The electric Moho

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Since Mohovicic[1] discovered a dramatic increase in compressional seismic velocity from 5.68 km/s to 7.75 km/s at a depth of 54 km beneath the Kulpa Valley in Croatia, the "Moho" has become arguably the most important seismic horizon in the Earth in its adopted geological role as defining the crust-mantle boundary. It is now known to be a ubiquitous feature of the Earth, and is usually assumed to separate lower crustal mafic rocks[2] from upper mantle ultramafic rocks[3]. Electromagnetic experiments conducted to date have failed to demonstrate a convincing change in electrical conductivity at the base of the crust. Here we report on the interpretation of magnetotelluric data from the southwestern edge of the Slave craton which show an unequivocal change at the Moho, the seismically-defined base of the crust. This change is a conductivity increase with depth, contrary to expectations, and requires a conducting phase in the upper mantle beneath the Slave craton.

One still inadequately explained feature of the Earth is the enhanced conductivity of the continental lower crust[4] observed over the last 30 years using principally the natural-source magnetotelluric (MT) electromagnetic method. Suggestions of an interconnected brine below the brittle-ductile transition[5] are met with petrological scepticism by some[6], whereas counter suggestions of an interconnected thin grain-boundary carbon film[7] also has its detractors[8]. Notwithstanding its cause, one consequence of the existence of this lower crustal conducting layer is

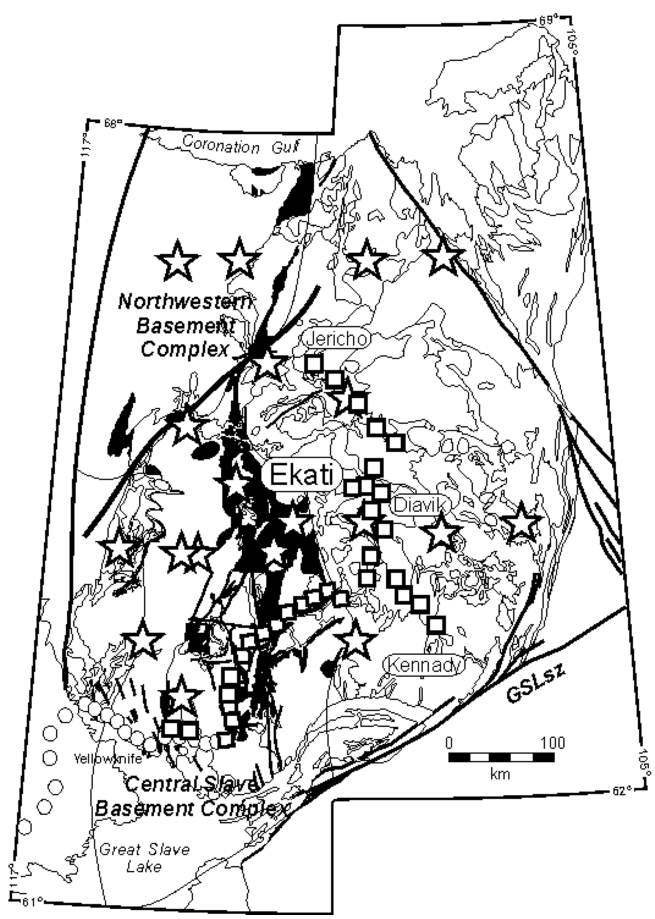

Figure 1: Tectonic map of the northwester part of the Slave craton with MT site locations

that it is virtually impossible to determine its thickness. The appropriate orthogonal parameterization of a electrically conducting layer sandwiched between two resistive ones is not in terms of the layer's conductivity (the inverse of its resistivity) and thickness, but rather in terms of the products and ratios of these two, i.e., its conductance (conductivity-thickness product) and resistance (resistivity-thickness product)[4,9], with the former typically well-resolved and the latter virtually unresolvable. One can trade-off the conductivity and thickness of the conducting lower crust and obtain the same MT response to within highly precise data error (see e.g. Fig. 3-6 in Ref. 4). Accordingly, all interpretations of MT data that include a conducting lower crust and a step-wise conductivity change at the base of the crust are suspect, as are most lack of interface correlations.

An electromagnetic survey conducted as part of LITHOPROBE's SNORCLE[10] (Slave-NORthern Cordillera Lithospheric Evolution) transect involved wide-band (10^{-4} – 10^{3} s) and long-period (10 – 10^{4} s) MT measurements at sites along the road crossing the southwestern corner of the Archaean Slave craton (Fig. 1). The Slave craton, located in the northwestern Canadian Shield, is one of the world's smallest Archaean cratonic provinces (400 x 600 km) and is distinct in its abundance of sedimentary rocks[11]. It currently holds the title of hosting the oldest rocks in the world, the Acasta gneisses dated at 4.03 Ga[12].

The 12 MT sites on the exposed craton were along an approx. 150 km east-west profile with the city of Yellowknife in the centre. The 7 sites west of Yellowknife were on the Anton complex, previously defined as a unique basement terrane[13] but now recognised as an integral part of a central Slave basement complex[14]. The time series data acquired at each MT site were processed using a robust multi-remote-reference

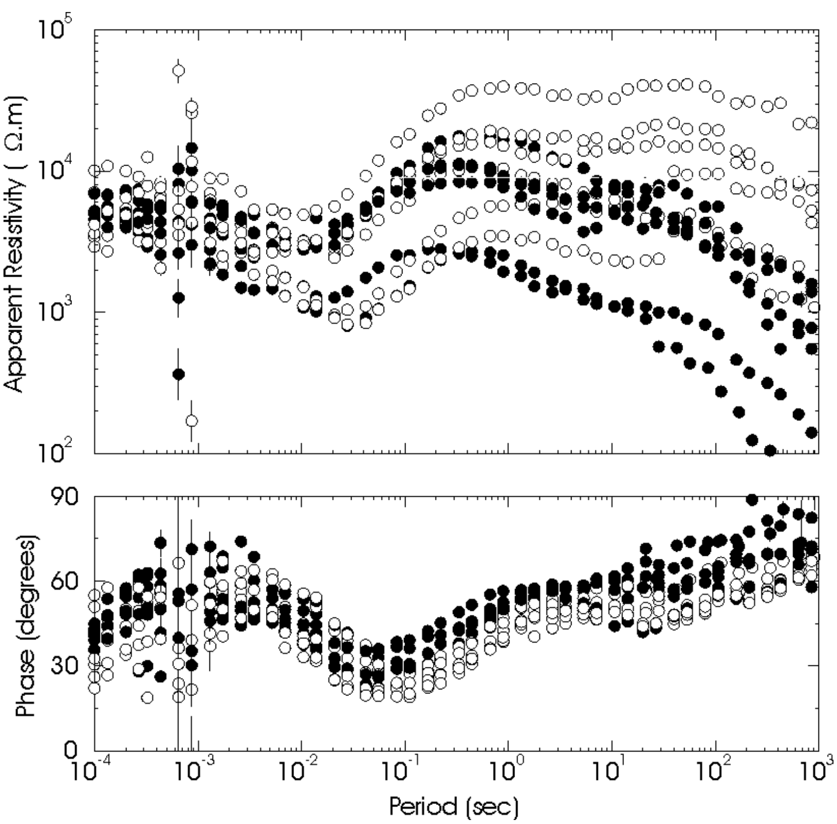

Figure 2: Magnetotelluric responses observed at the six sites west of Yellowknife on the exposed Slave craton.

algorithm[15], and the estimated responses were corrected for local distortions of the electric field [16] to obtain the regional responses in a strike direction of N41W. The local distortions were small at all sites, indicative of little near-surface conducting heterogeneity. The apparent resistivity and phase curves from all sites, except the westernmost one which was affected by the nearby Paleozoic sediments, are shown in Fig. 2, with the MT responses parallel to electrical structure (N41W) in solid circles, and those perpendicular to structure (N49E) in open circles. Note the similarity of phase response from all sites, and that the apparent resistivity curves are multiplicative versions of each other, indicative of minor static shifts[17]. The response curves from each site virtually overlie one-another from 10^{-4} – 1 s, suggestive of a region in which the conductivity varies with depth alone within the crust.

The data from the central site on this profile is representative of the whole profile, and is shown in Fig. 3. Apart from the scatter in the well-known high-frequency "dead-band" between 1 kHz – 3 kHz[18] and at the two lowest periods, the data are of excellent quality and the apparent resistivity and phase curves are self-consistent[19]. The parallel and perpendicular phases are identical to about 10 s, indicative of one-dimensional structure to depths in excess of 75 km (based on "depth of maximum eddy current flow"[20]). Inverting the 27 averaged[21] apparent resistivities and phases in the period range 10^{-3} – 10 s, with an assumed error floor of 1^{O} in phase and 3.5% in apparent resistivity, yields two of the three models shown in Fig. 4. These two models represent end-member cases of possible acceptable models in that the layered-Earth one[22] represents the model with the fewest number of uniform layers that fit the responses, whereas the continuous one represents the smoothest one in terms of having the smallest resistivity gradient with depth[23]. Both models fit the responses to

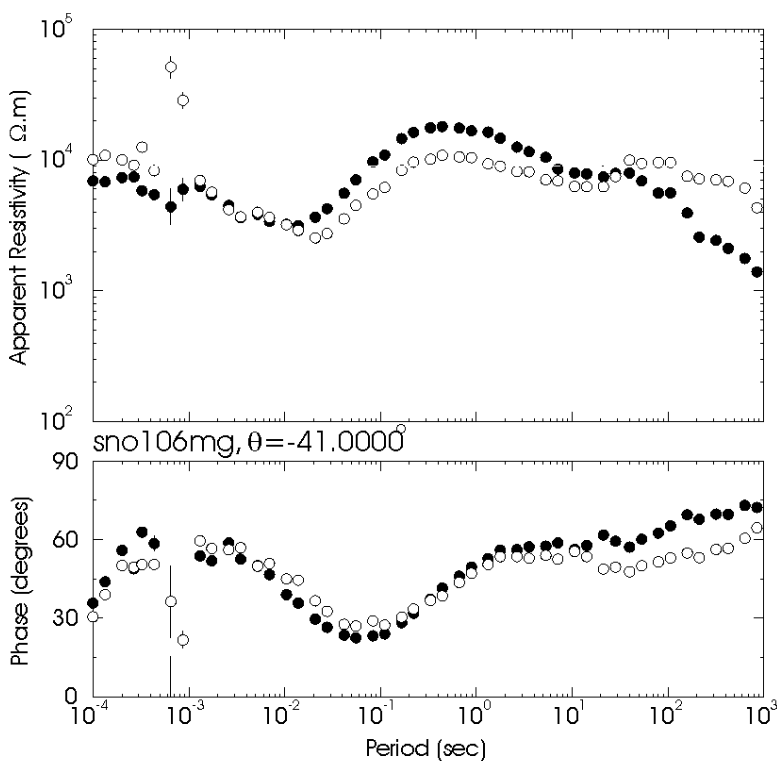

Figure 3: Magnetotelluric response from the central site on the profile.

approximately the same misfit tolerance equivalent to a normalised RMS of 1.4 – 1.5. The models are consistent in exhibiting a shallow (<1 km) resistive uppermost layer underlain by a less resistive layer to a few kilometres, then underlain by a highly resistive (>40,000 Ω.m) layer to some tens of kilometres beneath which is a moderately resistive (4,000 Ω.m) basal layer. Based on the layered Earth model, the change to the basal layer occurs at a depth of 36.2 +/- 1.5 km. This interface is the second best-resolved model eigenparameter[9], and the data most sensitive to its variation are the apparent resistivity values in the period range 0.4 – 5 s, and the phase values in the range 0.1 – 0.7 s.

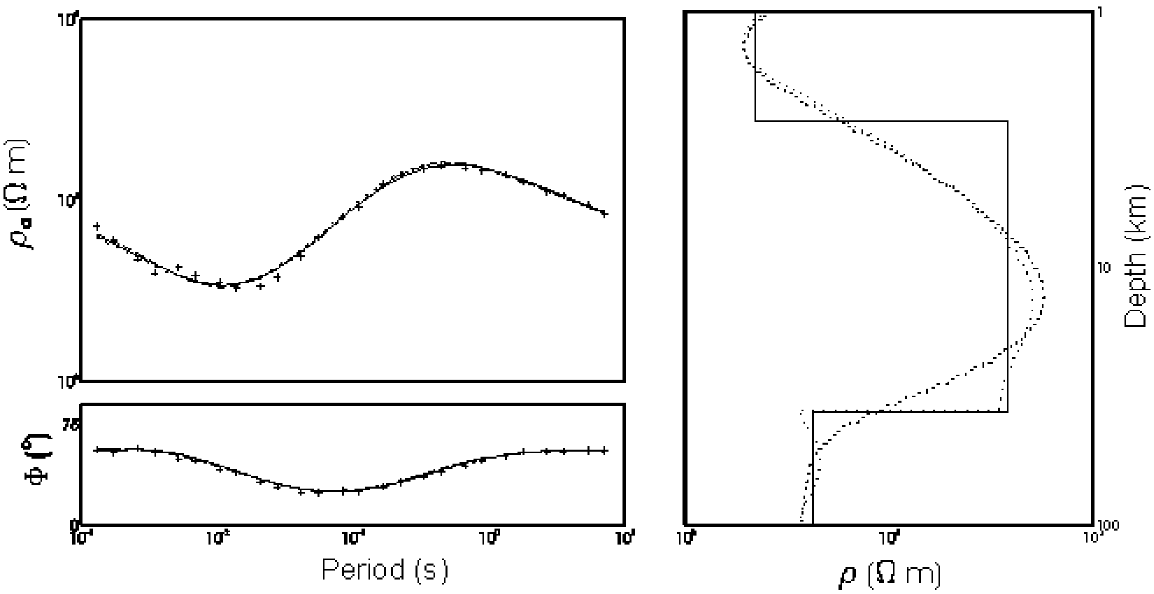

Figure 4: One-dimensional resistivity-depth models that fit the arithmetic average of the two orthogonal responses shown in Fig. 3.

Seismic reflection[24], refraction[25] and teleseismic[26] studies along the same profile are all consistent in giving a Moho depth of around 36 km. Accordingly, we can associate the deep resistivity change in the layered Earth model with the seismically-defined crust-mantle boundary. Re-performing the smooth inversion but removing any penalty associated with a stepwise change in resistivity at 36 km yields the third model plotted in Fig. 4. This model replicates the shape of the layered-Earth model almost exactly below 10 km and has an order-of-magnitude decrease in resistivity across the boundary.

This is the first time that there is definitive identification of a change in electrical resistivity at the crust-mantle boundary, and is a direct consequence of the resistive lower crust. The resistivity values for the lower crust, at around 40,000 Ω.m, are consistent with laboratory studies on candidate rock assemblages[27], but the resistivity of the uppermost mantle at around 4,000 Ω.m is too low by two orders of magnitude for an isotropic olivine mantle[28] at appropriate temperatures at the base of the crust (<400^{O}C). Oceanic uppermost mantle is consistent with an olivine conductivity model[29], as is the mantle observed beneath the Archaean Rae province to the east of the Slave craton[30]. Due to the screening effects of the lower crustal conductor seen in almost all regions, the actual resistivity of the continental uppermost mantle is unresolvable and only a minimum bound can be placed on its value[31]. Only in cases where this conducting layer is absent can the true resistivity of continental uppermost mantle be determined. Consequently, published values of this resistivity [32], typically in the range of 80-200 Ω.m, must be treated with caution.

The uppermost mantle beneath the Anton complex is laterally homogeneous in contrast to the Superior craton which displays strong horizontal electrical anisotropy [33]. This electrical anisotropy has been interpreted in terms of a carbon film on the grain boundaries interconnected in the aligned crystallographic fabric direction[34]. Other possible candidates for enhancing the electrical conductivity of the sub-crustal mantle include hydrogen diffusion [35], hydrated mineral phase[36] and partial melt[31], and the latter is clearly untenable for this region. None of these is without serious objection and, as with the lower crustal conductivity, more observations need to be undertaken and interpreted together with ancillary information.

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