AREA SELECTION FOR DIAMOND EXPLORATION USING DEEP-PROBING ELECTROMAGNETIC SURVEYING

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INTRODUCTION

Previously proposed methods of area selection for diamond-prospective regions have predominantly relied on till geochemistry (Griffin and Ryan, 1995; Gurney and Zweistra, 1995; Jennings, 1995), airborne geophysics (Macnae, 1995), and/or an appraisal of tectonic setting (Helmstaedt and Gurney, 1995). Herein we suggest that a novel deep-probing geophysical technique - electromagnetic studies using the natural-source magnetotelluric (MT) method (Jones, 1998, 1999) - can contribute to such an activity.

Essentially, diamondiferous regions must have:

1. thick lithosphere
2. old lithosphere,

and, what is not as appreciably discussed in the literature,

3. lithosphere that contains high concentrations of carbon.

As we will discuss and demonstrate in our paper, deep-probing MT studies are able to address all three of these. The first and the third of these can be done virtually independently by MT, but for the second the geometries produced from modelling the MT observations must be interpreted with appropriate interaction with geologists, geochemists and other geophysicists.

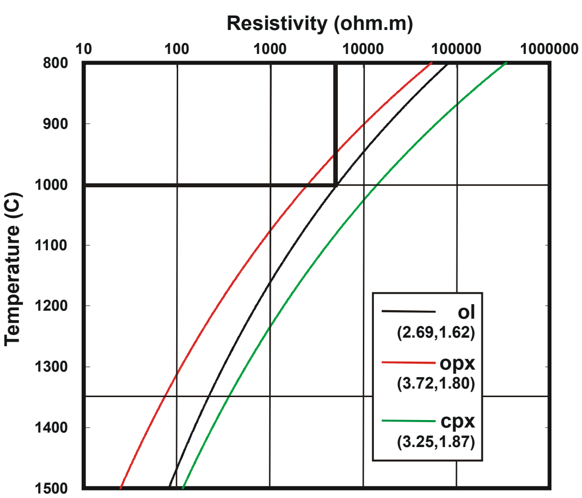

Figure 1: Resistivity-temperature variation of olivine, opx and cpx (taken from Xu et al., 2000).

THICK LITHOSPHERE

Diamonds only exist in thick cold lithosphere at depths where the geotherm lies below the graphite-diamond stability field. In the absence of any interconnected conducting material, the sub-continental lithospheric mantle (SCLM) is highly resistive. Laboratory studies of the resistivity variation with temperature of mantle materials, olivine, orthopyroxene and clinopyroxene, show that resistivity values of many hundreds to tens of thousands of ohm-metres are to be expected (Xu et al., 2000). This variation is shown in Figure 1 for those three minerals, calculated from the formulae in Xu et al. (2000). Using appropriate mixing relationships, it is possible to determine the resistivity of the mantle for any given mineral modal composition (Ledo and Jones, 2003).

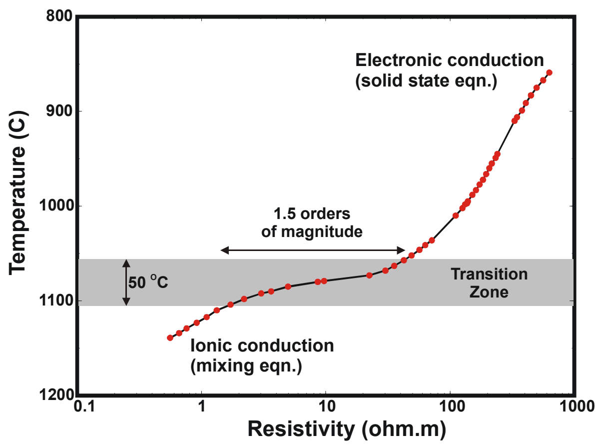

Figure 2: Resistivity-temperature variation of pyroxene granulite during heating and the onset of partial melt (derived from the data in Schilling et al., 1997, and Partzsch et al., 2000).

MT can determine the thickness of the lithosphere, i.e., the depth to the lithosphere-asthenosphere boundary (LAB), due to the two orders of magnitude increase in electrical conductivity at the onset of partial melt. This is shown in Figure 2 below derived from the data in Schilling et al. (1997) and Partzsch et al. (2000). The figure shows the results of heating experiments on a sample of pyroxene granulite. At low temperatures (<1050 ºC), the material conducts electric currents by the flow of electrons, and this can be described be described by the solid-state Arrhenius equation. At high temperatures (>1100 ºC) ionic conduction becomes dominant and can be described by an appropriate mixing law.

Between these two, in the transition zone where partial melt is very low (<2%), both mechanisms are important and resistivity decreases by over 1.5 orders of magnitudes within 50 ºC. Quenching studies show that the melt becomes interconnected, which is critical for reducing electrical resistivity, at very low partial melt fractions. Minarik and Watson (1995) and Drury and Fitz Gerald (1996) both demonstrate that interconnectivity can be achieved with partials melts below 0.1%.

It should be noted that these laboratory experiments are very difficult to perform; the results of Schilling et al. (1997) and Partzsch et al. (2000) required holding the temperature constant for 200 hours to obtain a stable result.

Such high sensitivity to the onset of partial melt, with resistivity decreasing by over 1.5 orders of magnitude over a temperature range of less than 50 ºC, means that precise MT data have the highest potential precision of any geophysical method to the depth to the LAB. This boundary is generally taken to have a temperature of ~1350 ºC, so the resistivity is expected to decrease from some hundreds of ohm-metres (Figure 1) to ten ohm-metres (Figure 2) over about 25 km in depth (which is equivalent to a temperature increase of around 50 ºC).

Thus, the MT method can detect whether the LAB exceeds the graphite-diamond (G-D) stability field, or not. A cartoon to illustrate this sensitivity is given in Figure 3.

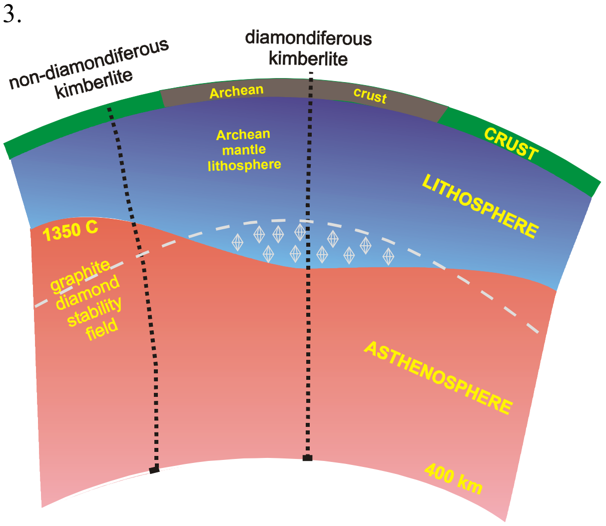

Figure 3: Cartoon to show sensitivity of MT to LAB

OLD LITHOSPHERE

That diamonds occur primarily in Archean regions is the well-known *Clifford's Rule* (Clifford, 1966). Geometries of structures imaged by EM studies within the sub-continental lithospheric mantle aid in the development of a model for the tectonic history of the craton, which relates to its age. This has been demonstrated for both the Slave craton and for the western part of the Superior craton.

Jones et al. (2001, 2003) have shown that the upper part of the SCLM beneath the central Slave craton contains a region of anomalously low electrical resistivity, named the Central Slave Mantle Conductor (CSMC). The top of the body lies at a depth of ~80-100 km. The model of the MT data acquired along the winter road from Tibbit Lake to the northern part of Contwoyto Lake is shown below in Figure 4.

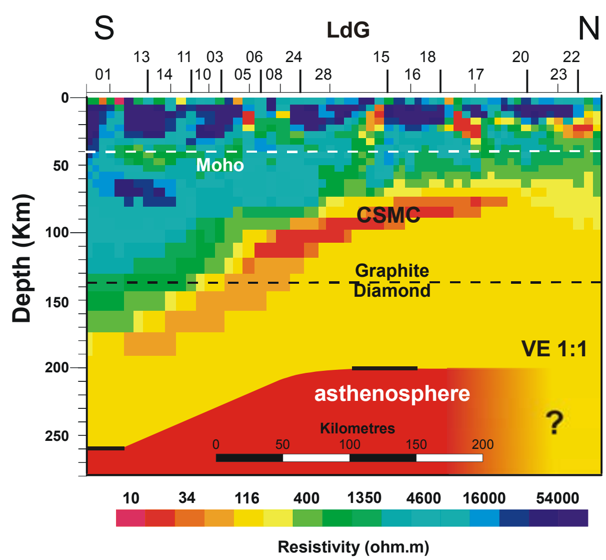

Figure 4: Resistivity model from the southern Slave, through Lac de Gras, to the northern Slave along the winter road (taken from Jones et al., 2003)

Based on xenolith studies (Kopylova et al., 1997), the expected temperatures at 80-100 km depths are 700-750 ºC, which, by reference to Figure 1, suggests an ambient resistivity of the order of >30,000 Ω.m is to be expected, and is as seen in the southern Slave (Figure 4). In contrast, the CSMC has a resistivity <15 Ω.m (Jones et al., 2003). The modelled three-dimensional geometry of this body, with a NE-SW strike and a NW dip, was one of the key geometric factors used by Davis et al. (2003) in their argument for proposing that the SCLM beneath the Slave today is not the original SCLM formed in the Mesoarchean. Davis et al. (2003) postulate that the Slave's SCLM is the consequence of subcretion of exotic lithosphere during an orogenesis at 2630-2590 Ma postdating Slave crustal formation at 2690 Ma.

In the western part of the Superior craton, Craven et al. (2001) have discovered a conducting body within the SCLM that displays the same properties as the CSMC. The western Superior conductor lies within the North Caribou Terrane (NCT), a Mesoarchean terrane within the mélange of predominantly Neoarchean terranes that form that part of the Superior craton. It is bounded on either side by regions displaying high electrical anisotropy, or two-dimensionality, with electrical strike directions parallel to the major syn- and post-Kenoran zones of transpression on either side of the NCT. A preliminary model of the electrical structure in the northwestern Superior Province showing the 2-D zone south of the NCT is shown in Figure 5.

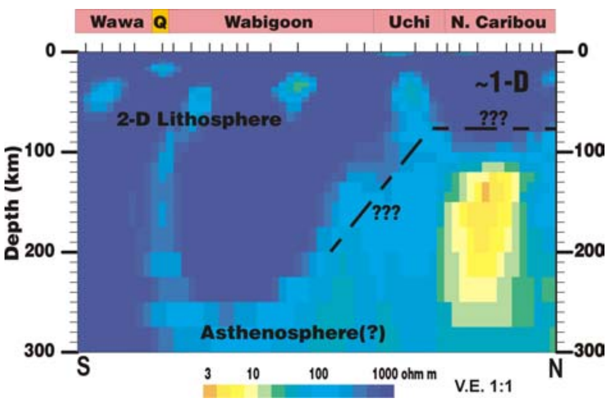

Figure 5: Preliminary resistivity model from the west-uperior Province.

PRESENCE OF CARBON

There are many candidates that can be introduced into mantle minerals for reducing electrical resistivity. These are discussed in Jones et al. (2001). We interpret both the Slave and Superior conductors as evidence for interconnected graphite, and, taken together with independent estimates of upper mantle oxygen fugacities within two log units of the iron-wüstite buffer, suggest that partial melting and formation of the cratonic root are related to redox melting during the Meso- and Neoarchean times. Above the graphite-diamond (G-D) stability field an interconnected graphite phase decreases electrical resistivity by two or more orders of magnitude over that predicted from laboratory studies and petrophysical modelling for an olivine or pyroxene mineralogy dominant upper mantle. Below the G-D field, carbon exists in the form of diamond, and is highly resistive.

CONCLUSIONS

As discussed by Morgan (1995), regional scale geophysical methods can aid in area selection for diamondiferous provinces. Of available methods, magnetotellurics and teleseismics are the two methods available to "look" into the mantle, and they compliment each other well. They are, in fact, the only geophysical methods with true depth resolving capability of material property variations – the other methods use inference rather than direct detection. To date, teleseismics has been used to derive the geometries of Archean sub-cratonic lithospheric mantles. Herein we propose that deep-probing regional-scale MT surveys offer an attractive additional, and on occasion alternate, cost-effective means for rapid area selection for diamond-prospective regions. MT surveys have the advantages that the technique is sensitive to electronic conduction in carbon and that the data acquisition generally requires only one month per site, rather than the one to two years that is required for teleseismic surveys.

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