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Imaging Archaean-age whole mineral systems

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ABSTRACT

Structural fabrics that cause seismic wave anisotropy within the lithospheric mantle of the Slave craton of northwest Canada are interpreted as fluid conduits that form a macroscopic-scale stockworks of metasomatised peridotite dykes within depleted harzburgitic mantle. These metasomatised peridotite conduits probably are composed of rocks such as pyroxenite or wehrlite and must occupy 10% of the mantle in order to explain this distinct anisotropy where it is present. Reduced mantle shear-wave speeds associated with these stockworks may prove diagnostic of their presence deep in the sub-continental lithospheric mantle. The former (and present?) fluid conduits have been hypothesized as source regions for diamonds and kimberlite magmas, and may also be metal-enriched regions. In order to form a whole mineral system, such stockworks of metasomatised mantle conduits must communicate with crustal conduits leading to near-surface mineral deposits. Seismic evidence for these conduits at all levels has been observed beneath a few major mining camps.

The question as to why large ore systems form involves numerous geological factors that together control the generation and preservation of mineral deposits at all scales (e.g., McCuaig et al., 2010). It is increasingly recognized that key questions that guide exploration after appropriate re-scaling include geodynamic setting, architecture, fluid reservoirs, flow pathways and drivers, and deposition mechanisms (Barnicoat et al., 2007; O'Reilly et al., 2008). Here the focus will be on evidence for the largest lithospheric-scale architecture that hosted fluids at the oldest possible times, when cratons and their sub-continental mantle lithosphere were first forming. This is not to suggest that such processes are limited in time or scale, only that the evidence presented here is limited in this way. Although geodynamic, geochemical, and pressure-temperature histories of the mineral systems are all important, the geophysical methods discussed here are best able to address most directly questions of overall system architecture and relative locations of specific fluid pathways and reservoirs. The majority of the teleseismic and magnetotelluric surveys were originally undertaken to aid terrane and area selection in diamond exploration. The resulting, current working hypothesis that carbonated, hydrated or otherwise metasomatised lithospheric peridotite represents a multi-stage source region for both diamonds and kimberlites also has important applications and relevance to the fluid sources and metallogeny of Archaean mineral systems.

1. Insights into mantle reservoirs and fluid pathways from teleseismic surveys

The architecture of the whole lithosphere (Fig. 1) must be imaged by deeply penetrating geophysical exploration methods such as earthquake-source seismology and magnetotellurics. These methods can show large-scale lateral and vertical variations (heterogeneity) in bulk physical properties such as seismic wave velocities (Fig. 2) and conductivity. Seismic waves also locate discontinuities in these properties, such as the crust–mantle boundary, the Moho. Both methods are also sensitive to strongly or pervasively aligned fabric that manifests itself as anisotropy, most typically as azimuthal dependence in observed parameters (Savage, 1999). Previous workers studied crustal properties relevant to mineral systems using these methods (e.g., Drummond et al., 1998, 2004; Goleby et al., 2004; Heinson et al., 2006), but not the whole lithosphere. Recent diamond exploration in northwest Canada has surveyed to these greater depths (Snyder, 2008).

Characterization of sub-continental mantle lithosphere has required a multi-disciplinary approach. Major- and trace-element data on garnet concentrates from kimberlites and related volcanic rocks were used as early as a decade ago to construct lithospheric cross sections and mantle maps showing the lithosphere thickness, thermal state, composition and structure (Griffin et al., 2004). More recently, mantle conductivity structure, controlled primarily by temperature and composition, was hypothesized to represent another indicator of mantle state (Jones et al., 2009). Propagation parameters of seismic S- and surface waves generated by earthquakes, have been used for several decades to locate continental

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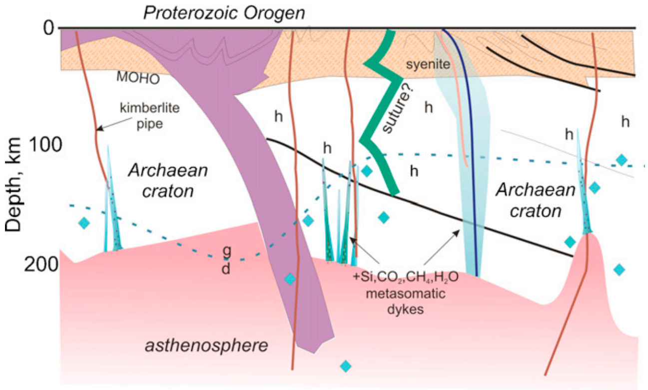

Fig. 1. Schematic cross section across an imagined continental shield illustrating where diamond-bearing mantle and metasomatic stockworks might form. Horizontal scale is arbitrary. Light lines sketch important generic lithospheric structures such as the Moho discontinuity, plate sutures and former subduction zones. Dotted line labelled g:d marks the graphite-diamond equilibrium boundary (Francis and Patterson, 2009). Solid diamond symbols indicate mantle depths at which paleobarometry on diamond inclusions indicates that diamond forms; similarly, h indicates harzburgitic mantle composition determined from the geochemistry of inclusions, xenoliths and xenocrysts (e.g., Griffin et al., 2004). Diamond-bearing kimberlitic and metalliferous syenitic magmas that reach the surface are here hypothesized to originate either from within the metasomatic dykes and stockworks or within the underlying asthenosphere for kimberlites.

keels and to define shield areas (Grand, 1994; Bedle and van der Lee, 2009). Other methods of analysing teleseismic waves at higher spatial resolution help characterize the Archaean cratonic cores of continental shields (e.g., Silver, 1996; Savage, 1999). Key Archaean cratons (Kaapvaal, Zimbabwe, Slave, Superior, Aldan) have the best-understood mantle properties because of extensive diamond exploration and resultant large populations of mantle xenoliths and xenocrysts available for study and analysis (Griffin et al., 2004). Seismic methods enable indirect outward extrapolation from these "point source" localities within these cratonic regions, via similarities in seismic properties such as anisotropy or strong discontinuities that can be assumed to be margins of key lithospheric building blocks when placed in the context of known surface geology (e.g., Shirey et al., 2002; Snyder, 2008; Begg et al., 2009).

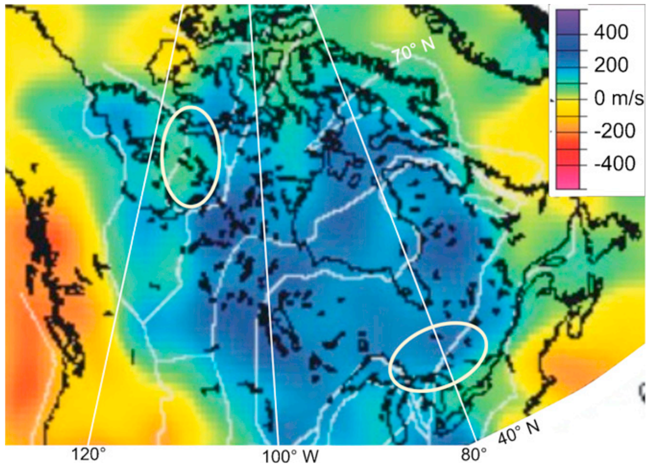

Fig. 2. Location map of areas (elipses) within the Slave and Superior cratonic parts of the Canadian Shield discussed here, shown superposed on the 150-km depth slice of the NA07 S-wavespeed tomographic model of Van der Lee and Frederickson (2005). Velocities associated with green-blue colours outline the Canadian Shield; green colours within this region represent areas with velocities reduced by 100–300 m/s that are here hypothesized to indicate more intensely metasomatised parts of the subcontinental mantle lithosphere. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of the article.)

Seismic wave-speed variations at continental scale due to mantle heterogeneity and anisotropy have been variably attributed to thermal and compositional variations (Griffin et al., 2004; Deen et al., 2006; Artemieva, 2009; Begg et al., 2009). Lithospheric thickness beneath oceans and younger parts of the continents is widely assumed to be temperature controlled based on seismic velocity models (e.g., Priestley and McKenzie, 2006). The older, cooler core of North America, as generally represented by its Canadian Shield, is demarcated by higher than average surface wave velocities at 150 km depth (blue and green colours in Fig. 2). Within continental interiors and shield areas, temperature estimated via available heat flow measurements does not vary sufficiently to explain all seismic S-wave variation so that perhaps half is attributable to compositional variation (Artemieva, 2009). Some of the regional variations may also be due to compositional fabric that is related to age and tectonic history; the Canadian Shield is defined as Archaean cratons sutured together by Proterozoic orogens (Fig. 1; Hoffman, 1988). Multi-azimuthal studies of teleseismic wave propagation indicate 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 within the lithospheric mantle cannot be explained entirely by stronger alignment of minerals or recent temperature effects beneath the kimberlite field and forward modelling of the observed anisotropy implies the superposition of an additional fabric related to kimberlite eruption.

One source of structural fabric that causes seismic wave anisotropy within the mantle of the Slave craton of northwest Canada can be interpreted in a non-traditional way (Snyder and Lockhart, 2009) as fossil fluid conduits that are independently theorized to form a macroscopic stockwork (Sleep, 2003, 2009) of carbonated, hydrated or otherwise metasomatised peridotite dykes within depleted harzburgitic peridotite mantle (Fig. 3; Malkovets et al., 2007). Here the term dyke or stockwork is used broadly to include intruded material, deformation (shear) zones and flanking alteration halos that together comprise the fossil fluid conduits. The superimposed fabric is thus composed of residual dyke stockworks that record the passage of kimberlite magmas (<1% partial melts of carbonated lherzolite, Francis and Patterson, 2009). These metasomatised peridotite conduits probably are composed of rocks such as pyroxenite or wehrlite and must occupy at least 10% of the mantle in order to explain this distinct anisotropy where it is present (Snyder and Lockhart, 2009).

Using teleseismic anisotropy to reliably locate and predict the alignment of these dyke stockworks in the mantle lithosphere beneath known diamondiferous kimberlites aids target selection for diamond exploration. Dense stockworks of kimberlite-metasomatised mantle may only occur, or only be currently recognized, beneath populous kimberlite fields such as Lac de Gras in the central Slave craton. Elsewhere within continental shields such deep-seated stockworks could exist, but have few dykes or pipes that reached the present surface due to the vertical distribution of stress/strain predicted for shields (Sleep, 2009). The hypothesized metasomatised peridotite volumes beneath Lac de Gras can produce sufficient reduction in P- or S-wave velocities to cause anomalies on regional- or continental-scale seismic wave propagation models. Such anomalies observed within 3D P-wave velocity models beneath the central Slave craton (Snyder and Lockhart, 2009) may be recognizable on some continental-scale surface wave velocity models (Bedle and van der Lee, 2009) in that the Slave craton is not underlain by the highest velocities within North America (Fig. 2). The cause of this metasomatism remains uncertain, and is not necessarily related to subduction of crust and ocean lithosphere, although such a model has been proposed (Snyder, 2008). More importantly to mineral system investigations, reduced mantle shear-wave speeds associated with these