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Upper Mantle Electrical Conductivity Distribution beneath the Indian Sub-continent

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Abstract: Determination of electrical conductivity of sub-lithospheric mantle beneath the Indian Sub-continent is currently underway at the Indian Institute of Geomagnetism (IIG). The work is based on estimating the electromagnetic (EM) induction response of the Earth to long period geomagnetic variations. Taking advantage of a dense network of observatories along the Indo-Russian sector, special "slice-mirror" spherical harmonic technique is applied to separate the quiet-day geomagnetic variations (Sq) into external and internal parts. The separated time-harmonics of Sq and 27-day variations are inverted to provide conductivity profile for the depth range of 50-1200 km by the Schmucker equivalent substitute conductor method. In addition to the usual steep rise of conductivity at a depth of about 400 km, the deduced conductivity profile for the Indian sector brings out the evidence of a second discontinuous conductivity increase at around 850 km depth. Comparison with some recently derived regional models show that the presence of a mid-mantle conductor in the depth range of about 850-km may be a global phenomenon. In the upper section of the mantle, two marginally enhanced conductivity layers are seen centered around 125 and 275 km. Noting their correlation with low velocity seismic zones, the role of hydrous phase in pyroxene is emphasized as a source for high conductivity at these depths.

INTRODUCTION

The transient geomagnetic variations have their origin in distant electric current systems in the Earth's magnetosphere and ionosphere, resulting from the interaction of the solar radiation with the Earth's permanent magnetic field. These externally produced magnetovariational fields (e) diffuse through the conducting layers of the Earth and produce eddy currents within the Earth, which in turn produce secondary magnetic field variations (i), measurable at the Earth's surface. The ratio of internal to external parts (i/e) is a measure of electromagnetic (EM) response of the Earth and is dependent upon both the form (spatial) and frequency of the inducing external source field variations as well as on the distribution of the electrical conductivity within the Earth. In principle, the depth of penetration of inducing field increases with increasing period of the external variations and, therefore, the EM response of the Earth at increasing periods yields information on the conductivity variation from progressively greater depths. The long period geomagnetic variations, e.g., solar quiet-day daily variations (Sq), storm-time variations and quasi-periodic variations of 27-day and its harmonics, with their appropriate frequency composition can penetrate to greater depths and are, thus, employed to image the radial distribution of electrical conductivity at sub-lithospheric mantle depths from about 100 km to 1500 km. The procedure is effective because the external source currents for these variations occur on global scale and their morphology can adequately be quantified by spherical harmonic expansion (SHE) of limited order and degree. The SHE of the observed fields at a specified frequency also allows their separation into parts of their external and internal origins, a prerequisite to compute the EM response. Given the EM response for several frequencies, the electrical conductivity model of the Earth can be deduced by model fitting or by direct inversion. Although the potential of the natural source EM method to infer the internal electrical conductivity distribution was recognized by the end of the last century, their regular applications for upper mantle electrical conductivity distribution are typified by the pioneering works of Chapman (1930), Lahiri and Price (1939), Eckhardt et al., (1963), Banks (1969) and several others. Due to the extreme sensitivity of electrical conductivity to variations in chemical composition and temperature at different depths, the derived conductivity-depth profiles help in defining the depths of phase transition, as well as to deduce temperature distribution at upper mantle depths (Banks, 1969; Duba, 1976; Adam, 1980). Since most of the earlier studies combined the data from a number of observatories, though sparsely distributed, over the Earth's surface, it was implicit that electrical conductivity distribution has a radially symmetric character over the entire globe. However, subsequently as the data quality and analysis procedures improved with time, this assumption of radial symmetry has become sceptical (see Roberts, 1986 for review). Since then, there has been growing interest to establish regional upper mantle conductivity models to check, whether there are any resolvable lateral conductivity variations at shallow or deeper depths, and if so, whether they can be related to the thermal and dynamic environments of the region.

A program to determine the upper mantle electrical conductivity distribution beneath the Indian sub-continent was motivated by this current global interest and was launched as a collaborative exercise between IIG and Global Seismological and Geomagnetism Division of the U.S. Geological Survey. The initiation to this exercise was facilitated by two major developments. First, as a part of the International Magnetospheric Study project between 1975-77, a network of geomagnetic observatories along the Indo-Russia sector (Fig.1) was upgraded, providing the best chain of observatories extending from the dip-equator to the polar region. Second, there have been attempts to modify the SHE technique that allows characterization and separation of magnetic fields, particularly corresponding to Sq, into its external and internal parts, from a longitudinal chain of observatories confined to continental half-sectors (one hemisphere) of the Earth. This technique is known as *slice-mirror* technique (Campbell, 1990). In the following paper, a brief overview of slice-mirror technique and its application to Sq-fields, recorded along the Indo-Russian chain of stations, is presented. The salient features of the derived conductivity-depth profile are discussed and compared with global and other regional models.

APPLICATION OF SLICE-MIRROR SHE

It is assumed that the vector components (X,Y,Z) of magnetic field variations (**B**) can be derived from a scalar magnetic potential V with **B** = -grad V. The potential function for each time-harmonic is expanded into series of spherical harmonics:

$$V(r,\theta,\lambda)=a\Sigma[e_n^m(r/a)^n + i_n^m(a/r)^{(n+1)}]P_n^m(\cos\theta)\, e^{im\lambda}$$

where e_n^m and i_n^m are the complex spherical harmonic coefficients of the external and internal potential parts of degree n and order m, (r,θ,λ) are spherical co-ordinates with r as radius of the Earth (in km) and θ and λ are geographic colatitude and longitude respectively. This series representation includes sine and cosine Fourier m-harmonic expansions along parallels of latitudes and associated Legendre polynomials P_n^m expansions along great circle of longitude.

Conventional numerical estimation of potential-function requires field measurements distributed all over the surface of the Earth. For the present regional conductivity analysis, we used modified "slice-mirror" SHE method, tailored from Campbell (1990), that allows creating the working sphere mathematically from a half-sector of the Earth. Fig.1 gives the schematic presentation of this approach. This method takes advantage of the fact that double vortex Sq current system, one in each hemisphere, is relatively stationary with respect to the position of the Sun (Fig.1). As the longitudinal line of observatories from equator to the pole in a narrow (slice) longitude band rotates through 360° in 24 hours under this fixed system, the recorded daily variations represent the source (external) current variations plus the induced (internal) currents within the Earth. The main theme of this technique is that the local time variations can be expressed as a function of longitude. The smoothing applied to Fourier components over the latitude range of observatories provides representation of field at regular intervals along the great circle of longitude. Since the longitudinal line of observatories are confined only to northern (primary) hemisphere, the field representations in the southern hemisphere are obtained by mirroring the field from primary hemisphere after correcting the field values for the expected seasonal and main field reversal.

CONDUCTIVITY-DEPTH PROFILE

In the spherical harmonic expansion, each polynomial term with specific degree (n) and order (m) defines the definite space-time component of the oscillating field, which independently abides by the laws of EM induction. Therefore, each polynomial term with varying (n-m) combinations can be treated as an independent physical entity in the determination of EM response of the Earth. The principal contribution to the potential function defining the Sq, comes from the fields that describe the region of the major Sq current vortex, centered at around 25°-30° geomagnetic

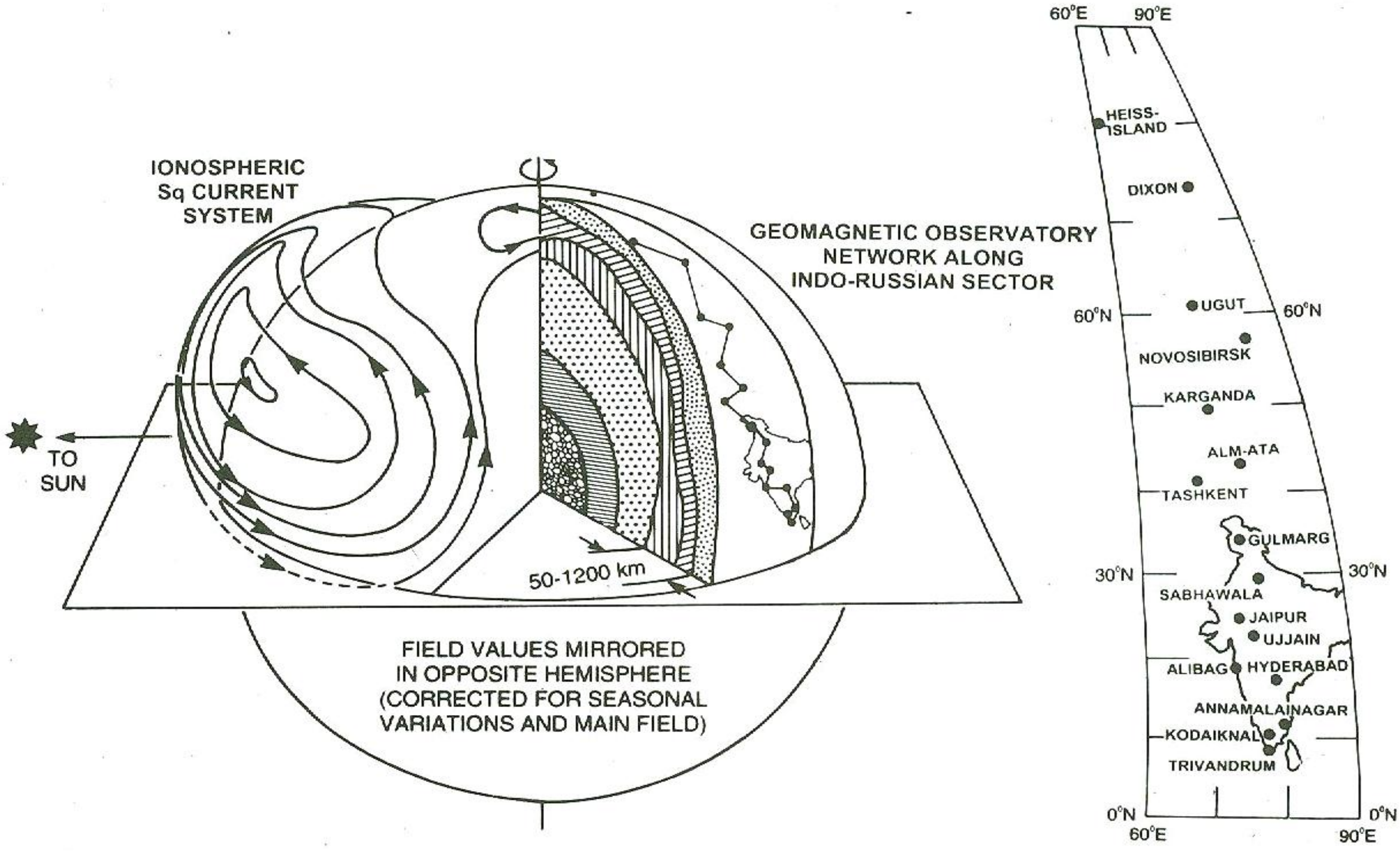
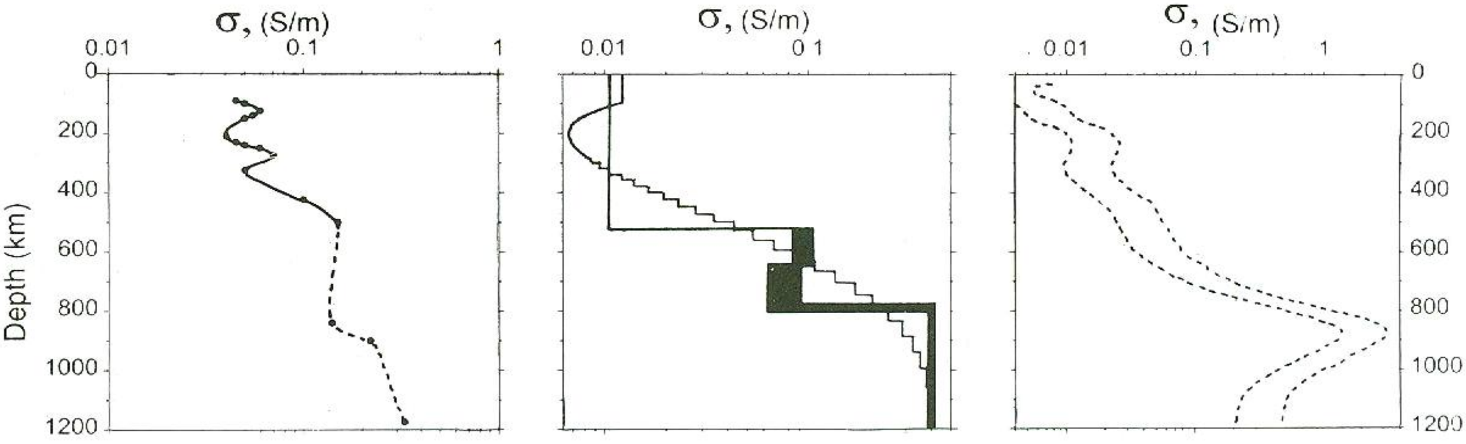


Fig.1. A schematic representation of the "slice-mirror" technique of SHE for the regional determination of upper mantle conductivity profiles using ionospheric Sq current system. The "slice" of the continental region depicts the Indo-Russian chain of observatories, extending from equator to polar regions. A cartoon of conductive layers within the Earth derived from such long period geomagnetic variations is also shown.

latitude. Such fields are best represented by the dominant (n-m) = 1 polynomial terms (Campbell, 1990) and hence only such terms are used to obtain conductivity-depth profile. The internal and external parts corresponding to polynomial terms (n-m) = 1 are employed to compute the Schmucker's C-response functions, which provide depth and conductivity of the substitute conductor, where EM response is compatible with the observed response at the frequency in question (Schmucker, 1987). Determination of the paired values of conductivity and depth for the equivalent substitute conductor for different polynomial terms served as a guide to depict conductivity variation with depth. In all, some 48 separate spherical harmonic coefficients are made, fitting the Sq fields on two representative days of each month of 1976-1977 (Campbell et al., 1993; Arora et al., 1995). The smooth conductivity-depth profile obtained, using locally weighted regression fitting, is shown as solid curve in Fig. 2a. The frequencies available in Sq variations limited the conductivity determination to the depth of about 500 km. The conductivity variation in Fig.2a from 500 km to 1200 km (dashed line) is obtained by the analysis of 27-day variation and its harmonics (Chandrasekhar and Arora, 1996). The surface magnetic field associated with this class of variations are due to fluctuations in the intensity of the extra terrestrial ring current, encircling the Earth in the equatorial plane at a distance of about 3-4 Earth radii. Thus the spatial characteristics of these long period geomagnetic variations in the SHE can adequately be represented by a single zonal harmonic, i.e., P_1^0 term (Roberts, 1986). The daily mean values of the horizontal and vertical components for the period of July15, 1975 to December 31, 1977 from the same chain of stations used in the Sq analysis are subjected to complex demodulation technique, to isolate the periodic signals corresponding to the 27-day and its sub-harmonics. Unique latitudinal distribution of the stations is effectively utilized to test, statistically, the validity of the P_1^0 dependence of the spatial behaviour of the inducing fields at selected frequencies. Those demodulates that satisfied the P_1^0 dependence are employed to obtain the conductivity and depth estimates of the substitute conductor in a manner adopted for the Sq fields.

CORRELATION OF DERIVED CONDUCTIVITY-DEPTH PROFILE WITH GLOBAL/REGIONAL MODELS

The most significant feature of the conductivity-depth profile in Fig. 2a is that conductivity variations are marked by two discontinuous steps: first in the depth range of 350-500 km and the second centered around 850 km. In terms of the rapid rise between 350-500 km, the present model is similar to the global models (e.g., Eckhardt et al.,1963; Banks,1969). Schultz and Larsen (1990) have shown that inversion of global response functions obtained under the assumption of radially symmetric distribution of conductivity are unequivocally marked by a rapid rise some where in the depth interval of 400-800 km. Campbell and Schiffmacher (1988) independently observed that a steep rise in conductivity around the depth of 400 km forms the conspicuous features of conductivity profiles derived separately for seven continental regions. Following the laboratory results of Akimoto and Fujisawa (1965), such sharp jump in conductivity is related to the phase changes of mantle material from olivine to spinel structure (Adam, 1980; Omura, 1991 and several others). When smooth global models of mantle conductivity distribution are transformed to temperature-depth profile, using laboratory based conductivity-temperature (σ-T) relationship for dry subsolidus olivine, a temperature of 1750°C at a depth of 410 km is deduced (Duba, 1976; Constable, 1993). This temperature is much higher than an independent estimate of 1400°C at 410 km based on laboratory values of the temperature-pressure for the $\alpha \rightarrow \alpha+\beta$ transition in olivine (Katsura and Ito, 1989). Duba and von der Gonna (1994) have argued that this temperature discrepancy may manifest from the difficulty in elucidating the true character of conductivity jump at the $\alpha \rightarrow \alpha+\beta$ transition due the lack of oxygen fugacity control in laboratory simulated



(a) (b) (c)

Fig. 2. Comparison of the conductivity-depth profiles for the (a) Indian, (b) European regions (Olsen,1998) and (c) Pannonian basin (Semenov et al., 1997). The solid line in (a) depicts the profile obtained by Sq analysis results of Arora et al., (1995) and the dashed line depicts the profile, obtained by the analysis of 27-day variation and its harmonics (Chandrasekhar and Arora, 1996). The sharp conductivity transitions at 400 and 800-km depth, are clearly seen in all the regions.

experiments. However, on the other hand, Constable (1993) showed that allowing a sharp boundary in conductivity at the 670-km seismic discontinuity in the regularized conductivity inversion of the global geomagnetic response functions, lowers the electrogeotherm to about only 1600° C at 410 km. From his regularized conductivity modelling, he also showed that the currently predicted value of 1400°C at the $\alpha \rightarrow \alpha+\beta$ transition could be achieved by incorporating a more conducting layer above 410-km discontinuity. More recently, Bahr et al., (1993) also arrived at similar conclusions. They observed that the EM response for a wide range of periods, from 3 hours to 600 hours, could not be explained by a single conductivity jump at either 400, 500 or 700 km. The smallest misfit was obtained from a model including an intermediate conductive layer at 300-400 km depth and a large conductivity increase at 670-km depth. The conductivity-depth profile established here for the Indian sector unambiguously brings out the evidence on the presence of additional layers of marginally enhanced conductivity above, as well as below, the 410-km discontinuity. In the global models, the upper mantle down to 400-500 km depth is seen as a single homogeneous layer, perhaps as a consequence of the effect of averaging of regional conductivity variations. In variance to this, the present conductivity distribution model for India depicts the uppermost mantle as a stack of inhomogeneous layers. The present study shows conductivity variations in the depth interval of 50-350 km are characterized by well-resolved peaks centered at 125 km and 275 km, interspersed by relative minimum near 210 and 330 km. The presence of a conducting high layer between the depth interval 100-150 km has been a common feature of many continental regions as revealed by regional magnetotelluric studies and have been reckoned to mark the conductivity transition between lithosphere and asthenosphere. Magnetotelluric soundings provide information on the conductivity distribution below the depths of 200 km only in exceptional cases. However, the present evidence of a marginally enhanced conductivity in the depth interval of 250-300 km is consistent with the requirement of a conducting layer above the 410 km discontinuity, as emphasized by the modelling results of Constable et al., (1993) and Bahr et al., (1993), discussed earlier.

The analysis and inversion of EM response functions at long period of 27-day and its harmonics have brought out the evidence of another large conductivity increase at much greater depth of about 850 km (Fig. 2a, dashed curve), a feature not seen on earlier global models. However, some recently derived regional conductivity models for the Pannonian basin (Semenov et al., 1997) and European region (Olsen, 1998) clearly indicate the presence of a sharp conductivity transition at a depth of about 850 km, which was termed as mid-mantle conductor by Semenov et al., (1997). These models are shown in Fig. 2b & 2c. All these model show fairly good agreement in terms of the depth of mid-mantle conductor, although, the magnitude of the conductivity jump varies from one region to other. The geo-electrical structure determined up to mantle depths beneath the Tucson observatory in North America (Egbert and Booker, 1992) and under the stable Canadian craton (Schultz et al., 1993) indicate the possible existence of mid-mantle conductor at around 850 km. From the evidence that electrical discontinuity is mapped in many regions, it may be surmised that the mid-mantle conductor could be a global phenomena. The main feature of the mid-mantle conductor is that it is located much deeper than the "670-km" seismic discontinuity as well as below the 520 km depth, where the b- gamma phase change is postulated to produce discontinuous conductivity change (Omura, 1991). It may be possible to relate the electrical discontinuity around 850 km with the 920-km seismic discontinuity, recently detected by Kawakatsu and Niu (1994). However, the cause for the discontinuities at these depths still remains elusive.

CORRELATION WITH SEISMIC WAVE – VELOCITY STRUCTURE

Fig. 3a & 3b show the P-wave velocity structure beneath northern and southern Eurasia, obtained, using seismic data generated by peaceful nuclear explosions (Michie et al., 1993). The velocity models are marked by a well-developed low velocity zone (LVZ) in the depth range of 200-350 km. In the upper part of the mantle above the LVZ, two layers having typical velocities of 8 km/sec ar 8.5 km/sec, respectively, are separated by a 30 – 40 km thick velocity gradient zone. This transition zone and the LVZ, both in respect of the thickness and central location, show a fairly good correspondence with the high conductivity zones indicated by the present study, based on the Sq analysis (Fig. 3d). The marginally high conductivity zone mapped around 275 km is also in excellent agreement with the low velocity zone indicated on the velocity model for the Tibetan Plateau (Fig. 3c) (Beghoul et

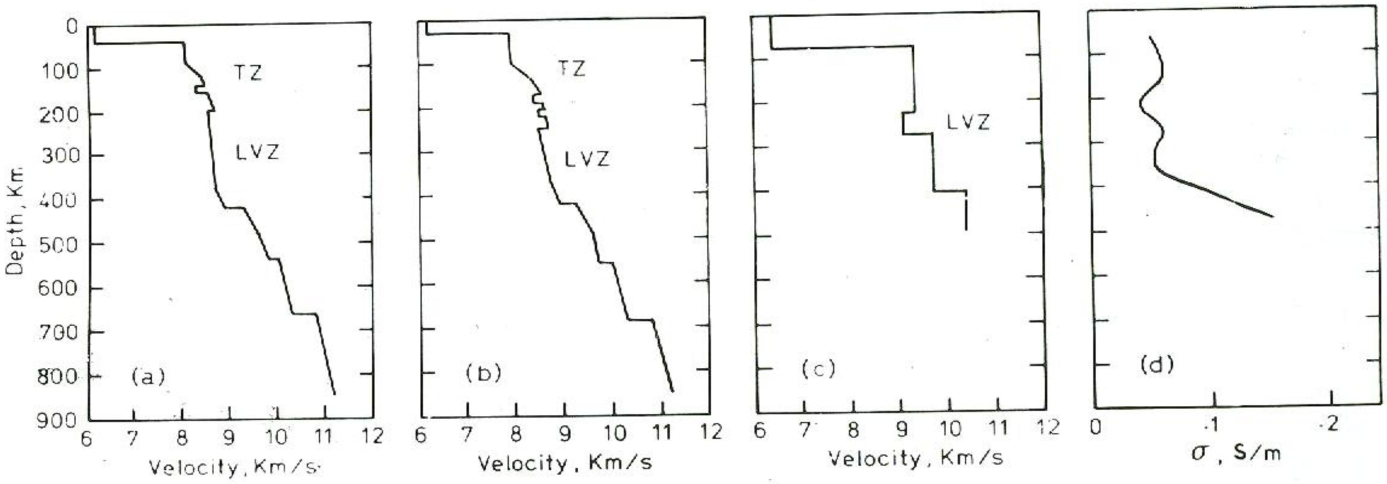


Fig. 3. P-wave velocity-depth models for (a) northern and (b) southern Eurasia (adopted from Mechie et al., 1993). (c) P-wave velocity model for Tibet Plateau (Beghoul et al., 1993). (d) smooth conductivity-depth profile given by solid line in Fig. 2a.

al., 1993). The general correspondence noted between high conductivity and low velocity zones perhaps highlight the role of volatile-bearing phases in determining the electrical properties of the mantle material. Major advances have been made in the characterization of the volatiles in nominally anhydrous mineral phases in mantle. Laboratory measurements on mantle derived xenoliths have revealed that among the major mantle materials, pyroxene is the most stable repositories of the hydrous phase (Bell and Rossman, 1992). It is also shown that presence of minor constituents, e.g., K, Na, Fe, etc., tend to stabilize the hydrous phases at mantle pressure and temperature. An exciting possibility is that marginal enhancement of conductivity in the depth range of 250-300 km may correlate with the pyroxene-rich layer, which was called 'anti-crust' by Gasparik (1991).

CONCLUSIONS

The inversion of EM response functions of the Earth at long period geomagnetic variations along the Indian sector has enabled to provide the conductivity distribution up to 1200 km depth. Apart from the features noted on the global model, the derived profile brings unambiguous evidence of conductivity changes, which appear to be a characteristic of the Indian Sub-continent at upper mantle depths. The very nature of SHE formulation permits study of the average conductivity distribution over the entire study region. Small scale variation, if any, under different tectonic blocks, remain unresolved. Further, the extent to which such a regionally averaged response is contaminated by the effects of near surface (oceanic) and crustal heterogeneities is hard to assess. The significant improvements in depth resolution and isolating effects of shallow structures are evident from the work of Egbert and Booker (1992) and Semenov et al., (1997), where both MT and geomagnetic response functions are jointly inverted. The current MT measurements on the Indian shield, mostly up to periods of 1000s, generally do not give information beyond 200 km. By introducing long period MT measurements, involving the periods in the range of 10000s, or beyond, the precision in depth resolution can be greatly enhanced. The development towards this end would be both timely and rewarding.

REFERENCES

Adam, A., 1980, Relation of mantle conductivity to physical conditions in the asthenosphere, Geophys. Surv., 4, 43-55.

Akimoto, S. and H. Fujisawa, 1965, Demonstration of the electrical conductivity jump produced by the olivine-spinel transition, J. Geophys. Res., 70, 443-449.

Arora, B.R., W.H. Campbell and E.R. Schiffmacher, 1995, Upper mantle electrical conductivity in the Himalayan region, J. Geomag. Geoelectr., 47, 653-665.

Banks, R.J., 1969, Geomagnetic variations and the electrical conductivity of the upper mantle, Geophys. J. Roy. Astr. Soc., 74, 713-746.

Bahr, K., N. Olsen, and T.J. Shankland, 1993, On the combination of the magnetotelluric and the geomagnetic depth sounding method for resolving an electrical conductivity increse at 400 km depths, Geophys. Res. Lett., 20, 2937-2940.

Beghoul, N., M. Barazangi, and B. Isacks, 1993, Lithospheric structure of Tibet and western north America: Mechanisms of uplift and comparative study, J. Geophys. Res., 98, 1997-2016.

Bell, D.R. and G.R. Rossman, 1992, Water in Earth's Mantle: The role of nominally anhydrous minerals, Science, 255, 1391-1396.

Campbell, W.H., 1990, Differences in geomagnetic Sq field representations due to variations in spherical harmonic anslysis techniques, J. Geophys. Res., 95, 20923-20936.

Campbell, W.H. and E.R. Schiffmacher, 1988, Upper mantle electrical conductivity for seven subcontinental region of the Earth, J. Geomag. Geoelectr., 40, 1387-1406.

Campbell, W.H., B.R. Arora, and E.R. Schiffmacher, 1993, External Sq currents in the India-Siberia region, J. Geophys. Res., 98, 3741-3752.

Chandrasekhar, E. and B.R. Arora, 1996, Complex demodulation and electromagnetic response function for geomagnetic field variations at 27-day and its harmonics, J. Assoc. Explr. Geophys., XVII, 91-98.

Chapman, S., 1990, The solar and lunar diurnal variation of the Earth's magnetism, Phil. Trans. Roy. Soc. London, A218, 1-118.

Constable, S., 1993, Constraints on mantle electrical conductivity from field and laboratory measurements, J. Geomag. Geoelectr., 45, 1-22.

Duba, A., 1976, Are laboratory electrical conductivity data relevant to the Earth?, Acta Geod. Geophys. Mont. Hung., 11, 485-495.

Duba, A. and von der Gonna, 1994, Comment on change of electrical conductivity of olivine associated with the olivine-spinel transition, Phys. Earth Planet. Inter., 82, 75-78.

Eckhardt, D. K. Larner, and T. Madden, 1963, Long period magnetic fluctuations and mantle electrical conductivity estimates, J. Geophys. Res., 68, 6279-6286.

Egbert, G.D and J.R. Booker, 1992, Very long period magnetotellurics at Tucson observatory: Implications for mantle conductivity, J. Geophys. Res., 97, 15099-15115.

Gasparik, T., 1991, The role of volatiles in the transition zone, EOS Suppl., 72, 498-499.

Katsura, T. and E. Ito, 1989, The system Mg_2SiO_4-Fe_2SiO_4 at high pressures and temperature: precise determination of stabilities of olivine, modified spinel and spinel, J. Geophys. Res., 94, 15, 663-15,670.

Kawakatsu, H. and F. Niu, 1994, Seismic evidence for a 920-km discontinuity in the mantle, Nature, 371, 301-305.

Lahiri, B.N. and A.T. Price, 1939, Electromagnetic induction in non-uniform conductors and the determination of the conductivity of the Earth from terrestrial magnetic variations, Phil. Trans. R. Soc. London, (A), 237, 509-540.

Mechie, J., A.V. Egorkin, K. Fuchs, T. Ryberg, L. Solodilov, and F. Wenzel, 1993, P-wave mantle velocity structure beneath northern Eurasia from long-range recordings along the profile Quartz, Phys. Earth Planet. Inter., 79, 269-286.

Olsen, N., 1998, The electrical conductivity of the mantle beneath Europe derived from C-responses from 3 to 720 hr, Geophys. J. Int., 133, 298-308.

Omura, K., 1991, Change of electrical conductivity of olivine associated with the olivine-spinel transition, Phys. Earth Planet, Inter., 65, 292-307.

Roberts, R.G., 1986, Global electromagnetic induction, Surv. Geophys., 8, 339-374.

Schmucker, U., 1987, Substitute conductors for electromagnetic response estimate PAGEOPH, 125, 341-367.

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

Schultz, A., R.D. Kurtz, A.D. Chave, A.G. Jones, 1993, Conductivity discontinuities in the upper mantle beneath a stable craton, Geophy. Res. Lett., 20, 2941-2944.

Semenov, Yu. V., A. Adam, M. Hvozdara, V. Wesztergom, 1997, Geoelectrical structure of the Earth's mantle in pannonian basin, Acta. Geod. Geoph. Hung., 32(1-2) 151-168.