Electric lithosphere of the Slave craton

Alan G. Jones Geological Survey of Canada, 615 Booth Street, Ottawa, Ontario K1A 0E9, Canada
Ian J. Ferguson Geological Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada
Alan D. Chave Deep Submergence Laboratory, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA
Rob L. Evans Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA
Gary W. McNeice* Phoenix Geophysics Ltd., 3781 Victoria Park Avenue, Scarborough, Ontario M1W 3K5, Canada

ABSTRACT

The Archean Slave craton in northwestern Canada is an ideal natural laboratory for investigating lithosphere formation and evolution, and has become an international focus of broad geoscientific investigation following the discovery of economic diamondiferous kimberlite pipes. Three deep-probing magnetotelluric surveys have recently been carried out on the craton using novel acquisition procedures. The magnetotelluric responses reveal an unexpected and remarkable anomaly in electrical conductivity, collocated with the kimberlite field that is modeled as a spatially confined upper mantle region of low resistivity ($<$30 Ω·m) at depths of 80–100+ km, and is interpreted to be due to dissolved hydrogen or carbon in graphite form. This geophysically anomalous upper mantle region is also spatially coincident with a geochemically defined ultradepleted harzburgitic layer. The tectonic processes that emplaced this structure are possibly related to the lithospheric subduction and trapping of overlying oceanic mantle at 2630–2620 Ma.

Keywords: Slave Province, magnetotelluric surveys, electromagnetic, Archean, electrical conductivity, plate tectonics.

INTRODUCTION

The Slave craton (Fig. 1) in the northwestern part of the Canadian shield is a small Archean geologic province, ~600 × 400 km in exposed extent, that hosts the oldest dated rocks on Earth, the 4.027 Ga Acasta gneisses (Stern and Bleeker, 1998). It has become the focus of intense geoscientific scrutiny following the discovery of diamonds in 1991 (Fipke et al., 1995) and the opening of North America's first producing diamond mine, Ekati, in 1998 (Rylatt and Popplewell, 1999). Excellent outcrop and existing geoscientific data make the Slave craton an unparalleled natural laboratory for testing competing theories of Early Archean lithospheric assembly, growth, and subsequent evolution.

Models for assembly processes include repeated cycles of differentiation and collisional thickening (Jordan, 1988), collision of island arcs comprising depleted material (Ashwal and Burke, 1989), buoyant subduction and imbrication by lithospheric-scale stacks (Helmstaedt and Schulze, 1989), and basal accretion by cooling asthenospheric material (Thompson et al., 1996). These models imply different physical characteristics that are measurable using geophysical methods; in particular, deep-probing electromagnetic methods are well suited for defining lithospheric structures (Jones, 1999).

Geoscientific studies of the Slave craton and its relationship to the Proterozoic terranes to the west have been undertaken as part of Lithoprobe's SNORCLE transect investigations (Slave Northern Cordillera Lithospheric Evolution transect; Clowes, 1997). In addition, a wealth of geologic data for the craton has been accumulated as part of ongoing Geological Survey of Canada activities and scientific studies of mantle samples provided to academia by industry.

The primary objectives of the electromagnetic experiments were to determine structures within the subcontinental lithospheric mantle of the craton and the topology of the lithosphere-asthenosphere boundary. Serendipitously, we have discovered an anomalous upper mantle conducting region that is collocated both with the central Slave Eocene diamondiferous kimberlite field and with a geochemically defined ultradepleted harzburgitic layer.

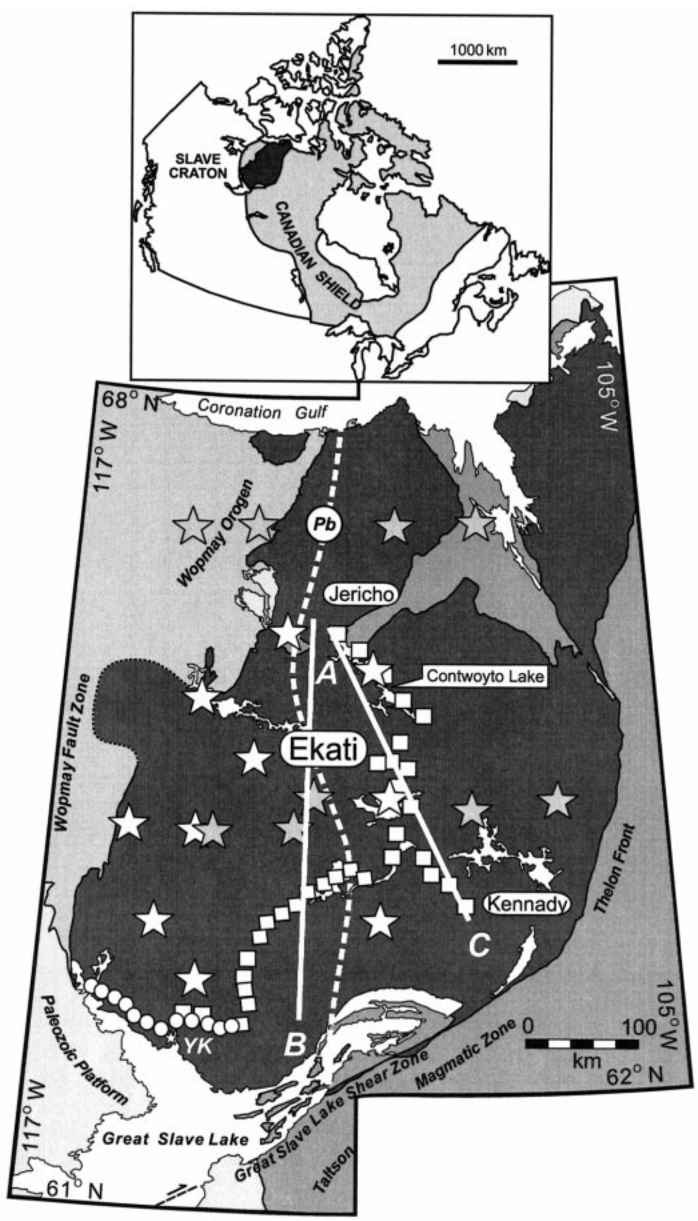

Figure 1. Slave craton and locations of magnetotelluric sites. Open circles—1996 all-weather road sites. Open squares—1998 and 1999 winter road sites. Stars—1998–1999 (white) and 1999–2000 (gray) lake-bottom sites. Models were derived for profiles A-B and A-C. Also shown is north-trending Pb isotope line. YK—Yellowknife.

*Present address: Geosystem Canada Ltd., 927 Raftsman Lane, Ottawa, Ontario K1C 2V3, Canada.

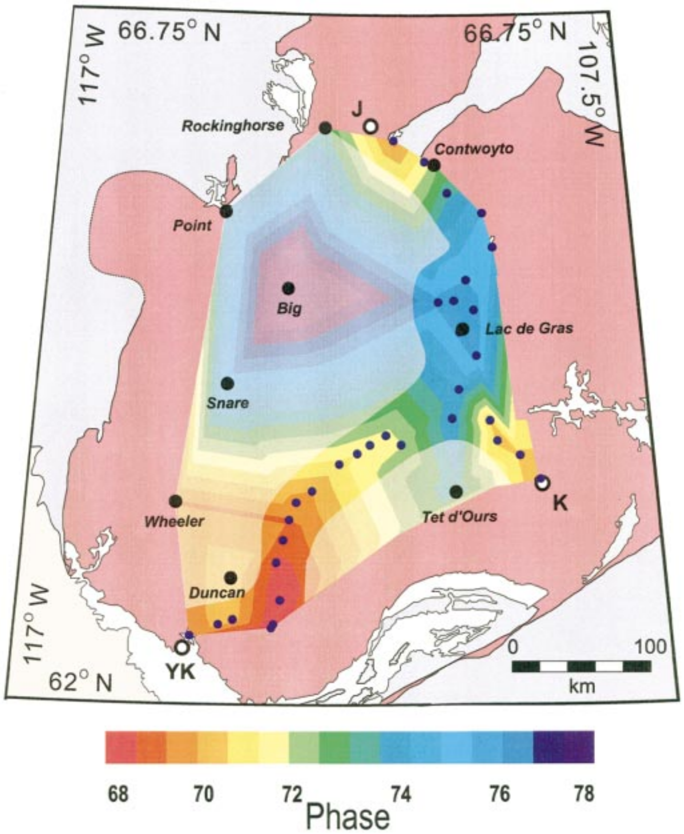

Figure 2. Map of averaged magnetotelluric phases at 300 s period based on data from land sites (small dots) and preliminary processing of 1998–1999 lake-bottom sites (large named dots). YK—Yellowknife; J—Jericho pipe; K—Kennady lake pipes. On Slave craton at 300 s period, electromagnetic waves are penetrating 100–150 km into lithosphere. VE—vertical exaggeration.

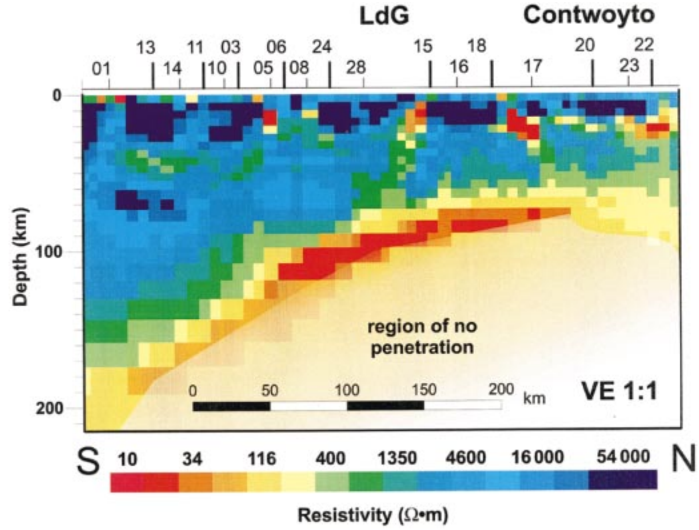

Figure 3. Resistivity model of winter road magnetotelluric data projected along north-south profile A-B (Figure 1). LdG—Lac de Gras.

ELECTROMAGNETIC EXPERIMENTS, DATA PROCESSING, AND OBSERVATIONS

Three electromagnetic experiments using the magnetotelluric technique (Jones, 1999) have been conducted on the Slave craton since 1996. The first survey in fall 1996 comprised conventional broadband (periods of 10^{-4}–10^{4} s) acquisition every 10 km along the only all-weather road on the craton. This profile, located in the southwest corner of the Slave craton, extends east-west ~100 km on either side of Yellowknife (Fig. 1).

Subsequently, broadband data acquisition took place along ice roads over frozen lakes (Fig. 1) during March 1998, 1999, and 2000 by using a novel deployment procedure. At each site, five electrodes were lowered to the lake bottom, through holes drilled through the ice, to record the electric fields; the magnetometers were installed on the nearby shores to avoid noise caused by ice movement.

The third experiment involved deploying seafloor magnetotelluric instrumentation (Petitt et al., 1994) into lakes around the craton from float planes. The 10 instruments were deployed at 19 locations (Fig. 1), with a year's recording at each location.

The magnetotelluric data processing code used to estimate the magnetotelluric tensor response functions was a multiremote reference variant of the Jones-Jödicke scheme (method 6 in Jones et al., 1989). Subsequently, the response functions were analyzed for electric-field distortions caused by local, near-surface inhomogeneities and to determine the appropriate geoelectric strike direction (McNeice and Jones, 2001). The responses showed weak dependence on geoelectric strike, requiring conductivity structure to vary slowly with lateral distance in both the crust and mantle.

Given this rotational invariance, we can obtain qualitative information about lateral variation in Earth conductivity from response maps. Figure 2 shows the arithmetically averaged phases (Berdichevsky and Dmitriev, 1976) for a period of 300 s from the all-weather and winter road sites, plus phases from preliminary processing of data from the first year of lake-bottom deployments. The phases show a distinct high of almost 80° at sites in the Lac de Gras region. Phases decrease away from this region along all three roads; 6° decrease to the north toward the Jericho kimberlite pipe (J), 6° decrease to the southeast toward the Kennady kimberlite pipes (K), and 10° decrease to the southwest toward Yellowknife (YK). The phases from the lake-bottom data (lighter shaded regions in Fig. 2) are consistent with those from the winter road sites, i.e., high phases in the center of the craton and low phases to the north and south. These lake-bottom phases suggest that the phase maximum extends west of the north-trending Pb isotope boundary (Thorpe et al., 1992) to at least Big Lake. Verification of this westerly extension requires complete analysis of the lake-bottom data, including those only now becoming available.

The winter road magnetotelluric responses along profiles A-B and A-C were modeled by using a two-dimensional inversion code that simultaneously fits the data and minimizes structure (Rodi and Mackie, 2001). The dominant feature of the best-fitting resistivity model obtained for profile AB (Fig. 3) is the high-conductivity upper mantle region ($\rho < 30\ \Omega \cdot m$) at a depth of ~80 km beneath the Lac de Gras region. Along the winter roads, the anomaly does not exist north of ~65.25°N or south of ~63.75°N. The resistivity model for profile A-C (not shown) also images an anomaly at ~80 km beneath Lac de Gras that is absent to the north (beneath Contwoyto Lake) and south (beneath Kennady Lake). Sensitivity studies show that the anomaly must be at least 15 km thick for an internal resistivity of ~15 $\Omega \cdot m$. The attenuating effects of the anomaly make imaging the resistivity structure beneath the anomaly impossible—deeper imaging requires longer periods than in the present data set and will be addressed with the lake-bottom data.

A plan view of the central Slave mantle conductor mapped by our winter road data is shown in Figure 4A (dark gray). The high phase value observed at Big Lake suggests that the conductor extends to the west (light gray) across the Pb isotope boundary. This boundary indicates that the crust of the western Slave province is fundamentally different from that of the eastern Slave, but the mantle-conductivity anomaly may not respect this crustal boundary.

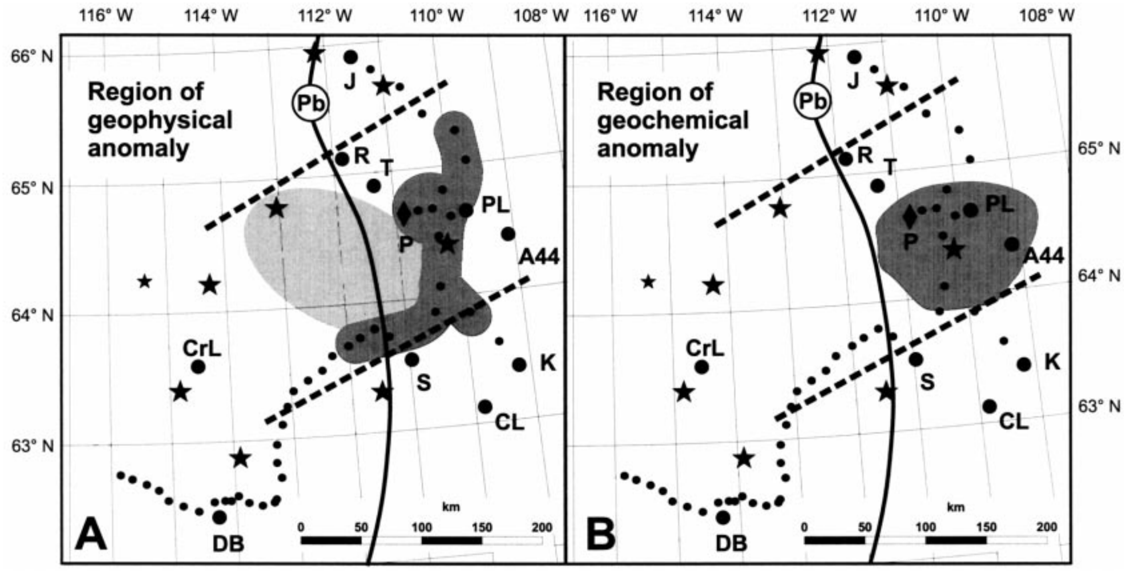

Figure 4. Spatial locations of geophysical and geochemical mantle anomalies in center of Slave craton. Also shown are locations of magnetotelluric sites (dots—winter road; stars—lake bottom), Pb isotope line, mantle-zonation boundaries of Grütter et al. (1999), and important kimberlite pipes on craton. DB—Drybones; CrL—Cross Lake; S—Snap Lake; CL—Camsell Lake; K—Kennady Lake; A44—Diavik's pipe A44 on Lac de Gras; PL—Point Lake; P—Panda pipe at Ekati mine; T—Torrie; R—Ranch; J—Jericho. A: Spatial location of discovered central Slave mantle conductor and its possible extension to west to account for high phase observed at Big Lake. B: Spatial location of discovered ultradepleted harzburgitic layer from Griffin et al. (1999).

GEOCHEMICAL CORRELATION

From studies of mantle xenoliths from 21 kimberlites in the Lac de Gras region, Griffin et al. (1999) mapped the geochemical composition, structure, and thermal state of the mantle; they discovered a unique, two-layered lithospheric mantle in the central Slave craton extending over $>$9000 km^2. The lithospheric mantle comprises an ultradepleted, harzburgitic upper layer (top undefined but shallower than $\sim$100 km) separated sharply at 140–150 km depth from a less depleted, lherzolitic lower layer. This ultradepleted layer was not found at a pipe north of the Lac de Gras kimberlite field (Torrie, T), nor at pipes to the south and southwest (Cross Lake, CrL: Drybones, DB: Camsell Lake, CL). It is found, although much weaker, beneath Ranch Lake pipe (R). Comparison of the spatial extent, location, and depth of the mapped mantle conductor (Fig. 4A) and the mapped ultradepleted harzburgitic layer (Fig. 4B) shows a remarkable coincidence between the two. Grütter et al. (1999) used a larger garnet xenocryst database to suggest a northeast-trending mantle zonation with three lithospheric domains (Fig. 4B), and these geochemical mantle domains are broadly consistent with a geophysical mantle zonation suggested by our work (Fig. 4A).

CAUSES OF CONDUCTIVITY ENHANCEMENT

Laboratory measurements on olivine under uppermost mantle conditions show very high electrical resistivity ($>$100 000 Ω·m, Constable and Duba, 1990), implying that there must be other phases present in the ultradepleted layer to provide conducting pathways. Either emplacement processes or subsequent modification of the ultradepleted layer must have resulted in a connected conducting phase.

There are two dominant mechanisms for flow of current in Earth materials; ionic and electronic conduction. For the former, we rule out melt or free water as potential conduction mechanisms. There is no evidence of high heat flow or uplift that would be associated with recent (after $<$50 Ma) thinning of the lithosphere. Nor would we expect free conductive aqueous phases to have remained trapped in the mantle over geologic time scales to explain the conductivity of such an ancient craton. Similarly, we exclude hydrated minerals because they are not found in xenolith samples (Pearson et al., 1999).

Following Karato (1990), one can appeal to diffusion of hydrogen in the mantle, although the observed conductivity at 80 km depth would require olivine to be saturated in hydrogen (Bai and Kohlstedt, 1992).

For electronic conduction, carbon may be responsible for the enhanced conductivity. Above the diamond stability field ($\sim$125 km, Griffin et al., 1999), carbon would be in the form of highly conductive graphite, and below it would be in the form of highly resistive diamond, and diamonds from those depths are found in Lac de Gras pipes. In the laboratory, carbon has been observed at crustal conditions to be deposited as graphite on mineral surfaces during fracturing (Roberts et al., 1999), leading to the speculation that carbon in the lithosphere below Lac de Gras could have been deposited as continuous graphite films during tectonic processes.

Recent studies show evidence that sulfide is mobile in the lithosphere and can concentrate upward to crystallize at shallow depths (Alard et al., 2000). There is also evidence that sulfides can form an interconnected network in the mantle (M. Gaetani, 2001, personal commun.), and sulfide melts have been invoked to explain high conductivities in the mantle beneath the Sierra Nevada (Ducea and Park, 1999). However, Pearson et al. (1999) noted that the mantle of the Slave craton is far less metasomatised than that of the Kaapvaal craton, for which sulfide contents of as much as 330 ppm have been measured in xenoliths (Alard et al., 2000), implying that the sulfide content for the Slave craton is too low to explain the conductivity values observed.

TECTONIC INTERPRETATION

Given the geochemical data, we suggest that either dissolved hydrogen or carbon, and less likely sulfides, are the probable cause for the enhanced conductivity beneath Lac de Gras, and the provenance of any of the three is linked to causative tectonic processes. Of critical importance to interpretation is to determine an age for the anomaly, and we suggest that the spatial association of the conductor with the ultradepleted layer argues for an ancient origin, rather than processes linked to the Eocene kimberlite event.

Dissolved hydrogen and carbon could have been emplaced through subduction processes associated with the formation of the Slave craton. In this model a portion of hydrated oceanic mantle was trapped above the subducting slab and accreted onto the base of the existing lithosphere (Griffin et al., 1999). The fluxing of CO_2 through this mantle wedge could have emplaced a connected carbon phase. Emplacement of sulfides would be linked to melting processes, possibly associated with backarc volcanism during subduction.

If the anomaly was emplaced during lithospheric assembly, given the northeast-trending geometry and its central location, it is unlikely to have been during the ca. 2690 Ma north-south suturing of the Central Slave basement complex and the eastern Slave arc (Hackett River) terrane (Bleeker et al., 1999a, 1999b). Subsequent approximately east-northeast deformation and plutonism occurred at 2630–2620 Ma and are restricted to the southern part of the newly amalgamated Slave craton (Davis and Bleeker, 1999). These events are in the same orientation as our anomaly, and may record the northward subduction of lithosphere of a craton of unknown provenance beneath the southern Slave craton.

Recent Re-Os evidence (Pearson et al., 2000) suggests that the central Slave craton ultradepleted layer and the lherzolitic layer below it are older than 3 Ga. This evidence appears to be at variance with the widespread granite plutonism and high-temperature–low-pressure metamorphism that affected the entire Slave craton at 2.6 Ga modeled as the consequence of a Slave craton-wide lithospheric delamination event (Davis et al., 1994). Perhaps the Re-Os observations can be reconciled if the subcontinental lithospheric mantle below the Slave craton was not assembled in place beneath the Slave craton, but formed by lithospheric underplating

Further work will be undertaken on xenolith samples to try to determine the cause of the observed conductivity enhancement. Whichever mechanism is determined to be responsible, it is clear that understanding the geometry and physical and chemical properties of the mantle contributes to unraveling the history of the formation and development of the Slave craton. Our conductivity anomaly will aid in discriminating between competing models for lithospheric assembly.

ACKNOWLEDGMENTS

Financial support for the electromagnetic activities came from Lithoprobe, Geological Survey of Canada, Canadian Department of Indian and Northern Development, the U.S. National Science Foundation's Continental Dynamics Program, De Beers Canada Exploration Inc., Kennecott Exploration Inc., and BHP Diamonds, Inc. Accommodation was provided by Diavik, BHP, De Beers, Winspear, Royal Oak Mines, and Miramar Mining. Data acquisition in 1996, 1998, and 1999 was undertaken by Phoenix Geophysics Ltd., and in 2000 by Geosystem Canada Ltd.; we thank them for their reduced academic survey rates and their close attention to detail that resulted in high-quality responses. The Yellowknife Seismological Observatory provided essential preparation facilities. We thank our colleagues, especially Wouter Bleeker, Bill Davis, and Herman Grütter, for enlightening discussions, and Bill Griffin and a second reviewer for their thoughtful comments on the submitted version of this paper. Wouter Bleeker provided the base map for Figures 1 and 2. Geological Survey of Canada Contribution 2000114 and Lithoprobe publication 1214.

REFERENCES CITED

Alard, O., Griffin, W.L., Lorand, J.P., Jackson, S.E., and O'Reilly, S.Y., 2000, Non-chondritic distribution of the highly siderophile elements in mantle sulphides: Nature, v. 407, p. 891–894.

Ashwal, L.D., and Burke, K., 1989, African lithospheric structure, volcanism, and topography: Earth and Planetary Science Letters, v. 96, p. 8–14.

Bai, Q., and Kohlstedt, D.L., 1992, Substantial hydrogen solubility in olivine and implications for water storage in the mantle: Nature, v. 357, p. 672–674.

Berdichevsky, M.N., and Dmitriev, V.I., 1976, Basic principles of interpretation of magnetotelluric sounding curves, *in* Adam, A., ed., Geoelectric and geothermal studies: KAPG (Committee of the Academies of Sciences of Socialist Countries for Planetary Geophysical Investigation) Geophysical Monograph, Akademiai Kiado, p. 165–221.

Bleeker, W., Ketchum, J.W.F., Jackson, V.A., and Villeneuve, M.E., 1999a, The Central Slave Basement Complex, Part I: Its structural topology and autochthonous cover: Canadian Journal of Earth Sciences, v. 36, p. 1083–1109.

Bleeker, W., Ketchum, J.W.F., and Davis, W.J., 1999b, The Central Slave Basement Complex, Part II: Age and tectonic significance of high-strain zones along the basement-cover contact: Canadian Journal of Earth Sciences, v. 36, p. 1111–1130.

Clowes, R.M., editor, 1997, Lithoprobe Phase V proposal: Vancouver, University of British Columbia, Lithoprobe Secretariat, 292 p.

Constable, S.C., and Duba, A., 1990, Electrical conductivity of olivine, a dunite, and the mantle: Journal of Geophysical Research, v. 95, p. 6967–6978.

Davis, W.J., and Bleeker, W., 1999, Timing of plutonism, deformation, and metamorphism in the Yellowknife domain, Slave province, Canada: Canadian Journal of Earth Sciences, v. 36, p. 1169–1187.

Davis, W.J., Fryer, B.J., and King, J.E., 1994, Geochemistry and evolution of late Archean plutonism and its significance to the tectonic development of the Slave craton: Precambrian Research, v. 67, p. 207–241.

Ducea, M.N., and Park, S.K., 2000, Enhanced mantle conductivity from sulfide minerals, southern Sierra Nevada, California: Geophysical Research Letters, v. 27, p. 2405–2408.

Fipke, C.E., Dummett, H.T., Moore, R.O., Carlson, J.A., Ashley, R.M., Gurney, J.J., and Kirkley, M.B., 1995, History of the discovery of diamondiferous kimberlites in the Northwest Territories, Canada, *in* Sixth international kimberlite conference; extended abstracts: Proceedings of the 6th International Kimberlite Conference: Novosibirsk, Russia, United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of the Russian Academy of Sciences, p. 158–160.

Griffin, W.L., Doyle, B.J., Ryan, C.G., Pearson, N.J., O'Reilly, S.Y., Davies, R., Kivi, K., van Achterbergh, E., and Natapov, L.M., 1999, Layered mantle lithosphere in the Lac de Gras area, Slave craton: Composition, structure and origin: Journal of Petrology, v. 40, p. 705–727.

Grütter, H.S., Apter, D.B., and Kong, J., 1999, Crust-mantle coupling; evidence from mantle-derived xenocrystic garnets, *in* Gurney, J.J., et al., eds., Proceedings of the 7th international Kimberlite conference, J.B. Dawson Volume 1: Cape Town, Red Roof Design, p. 307–313.

Helmstaedt, H.H., and Schulze, D.J., 1989, Southern African kimberlites and their mantle sample: Implications for Archean tectonics and lithosphere evolution, *in* Ross, J., ed., Kimberlites and related rocks, Volume 1: Their composition, occurrence, origin, and emplacement: Geological Society of Australia Special Publication 14, p. 358–368.

Jones, A.G., 1999, Imaging the continental upper mantle using electromagnetic methods: Lithos, v. 48, p. 57–80.

Jones, A.G., Chave, A.D., Egbert, G., Auld, D., and Bahr, K., 1989, A comparison of techniques for magnetotelluric response function estimation: Journal of Geophysical Research, v. 94, p. 14 201–14 213.

Jordan, T.H., 1988, Structure and formation of the continental tectosphere, *in* Menzies, M.A., and Cox, K.G., eds., Oceanic and continental lithosphere; similarities and differences: Journal of Petrology, Special Lithosphere Issue, p. 11–37.

Karato, S., 1990, The role of hydrogen in the electrical conductivity of the upper mantle: Nature, v. 347, p. 272–273.

McNeice, G.W., and Jones, A.G., 2001, Multi-site, multi-frequency tensor decomposition of magnetotelluric data: Geophysics, v. 66 (in press).

Pearson, N.J., Griffin, W.L., Doyle, B.J., O'Reilly, S.Y., Van Achterbergh, E., and Kivi, K., 1999, Xenoliths from kimberlite pipes of the Lac de Gras area, Slave craton, Canada, *in* Gurney, J.J., et al., eds., Proceedings of the 7th international Kimberlite conference, P.H. Nixon Volume 2: Cape Town, Red Roof Design, p. 644–658.

Pearson, N.J., Alard, O., Griffin, W.L., Graham, S., and Jackson, S.E., 2000, LAM-MC-ICPMS analysis of mantle-derived sulfides: The key to Re-Os systematics of mantle peridotites: Journal of Conference Abstracts, v. 5, p. 777–778.

Petitt, R.A., Jr., Chave, A.D., Filloux, J.H., and Moeller, H.H., 1994, Electromagnetic field instrument for the continental shelf: Sea Technology, v. 35, p. 10–13.

Roberts, J.J., Duba, A.G., Mathez, E.A., Shankland, T.J., and Kinzler, R., 1999, Carbon-enhanced electrical conductivity during fracture of rocks: Journal of Geophysical Research, v. 104, p. 737–747.

Rodi, W., and Mackie, R.L., 2001, Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion: Geophysics (in press).

Rylatt, M.G., and Popplewell, G.M., 1999, Ekati diamond mine—Background and development: Mining Engineering, v. 51, p. 37–43.

Stern, R.A., and Bleeker, W., 1998, Age of the world's oldest rocks refined using Canada's SHRIMP: The Acasta Gneiss Complex, Northwest Territories, Canada: Geoscience Canada, v. 25, p. 27–31.

Thompson, P.H., Judge, A.S., and Lewis, T.J., 1996, Thermal evolution of the lithosphere in the central Slave Province: Implications for diamond genesis, *in* LeCheminant, A.N., et al., eds., Searching for diamonds in Canada: Geological Survey of Canada Open File Report 3228, p. 151–160.

Thorpe, R.I., Cumming, G.L., and Mortensen, J.K., 1992, A significant Pb isotope boundary in the Slave Province and its probable relation to ancient basement in the western Slave Province, *in* Project summaries, Canada Northwest Territories mineral development subsidiary agreement: Geological Survey of Canada Open File Report 2484, p. 279–284.

Manuscript received September 15, 2000
Revised manuscript received January 24, 2001
Manuscript accepted January 26, 2001

Printed in USA