Do Diamondiferous Kimberlites Preferentially Erupt at Margins of Archean Blocks within the Canadian Shield?

David B. Snyder*
Geological Survey of Canada, Ottawa, Ontario
DSnyder@NRCan.gc.ca

Summary

The source of anisotropic fabric within the mantle of the Slave craton is here interpreted to be fluid conduits that form a macroscopic stockwork of carbonated, hydrated or otherwise metasomatised peridotite dykes within depleted harzburgite. The fabric is thus composed of residual rocks that record the passage of kimberlite clan rocks formed from <1% partial melts of carbonated lherzolite. These metasomatised peridotite conduits probably are composed of rocks such as pyroxenites or wehrlites and occupy 10% of the mantle where present. Using teleseismic anisotropy to reliably locate and predict the alignment of these dyke stockworks in the mantle lithosphere beneath known diamondiferous kimberlites has general application for informed target selection, both for diamond and for kimberlite exploration. In addition, reduced bulk shear wave speeds near these stockworks may be diagnostic of their presence deep in the sub-continental lithospheric mantle.

Introduction

Cratonic margins must be indirectly determined because defining mantle ages are available only where suitable xenoliths have been recovered. Nearly a decade ago major- and trace-element data on garnet concentrates from kimberlites and related volcanic rocks were used to construct cross sections and mantle maps showing the lithosphere thickness, thermal state, composition and structure; these parameters were then used to infer which mantle characteristics were important to diamond production and preservation (Griffin et al. 2004). Recently mantle conductivity structure, controlled primarily by temperature and composition, was hypothesized to represent another indicator that aids in area selection for diamond exploration (Jones et al. 2009). The conclusions of both studies is that diamondiferous kimberlites are found preferentially above strong gradients in these various parameters, hence along the margins between Archean cratonic blocks and Proterozoic tectonized zones.

A third method of characterizing properties of the mantle, propagation parameters of seismic S- and surface waves generated by earthquakes, has been used even longer to locate continental keels and to define shield areas (e.g., Grand 1994). Here several other methods of analysing teleseismic waves at higher spatial resolution are used to delimit the cratonic cores that comprise key continental shields such as those of southern Africa, Canada, and Siberia. Component cratons (Kaapvaal, Zimbabwe, Slave, Superior, Aldan) locally have the best-understood mantle properties because of both extensive diamond exploration and resultant large populations of mantle xenoliths and xenocrysts. Seismic methods enable indirect outward extrapolation from these select known cratonic regions via similarities in seismic properties or strong discontinuities that can be assumed to be plate margins when placed in the context of known surface geology (e.g., Snyder, 2008).

The Canadian National Seismic Network (CNSN) has operated seismic observatories with digital, 3-component, broadband sensors since 1992. These stations typically have 2000 km spacing in Nunavut and the Northwest Territories (NWT). Beginning in 1996 broadband seismometers were deployed in the NWT for several months at ~200 km spacing. Beginning in 1999 POLARIS stations were established for several continuous years at 20–50 kilometre spacing in parts of both Nunavut and the NWT. While approaching neither station coverage nor densities found in southern Canada and the USA, this coverage represents a considerable improvement in analytical potential for various seismic wave techniques such as multi-azimuthal receiver function, surface wave and SKS-splitting studies.

Defining cratons at depth in northern Canada

Five to ten cratons or micro-cratonic blocks are hypothesized to exist across northern Canada based primarily on isotopic dating of crystallization, metamorphic and deformation ages of rocks mapped at the surface. What lies at depth? Whole-rock isotopic ages of xenoliths indicates the depth extent of these definitions very locally. Neither rootless Archean crust nor unexposed cratons are adequately defined in this manner. By definition, cratons represent strong lithosphere and are therefore assumed to be cold, homogeneous blocks. Seismic wave-speed variations at continental scale due to mantle heterogeneity and anisotropy have been variably attributed to thermal and compositional variations (Grand 1994; Griffin et al. 2004; Artemieva 2009). Lithospheric thickness beneath oceans and younger parts of the continents is widely assumed to be temperature controlled. Within continental interiors and shield areas, temperature estimated via available heat flow measurements does not vary sufficiently to explain seismic S-wave variation so that perhaps half is attributable to compositional variation (Artemieva 2009)

Some regional variations may be due to compositional fabric. Teleseismic wave propagation indicates that wave-speed anisotropy nearly doubles within the Lac de Gras kimberlite field in NW Canada when compared to surrounding parts of the Slave craton (Snyder 2008). The implied increase in structural fabric in the lithospheric mantle cannot be explained entirely by stronger alignment of minerals or temperature effects beneath the kimberlite field and forward modelling of the observed anisotropy implies the superposition of an additional fabric related to kimberlite eruption. The source of this fabric is interpreted to be fluid conduits that form a macroscopic stockwork of carbonated, hydrated or otherwise metasomatised peridotite dykes within depleted harzburgite (Malkovets et al. 2007; Snyder and Lockhart 2009). The superimposed fabric is thus composed of residual rocks that record the source or the passage of kimberlite clan rocks formed from <1% partial melts of carbonated lherzolite. These metasomatised peridotite conduits probably are composed of rocks such as pyroxenites or wehrlites and occupy 10% of the mantle where present.

Dense stockworks of metasomatized kimberlitic mantle may only occur, or only be currently recognized, beneath populous kimberlite fields such as Lac de Gras. Within some cratons or continental shields such stockworks could exist, but have few dykes or pipes that reached the present surface. The metasomatized peridotite volumes beneath Lac de Gras of 10–30% should, however, produce sufficient variation is P- or S-wave velocities to cause anomalies on regional- or continental-scale velocity models. Such anomalies do occur within 3-D P-wave velocity models beneath the central Slave craton (Snyder and Lockhart 2009) and may be recognizable on some continental-scale surface wave models (Bedle and van der Lee 2009) in that the Slave craton is not underlain by the highest velocities. Thus metasomatic stockworks within cratonic interiors would be mistaken for non-cratonic mantle regions. Similar variation in surface-wave velocities occur beneath the southern Superior craton and the northern Rae craton. The former feature has good station coverage and is attributed to thermo-compositional effects of the Meteor hotspot (Eaton and Frederickson 2007). The latter has only weak seismological constraints at present.

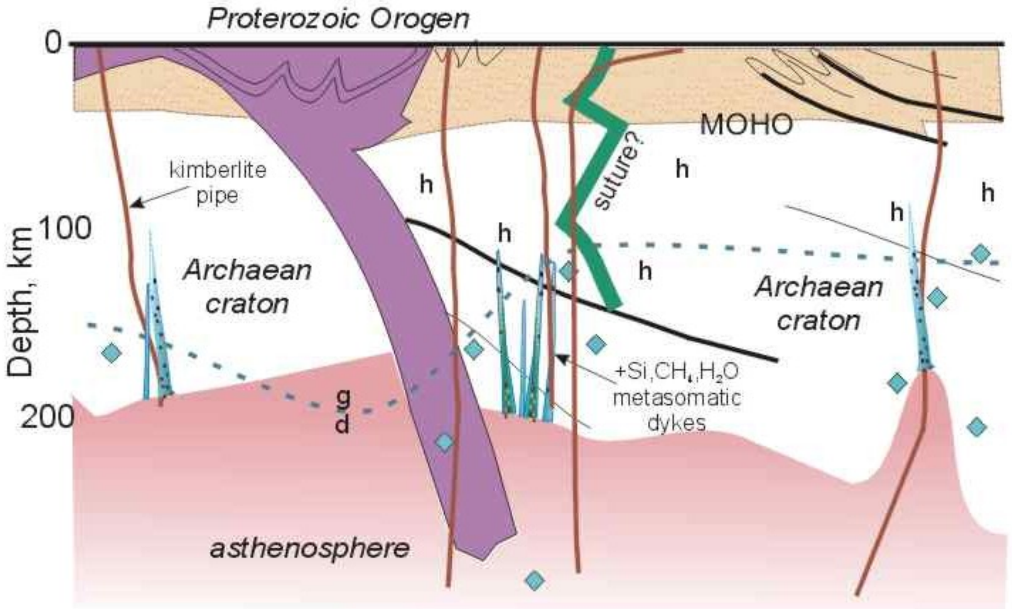

Figure 1: Schematic cross section illustrating diamond-bearing mantle beneath generic parts of shields and where metasomatic stock works might form. Horizontal scale is arbitrary. Light lines sketch important generic lithospheric structures such as the Moho discontinuity, plate sutures and former subduction zones. Dotted line labeled g:d marks the graphite-diamond equilibrium boundary. Solid diamond symbols indicate mantle depths at which paleobaromery on diamond inclusions indicates the diamond formed; similarly, h indicates harzburgitic mantle composition determined from the geochemistry of inclusions, xenoliths and xenocrysts.

Defining the craton margins

If metasomatism plays such a role in decreasing mantle seismic velocities, then craton margins defined by this method alone are suspect. The potential continuous mapping that is only possible with conductivity (magneto-telluric) and seismic wave-speed models enables outward extrapolation from known cratonic cores, but may indicate false margins because of metasomatism. Similarities in seismic properties such as bulk P- or S-wave velocities or anisotropic polarization directions may provide alternative, more robust, indicators of cratonic mantle continuity.

Strong discontinuities in seismic properties can be interpreted as plate margins when placed in the context of known surface geology and used to help infer craton construction (e.g., Snyder, 2008). Crustal and mantle seismic discontinuities and conductivity indicate that the Slave craton continues at depth 100-200 km beyond where surface mapping has placed its margin on its western and southeastern boundaries. Similar ongoing studies are characterizing edges of the Rae and Superior cratons. Older studies provided first recognition and some estimate of the lateral extent of the Sask craton. A much larger population of diamondiferous and non-diamondiferous kimberlites is now available than a decade ago (Griffin et al. 2004) and correlations of these kimberlites with presently recognized craton margins are varied. Similar correlations in southern Africa appear scale-dependent and debatable (Jones et al. 2009).

Conclusions

Carbonated, hydrated or otherwise metasomatised peridotite dyke stockworks within depleted harzburgite may facilitate both diamond occurrence and kimberlite generation. Distinct teleseismic anisotropy may reliably predict the alignment of dyke stockworks in the mantle lithosphere beneath known diamondiferous kimberlites and reduced bulk shear wave speeds near these stockworks may also be diagnostic of their presence deep in the sub-continental lithospheric mantle whether or not kimberlites are known at surface. Seismic discontinuities and some gradients in conductivity can help delimit cratonic margins at depth of interest for diamonds and kimberlites. Carbonated dykes do not necessarily have petrogenetic relationship to these margins.

Acknowledgements
Acquisition of the seismic data was made possible by support from the POLARIS consortium and the Natural Science & Environment Research Council in Canada.

References
Artemieva, I., 2008. Compositional variations in the continental lithosphere constrained by non-geochemical data. Lithos, 109, 23-46.

Bedle, H. and van der Lee, S., 2009, S-velocity variations beneath North America: Journal Geophysical Research, 114, B07308, doi:10.1029/2008JB005949.

Eaton, D., and Frederickson, A., 2007, Seismic evidence for convection-driven motion of the North American plate: Nature, 446, 428–431.

Grand, S., 1994, Mantle shear structure beneath the Americas and surrounding oceans, Journal Geophysical Research, 99, 11591–11621.

Griffin, W. L., O'Reilly, S. Y. , Doyle, B.J., Pearson, N.J., Coopersmith, H., Kivi, K., Malkovets, V., and Pokhilenko, N., 2004, Lithosphere mapping beneath the North American plate, Lithos, 873-922.

Jones, A. G. Evans, R. L., Muller, M. R., Hamilton, M. P., Miensopust, M. P., Garcia, X. , Cole, P., Ngwisanyi, T., Hutchins, D., Fourie, C.J.S., Jelsma, H., Evans, S., Aravanis, T., Pettit, W., Webb, S., Wasborg, J., and The SAMTEX Team, 2009, Area selection for diamonds using magnetotellurics: Examples from southern Africa, Lithos, 112S, 83-92.

Malkovets, V. G., Griffin, W. L., O'Reilly, S. Y., Wood, B. J., 2007. Diamond, subcalcic garnet, and mantle metasomatism: kimberlite sampling patterns define the link. Geology 35, 339–342.

Snyder, D. B., 2008, Stacked uppermost mantle layers within the Slave craton of NW Canada as defined by anisotropic seismic discontinuities, Tectonics, 27, TC4006, doi:10.1029/2007TC002132.

Snyder, D. B., and Lockhart, G. D., 2009. Does seismically anisotropic subcontinental mantle lithosphere require metasomatic wehrlite-pyroxenite dyke stockworks? Lithos, 1125, 961–965.