Implications of novel results about Moho from magnetotelluric studies

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Moho boundary is well established on the basis of seismological studies. Magnetotelluric (MT) studies have not been able to establish this boundary due to the presence of highly conducting continental lower crust (CLC). MT studies over the Eastern Indian (3.3 Gyr) and Slave (4.03 Gyr) cratons resolve the crust–mantle boundary due to the absence of highly conducting CLC. The upper mantle beneath these two cratons cannot be of pure olivine as resistivity of the uppermost mantle is much less than the laboratory studies on pure olivine. From these two studies it can be speculated that a dynamics other than the plate tectonics possibly existed up to the mid-Archaean.

The electrical conductivity of rocks is more closely related to geochemical changes than other bulk physical properties such as acoustics impedance, density and seismic velocity. The magnetotelluric (MT) method used for the investigations of deeper structures, therefore, provides complementary, sometimes supportive but other times alternative interpretations of geochemical characters in geological units. It has been suggested on the basis of laboratory studies that for dry rock assemblages there may be an observable difference in conductivity between deep crustal mafic and upper mantle ultramafic rocks1.

Ionic conduction is a dominant type of conduction in the crust and upper mantle. It is responsible for conduction in fluids and also for olivines at high temperatures. Dry silicate rocks are highly resistive. The electronic conduction in most solids is a thermally activated process governed by the appropriate activation energy for the material, Boltzmann constant and the absolute temperature. A region of enhanced electrical conductivity therefore represents interconnected network of fluid and/or mineral conducting phase. The enhanced conductivity of the continental lower crust (CLC) remains one of the puzzles regarding the earth about which comparatively little is known. This characteristic of the deep crust has been observed globally, using MT method, but explanations for its existence remain controversial. The enhanced conductivity of CLC can be explained either by interconnected brine below the brittle–ductile transition2–5 or by interconnected, thin, grain-boundary carbon film6–8. The MT method becomes unsuitable in determining the depth of Moho due to the presence of highly conducting CLC. The presence of enhanced conductivity in CLC limits the ability to resolve the uppermost mantle conductivity structure and only a maximum limit can be placed on its value6. Therefore, in such cases, upper mantle resistivity and the nature of olivine as upper mantle constituent cannot be determined. Thus, when the enhanced conductivity of CLC is absent, only then can one resolve the conductivity structure of the uppermost mantle. Here we report the definite identification of crust–mantle boundary due to the lack of a conducting lower crust over Eastern Indian Craton (EIC)10–12 and Slave province, Canada13 using MT data and discuss its implication in delineating the crust–mantle boundary.

The eastern part of the Indian Precambrian shield is characterized by Archaean nucleus of Singhbum Granite (SG) batholithic complex and ancient supracrustals surrounded by several elongate and arcuate Proterozoic belts. The major units of the EIC are shown in Figure 114. This Archaean nucleus is bounded by the arcuate Copper Belt thrust zone (or Singhbum shear zone) in the east, north and northwest and Sukhinda thrust in the south (not shown in Figure 1). Geochronologically, the Archaean nucleus is at least ~ 3.3 Gyr old15, represented by tonalite–trondhjemite–gneiss (TTG) and amphibolites of older metamorphic group (OMG). The OMG rocks are intruded by SG of ~ 3 Gyr age which occupies most of the craton. Both OMG and SG are unconformably overlain by supracrustals of Iron Ore Group (IOG) rocks con-

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sisting of shales, schists, phyllite, banded haematite jasper and banded haematite quartzite. Along the southern fringes of the Singhbhum craton, outcrops of charnockites and khondalites (graphite-bearing) occur to the north and south of the Sukhinda thrust respectively.

Remote reference (RR) MT measurements were carried during 1996–97 field season over a part of the southern Archaean nucleus of EIC to map the electrical conductivity of the crust and upper mantle with reference to a fixed remote site16,17 (inset Figure 1). The measurements, both at the local and RR sites, were carried out for 18 h using GPS clock synchronization. Out of the 18 h of measurements, 3 h were for high range (30 to 7.5 Hz) and 15 h for low range (6.0 to 0.00055 Hz). Time series for all the five components for the entire frequency range were converted to tensor impedances using least square technique. Apparent resistivities and phases were then obtained from impedance data.

All the data collected were processed by hybrid robust, i.e. combination of robust separately with coherency weighted estimates (CWE)18,19 and rho-variance19. These schemes improve the data quality in all the frequency range, including the ‘dead band’ (5.0 to 0.1 Hz) which lies between the frequency range of two types of sources, thunderstorm and micropulsations. In this range the noise is either equal or stronger than the signal. The static shift was applied following Jones and Dumas20 by shifting the apparent resistivity (\(\rho\)) curve so that the E-polarization apparent resistivity data had the same long-period asymptote of 8000 ohm-m at 1 Hz. The corrected data are displayed in pseudosection form (Figure 2). The apparent resistivity pseudosection (top) shows a resistive model, specially in the central part of the profile. The corresponding phase values (bottom) are uniformly around 0°. These two indicate a thick electrically homogeneous resistive model. In the southeastern part of the profile, the lower resistivity is observed at relatively higher frequencies where corresponding phase values are high. Similar features are also seen in the northwestern part of the profile. Occam inversion21,22 scheme which uses the finite element forward modelling technique23,24 was applied to the hybrid processed RR MT data for 2-D conductivity modelling. The inversion scheme determines the smoothest model which matches with the observed data with certain tolerance. One determines how well to fit the data, and the inversion determines how much structure the model requires. If the required tolerance is too small, there will be no opportunity to smooth the data.

The tipper value for frequencies less than 1 Hz for the data set ranged between 0.2 to 0.3. Therefore, a 2D modelling25 to fit the data was considered. The strike direction of the structure was obtained from Swift’s strike26, polar diagrams and rotation angle plots. The average strike direction was N25°W. Data at eight frequencies were used in the range of 1 Hz to 1000 s. At first, 1-D inversion of the processed MT data was carried out. A two-dimensional cross-section consisting of a number of side by side one-dimensional models, commonly called a ‘stitched’ section was prepared (Figure 3) along section AB (Figure 1). The prepared stitched section served as the initial model for 2-D inversion. The 2-D subsurface along section AB was approximated by 67 grid points in y direction and 46 grid points in z direction. The vertical mesh was created with rows which increased in thickness with depth.

Figure 4 gives a 2D geoelectric model along AB10–12 which shows 38 km thick electrically homogenous granitic crustal layer of very high resistivity (30,000 ohm-m) below the EIC. The model fit the data to within 2.8° in phase and 0.0217 in log \(\rho_a\). A uniform layer of 8 km thickness below the granitic crust with relatively lower resistivity is found at a depth of 38 km. The resistivity of this layer is \(\approx\) 8500 ohm-m. Keeping in view the outcrops of charnockites along the southern fringes of the Singhbhum craton north of the Sukhinda thrust and of khondalites (graphite-bearing) to the south of the Sukhinda thrust, these rocks may be candidates for the 8500 ohm-m layer. This implies a greater crustal thickness, i.e. 46±2.1 km below the craton12. Seismic data in this area are not available for comparison. However, an early work based only on Bouguer anomaly and elevation data27...
Figure 2. Pseudosection of the corrected MT data: Apparent resistivity (top) and Phase (bottom).

shows the depth to the Moho near EIC around 40 km against 46 ± 2.1 km obtained from this MT study over EIC.

The resistivity of the upper mantle at a depth of 46 ± 2.1 km is about 750 ohm-m showing a decrease in resistivity by an order from that of the lower crust of about 8500 ohm-m. Constable et al. obtained the conductivity of pure olivine to a reasonable approximation in the temperature range 720–1500°C as:

\[ \sigma = 10^2 \cdot 402 \cdot e^{-1.60eV/kT} + 10^9 \cdot 17 \cdot e^{-4.25eV/kT} \]  

(1)

where \( T \) is the temperature, \( k \) is the Boltzmann constant and eV is the electron volt.

From eq. (1) the resistivity of upper mantle at a depth of 46 km (temperature gradient 25°C/km = 1150°C) should have been 4000 ohm-m. However, the resistivity from MT studies at this depth is 750 ohm-m only.

In the southeastern end of the profile, the thickness of the granitic crust remains 38 km. But at a depth of 8–10 km to 20–25 km, a low resistivity zone is seen. This low resistivity zone extends beyond the profile of measurement. Similarly, in the north western end of profile a low resistive zone is seen at a depth of about 18 km and extends up to 33 km. The source area for basic enclaves and intrusive basic dykes in SG can explain conducting zones of the northwestern and southeastern parts of the profile. As compared to southeastern end, the granitic
crust is around 23 km in north western part towards the Dalma volcanic belt. 2-D modelling also was carried out using Very Fast Simulated Annealing (VFSA) technique. Moho depth obtained by VFSA is 46 ± 2.6 km. The models obtained by using Occam and VFSA inversion schemes are in agreement. The thinning can be attributed to a much younger (1.6 Gyr) plume magmatism in Dalma volcanic belt. The presence of a mantle plume has important implications for the breakup of continents and evolution of volcanic margin. Plume arrival beneath a continent is not marked by sudden onset of mafic volcanism. The initial thermal input of the plume promotes gentle doming and low-extension-factor rifting, possibly accompanied by thinning of the subcontinent lithosphere.

Bhattacharya et al. obtained the conductivity of 0.00012 S/m for CLC under EIC which is in broad agreement with the experimental results. A possible explanation for the CLC below EIC is the absence of imbrication of sedimentary material and underplating of mafic crust related to subduction processes. About 8 km thick lower crustal layer occurring at a depth of 38 km, and extending...
horizontal for more than 40 km as revealed by this MT study will be difficult to explain by sub-horizontal disposition along a thrust. Near subduction boundary the down-going slab usually becomes steeper. Plume magnetism can potentially explain the horizontal disposition and layered pattern of the crustal structure of the region\(^\text{12}\). Indeed Nd-isotope studies of the TTG-amphibolites of OMG rocks strongly suggest their derivation from a depleted plume source\(^\text{13}\).

Jones and Ferguson\(^\text{13}\) presented the result of the MT survey conducted as part of Lithoprobe’s Slave-northern Cordillera lithospheric evolution (SNORCLE). The RR MT data were acquired in the frequency range of 10000–1 Hz on the south-western corner of the Archaean Slave Craton – the oldest craton (~4.03 Gyr).

The acquired time series data at each site were processed using a robust multi-remote-reference algorithm (method 6, ref. 32). The effect for local distortions of the electric field of the estimated responses were corrected\(^\text{13}\). The conductivity varies with depth only as the contoured MT phases for all the sites in two orthogonal direction shows uniform lateral behaviour. Therefore, 1-D inversion of the processed data using Occam inversion scheme\(^\text{14}\) was carried out by them. In this work, 27 frequencies in the range of 1 Hz – 1000 s were used.

The model obtained over Slave Craton shows a low conductivity uppermost layer of <1 km underlain by a more conductivity layer to a depth of 2–3 km. Below this there is a region of very low conductivity (<0.000025 S/m) to some tens of kilometres depth, beneath which is a moderately conductive (0.00025 S/m) homogeneous basal layer. The obtained Moho depth was 35.8 ± 1.5 km. The obtained result is consistent with the obtained depth from seismic reflection, refraction and teleseismic studies. The resistivity of upper mantle at the Moho depth as obtained in the Slave Craton using eq. (1)\(^\text{13}\) should be 300,000 ohm-m which is much higher than the value of 4000 ohm-m obtained from MT studies.

The comparison of relevant parameters and features of the geoelectric models for EIC and Slave Craton are given in Tables 1 and 2.

It is emphasised that these are the only two rare instances where the absence of conducting CLC, i.e. lower crustal conductor (LCC) is observed. This enabled identification of definite crust–mantle boundary, upper mantle resistivity and the nature of olivine as the upper mantle material.

The conductance of CLC under EIC\(^\text{12}\) and Slave Craton\(^\text{13}\) are less than 1S as against the minimum conductance of 20 S generally obtained for mid- to late-Archaean cratons\(^\text{13}\). MT study over Slave province, indicates that in the early Archaean rocks (~4 Gyr) absence of conducting CLC suggest a quite different dynamics than the plate tectonics process\(^\text{15}\). One speculates that this difference addresses questions of early earth development and tectonic processes, and the applicability of plate-tectonic theory to the early- to mid-Archaean.

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