Using deep-probing EM studies as an aid to area selection of diamond provinces

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Summary

Over the last decade significant exploration for diamonds has expanded beyond the traditional Kaapvaal and Siberian Cratons. However, the globe is a large place, and area selection is clearly key to efficient and effective exploration. Whilst diamond companies traditionally use mainly geochemical methods for area selection, the recent results from deep probing electromagnetic (EM) studies on the Slave craton and western Superior Province indicate that such studies can aid area selection considerably. EM surveys can define the base of the lithosphere-asthenosphere boundary, they can contribute to knowledge about a region's tectonic history, and they can identify whether a region is likely to contain high concentrations of carbon in its sub-continental lithospheric mantle.

Introduction

Over the last decade significant exploration for diamonds has expanded beyond the traditional Kaapvaal and Siberian cratons. North America's first commercial diamond mine, BHP Billiton Diamonds' Ekati mine, was opened in 1999 in the center of the Slave craton of northern Canada, and provides 5% of the global gem quality production. Two mature exploration properties in the southern Slave craton, Aber/RTZ's Diavik kimberlite pipes and DeBeers' Snap Lake kimberlite dyke, are expected to become producing mines within 3-4 years. Other exploration properties on the Slave craton that are at advanced exploration stage and may be taken to mining are DeBeers/Mountain Providence's Kennady Lake kimberlite pipes and dykes (southern Slave) and Tahera's Jericho kimberlite pipes (northern Slave). It is estimated that by 2006 at least 15% of the world's gem quality diamonds will come from Canada's Slave craton.

As a consequence of these diamond exploration activities, the central and southern parts of the Slave craton are thought to be reasonably well-known geochemically and geophysically. Exploration is now focused on other parts of the Canadian Shield, including northern Slave, northeastern (northern Quebec), northern (Hudson Bay lowlands) and northwestern Superior Province (Kirkland Lake) and northeastern Rae Province (northern Baffin Island). Additional activities occur in the Prairies, especially at the huge Fort à la Corne kimberlite in Saskatchewan, thought to be rooted by the enigmatic Archean (?) "Sask" craton lying within the Paleoproterozoic Trans-Hudson orogen.

Key to efficient and effective future exploration of the Canadian Shield, as well as other Archean cratonic regions around the world, is area selection for regions that have high diamond potential. Three criteria are required for such regions:

1. The sub-continental lithospheric mantle (SCLM) has to be sufficiently thick that it exceeds the graphite-diamond (G-D) stability field.
2. The SCLM has to be Archean in age, and
3. The SCLM has to contain anomalously high concentrations of carbon.

In the main, area selection has been dictated by geochemical information (e.g., Griffin and Ryan, 1995; Jennings, 1995), with some consideration of tectonic setting (Helmstaedt and Gurney, 1995). However, geophysical information can contribute to area selection, and this paper will describe how deep-probing electromagnetic surveys, using the natural-source magnetotelluric (MT) technique, can address all three of the above criteria.

Resolution of the lithosphere-asthenosphere boundary

The fundamental physical boundary for the SCLM is its base, the lithosphere-asthenosphere boundary (LAB), commonly taken as an isotherm at ~1350 ºC. It is generally thought that the asthenosphere is a region of partial melt, and values of 1-2% melt are often quoted to explain seismic and EM results.

The electrical resistivity of olivine at temperatures and pressures appropriate for the cratonic SCLM is >1,000 Ω.m, to values as high as 100,000 Ω.m (Constable et al., 1992). Pyrozene mineralogies are even more resistive. Electronic conduction is weak because the electrons are bound strongly to the molecules. However, when partial melt initiates and interconnects, then electric current flow is enhanced due to the movement of charged ions.

Laboratory studies on two-phase mixtures of $NaCl$ and H_2O demonstrate that interconnection is achieved at low degrees of partial melt, and electrical resistivity decreases in an almost step-like fashion (Watanabe and Kurita, 1993). This was confirmed in real rocks by Partzsch et al. (2000) in their study of pyroxene granulite (Fig. 1). In the temperature range 1050-1100 °C resistivity decreased by over 1.5 orders of magnitude. This temperature range represents the transition from electronic conduction, described by a solid state equation (Aarhenius equation), to ionic conduction that can be described by a mixing equation. Quenching at different temperatures demonstrated interconnectivity of melt at very low orders of melt fraction (0.1%).

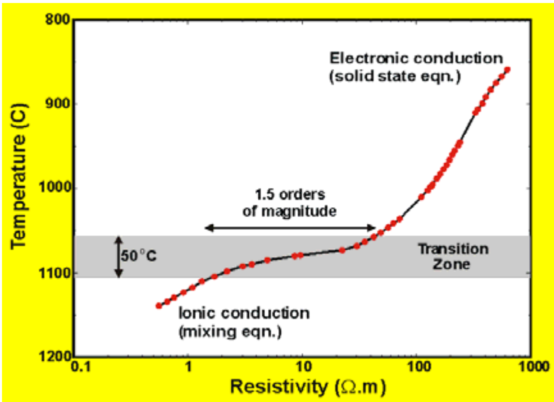

Figure 1: Change of resistivity at the onset of partial melt (modified from Partzsch et al., 2000)

Such electrical behavior is expected at the base of the SCLM. Given continental geotherms, a transition zone of 50 °C will have a thickness of ~10-15 km. Accordingly, if the lithosphere comprises a typical resistive upper crust underlain by a more conductive lower crust, and a SCLM with a temperature-dependent resistivity (as given by Constable et al., 1992), above an asthenosphere of 25 Ω.m, then high quality (1% error in impedance) MT data can resolve an LAB at 250 km to within ±11 km (Fig. 2).

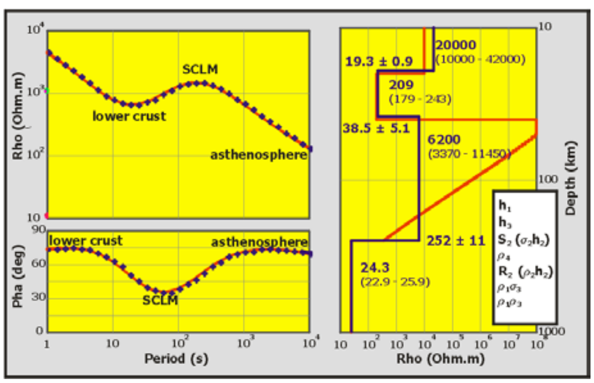

Figure 2: Resolution of the LAB with 1% MT data

Tectonic age and history

Tectonic controls on diamond deposits were discussed by Helmstaedt and Gurney (1995). The prevailing paradigm for diamond exploration is that the lithosphere must be "old", generally taken as Archean, but Proterozoic-aged diamonds do exist. Knowing the tectonic history of a region requires understanding of lithospheric formation and deformation processes. The plate tectonic model can be successfully applied from the Paleoproterozoic on, and some would argue that there is evidence for plate tectonics back to the Neoarchean. However, during the formation of the bulk of cratonic lithospheric mantle, in the Mesoarchean, plate tectonics may not have been the dominant process. In the early Earth processes of density and chemical differentiation dominated, followed by bombardment during the Hadean. Likely plume processes dominated during the Eoarchean and Paleoarchean. Thus, the Mesoarchean represents a transition period between competing processes, and therefore predictive models are difficult to apply. Perhaps the most appealing model currently is the lithospheric-stacking concept of Helmstaedt and Schultze (1989).

Deep-probing MT studies on the Slave craton have identified a three-part subdivision of the Slave's SCLM into NE-SW-trending zones (Jones et al., 2001). This was confirmed by 3-D modeling of the data (Jones et al., 2002), and a horizontal slice at a depth of 140 km through the 3-D resistivity model is shown in Fig. 3.

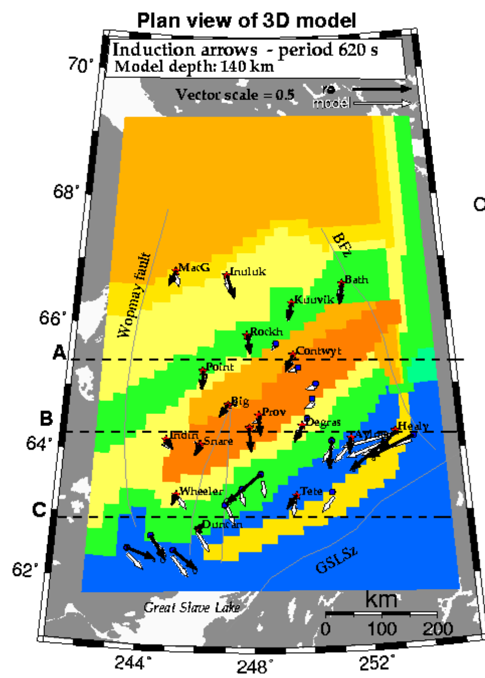

Figure 3: 3-D model of the Slave MT data

Such a subdivision accords with a geochemical subdivision based on G10 garnets (Grütter et al., 1999), with differences in teleseismic shear-wave splitting (SKS) directions (Jones et al., 2002), and with ages of plutonism (Davis and Bleeker, 1999) and F1-folding (Bleeker et al., 1999).

Taken together, Davis et al. (2002) suggest that the Slave's mantle lithosphere developed by tectonic imbrication of one or more slabs subducted beneath the craton at 2.63-

2.58 Ga. An implication of this model is that diamond formation occurred at the earliest in the Neoarchean.

Imaging carbon in the SCLM

Carbon is an unusual element electrically. When in diamond form, the four valence electrons are tightly bound to the tetrahedral structure, and consequently diamond is an insulator – its electrical resistivity is extremely high, $>10^{12}$ Ω.m. In stark contrast, when in graphite form only three of the electrons are bound and the fourth is free, thus graphite is a conductor with resistivity $<10^{-4}$ Ω.m. Consequently, if carbon exists in the SCLM the graphite-diamond (G-D) stability field can represent a boundary between an upper lithospheric region of reduced resistivity due to interconnected graphite, and a lower region of typical resistivity governed by the thermal behavior of olivine and pyroxene.

Accordingly, if a region of reduced resistivity, attributable to interconnected graphite, is imaged in the SCLM above the G-D, then there is a reasonable likelihood that carbon will exist throughout the whole lithospheric column.

In the Slave craton, deep-probing MT studies by Jones et al. (2001, 2002) have covered the craton in a 3-D sense. Novel procedures enabled MT sites to be acquired along winter ice roads with a spacing of <20 km. The broad scale EM measurements were accomplished through unique installation of ocean-bottom MT equipment into lakes by float plane. Together, these data define a phase maximum at ~300 s in the center of the craton collocated with the Eocene Lac de Gras kimberlite field and with Grütter's mantle domain boundaries (Fig. 4).

The 2-D resistivity model of the data along the NE-SW craton-crossing profile is shown in Fig. 5. The phase response is caused by an anomalous region (Central Slave Mantel Conductor, CSMC) of low resistivity (<30 Ω.m) beginning at a depth of some 80-100 km beneath the Lac de Gras (LdG) kimberlite field. The CSMC does not penetrate below the G-D stability field.

A similar conductor was found beneath the North Caribou terrane (NCT) of the western part of the Superior Province (Craven et al., 2002). However, in contrast to the Slave craton, the bounding regions on either side of the NCT exhibit strong electrical anisotropy in the SCLM (3-D view shown in Fig. 6). The most conductive direction of the anisotropic regions correlates with Kenoran zones of transpression. This dates the conductive structures to Paleoproterozoic or older.

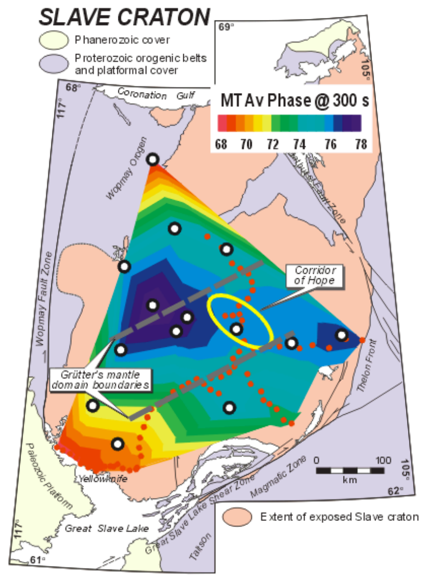

Figure 4: MT phase map at 300 s with Eocene kimberlite field and Grütter's domain boundaries

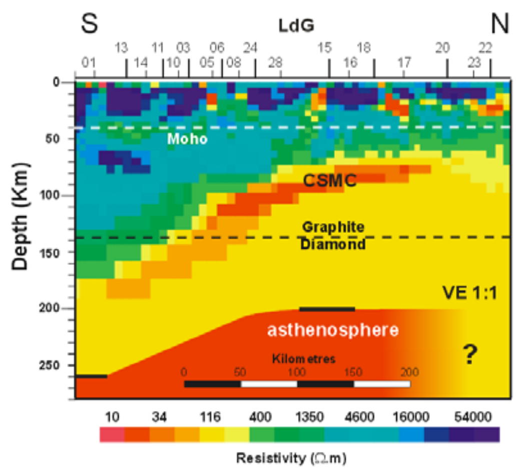

Figure 5: 2-D resistivity model of the Slave craton

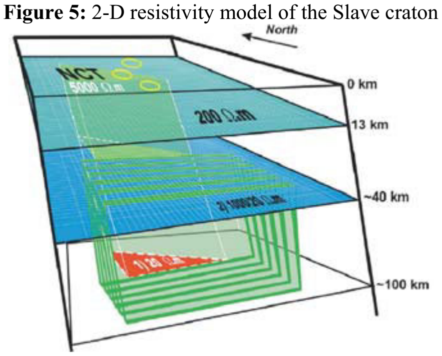

Figure 6: 3-D perspective view of the resistivity structures within the SCLM of western Superior Province

Conclusions

Long period magnetotelluric experiments on cratons are able to define the physical properties of, and the geometries of structures within, the sub-continental lithospheric mantle. Such knowledge can be used as an aid for area selection of diamond provinces.

Studies on the Slave craton and the western part of the Superior Province both detect and delineate regions of low resistivity within the uppermost 80-120 km of the SCLM. These anomalous regions are best explained in terms of interconnected graphite, and models for their genesis invoke redox melting, within two log units of the iron-wüstite buffer, of the cratonic root (Craven et al., 2002). Processes for such melting in the Mesoarchean could be related either to mantle plumes or to plate tectonics. Either way, deep MT data add significantly to our knowledge of Archean lithospheric formation and evolution.

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Acknowledgements

The author wishes to acknowledge the financial support of the following for his Slave craton studies: Lithoprobe, Geological Survey of Canada, National Science Foundation's Continental Dynamics program, Indian and Northern Affairs Canada, DeBeers Canada Exploration Inc., Kennecott Canada Exploration Ltd., Diavik Diamond Mines Inc., and BHP Billiton Diamonds Inc. Logistical support was supplied by many companies and colleagues in Yellowknife, and all are thanked profusely. Many colleagues contributed to the ideas expressed herein, and include Wouter Bleeker (GSC), Alan Chave (WHOI), Jim Craven (GSC), Bill Davis (GSC), Buddy Doyle (Kennecott), Rob Evans (WHOI), Herman Grütter (Mineral Services Canada), and Herb Helmstaedt (Queen's). A very special thanks to Hendrik Falck (GNWT), the tireless miracle-worker.