Mantle electrical conductivity profile of Niger delta region

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The mantle electrical conductivity-depth profile of the Niger delta region in Nigeria has been determined using solar quiet day ionospheric current (Sq). The magnetometer data obtained in 2010 from geomagnetic stations installed in Lagos by magnetic dataset (MAGDAS) in 2008 and data from magnetometers installed in some parts of Niger delta by Center for Basic Space Science, University of Nigeria, Nsukka, were employed in this study. Gauss spherical harmonic analysis (SHA) method was used to separate the internal and external field contributions to Sq current system. The result depicted that the conductivity profile rose steadily from about 0.032 S/m at a depth of 89 km to 0.041 S/m at 100 km and 0.09 S/m at 221 km. This high conductivity region agreed with the global seismic low velocity region, the asthenosphere. The conductivity profile continued increasing downward until it got to 0.157 S/m at a depth of about 373 km (close to the base of upper mantle), 0.201 S/m at 784 km and reached 0.243 S/m at a depth of 1179 km at the lower mantle.

1. Introduction

Electrical conductivity is the property of a material which describes the relative ease with which the material can allow the flow of current through it. The current which flows in deeper regions of the Earth such as the upper mantle has been noted to be induced from the geomagnetic field of external origin. Specifically, the quiet-day ionospheric current flowing in the Earth's upper atmosphere produces a varying magnetic field having a 24-h period described as Sq field. Both the Sq field (external source) and the field from the current induced in the Earth (internal source) can be measured by magnetometers in magnetic observatories.

The magnitude, direction and depth of penetration of the induced currents are determined by the characteristics of the source current as well as

the distribution of electrically conducting materials on the Earth. At the Earth's surface, the measured field is a mixture of both external (source) and internal (induced) components from the current. Using spherical harmonic analysis (SHA), these currents are separated into their external and internal components and this separation is used to determine the electrical conductivity of the Earth.

This method of probing the conductivity of the Earth started with the work of Chapman and Bartels (1940) who made the first significant Earth conductivity determinations with the separated external and internal fields. Schmucker (1970) devised a method of profiling the Earth's conductivity with a transfer function that uses the external and internal spherical harmonic coefficients at a given site. This function allowed the determination of a depth to equivalent substitute

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conductors that would produce the observed fields at the Earth's surface. Campbell and Anderssen (1983) and Campbell (1989) expanded the technique for application to the continental Sq system. Okeke (2000) from her work noted that a new model of the Sq current system could be used to obtain a mantle electrical conductivity profile for hemispheres.

This Sq method of probing the electrical conductivity of the Earth has been applied in other regions of the world (Campbell and Schiffmacher 1988; Arora *et al.* 1995; Campbell *et al.* 1998; Agha and Okeke 2007; Obiekezie and Okeke 2010) but none of these works had been carried out in Nigeria. Obiekezie and Okeke (2010) worked on conductivity-depth profile of upper mantle in the West African subregions but Nigeria was not part of the subregions they covered.

Obiora and Okeke (2011) applied solar quiet daily (Sq) ionospheric current variations in their preliminary study of application of Sq current in determining the depth to subsurface structure in Niger delta and found that Sq current could be used to probe the solid Earth up to a depth of 560 km.

The purpose of this study is to determine the mantle electrical conductivity-depth profile of Niger delta region using the solar quiet day ionospheric current.

2. Source of data

In 2008, the magnetic dataset (MAGDAS), Japan set up a geomagnetic observatory centre at the University of Lagos, Lagos (latitude: 6.813° and longitude: 3.460°). The hourly averaged geomagnetic data obtained from this station and from magnetometers installed in some parts of Niger delta (Benin 6.318°N, 5.615°E; Asaba 6.183°N, 6.750°E; Owerri 5.483°N, 7.03°E and Uyo 5.050°N, 7.933°E) by Center for Basic Space Science, University of Nigeria, Nsukka, in 2010 were employed in this study. Figure 1 shows the Google Earth map of the study area with the geomagnetic stations.

3. Method of analysis

The method of analysis involves the differential equations of Maxwell (1873), who showed that all the electromagnetic laws governing electric and magnetic field phenomena could be derived from a few compact mathematical expressions. For the situation in which field measurements are available about a spherical surface that separates the source from the induced currents (and current does not flow across this surface), Maxwell's equations

were given a separable series solution in the spherical coordinates r , θ , and ϕ by Gauss (1838) in his spherical harmonic analysis (SHA). A solution for the Earth's main field (devised by Gauss 1838) satisfying these requirements have the converging series of terms (Campbell 1997):

$$V = a \sum_{n=1}^{\infty} \left[\left(\frac{r}{a} \right)^n S_n^e + \left(\frac{a}{r} \right)^{n+1} S_n^i \right], \quad (1)$$

where a is the Earth's radius, R_e . The series solution means that for each value of n , the electromagnetic laws are obeyed as if that term was the only contribution to the field.

It is observed from equation (1) that there are two series. The first is made up of terms in r^n . As r increases, these terms become larger and larger which means that we must be approaching the current source of an external field in the increasing r direction. For the second series, the $(1/r)^n$ terms become larger and larger as r becomes smaller and smaller, which means we must be approaching the current source of an internal field in the decreasing r direction. For the Sq analysis, such series 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 allows the construction of the ionospheric dynamo current system and also the induced field gives information on the conductivity structure of the Earth.

When V is determined from measurements of the field about the Earth, analyses show that mostly all the contribution comes from the internal part of the potential function expansion. 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 is expressed by:

$$\begin{aligned} V_n^m = & C + a \sum_{n=1}^{\infty} \sum_{m=0}^n \left\{ \left(a_n^{me} \left(\frac{r}{a} \right)^n + a_n^{mi} \left(\frac{a}{r} \right)^{n+1} \right) \cos(m\phi) \right. \\ & + \left(b_n^{me} \left(\frac{r}{a} \right)^n + b_n^{mi} \left(\frac{a}{r} \right)^{n+1} \right) \\ & \left. \times \sin(m\phi) \right\} P_n^m(\theta) \end{aligned} \quad (2)$$

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, respectively. The 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. P_n^m are Legendre polynomial functions of colatitude θ only. They are quasi-sinusoidal oscillations having $n - m + 1$ waves (or

Figure 1. Google Earth map of the study area showing the geomagnetic stations.

just n waves if $m = 0$) as θ changes from 0° to 360° along a great circle of longitude. Since Sq is cyclic in 24 h, there are no $m = 0$ terms. The integers, n and m , are called degree and order respectively, n has a value of 1 or greater and m is always less than or equal to n . In Sq analysis, $r \approx a$ (a = the Earth's radius, R_e).

Taking $a_n^{me} + a_n^{mi} = A_n^m$ and $b_n^{me} + b_n^{mi} = B_n^m$, equation (2) could be written as:

$$V_n^m(\theta, \phi) = R_e \sum_{n=1}^{\infty} \sum_{m=0}^n [A_n^m \cos(m\phi) + B_n^m \sin(m\phi)] P_n^m(\theta). \quad (3)$$

From equation (3), it is observed that the functions multiplying the Legendre terms appear somewhat like a Fourier series: a harmonic series of cosine and sine terms that, when added, will produce the function they are to represent. 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 ($= 12$, used in this study).

The ionospheric Sq current system for a quiet day is assumed to be fixed in position with respect to the Sun. As the Earth spins 360° under this fixed system, surface observatories sense the 24 h change of Sq. Hence, data from a group of observatories distributed in latitude over a narrow sector of the

Earth may be used for spherical analysis. Because the quiet field changes vary slightly from day to day, the 24 h of time at the observatories can be equated to longitude in the analysis. Thus the 24-, 12-, 8-, and 6-h components of the daily field variations correspond to the $(360/m)^\circ$ components of longitudinal field change where the 'order' index m is equal to 1, 2, 3, or 4. The mirror technique using the slice method (Campbell 1997) is applied in analyzing the Sq variations.

For a geomagnetic component W (H, D or Z, in nT), the Sq fields are reconstructed using (Campbell 1989):

$$\Delta W = \sum_{m=1}^4 (C_m \cos 15mt + S_m \sin 15mt), \quad (3a)$$

where

$$C_m = A_m^0 + \sum_{Q=1}^2 (A_m^{AQ} \cos 30QM + B_m^{AQ} \sin 30QM) \quad (3b)$$

and

$$S_m = B_m^0 + \sum_{Q=1}^2 (A_m^{BQ} \cos 30QM + B_m^{BQ} \sin 30QM) \quad (3c)$$

m is 1, ..., 4 for the 24-, 12-, 8- and 6-h spectral components respectively; Q is 1 for annual and 2

for semiannual; M is the decimal month (0.0 is January 1 and 12.0 is December 31) and t is the local time in hours. The A 's and B 's are the Fourier cosine and sine coefficients.

We constructed the Fourier cosine and sine coefficients for each monthly analysis. For each analysis time sample, Sq field Fourier cosine and sine coefficients were represented by values of $X_c^m, X_s^m, Y_c^m, Y_s^m, Z_c^m$ and Z_s^m . At each co-latitude, θ , a Fourier analysis along the latitude line provides m sine and cosine coefficients to represent this field for each X , Y and Z component separately. Taking X_c^m for cosine coefficients and X_s^m for sine coefficients and in a similar way for the Y and Z field components, the intermediate coefficients; a_n^m, b_n^m, c_n^m and d_n^m are calculated for $m > 0$ using:

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

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

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

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

The integral sign in equation (4a–d) means a summation over a θ range of 0–180°. In the computation of the intermediate values, the integral is replaced by summing over the range in finite increments of $\Delta\theta$ (3° in this study) steps. The size of these steps is selected to be appropriate to the wavelength resolution that is to be accomplished by the SHA fitting. The three components H , D and Z of magnetic variations on the Earth's surface ($a = R_e$) are expressed as:

$$H = \sum_n \sum_m (a_n^m \cos m\phi + b_n^m \sin m\phi) X_n^m(\theta) \quad (5a)$$

$$D = \sum_n \sum_m (-b_n^m \cos m\phi + a_n^m \sin m\phi) Y_n^m(\theta) \quad (5b)$$

$$Z = \sum_n \sum_m (c_n^m \cos m\phi + d_n^m \sin m\phi) P_n^m(\theta) \quad (5c)$$

where

$$X_n^m(\theta) = \frac{1}{n} \frac{\partial P_n^m(\theta)}{\partial \theta}$$

and

$$Y_n^m(\theta) = \frac{m}{n} \frac{P_n^m(\theta)}{\sin \theta}. \quad (6)$$

The intermediate coefficients, a_n^m, b_n^m, c_n^m and d_n^m are related to the quiet day SHA coefficients by:

$$a_n^{me} = \frac{(n+1)a_n^m + c_n^m}{2n+1} \quad (7a)$$

$$a_n^{mi} = \frac{na_n^m - c_n^m}{2n+1} \quad (7b)$$

$$b_n^{me} = \frac{(n+1)b_n^m + d_n^m}{2n+1} \quad (7c)$$

$$b_n^{mi} = \frac{nb_n^m - d_n^m}{2n+1}. \quad (7d)$$

Further details of computation of Legendre polynomials are given in Campbell (1997).

The external fields in orthogonal directions with X pointing geomagnetic northward, Y eastward and Z into the Earth could be reconstructed from the external SHA coefficients as series of Fourier cosine and sine terms of the form:

$$X_c^m(\theta) = \sum_{n=m}^{12} (a_n^{me}) \left(\frac{dP_n^m}{d\theta} \right) \quad (7e)$$

$$X_s^m(\theta) = \sum_{n=m}^{12} (b_n^{me}) \left(\frac{dP_n^m}{d\theta} \right) \quad (7f)$$

$$Y_c^m(\theta) = - \left(\frac{m}{\sin \theta} \right) \sum_{n=m}^{12} (b_n^{me}) P_n^m \quad (7g)$$

$$Y_s^m(\theta) = \left(\frac{m}{\sin \theta} \right) \sum_{n=m}^{12} (a_n^{me}) P_n^m \quad (7h)$$

$$Z_c^m(\theta) = \sum_{n=m}^{12} n (a_n^{me}) P_n^m \quad (7i)$$

$$Z_s^m(\theta) = \sum_{n=m}^{12} n (b_n^{me}) P_n^m \quad (7j)$$

X_c^m, Y_c^m and Z_c^m are the cosine coefficients of the external orthogonal field components, while X_s^m, Y_s^m and Z_s^m are the sine coefficients. The 'e' is replaced by 'i' in equation (7e–h) when

representing the internal horizontal components. For the vertical internal component, one should use

$$Z_c^m(\theta) = - \sum_{n=m}^{12} (n+1) (a_n^{mi}) P_n^m \quad (7k)$$

$$Z_s^m(\theta) = - \sum_{n=m}^{12} (n+1) (b_n^{mi}) P_n^m. \quad (7l)$$

Hence, at any geomagnetic latitude $(90 - \theta)$ or hour of the day $(\Phi/15)$, the three orthogonal external or internal field components may be obtained from

$$X(\theta, \Phi) = \sum_{m=1}^4 [X_c^m(\theta) \cos m\Phi + X_s^c(\theta) \sin m\Phi] \quad (7m)$$

$$Y(\theta, \Phi) = \sum_{m=1}^4 [Y_c^m(\theta) \cos m\Phi + Y_s^c(\theta) \sin m\Phi] \quad (7n)$$

$$Z(\theta, \Phi) = \sum_{m=1}^4 [Z_c^m(\theta) \cos m\Phi + Z_s^c(\theta) \sin m\Phi] \quad (7o)$$

using the separated external or internal coefficients or the sum of the two for the total Sq field.

Schuster (1889, 1908) used Gauss SHA method to prove that the daily quiet time geomagnetic field variations came mostly from sources of current external to the Earth. Using SHA method to separate the Sq ionospheric source currents from the induced currents within the Earth, the quiet fields were analyzed. Applying Schmucker (1970) transfer equations necessary for obtaining conductivity *versus* depth profile from the separated external and internal SHA as described in Campbell (1997), the depth (in km) to a conductive layer was obtained from

$$d_n^m = z - p. \quad (8)$$

The conductivity σ_n^m is given by:

$$\sigma_n^m = \frac{5.4 \times 10^4}{m(\pi p)^2} \text{ (Siemens/metre)} \quad (9)$$

where

$$z = \frac{R}{n(n+1)} \left\{ \frac{A_n^m [na_n^{me} - (n+1)a_n^{mi}] + B_n^m [nb_n^{me} - (n+1)b_n^{mi}]}{(A_n^m)^2 + (B_n^m)^2} \right\} \quad (10)$$

and

$$p = \frac{R}{n(n+1)} \left\{ \frac{A_n^m [nb_n^{me} - (n+1)b_n^{mi}] - B_n^m [na_n^{me} - (n+1)a_n^{mi}]}{(A_n^m)^2 + (B_n^m)^2} \right\} \quad (11)$$

with

$$a_n^{me} + a_n^{mi} = A_n^m$$

and

$$b_n^{me} + b_n^{mi} = B_n^m \quad (12)$$

where R is the Earth's radius, a_n^{me} and b_n^{me} are the external cosine and sine coefficients and a_n^{mi} and b_n^{mi} are the internal cosine and sine coefficients from the SHA of the Sq field.

For equations (8 and 9) to be valid for the analysis, it is required that

$$0^\circ \geq \arg(C_n^m) \geq -45^\circ$$

and

$$80^\circ \geq \arg(S_n^m) \geq 10 \cdot 5^\circ \quad (13)$$

where S_n^m is the ratio of the internal to external components of the geomagnetic surface field and is given by

$$S_n^m = u + i\nu \quad (14)$$

and

$$u = \frac{(a_n^{me})(a_n^{mi}) + (b_n^{me})(b_n^{mi})}{(a_n^{me})^2 + (b_n^{me})^2},$$

$$\nu = \frac{(b_n^{me})(a_n^{mi}) - (a_n^{me})(b_n^{mi})}{(a_n^{me})^2 + (b_n^{me})^2} \quad (15)$$

C_n^m is Schmucker's complex transfer function (with real z and imaginary $-p$ parts expressed by equations 10 and 11 respectively) which was modified by Campbell (1989) and is given by:

$$C_n^m = z - ip. \quad (16)$$

It is also required that 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 analysis involved the selection of five magnetically quietest days from the internationally quietest days in each month. These five magnetically quietest days for each month are summed up hour by hour and the average computed. The Sq variations were determined followed by the Fourier

analyses of the two components of the magnetic field (H, the horizontal and Z, the vertical components). This was followed by the computation of Fourier analyzed values of H- and Z-components. Schmidt functions were then computed for the colatitude, followed by the determination of intermediate coefficients. Using the intermediate coefficients, the SHA coefficients were calculated to degree 12 and order 4. The depths to conductive layers were then computed from equations (8, 10 and 11). The associated conductivities were calculated from equation (9). The procedure for data analysis is summarized by the flow chart shown in figure 2.

4. Results

The mantle electrical conductivity-depth structure of Niger delta in Nigeria is shown in figure 3. The scatter observed in the conductivity-depth values could be due to:

- (i) error from field measurements,
- (ii) error from the SHA fitting,
- (iii) variability of source current location, and
- (iv) magnetic field contributions produced by other than quiet time field conditions.

The small star is the conductivity-depth computation values while the solid line is the regression fitted values. The errors in profiling determination that arise from the noises in the original data and from the effects of lateral inhomogeneities are very difficult to evaluate accurately. What could be determined as error is only the measure of the profile regression fitting from the distribution of computed values. A detailed error analysis based on the standard deviation of the conductivity values from the profile regression fitting was carried out and the error bars on the conductivity-depth profile were plotted. The error bars on the conductivity-depth profile of figure 3 is shown in figure 4. The error bars represent the standard deviations of the conductivity values from the profile regression fitting. The value of the standard deviation was found to be 0.016.

The conductivity observed at a depth of about of 89 km was 0.032 S/m which rose steadily to a value of 0.041 S/m at 100 km and 0.09 S/m at 221 km. The conductivity profile continued increasing downward till it got to a value of 0.157 S/m at a depth of 373 km (close to the base of upper mantle), 0.186 S/m at 483 km and 0.201 S/m at 784 km. Finally it reached a value of 0.243 S/m at a depth of 1179 km in the lower mantle. The steep increase in conductivity below 400 km indicates that in

Figure 2. Data processing chart.

West Africa and Asian regions, conductivity is very high below 400 km which agrees with Campbell and Schiffmacher's (1988) findings. There seemed to be some evidence of discontinuities near 100–290 km, 290–420 km, 420–630 km and 630–900 km and these locations are near phase change depths identified on seismic records by Dziewonski and Anderson (1981).

Our result compares favourably well with the results of similar works done by other researchers in different regions. Campbell and Schiffmacher (1988) worked in the South African region and found high conductivity values between about 150 and 350 km and a general increase thereafter which agrees with the result of this work. Arora *et al.* (1995) worked in the Himalayan region and

obtained conductivity values of 0.06 S/m from 50 km to approximately 350 km depth with alternating relative maxima near 125 and 275 km interspersed by relative minima near 210 and 330 km. The conductivity thereafter rises rapidly towards a value of 0.18 S/m at 500 km depth with no sign of leveling off. In the work of Campbell *et al.* (1998) in the Australian region, the conductivity profile starts at 0.025 S/m at a depth of 130 km and rises gradually to about 0.045 S/m at 250 km. The profile then steepens to 0.11 S/m near 360 km and rises more gradually to about 0.13 S/m at 470 km. There were no further conductivity values until the region of near 800 km was reached showing about 0.18 S/m. Our conductivity profile is relatively higher than that of Campbell *et al.* (1998), which could be as result of lateral inhomogeneity. Obiekezie and Okeke (2010) worked in the West African subregion and got a conductivity profile which rose rapidly from 0.037 S/m at a depth of 100 km to 0.09 S/m at 205 km. The profile then rose steadily till it reached 0.15 S/m at 476 km near the base of the upper mantle, 0.2 S/m at 880 km and 0.22 S/m at 1200 km at the lower mantle. The conductivity profile of this work is in close agreement with that of Obiekezie and Okeke (2010). Figure 5 is a comparison of the conductivity-depth profile of this study with the conductivity-depth profiles of Obiekezie and Okeke (2010) and Campbell *et al.* (1998).

The results suggest that there may be detectable lateral differences in the electrical conductivity structure of the subcontinental mantle. The general correspondence observed in this work between high conductivity zone and low velocity zone, the asthenosphere, is in agreement with the global results of Tarits (1992). The main feature of

Figure 3. Mantle electrical conductivity-depth profile of Niger delta region.

Figure 4. Error bar of mantle electrical conductivity-depth profile of Niger delta region.

Figure 5. Comparison of the Niger delta region conductivity profile with other models. The result is labelled OOO (dash-dotted line); OO: Obiekezie and Okeke 2010 (solid line); CBCW: Campbell *et al.* 1998 (dashed line).

the conductivity-depth distribution in the mantle revealed by global studies is a downward increase of conductivity between depths of 300 and 1000 km (Bott 1982) which is evident in the result of this work.

The conductivity-depth profile of this study shows that the uppermost mantle in Niger delta in Nigeria could be seen as a stack of inhomogeneous layers in variance with the global model obtained under the assumption of a spherically symmetric earth (Banks 1972; Berdichevski et al. 1979) in which the upper mantle, down to 400–500 km, depth is seen as a single homogeneous layer (Arora et al. 1995). The rapid increase in conductivity observed below 400 km depth is in conformity with the works of Campbell and Schiffmacher (1988) and Obiekezie and Okeke (2010) that the upper mantle under Africa and Asian regions is highly conductive.

The downward increase in conductivity agrees with the global models which depicted a steep rise in conductivity from 300–700 km (Campbell and Schiffmacher 1988; Arora et al. 1995; Campbell et al. 1998; Obiekezie and Okeke 2010).

Seismology has revealed some features of the upper mantle, such as the low velocity region between about 60 and 150 km depths and the large regional variations in primary (P) and secondary (S) velocity structure. The most significant seismological feature of the upper mantle is the low velocity zone, which approximately coincides with the region of high seismic attenuation (low Q). Beneath the oceans and the continental tectonic regions, the low velocity zone may also coincide with a region of high electrical conductivity (Bott 1982). The most widely accepted explanation of the low velocity zone in oceanic and tectonic continental regions is that it contains a small melt fraction. The influence of a small melt fraction on seismic properties depends critically on whether the melt occupies isolated or interconnected cracks. O'Connell and Budiansky (1977) have shown that a liquid fraction of less than 1% occupying an interconnected network of cracks at grain boundaries could account for the observed reduction in seismic velocities and Q value. Such an interpretation is supported by the high electrical conductivity zone underlying the oceanic lithosphere which appears to require the presence of a melt fraction occupying interconnected cracks.

5. Conclusion

This very first study of the mantle electrical conductivity structure in the Niger delta region using solar quiet day ionospheric current has yielded some interesting results which are entirely new for

the area. Some of our results are in agreement with some existing results in other regions where similar studies had been done. Hence, we draw the following conclusions:

- The high conductivity zone observed from 100 km depth to about 219 km corresponds to the global seismic low velocity region (Dziewonski and Anderson 1981; Tarits 1992; Mechie et al. 1993; Arora et al. 1995; Campbell et al. 1998; Obiekezie and Okeke 2010).
- The downward increase in conductivity agrees with the global models which depicted a steep rise in conductivity from 300–700 km (Schultz and Larsen 1990; Arora et al. 1995).
- The sharp character of conductivity increase below 350–400 km depth, noted in this work supports the earlier inference of Campbell and Schiffmacher (1988) that, below 400 km depth, the upper mantle beneath central Asia and Africa is highly conductive.
- There seemed to be some evidence of discontinuities near 100–290 km, 290–420 km, 420–630 km and 630–900 km and these locations are near phase change depths identified on seismic records by Dziewonski and Anderson (1981) and Kennett and Engdahl (1991).

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