) d\theta \quad (2d)$$

The integral sign in equations 2a-d means a summation over a θ range of 0 to 180°. The angle θ is the geomagnetic colatitudes and dθ is the step increment (2.5°) of the analysis; P_n^m is the Schmidt normalized associated Legendre function (Campbell, 1997). The size of these steps is selected to be appropriate to the wavelength resolution that is to be accomplished by the SHA fitting.

The conductivity determination depends upon the separated external and internal SHA coefficients computed for the analysis area. Schmucker (1970) first introduced the method of profiling the Earth's conductivity with a transfer function using the external and internal spherical harmonic coefficients at a given site. This function gave the depth to equivalent substitute conductors that would produce the observed fields at the Earth's surface. Schmucker's complex transfer function C_n^m, has real z and imaginary –p parts which Campbell and Anderssen (1983) wrote in terms of external and internal SHA coefficients:

$$z = \frac{R}{n(n+1)} \left\{ \frac{A_n^m \left[na_n^{me} - (n+1)a_n^{mi} \right] + B_n^m \left[nb_n^{me} - (n+1)b_n^{mi} \right]}{\left(A_n^m\right)^2 + \left(B_n^m\right)^2} \right\}, \quad (3)$$

and

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

where R in kilometer is the Earth's radius, z and p are in kilometers and the coefficient sums are given by

$$a_n^{me} + a_n^{mi} = A_n^m \text{ and } b_n^{me} + b_n^{mi} = B_n^m \quad (5)$$

For each n, m set of coefficients, the depth (km) to the uniform substitute layer is given by

$$d_n^m = z - p, \quad (6)$$

with a substitute layer conductivity (S/m) of

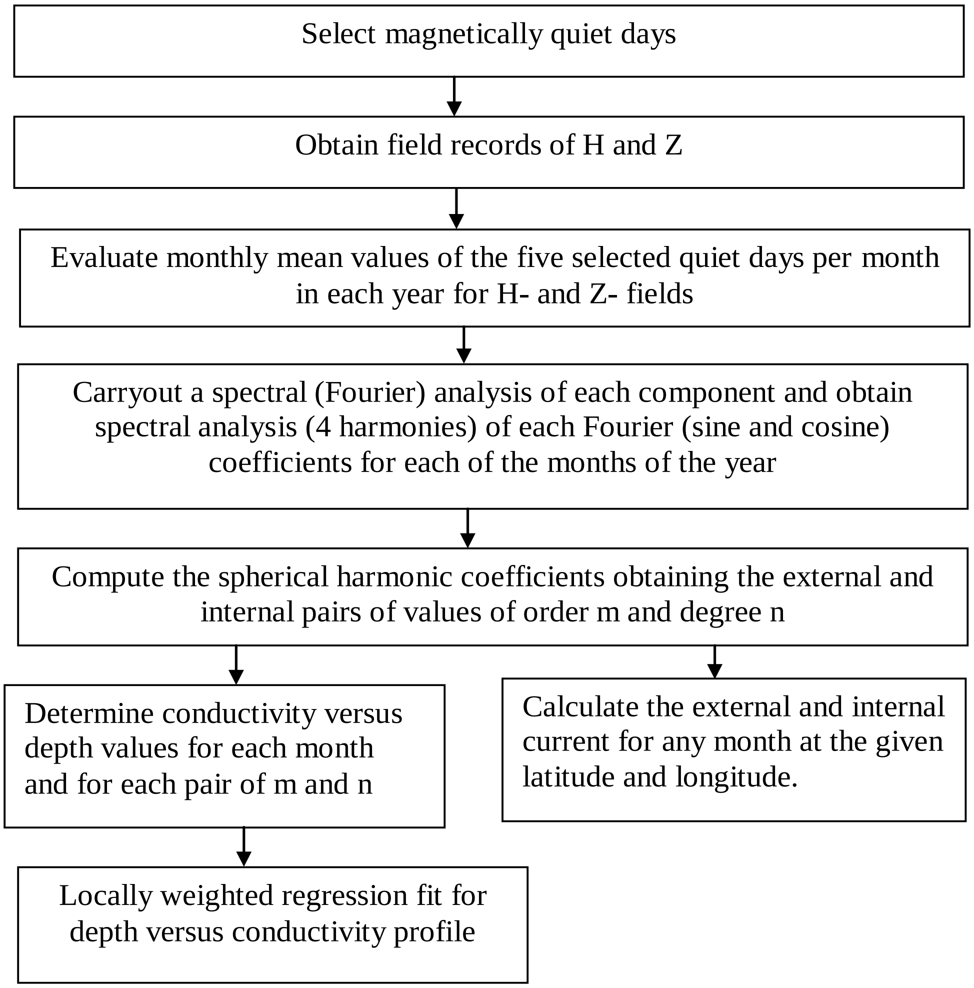

Figure 1. Data processing flow chart.

$$\sigma_n^m = \frac{5.4 \times 10^4}{m(\pi p)^2} \tag{7}$$

The ratio S_n^m of the internal to external components of the geomagnetic surface field is

$$S_n^m = u + iv \tag{8}$$

Where

$$u = \frac{\left(a_n^{me}\right)\left(a_n^{mi}\right) + \left(b_n^{me}\right)\left(b_n^{mi}\right)}{\left(a_n^{me}\right)^2 + \left(b_n^{me}\right)^2} \tag{9}$$

and

$$v = \frac{\left(b_n^{me}\right)\left(a_n^{mi}\right) - \left(a_n^{me}\right)\left(b_n^{mi}\right)}{\left(a_n^{me}\right)^2 + \left(b_n^{me}\right)^2} \tag{10}$$

The validity of Equations 6 and 7 is limited by the conditions that:

$$0^0 \geq \arg\left(C_n^m\right) \geq -45^0 \tag{11a}$$

and

$$80^0 \geq \arg\left(S_n^m\right) \geq 10 \cdot 5^0 \tag{11b}$$

Also the SHA coefficient amplitudes must not be too small because the relative errors inherent in the SHA coefficients increase as the amplitudes of the coefficients decrease.

The procedure for method of analysis is summarized in Figure 1. The original data set for this study comprised the Sq variations of five quietest days for the stations for each month of the year; 2008, 2009 and 2010. The analysis started with the selection of five magnetically quietest days from international quiet days (IQDs) in each month for the years in which the data were obtained. The hourly values for the five quietest days were summed for each month hour by hour and the average value calculated. This monthly average helps to eliminate the daily variability in the data. The Fourier coefficients were appropriately smoothed with respect to geomagnetic latitude and then, the SHA method was used on 2.5°

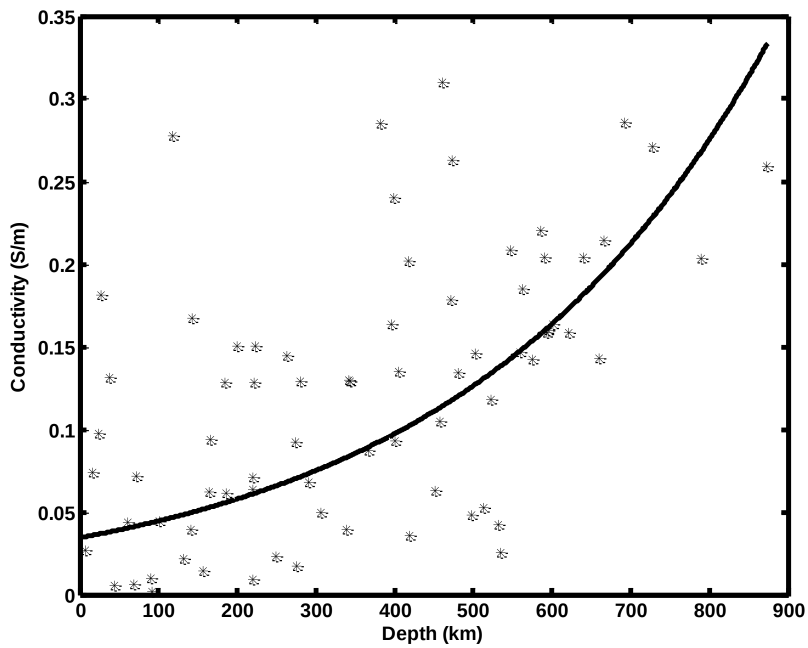

Figure 2. Crust-mantle electrical conductivity profile of North Central Nigeria.

latitude samples to obtain the Gauss coefficients for order 4 and degree 12. The local time change of field was made equivalent to longitude position. The depths to conductive layers were then computed from Equations 3, 4 and 6, while the associated conductivities were calculated from Equation 7.

RESULTS AND DISCUSSION

Figure 2 shows the resulting conductivity profile. The conductivity values clustered more between 60 and 666 km depths. The small blocks represent the conductivity-depth computation values while the solid line is the exponential regression fitted curve represented by:

$$\sigma = 0.0344e^{0.0026d}\ \text{(S/m)} \qquad (12)$$

where d is depth in kilometers. Within the crust, the conductivity increased from 0.027 S/m at a depth of 7.4 km to 0.074 S/m at 15.5 km and 0.098 S/m at 24 km depth. It suddenly rose to 0.181 S/m at 26.5 km and then decreased to 0.131 S/m at 37.1 km depth. The conductivity within the upper mantle rose gradually from 0.043 S/m at 60.4 km to 0.045 S/m at 100.7 km and reached 0.071 S/m at 220.6 km. It fluctuated from 0.092 S/m at 273.6 km to 0.105 S/m at 457.5 km and got to 0.118 S/m at 523.1 km. Finally, it reached 0.163 S/m at 601.9 km and 0.271 S/m at 727.3 km depth. There seemed to be some evidence of discontinuities near 71-165 km, 165-221 km, 221-405 km and 405-666 km. These locations are near phase change depths identified on seismic records (Dziewonski and Anderson, 1981). Equation 12 indicates the general trend of the conductivity with depth in the studied range. Although the function is drawn from the surface to 873 km, the reliable section lies between about 15 to 666 km. The notable high conductivity value seen at a depth of 462 km may be due to the same effect noted in global studies and may correspond to the olivine-spinel phase transition (Garland, 1981; Lilley et al., 1981).

The profile indicates the existence of high conductivity zone at depths between 15.5 and 37 km in the crust which is close to the result obtained by Ritz (1984) in Kedougou site, Senegal. Two interpretations may be proposed to explain this high conductivity values in the crust: (i) the existence of conductive graphite associated with extensive shear zones in the Precambrian basement (Gough, 1983); (ii) the incorporation of hydrated conductive oceanic materials in the continental crust (Drury and Niblett, 1980). The North Central Nigeria is located within the Precambrian basement in the geology of Nigeria (Obaje, 2009).

Velocity-depth profiles obtained from seismic waves by Dziewonski and Anderson (1981) averaged for the full Earth show that an abrupt rise in velocity bounds the crust and upper mantle at about 6 to 75 km. Between about 100 and 220 km deep, a low velocity zone is encountered beyond which the velocity increases gradually with steps near 400 and 670 km and high conductivity values are noted at 462 and 666 km depths in this work. The noted correlation between our conductivity profile and seismic zones might be an indirect manifestation of common process acting differently on both parameters. For a particular composition and phase of Earth material, the electrical

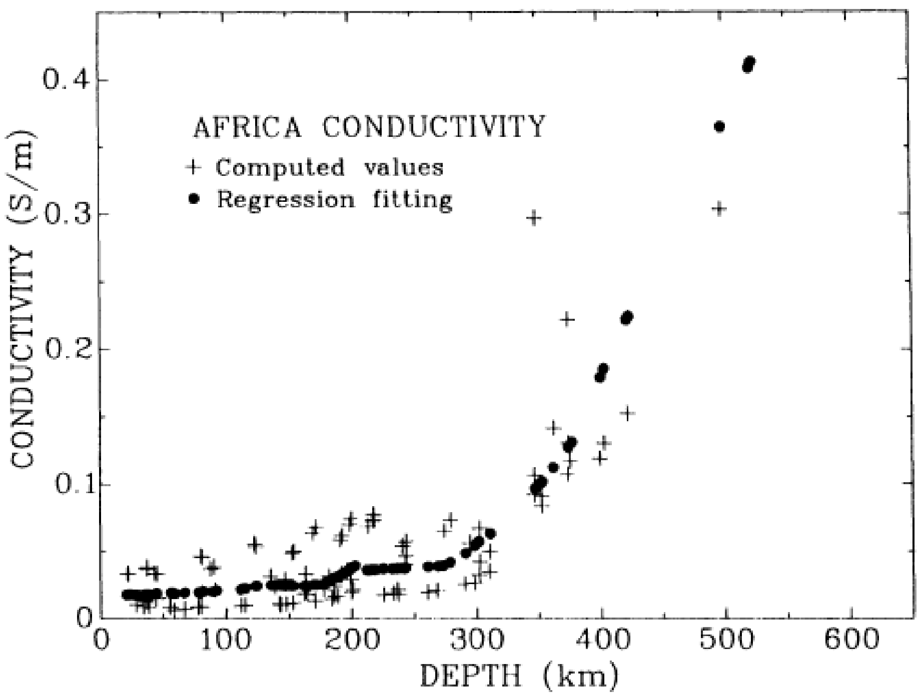

Figure 3. African region conductivity profile (Campbell and Schiffmacher, 1988).

conductivity rises almost exponentially with the negative reciprocal of the temperature (Tozer, 1970). The Earth's temperature increases with depth; therefore, for a homogeneous region the electrical conductivity increases with depth. Phase transition steps in seismic velocity occur at depths in the Earth where enhanced temperatures and pressures cause a readjustment of the mineral structure or a major composition change.

The results of this study could be compared with the results of Campbell and Schiffmacher (1988) on upper mantle electrical conductivity for seven sub-continental regions of the Earth. Their result for North American profile showed elevated conductivity from about 20 to 60 km depth; South America has an extremely high conductivity at depths less than 100 km; African and East Asian regions show no highly conducting regions at shallow depths (which corresponds with the result of this study); the central Asian region indicates increased values between about 150 to 200 km and at more than 400 km depth, Africa and central Asia have high conductivity values which agrees with the results of this study. Figure 3 is the African region conductivity profile by Campbell and Schiffmacher (1988) which is compared with the profile of the present study.

We also compared our work with that of Campbell and Anderssen (1983) on conductivity of the sub-continental upper mantle: an analysis using quiet-day geomagnetic records of North America. Their result showed that from depths of about 140 to 540 km, the conductivity in $(\Omega\text{-m})^{-1}$, may be represented by:

$$\sigma = 0.0067e^{0.0070d}$$

where d is depth in km. They also had small perturbations of conductivity indicating some layering at 140 to 220, 220 to 400 and 400 to 600 km which are close to our result. Figure 4 shows the conductivity profile of Campbell and Anderssen (1983).

These three profiles (present study, Campbell and Schiffmacher, 1988 and Campbell and Anderssen, 1983) show similar trend. Figure 5 shows the three profiles. The maximum depths for Campbell and Schiffmacher (1988) was not up to 600 km while that of Campbell and Anderssen (1983) was around 600 km, but the depth for this study exceeded 700 km. Our results have higher conductivity values above about 350 km depth than that of Campbell and Schiffmacher (1988) and above about 380 km for Campbell and Anderssen (1983). The conductivity values for the three profiles agreed between about 350 and 400 km. All the profiles show high conductivity values from about 380 km and below. Our conductivity values are smaller from about 380 km and below. The difference in the conductivity values may be due to lateral inhomogeneities.

Electrical conductivity in the Earth depends on the amount of free particle charges and their mobility. It is usually considered that the solid rock forming minerals are almost insulators and that any conductivity above about 10^{-4} S/m is due to interstitial water. The conductivity of this water varies depending on the amount and nature of dissolved salts, but the main controlling parameter is

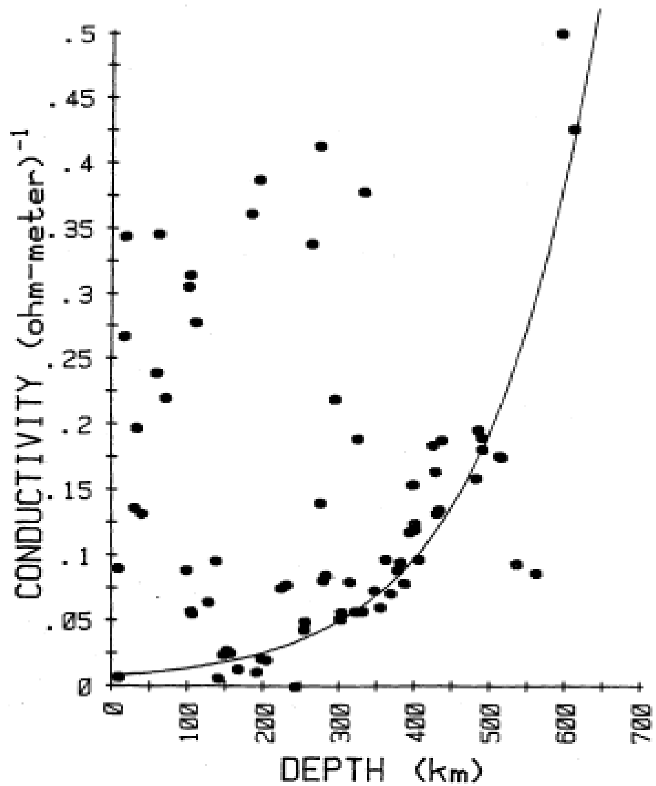

Figure 4. Conductivity profile of the Sub-continental upper mantle (Campbell and Anderssen, 1983).

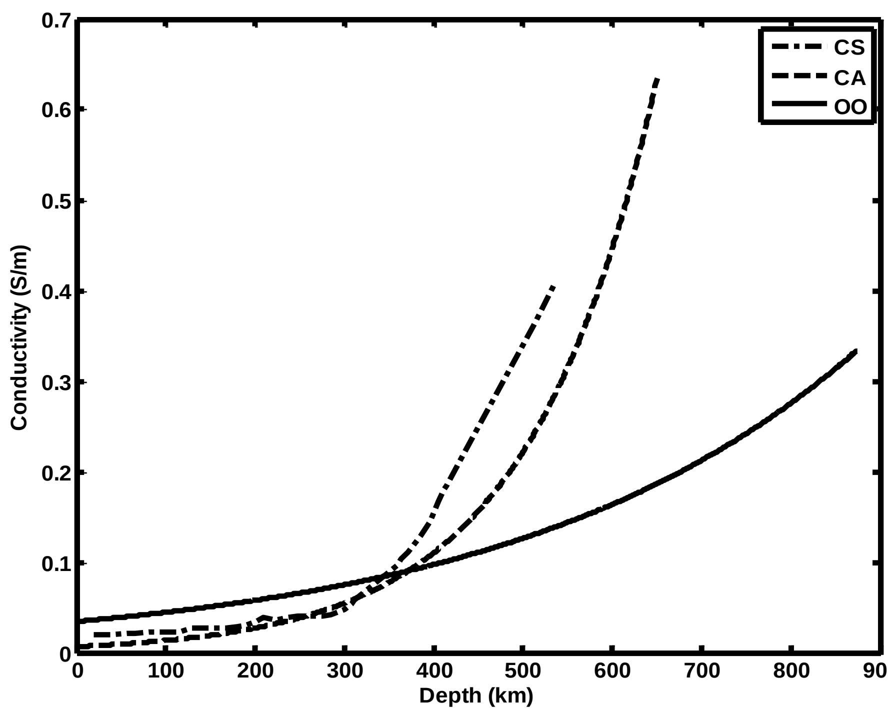

Figure 5. Comparison of the conductivity profile of the present work with other models: OO (Present study); CS (Campbell and Schiffmacher, 1988); CA(Campbell and Anderssen, 1983).

porosity. In many parts of the world, conductivities of about 0.2 S/m are found in the middle or lower crust (Parkinson and Hutton, 1989). The amphibolites-granulite transition causes the release of water. The presence of this water may be sufficient to account for the conductivity anomalies in the crust (Hyndman and Hyndman, 1968). Alternatively, the water released may depress the solidus sufficiently to cause partial melting (Adam, 1978). Hermance and Pedersen (1980) favour partial melting to explain the crustal (20 km) conductivity anomaly beneath the Rio Grande rift zone, which is an area of heat flow. Factors for increase in electrical conductivities of the continental crust include: free water with a high ionic content (fluids); free carbon (graphite); other conducting minerals (such as magnetic oxides or sulphur) and rock melts (Schwarz, 1990).

At depths of about 80 km under continents, seismic S waves are found to have a lower velocity and higher attenuation than immediately above and below this level. Conductivity is found to increase in the same depth range, giving rise to the intermediate conducting layer (ICL). This region was suggested for low velocity layer, known as the asthenosphere hypothesized to account for the replacement of crustal material on the release of stress (Jeffreys, 1952). The concept that explained these three physical parameters (conductivity, seismic velocity, and viscosity) is the presence of a small percentage of partial melt (Shankland and Waff, 1977; Adam, 1980). The best estimates of geotherms and solidus of mantle material as a function of depth indicate that, except where heat flow is unusually low, the geotherm crosses the solidus near this depth. Tozer (1981) pointed out the similarity between conductivity and seismic parameters and considered viscosity to be the common link between the two variables. He emphasized the importance of convection in the mantle and on this basis, believed that temperatures are never high enough for partial melt to be important and that water released by the instability of amphibole is the main agent controlling conductivity in the mantle.

Olivine is considered to be the chief constituent of mantle rocks. It is not stable at high temperature and pressure conditions (Katsura and Ito, 1989), implying that the mantle mineralogy changes with depth. It is believed that the transformation of α-phase of olivine into β - and γ - phases is primarily responsible for the discontinuous changes in the electrical conductivity at greater depths and that the much reported seismic discontinuity at 410 km is attributed to be α - β transformation at high pressure and temperature (Ito and Katsura, 1989). Both the β - and γ - phases have much higher elastic wave velocities than appropriate for mantle below 410 km (Anderson, 1989). The dissociation of γ -phase is believed to be related to the well-known seismic discontinuity at 660 km (Ito and Takahashi, 1988).

Magneto-telluric (MT) soundings in continental areas frequently showed a general reduction in mantle resistivity between depths of 80 and 190 km (Schmucker and Jankowski, 1972; Drury, 1978) and these depths might correspond to the lithosphere-asthenosphere boundary. This implies increase in conductivity which corresponds with our result. Patton (1980) in an analysis of data from the 'Northern Platforms and Shields', which included the East European platform, the Baltic shield, Greenland and part of the Canadian shield, concluded that there must exist a shear wave low-velocity-layer, LVsL, between 80-250 km depth underlying the whole region. Low velocity zones are identified with high conductivities.

Conclusion

The electrical conductivity profile of the crust and upper mantle of the North Central Nigeria at depths of about 7 to 873 km was determined using the quiet ionospheric current variations observed within the region. The conductivity increased exponentially with depth. There appeared to be distinct discontinuities near 71-165 km, 165-221 km, 221-405 km and 405-666 km. Although the function is drawn from the surface to 873 km, the reliable section lies within about 15 to 666 km. Our conductivity profile compares favourably with those of other regions (Campbell and Schiffmacher, 1988; Campbell and Anderssen, 1983). The trend of our conductivity profile is generally similar in values to that found for Africa and East Asia. Below 350 to 380 km, our conductivity values were smaller, and higher above 380 km depth. The high conductivity values observed in the crust may be due to the existence of conductive graphite associated with extensive shear zones in the Precambrian basement and the incorporation of hydrated conductive oceanic materials in the continental crust. The rapid increase in conductivity observed below 400 km depth is in conformity with the works of Campbell and Schiffmacher (1988) that the upper mantle under Africa and Asian regions is highly conductive.

ACKNOWLEDGEMENTS

We wish to thank International Center for Space Weather Science and Education, Kyushu University, Fukuoka, Japan, for providing us with data and Dan Okoh of Centre for Basic Space Science, University of Nigeria, Nsukka for helping us with matlab programme during the analysis of this work.

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