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Electrical Conductivity Profile of upper mantle in the West African Sub region.

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Abstract:

This study used o selected geomagnetic field records and established the 1993 quiet day current system (Sq) for West Africa and used the ionospheric current source of Sq for a determination of the Earths upper mantle electrical conductivity. The magnetometer data obtained from a chain of 10 geomagnetic stations installed in the African longitudes during the IEEY 1993 experiment was used. A spherical harmonic analysis (SHA) allowed the separation of the internal and external field contribution to the Sq variations. A special transfer function allowed the computation of the conductivity – depth profile for West Africa from the paired external and internal coefficient of the SHA. A regression line fitted to the data points enabled us to get an average of values from the many scattered individual depth-conductivity determinations. It was interestingly observed that conductivity profile rose rapidly from 0.037 S/m at a depth of 100km to about 0.09 S/m at 205km.The profile then rose steadily till it got up to 0.15 S/m at 476 km at the transition zone, it continued 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. Our results seemingly, are in consonance with the results obtained in the Himalayan region and in Australian region. The high conductivity values are in agreement with the earlier results obtained in the South African region.

Key Words: *Solar quiet day (Sq), Electrical conductivity, ionospheric currents, upper mantle*

Introduction:

The variations in the Earth's magnetic field with period of less than a year originates outside the solid earth, but they include a secondary internal component caused by induced currents flowing in the crust and mantle. These induced currents are known as telluric currents. The most common short period variation is the diurnal variation which is believed to be caused by the interaction of the conducting ionospheric layers of the upper atmosphere with the main magnetic field. The ionospheric layers move in response to solar and lunar tidal forces, the main diurnal tide probably being thermally driven; this causes a varying pattern of horizontal current loops in the ionosphere as the conducting layers cut the magnetic lines of force (Both, 1982). The diurnal variations (Solar quiet and lunar) are due to electric currents which flow mainly in the dynamo region at a height of about 80-140 Km. The lunar variations are usually very small and are overlain by other effects unlike the solar quiet variations that are large. The Sq variation could be applied in estimation of conductivity of the earth. The depth to which the current penetrate depends on its period of variation and the conductivity profile of the region of the earth. The method depends on the possibility of separating the external and internal parts of the field using spherical harmonic analysis 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.

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. Other methods available include the Magneto-Telluric (MT) and Geomagnetic Depth Sounding (GDS) methods. These MT and GDS methods are very cumbersome and they fail to give reliable results beyond 200Km from the crust. Again, these MT and GDS methods of probing the conductivity of the upper mantle at dip equator latitudes as applied by Vassal et al. 1998 yielded no result since they found that the dominant parts of both the electric and magnetic field diurnal regular variations were not related to the same ionospheric sources at the dip equator latitudes. On the other hand, the Sq method proves very reliable and has been found useful in the upper mantle and transition zone where ordinarily the MT and GDS methods would have failed. Okeke (2000) noted that Sq current system is very effective in obtaining mantle electrical conductivity profile for hemisphere.

This Sq method of probing the electrical conductivity of the earth has been applied in other regions of the world but not in West Africa this may be attributed to lack of observatories. Thus, in 1992 a chain of ten magnetotelluric stations were mounted in the West African region during the French participation in the international equatorial elctrojet year (IEEY) in the African sector from November 1992 to November 1994 along a 1200Km long meridian profile between Lamto (latitude 6.2^{0}N,Cote d'Ivoire) to the south and Tombouctou (latitude 16.7^{0}N, Mali) to the north. 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 (see table 1. for station coordinates).

This paper used the quiet-day field variation in profiling the electrical conductivity of the deep Earth in the West African region. This became necessary since Vassal 1998 reported a failure in the Magnetotelluric and Geomagnetic Deep Sounding methods of probing the conductivity of the upper mantle at dip equator latitudes.

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

Method of Analysis

The method of analysis involves the spherical harmonic analysis (SHA) devised by Gauss (1838) in solving the magnetic potential function V, in which he was able to show that the potential has two parts the external (source) and internal (induced) parts of the potential function.

$$\mathrm{V} = C + R\sum_{n}\sum_{m}\left\{ \left[a_n^{me} + a_n^{mi}\right] Cosm\phi + \left(b_n^{me} + b_n^{mi}\right) Sinm\phi \right\} P_n^m(\theta) \quad (1)$$

$$\mathrm{V} = C + R\sum_{n}\sum_{m}\left[V_n^{me} + V_n^{mi}\right] \quad (2)$$

Where $C, \theta, R, and \phi$ denote a constant of integration, the geomagnetic colatitude, the earths radius and the local time of the observatory. The $_n^{me}$ 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 polynomials and are functions of colatitude θ only. They are quasi-sinusoidal oscillations having n-m+1 wave as θ changes from 0° to 360° along a great circle of longitude. The integers n and m are degree and order respectively; n has a value of 1 or greater and m is always less than or equal to n.

The SHA is followed by the application of the Schumucker, 1970, transfer equations necessary for obtaining conductivity versus depth profile from the separated external and internal SHA. Campbell (1998), modified Schumucker's, and arrived at;

$$C_n^m = z - ip \qquad (3)$$

A complex number in which the real (z) and imaginary (-p) parts are given by

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

and

$$P = \frac{R}{n(n+1)}\left\{\frac{a_n^m\left[nb_n^{me}-(n+1)b_n^{mi}\right]-b_n^m\left[nd_n^{me}-(n+1)a_n^{mi}\right]}{\left(a_n^m\right)^2+\left(b_n^m\right)^2}\right\} \qquad (5)$$

Where, R,Z, and P are given in kilometers. The coefficient sums are given by

$$a_n^m = \left[a_n^{me} + a_n^{mi}\right]$$

$$b_n^m = \left[b_n^{me} + b_n^{mi}\right],$$

For each n, m set of coefficient, the depth (in Km) to the uniform substitute layer is given by

$$d_n^m = Z - P \quad \text{(Kilometers)} \qquad (6)$$

And the conductivity σ (in Siemens/meter) is

$$\sigma_n^m = \frac{5.4x10^4}{m(\pi p)^2} \text{ Siemens/meter} \qquad (7)$$

The analysis started with the selection of magnetically quiet days from the five internationally quite days (IQDS) in each month for the year 1993. The Fourier analysis of the three components of the magnetic field were then computed, followed by the polynomial fitting of the latitudinal variation of the station field Fourier components and the computation of the Legendre polynomial coefficients. Noise that is common in high harmonics, is reduced by computing the SHA coefficients to degree 12 and order 4.

Results

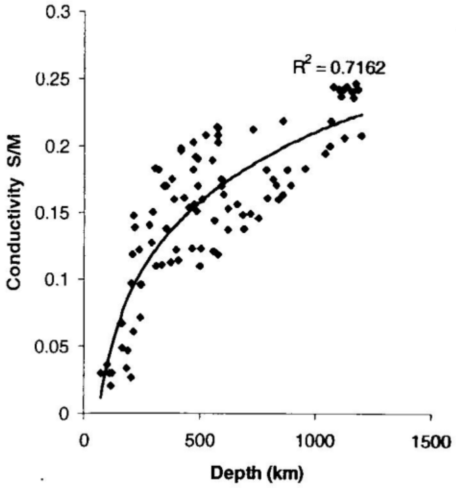

Fig 1. Computed conductivity (Siemens/meter) versus depth (Kilometer) data points (scattered values) and regression fitting (solid line) of these values.

Fig. 1 is the electrical conductivity-depth profile of the upper mantle and transition zone based on the West African solar quiet daily variation. The small square is the conductivity-depth computation results while the solid line is the regression fitted values. Our analysis result depends upon the averaging of values from the distribution of the many individual depth conductivity determinations .The scatter reflects such features as error from the SHA fitting, variability of source current location, magnetic field contributions produced by other than quiet time field conditions (ring, Lunar, etc), and random instrumental drifts.

The conductivity profile rose sharply from 0.037 S/m at a depth of 100km to about 0.09 S/m at 205km. This rise in conductivity corresponds with the global seismic low velocity region, the asthenosphere (Dziewonski and Anderson 1981, Kennett and Engdahl, 1991 Tarits 1992). Oldenburg's (1981) analysis of the upper oceanic asthenosphere and the inference of a high conductivity zone at about 200km depth is in agreement with this result.

Below the low velocity region the conductivity continued to increase downwardly until it got to 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 behaviour of the conductivity-depth profile shows that the Upper mantle can be viewed as a stack of inhomogeneous layers. The downward increase in conductivity agrees with the global models of Banks, (1969, 1972), Parker, 1971, Larsen 1975, Campbell and Schiffmacher, 1988. These models depict a steep rise in conductivity from 300km - 700km.

When compared with results obtained in Himalayan region by Arora et al. 1995, and in Australia by Campbell et al. 1998 we found that our conductivity values are very close to that obtained by Arora et al. 1995, who found conductivity values of about 0.06 S/m from 50 to approximately 350 km and about 0.18 S/m at 500 km but higher than that obtained by Campbell et al. 1997, who found conductivity values of about 0.045 S/m at 250 km and about 0.13 S/m at 470 km.

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

The steepy nature of the conductivity gradient observed at the lower part of upper mantle (the asthenospheric region) in this region and in the other regions (Himalayan, East African, Australian) are generally attributed to phase transition of mantle material from olivine to spinal structure, (Adam, 1980, Omura, 1991).The works of Duba (1992) and Duba and Von der Gonna (1994) questioned the validity of these phase transition mechanism for conductivity enhacement. Other mechanisms advanced to account for the high conductivity values observed in the Upper mantle include existence of partial melt (Shankland and Waff, 1977), Graphite carbon, (Duba and Shankland, 1982), O^- (Freund et al., 1991), defects caused during strain (Hirsch and Wang,1986), water (Tozer,1981) and hydrogen (Karato,1990). The validity of all these mechanisms has been questioned, except that of hydrogen. The geology of the region need to be considered before some of these mechanisms may be validated. Example is the mechanism of partial melt and free water which is only sustained in dynamic environment such as the volcanic system as such may not be petrologically stable throughout the upper mantle.

The diffusivities of hydrogen measured in olivine by Mackwell and Kohlstedt (1990) led Karato (1990) to suggest that considerable greater thermal stability and mobility of hydrogen may account for the high conductivity of the asthenosphere ,this suggestion is worthy of consideration though (Hirsch 1990) ascertained that the deduction is purely speculative, since it has not been disproved. The infrared spectroscopy measurement of Bell and Rossman (1992) on nominally anhydrous mantle materials, obtained from mantle derived xenoliths from the upper 150km of the mantle suggests presence of hydrogen in hydroxyl (OH) group, thus, supporting Karato's postulation. Constable (1993) argued that high concentration of hydrogen required to enhance the upper mantle conductivity sufficiently conspires the hydrogen conduction mechanism to be less effective than postulated by Karoto (1990). Independent geological and laboratory studies on the region of study need to be carried out as this will help elucidate whether the high conductivity seen in this present work between 100km-205km is due to hydrogen or other conductivity enhancing materials in the mantle.

Conclusion

This very first study of the upper mantle electrical conductivity Profile in the West African sub region using quiet day ionospheric currents has yielded some interesting results which are entirely new for the area of study. However, some of the results appear to be consonance with some existing results from other regions where such study had previously been carried out. The following conclusions are drawn from the present study:

The observed characteristics of the conductivity-depth profile reveals that the Upper mantle can be viewed as a stack of inhomogeneous layers. The downward increase in conductivity agrees with global models which indicate a steep rise in conductivity from 300km -700km.

The high conductivity zone observed from depth of 100km to 205km corresponds to the global seismic low velocity region, the asthenosphere.

The global mantle seismic discontinuity at around 400km and 670km depth were not evident in the profile.

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