Electrifying Images of the Slave Craton

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The Slave craton in northern Canada is one of the world's smallest Archean cratons (surface exposure of 300,000 km^2), but makes up for this diminutive stature with excellent exposure and by hosting the oldest dated rocks on Earth (4.03 Ga, Stern and Bleeker 1998). It records continental accretion processes, albeit cryptically, and potentially offers the best opportunity worldwide to address the question of the validity of applying plate tectonic theory in the early Archean.

Studies of the Slave craton and its relationship to the Proterozoic terranes to the east are being undertaken as part of SNORCLE transect LITHOPROBE investigations. These studies included reflection profiling, a refraction experiment, a series of electromagnetic (EM) experiments, and additional geochemical and geological activities. The EM experiments used natural sources for obtaining lithospheric information. At each location time series were recorded of the time varying horizontal north (*Ex*) and east (*Ey*) electric field components and the north (*Hx*), east (*Hy*) and vertical (*Hz*) magnetic field components in one or more of various frequency bands: audio-magnetotelluric (AMT) band of 10,000 - 100 Hz, magnetotelluric (MT) band of 100 Hz - 1000 s, and long period magnetotelluric (LMT) band of 20 s - 10,000 s.

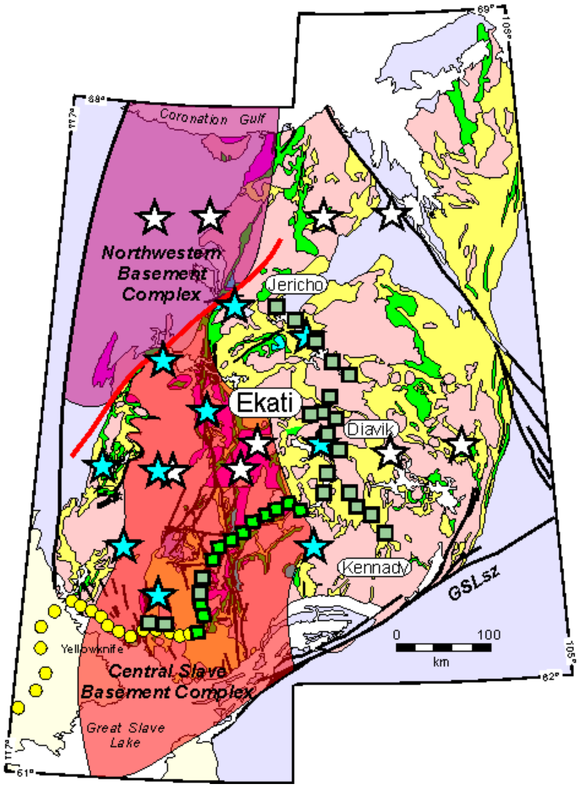

Figure 1: MT site locations on the Slave craton geology basemap from Bleeker and Davis (1999)

The three experiments were:

1) conventional AMT, MT and LMT acquisition during Fall 1996 along the all-weather road from Tibbit Lake to Rae in the southwest corner of the craton (yellow dots on Fig. 1);

2) MT and LMT acquisition in the winter along the ice road from Tibbit Lake to Lupin mine on Contwoyto Lake, including along the road to Kennady Lake (light green squares in Fig. 1 recorded in March 1998; dark green squares in March 1999), and
3) LMT acquisition in lakes around the Slave using instrumentation designed for the ocean-bottom (blue stars in Fig. 1 recorded from August 1998 to August 1999; white stars recording from August 1999 to August 2000).

MT Data Processing and Analysis

MT data processing involved rotation of the time series to geographic coordinates, then estimation of the MT transfer functions relating the horizontal electric field components to the horizontal magnetic field components and estimation of the magnetic transfer functions (TF) between the vertical magnetic field component and the horizontal magnetic field components. The code used was a multi-remote reference variant of the Jones-Joedicke scheme (method 6 in Jones et al., 1989). In addition, data segments were selected with low vertical field variations in order to avoid source field effects on the data (see, e.g., Garcia et al., 1997).

Subsequently, the MT response function estimates were analysed for electric-field distortions caused by local, near-surface inhomogeneities, and the appropriate geoelectric strike direction for interpretation. These steps were accomplished using the multi-site, multi-frequency tensor decomposition code of McNeice and Jones (1996). The data showed a low dependence on geoelectric strike, i.e., the MT phases are virtually direction-independent, which requires the conductivity structure of the crust and mantle to vary slowly with lateral distance in both the crust and mantle.

MT Phase Map

Given the low dependence on rotation, one can obtain qualitative information from a map of the averaged phase at a given period. Figure 2 shows a map of the phases for a period of 300 s.

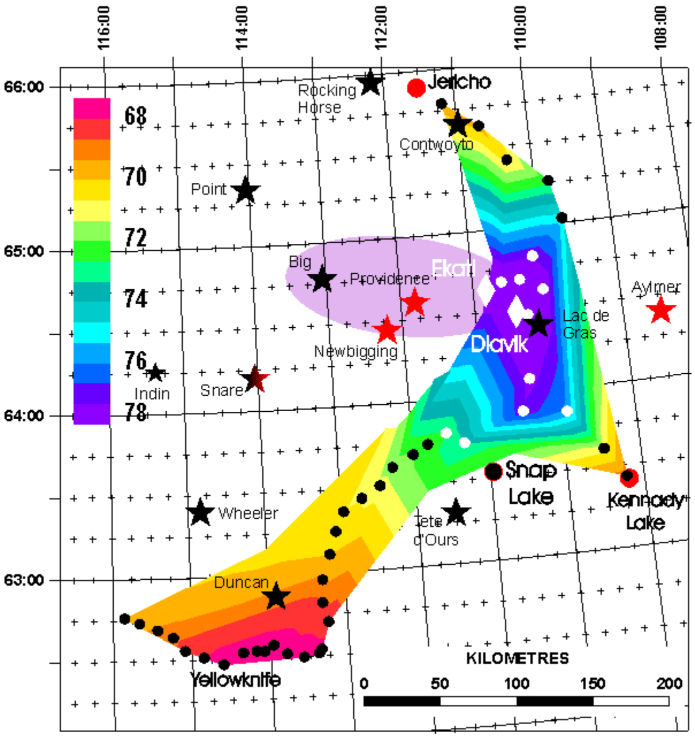

Figure 2: MT average phases at 300 s

At 300 s periodicity the EM waves are penetrating some 150-200 km down into the lithosphere. The averaged phases show a distinct high of almost 80^{O} at the sites in the Lac de Gras region. Phases decrease monotonically with distance away from this region along all three roads, to the north towards the Jericho pipe, to the southeast towards the Kennady pipe, and to the southwest to Yellowknife. The phase difference between Yellowknife and Lac de Gras is over 10^{O}, and between Kennady and Jericho and Lac de Gras is over 6^{O}. We have only undertaken preliminary processing of three lake bottom sites, namely Big, Lac de Gras and Wheeler. The averaged phases at 300 s for these three are consistent with the data from the winter road, with high phases for Big and Lac de Gras, and low phases for Wheeler. This suggests that the phase maximum extends to the west to at least Big Lake, and perhaps beyond.

A qualitative interpretation of the phase map is of either a higher conductivity of the mantle, or that the depth to the base of the lithosphere is closer to the surface, beneath Lac de Gras compared to neighbouring areas.

MT Modelling

The MT responses, rotated into a strike direction of NE-SW, were objectively modelled using the 2D inversion code of Rodi and Mackie (2000). The best-fitting model obtained is shown in Fig. 3.

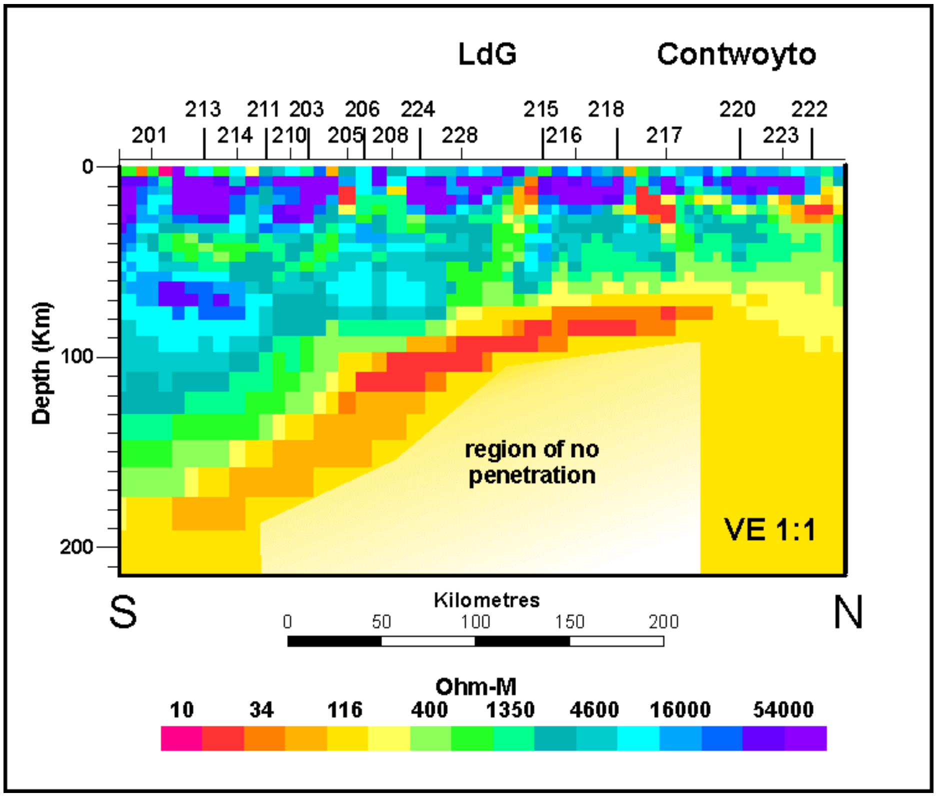

Figure 3: Resistivity model of Slave lithosphere

The dominant feature of the resistivity model is the shallowing high conducting upper mantle region ($\rho<30\ \Omega$.m) beginning at a depth of ~80 km beneath Lac de Gras. This anomaly is consistent with the phase map of Fig. 2. The anomaly does not exist north of site 217, i.e., at the start of Contwoyto Lake, nor south of site 205, which is at Nuna's Lockhart Lake camp. Due to the attenuating effects of the anomaly, it is not possible to image the resistivity structure below it. This would require much longer periods than in the present dataset, and would require a specialised experiment such as undertaken by

Schultz et al. (1993). In addition to the mantle feature, note that the crust of the Lac de Gras region contains more conducting features than to the south.
A resistivity model (not shown) for a line from Contwoyto Lake to Kennady Lake is consistent with imaging an anomaly at ~80 km beneath Lac de Gras, and the anomaly ceases half-way down the Kennady Lake road.

Inferences and Comparison with Geochemical Results

A map of the conducting mantle region is shown in Fig. 4 (left). The region mapped by the work along the winter road is shown in dark green. Given the high phase value observed at Big Lake, from preliminary processing of the lake bottom instrument, there is the suggestion that this region extends to the west (light green) beyond both the north-south Pb and Nd isotope boundaries (Thorpe et al., 1992; Davis and Hegner, 1992; Davis et al., 1996). These boundaries are considered to indicate that the mantle beneath the western Slave is fundamentally different than beneath the eastern Slave. Verification of the existence of the mantle conductor to the west requires complete analysis of the lake bottom data, including the data that will not be available until the retrieval of the second deployment in August 2000.

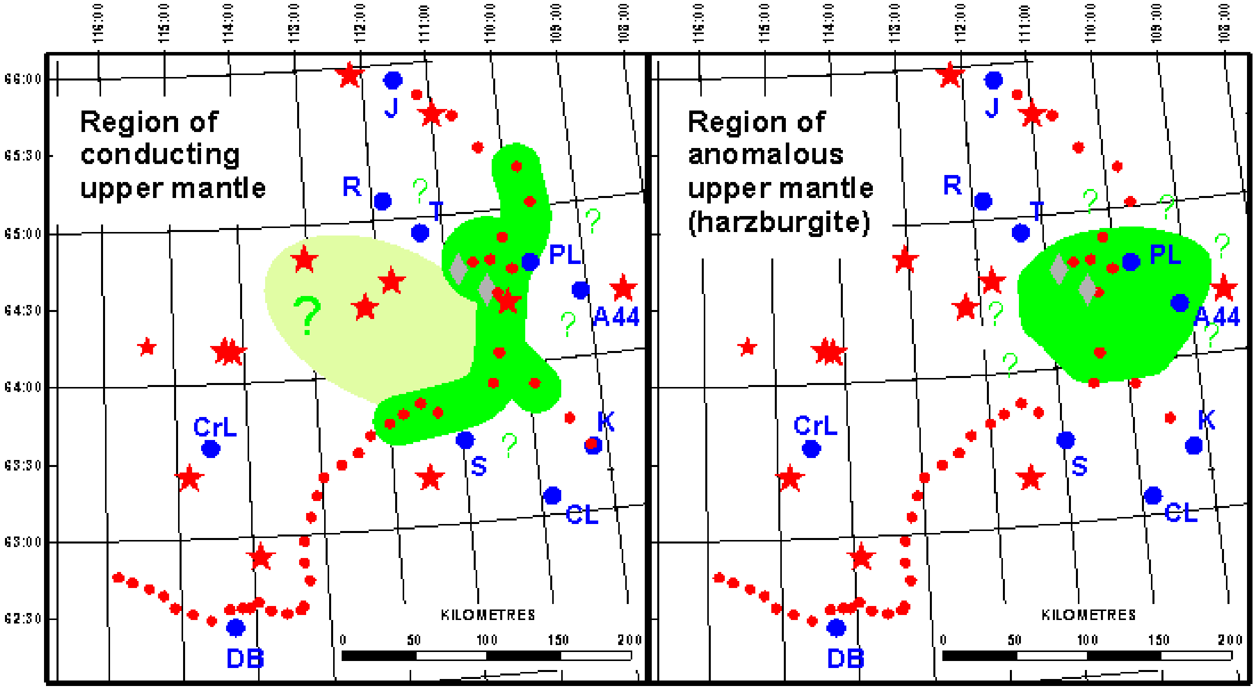

Figure 4: Location of conducting upper mantle (left) compared to region of anomalousgeochemical mantle (right). Blue dots show the locations of major kimberlite pipes: DB: Drybones; CrL: Cross Lake; S: Snap Lake; CL: Camsell Lake; K: Kennady Lake; PL: Pellet Lake; T: Torrie; RL: Ranch Lake; J: Jericho.

Griffin et al. (1999), studying the geochemistry of mantle xenoliths from 21 kimberlites in the Lac de Gras region, mapped the composition, structure and thermal state of the mantle. They discovered a unique two-layered lithospheric mantle, with an ultra-depleted, harzburgitic upper layer separated sharply at 140-150 km depth from a less depleted, lherzolitic lower layer, extending over >9,000 km^2 (Fig. 4: right). This ultra-depleted layer was not found at pipes north of the Lac de Gras kimberlite field (Jericho, Ranch Lake, Torrie), nor at pipes to the south (Cross Lake, Drybones, Camsell Lake).

Comparison of the spatial extent, location and depth of the mapped mantle conductor and the mapped ultra-depleted harzburgitic layer shows remarkable coincidence between the two. As olivine and harzburgite have very high electrical resistivity, then there must be other phases in the rocks to provide the conducting pathways. Processes of emplacement of the ultra-depleted layer must have resulted in this connected conducting phase.

Possible Conductivity Enhancement Mechanisms

There are two dominant mechanisms for the flow of current in the mantle: ionic conduction and electronic conduction. For the former, one can appeal to partial melt in the asthenosphere region and suggest, heroically, that there has been an upwarping of the lithosphere-asthenosphere boundary (LAB) since the emplacement of the Eocene-aged kimberlites in Lac de Gras. This thesis is untenable, given the lack of uplift and high heat flow in the central Slave craton. A free aqueous fluid (H_20) phase will enhance conductivity at depths greater than 60 km (2 GPa) as the fluid can interconnect due to the dihedral wetting angle dropping below 60^O (Mibe et al., 1998), and the conductor begins at ~80 km depth. Alternatively, following Karato (1990; see also Lizarralde et al., 1995), one can appeal to diffusion of hydrogen in the mantle.

For electronic conduction, Boerner et al. (1999) invoke hydrous mantle minerals, specifically phlogopite, generated by metasomatising events as a possible explanation of conducting Archean mantle. The arduous and detailed laboratory work has yet to be undertaken on such rocks (A. Duba, pers. comm., 1999), but hydrous mineral phases in the crust were demonstrated not to enhance conductivity once outgassing was controlled (Olhoeft, 1981). Alternatively, carbon in the mantle may be possible. Above the diamond stability field (<150 km), the carbon would be in the form of graphite, which is highly conducting. Below the stability field it would be in the form of diamond, and diamonds from those depths have been found in the Lac de Gras kimberlite pipes. At crustal conditions in the laboratory, carbon has been observed to be deposited in graphite form on mineral surfaces during fracturing (Roberts et al., 1999). This leads to the speculation that enhanced carbon in the Lac de Gras region could have been deposited as a continuous graphite film during tectonic processes associated with the Central Slave Basement Complex and the Eastern Slave Province (Bleeker et al., 1999a, b).

Given these scenarios, our preferred explanation is the role of enhanced carbon. This thesis must be tested by observations of carbon on grain-boundary surfaces in the ultra-depleted mantle xenolith material from the kimberlites in the Lac de Gras region, but not other regions. Alternatively, following Griffin et al. (1999) who interpret the ultra-depleted layer as trapped, hydrated oceanic or arc-related lithosphere, the hydrogen diffusion hypothesis (Karato, 1990) may be valid. In either case, the conducting layer was likely emplaced by tectonic processes, and therefore its interpretation will contribute to unravelling the complex history of the formation and development of the Slave craton.

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Bibliographic Note: Alan G. Jones (B.Sc. University of Nottingham 1972; M.Sc. University of Birmingham 1973; Ph.D. University of Edinburgh 1977) is a research scientist at the Geological Survey of Canada with over 25 years experience in the application of the MT method for addressing problems at all scales from the near-surface (mineral and geothermal exploration) to crustal scales (Lithoprobe, Tibet, Appalachians) to mantle imaging (Fennoscandian Shield; Superior and Slave cratons). He has integrated the results from MT studies in Europe, North America and Asia with other geophysical, geochemical and geological data.