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The electric Moho

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Since Mohorovičić[1] discovered a dramatic increase in compressional seismic velocity at a depth of 54 km beneath the Kulpa Valley in Croatia, the 'Moho' has become arguably the most important seismological horizon in Earth owing to its role in defining the crust–mantle boundary. It is now known to be a ubiquitous feature of the Earth, being found beneath both the continents and the oceans, and is commonly assumed to separate lower-crustal mafic rocks from upper-mantle ultramafic rocks. Electromagnetic experiments conducted to date, however, have failed to detect a corresponding change in electrical conductivity at the base of the crust, although one might be expected on the basis of laboratory measurements[2]. Here we report electromagnetic data from the Slave craton, northern Canada, which show a step-change in conductivity at Moho depths. Such resolution is possible because the Slave craton is highly anomalous, exhibiting a total crustal conductance of less than 1 Siemens—more than an order of magnitude smaller than other Archaean cratons. We also found that the conductivity of the uppermost continental mantle directly beneath the Moho is two orders of magnitude more conducting than laboratory studies on olivine would suggest, inferring that there must be a connected conducting phase.

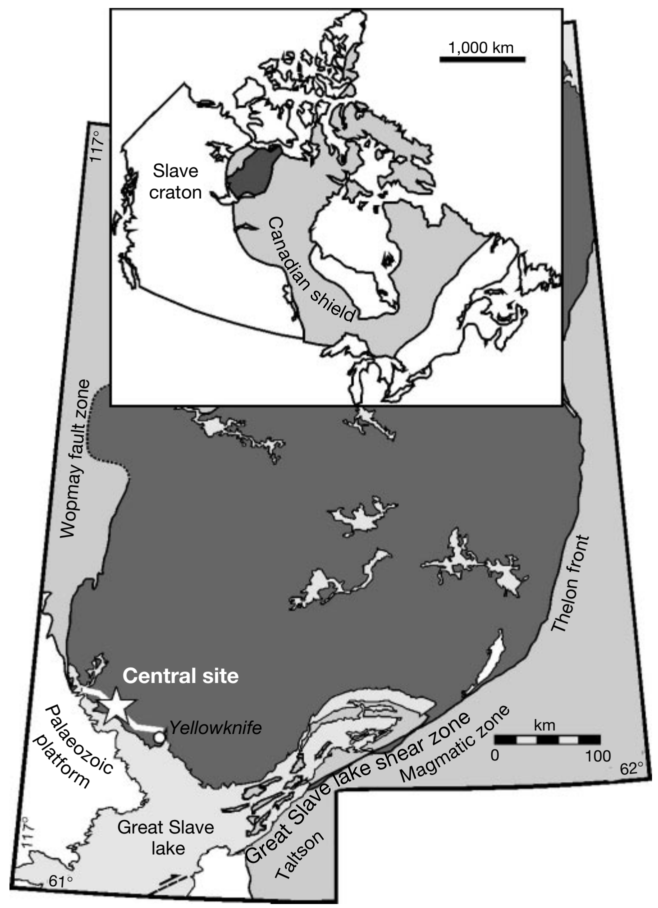

Figure 1 Tectonic map of the Slave craton in the northwestern part of the Canadian Shield. Also shown is the location of the profile and the central site (star).

Earth materials conduct electricity predominantly by the flow of ions in fluids and the flow of electrons in solids. Dry silicate rocks are highly resistive, so a region of enhanced electrical conductivity represents an interconnected network of a fluid and/or mineral conducting phase. Laboratory studies suggest that for dry rock assemblages there may be an observable difference in conductivity between deep crustal mafic rocks and upper-mantle ultramafic rocks[2]. However, a convincing step-change in conductivity at the base of the crust has not previously been reported because of one still inadequately explained feature of the Earth; the enhanced electrical conductivity of much of the continental lower crust[3]. This characteristic of the deep crust has been observed globally over the past 30 years, principally using the natural-source magnetotelluric (MT) method, and explanations for its existence remain controversial[3]. Suggestions of an interconnected brine below the brittle–ductile transition[4,5] have been met with scepticism on petrological grounds[6]. A counter suggestion of an interconnected, thin, grain-boundary carbon film[7] also has its critics[8]. Notwithstanding an explanation of its cause, a direct consequence of the existence of this lower-crustal conducting layer is that it is virtually impossible to determine its thickness, and hence derive total crustal thickness using electromagnetic (EM) methods.

Where the Earth consists of horizontal layers the external sources induce only horizontal electric currents in these layers, and the MT method is incapable of resolving independently the conductivity and thickness of a conductive layer sandwiched between two

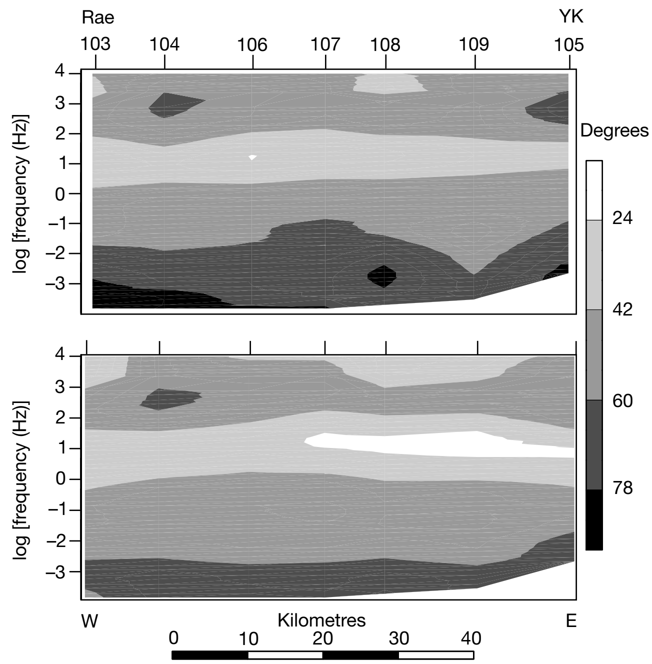

Figure 2 Contoured magnetotelluric phase responses for the seven sites from Yellowknife to the surface expression of the western boundary of the Slave craton. Distance is along the abscissa, and log(frequency) is along the ordinate. Top, phases with the electric component directed N41W. Bottom, phases with the electric component directed N49E.

resistive layers[5,9]. Vertical electric currents induced in the Earth near laterally varying structures will be influenced (as a function of their wavelength) by both the conductivity and the thickness of the lower crust[10]. However, without independent knowledge of the exact conductivity structure of the upper-crustal features, it is again impossible to resolve the thickness of a conducting lower crust. Given these considerations, all interpretations of MT data that include a conducting lower crust and a step-change in conductivity at the base of the crust are suspect.

In almost all regions thus far studied, the presence of an enhanced electrically conducting layer in the lower crust screens the region directly below from detailed investigation by conventional MT experiments[11]. In general, this effect limits the ability to resolve uppermost-mantle conductivity structure and only a maximum bound can be placed on its value[11]. Only when the lower-crustal conducting layer is absent can the conductivity of continental uppermost mantle directly beneath the Moho be determined. Consequently, published values of uppermost-mantle conductivity[12], typically in the range 0.005–0.0125 $\mathrm{S\,m^{-1}}$, must also be treated with caution. The conductivity of the deeper mantle below ~100 km has been defined by a number of other EM experiments; the greatest precision is that of ref. 13.

We conducted an MT survey as part of Lithoprobe's SNORCLE[14] (Slave-northern Cordillera lithospheric evolution) transect; this survey involved acquisition of wide-band (10,000–0.01 Hz) and low-frequency (0.1–0.0001 Hz) data at locations on the south-western corner of the Archaean Slave craton (Fig. 1). The Slave craton, located in the northwestern Canadian Shield (Fig. 1 inset), is one of the world's smallest Archaean cratonic provinces (400 × 600 km), and hosts the oldest-known terrestrial rocks, the 4.03-Gyr-old Acasta gneisses[15].

The MT sites on the exposed craton were along a 150-km-long east–west profile. The six sites west of Yellowknife (along line in Fig. 1) were on the Anton complex, an integral part of an early- to mid-Archaean basement complex covering much of the craton[16]. The time series data acquired at each site were processed using a robust multi-remote-reference algorithm (method 6 in ref. 17), and the estimated responses were corrected for local distortions of the electric field[18]. In contrast to MT responses obtained on other exposed shields, distortions were unusually small at all sites, indicative of little near-surface conducting heterogeneity. The high-frequency responses for crustal depths (10,000–0.1 Hz) show weak evidence of a preferred geoelectric strike, whereas the lower-frequency responses, corresponding to signal penetration into mantle lithosphere, suggest a geoelectric strike of ~N41W geographical. The contoured MT phases in the frequency range 10,000–0.1 Hz for all six sites in the two orthogonal directions, with distance on the ordinate and log(frequency) on the abscissa, show uniform lateral behaviour (Fig. 2). This is characteristic of a region in which conductivity varies with depth alone within the crust and uppermost mantle, consistent with the lack of preferred strike orientation. The apparent resistivity curves (not shown) are close to one other, indicative of small amplitude distortion effects[19].

The data from a central site on this profile, site 106, are representative of the whole profile and are shown in Fig. 3. Apart from scatter in the high-frequency 'dead-band' between 1 kHz and 3 kHz (ref. 20) and at the two lowest periods, the data are of excellent quality and the apparent resistivity and phase data are self-consistent[21]. Inverting the 27 averaged impedances[22], expressed as apparent resistivities and phases, in the frequency range 1,000–0.1 Hz, with minimum assigned errors of 1° in phase and 3.5% in apparent resistivity, yields two models shown in Fig. 4. These two models represent end-member cases of possible acceptable models; the layered-Earth model[23] (solid line in Fig. 4) represents the model with the fewest number of uniform layers that fits the responses, whereas the continuous model (dashed line in Fig. 4) represents the smoothest model in terms of having the smallest conductivity gradient with depth[24]. The models fit the observations to an r.m.s. misfit of 1.48 and 1.28 respectively, compared to a minimum possible misfit of 1.07 for a model of conductance spikes[25]. The models are consistent in exhibiting a shallow (<1 km), low-conductivity, uppermost layer underlain by a more conductive layer to a depth of 2–3 km. Below this is a region of very low conductivity (<0.000025 $\mathrm{S\,m^{-1}}$) to some tens of kilometres depth, beneath which is a moderately conductive (0.00025 $\mathrm{S\,m^{-1}}$) homogeneous basal layer. Based on the layered-Earth model, the depth to the basal layer occurs at 35.8 ± 1.5 km. This interface depth is the second-best-resolved model parameter[9], and the data most sensitive to it are the apparent resistivities at frequencies of 2–0.2 Hz and the phases at 10–1.25 Hz. Inverting only the 12 data at frequencies of

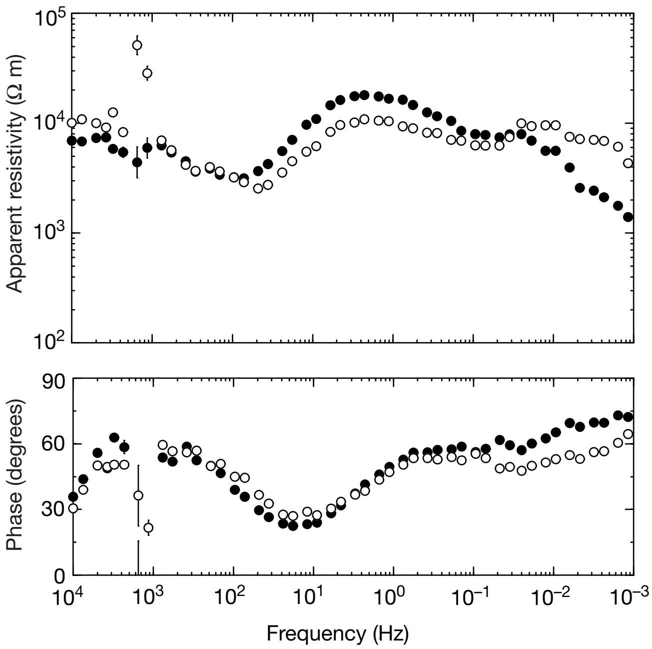

Figure 3 Magnetotelluric response from a central site on the profile, site 106 (Fig. 2). Filled circles, responses with the electric component directed N41W; open symbols, responses with the electric field directed N49E.

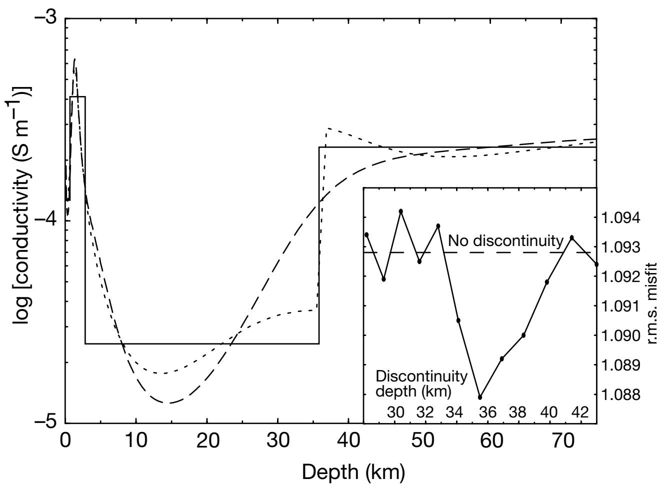

Figure 4 One-dimensional conductivity–depth models that fit the averaged impedances[21] of the responses shown in Fig. 3. Solid line, best-fitting layered-Earth model. Dashed line, best-fitting continuous model. Dotted line, best-fitting continuous model with a permitted step change at 35.5 km. Inset, r.m.s. misfit for best-fitting continuous models varying the depth to the permitted step change.

10–0.5 Hz with the smooth model code[26] results in a much larger resistivity gradient at 30–40 km depth for the same r.m.s. misfit, implying that the data sensitive to that depth range are better fitted with a large gradient in conductivity.

Seismic reflection[26], refraction[27] and teleseismic[28] studies along the same profile are consistent in interpreting Moho depth at ~36 km. Thus, we can associate the conductivity change in the layered-Earth model with the seismically defined crust–mantle boundary. Re-performing the smooth model inversion but allowing a stepwise change in conductivity at 35.5 km yields the third model shown in Fig. 4. This model has a lower minimum misfit than the model without the step change and closely resembles the layered-Earth model below 10 km, featuring an order-of-magnitude increase in conductivity across the boundary. Varying the depth of the permitted step from 28 to 42 km (Fig. 4 inset) yields a minimum achievable r.m.s. misfit at a depth of 35.5 ± 1.4 km for both the full dataset (1,000–0.1 Hz), and the reduced range dataset (10–0.2 Hz).

This is, to our knowledge, the first definitive identification of a change in electrical conductivity at depths corresponding to the crust–mantle boundary, and the required resolution is a consequence of the absence of conducting material in the crust. It is also, to our knowledge the first time that the conductivity of the uppermost continental mantle directly beneath the Moho has been obtained, which also can be attributed to the lack of a conducting lower crust[11]. The upper mantle beneath the Slave craton is two orders of magnitude more conducting than laboratory studies on olivine would suggest[29], inferring that there must be a connected conducting phase.

The conductivity for the lower crust of the Slave Province, at around 0.000025 S m^{-1}, is consistent with laboratory studies on candidate dry rock assemblages at appropriate facies conditions[30]. In contrast, other mid- to late-Archaean cratons (Superior, Siberian, Baltic, Kaapvaal) have conducting material in their lower crust[3], with a minimum conductance (conductivity-thickness product) of 20 S compared to less than 1 S for the Slave. Although the cause of the enhanced conductivity seen everywhere else remains contentious, what is clear is that whatever processes caused its existence elsewhere were not operating as crust was formed in the Slave craton. Recalling that the Slave craton hosts the oldest dated rocks, we speculate 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. If the enhanced conductivity in the continental lower crust of late-Archaean, Proterozoic and Palaeozoic terranes is emplaced by plate-tectonic processes of subduction and imbrication of sedimentary material (see, for example, ref. 31), then either such material was not available during the early Archaean or tectonic processes were operating differently. □

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Speciation in a ring

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The evolutionary divergence of a single species into two has never been directly observed in nature, primarily because speciation can take a long time to occur. A ring species, in which a chain of intergrading populations encircles a barrier and the terminal forms coexist without interbreeding, provides a situation in which variation in space can be used to infer variation in time[1–3]. Here we reconstruct the pathway to speciation between two reproductively isolated forms of greenish warbler (*Phylloscopus trochiloides*). These two taxa do not interbreed in central Siberia but are connected by a long chain of intergrading populations encircling the Tibetan Plateau to the south[4]. Molecular data and climatic history imply that the reproductively

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