The evolution of lithospheric domains: a new framework to enhance mineral exploration targeting

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Abstract. A new approach to global exploration targeting is essential for the discovery of new world-class ore deposits. Understanding the lithosphere-scale context of resource formation and location may provide the next step-change in enhancing exploration success. Knowledge of the nature of trans-lithospheric structure and discontinuities and the delineation of deep lithosphere domains with fundamentally different composition, architecture and evolution is providing a new framework for understanding and predicting the location of ore-deposits derived from a variety of deep lithospheric processes including mantle-derived magmatic and fluid flow (and associated thermal transfer) and deep crustal reworking and partial melting. Relevant resource deposits include Ni-PGE, Cu, Au, diamonds, while these methods also reveal important parameters about basin formation that are potentially important for oil and gas occurrence.

Keywords. Lithospheric mantle; exploration targeting; diamonds; magmatic nickel deposits

1 The lithospheric context

The last twenty years have seen a systematic decline in the performance of the global minerals exploration industry; in the 1990s approximately three times as much was spent to make a major discovery as in the 1970s. This decline is now widely recognised by the industry, leading to an increased emphasis in some of the exploration sector on focussed research, targeted at improving exploration performance. Economic analysis indicates that the Expected Monetary Value of an exploration project is most sensitive to the quality of the initial area selection decision. When searching for new giant ore deposits, the most important targeting is done at the broad regional scale, resulting in ground acquisition of the order of a few thousand square kilometres. Therefore, improving the quality of regional targeting decisions becomes a primary driver of enhancing exploration success.

The primary focus of modern mineral exploration must be on giant metal ore-deposits and high-grade diamond-producing deposits, in order to achieve profitability. The essential challenge in targeting lies in discriminating between areas prospective for such significant deposits and those likely to host only minor deposits. Historically, the discipline of Economic Geology has not focussed much on this problem, but has concentrated on developing an understanding of the processes of ore formation. The few published studies to consider the factors that produce giant ore deposits have compared and contrasted deposit-scale parameters. In all cases, the conclusions have been that there are no unique features at the deposit scale that characterise giant deposits.

However, giant ore deposits must be thought of as mass-concentrative systems that are constrained, for fundamental reasons of mass-balance, to operate over very large scales. In this perspective, the ore deposit itself becomes merely the final focus of a much larger-scale system. Therefore, the concepts and observations of the greatest significance to predictive targeting for giant ore systems are those related not to the deposit environment itself, but to the much larger entity -- the ore system. In this context, critical questions become:

- How large is the ore system?
- What are its fundamental controls?
- How can such systems be recognised in the datasets available to mineral exploration?

Our approach, based on detailed studies of the nature of the lithosphere, is based on the concept that giant ore systems are the product of *lithosphere-scale* processes. Although the details of such processes will vary between deposit styles, a critical common factor is the large-scale structure of the lithosphere; with large ore deposits more likely to be associated with lithosphere-scale domain boundaries.

2 *4-D Lithosphere Mapping*

4-D Lithosphere Mapping (eg O'Reilly and Griffin, 1996; O'Reilly et al., 2001a) is a unique approach to understanding lithospheric architecture and evolution based on integration of petrologic, geochemical, tectonic and geophysical datasets. The mantle is the ultimate source of Earth's atmosphere, oceans, crust and fluids that deposit a wide range of ores, so the nature of the bulk of the Earth lying beneath the crust is of fundamental importance to understanding the formation and localisation of many resources.

Several lines of evidence indicate that the subcontinental lithospheric mantle (SCLM) is heterogeneous, with domains hundreds to thousands of kilometres across that are underlain by different types of upper mantle with different histories and styles of crust-mantle interaction. Fragments of the upper mantle (xenoliths) brought to the surface in volcanic rocks show that mantle volumes of different age differ significantly in composition, thermal state and density (Griffin et al., 1998a; O'Reilly et al., 2001). These data also show abrupt changes in mantle composition and structure across major terrane boundaries, even within single cratons, indicating that these boundaries extend to depths of at least 200 km (Griffin et al., 2003a) and represent significant discontinuities in the SCLM. Such domain boundaries reflect the large-scale geodynamic processes by which continents have been constructed, broken up and reassembled throughout Earth's history. The mapping of such boundaries, and the definition of their timing and origin, therefore provides fundamental new insights into Earth processes, providing the basis for a new conceptual approach to global mineral exploration.

3 Change in nature of the subcontinental lithosphere through time

The secular evolution of SCLM composition has been documented by the detailed mapping of mantle sections in terms of composition, "stratigraphy" and

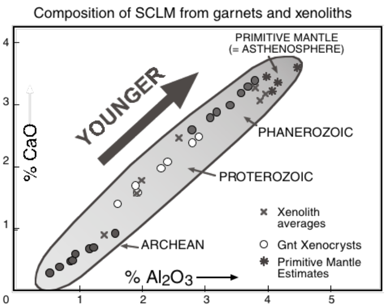

Figure 1: Change in average composition of newly-formed lithospheric mantle through time.

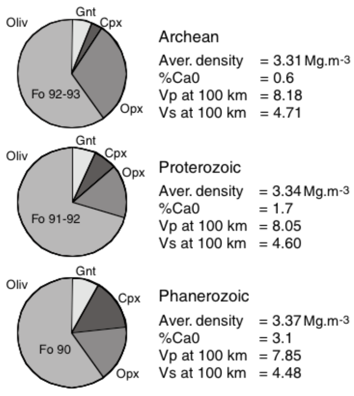

Figure 2: Properties of lithospheric mantle of different ages. Densities calculated at standard T and P, shear wave velocity (*V*s) and compressional wave velocity (*V*p) at 100 km (O'Reilly et al., 2001).

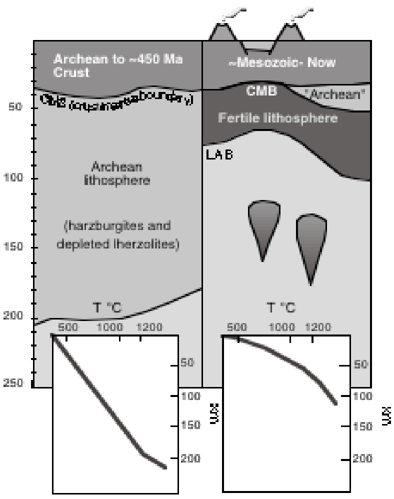

Figure 3: Lithosphere evolution in eastern part of Sino-Korean craton (Griffin et al., 1998b).

thermal state, using xenocrystic and xenolithic material brought to the surface in volcanic rocks (e.g. kimberlites, lamproites and basalts). This work has shown a clear correlation of SCLM composition with the age of the last major tectonothermal event in the overlying crust: the Archean/Proterozoic boundary represents a major change in the nature of lithosphere-forming processes: Archean SCLM is highly depleted (very low in basaltic components such as Ca, Al and Fe), commonly strongly stratified, and contains rock types not found beneath terranes affected by younger tectonothermal events (Fig. 1). It is relatively thick (180 – 220 km) and has a present-day low goethermal gradient. Phanerozoic lithospheric mantle is thinner (80-100km), has a high geothermal gradient and is compositionally more fertile (higher contents of Fe, Ca and Al). Proterozoic mantle has intermediate characteristics.

These compositional variations in different SCLM volumes result in differences in the density and elastic properties of lithospheric mantle of different age (Fig. 2; Poudjom Djomani et al., 2001a*). Archean and Proterozoic* mantle roots are highly buoyant; they cannot be delaminated but require mechanical disaggregation (lithospheric thinning and/or rifting) and infiltration of upwelling fertile material to be destroyed or transformed. This buoyancy, when combined with the refractory nature of Archean SCLM, offers a simple explanation for the thickness and longevity of Archean lithospheric keels. By contrast, *Phanerozoic* SCLM is relatively dense (compared with asthenosphere) for observed thicknesses (~100km) and tends to be in a precarious state of neutral buoyancy. Thus it is easily delaminated especially if there is a kinetic trigger such as collision.

The contrasting properties of different mantle domains require lateral contrasts in composition, density, depth and seismic response for present-day lithospheric domains. Such lateral contrasts create lithospheric discontinuities and may affect thermal convection geometries; these boundaries may be foci for fluid flow though the lithosphere.

4 Tracking linked crust and mantle events

The broad relationship between crustal age and SCLM composition suggests a strong link between crustal formation and the generation of continental roots, and a persistent coupling between the crust and the underlying SCLM.

GEMOC has developed the unique *TerraneChron*™ approach to studying the processes of crustal generation on the terrane scale, using integrated U-Pb dating, and Hf-isotope and trace-element analysis of single zircon grains from stream sediments (eg Belousova et al., 2004; O'Reilly et al, 2004). We have also developed unique techniques for dating mantle depletion events, using *in situ* Re-Os analysis of sulfides in mantle-derived xenoliths, providing geochronology about mantle events such as stabilisation age of the particular mantle volume and the timing (and nature) of subsequent fluid-related mantle events for the first time (eg Griffin et al, 2004; Spetsius et al., 2002). The combination of these novel approaches now allows a detailed analysis of the temporal and geochemical relationships between tectonic events in the crust and mantle. Such knowledge helps to provide information on the nature and timing of large-scale fluid movement and/or thermal transfer from the mantle to the crust with relevance to ore-forming processes related to magmatic episodes with or without significant crust reworking (eg fluid infiltration into and melting of deep crust regions).

5 Focussing the pathways for mantle fluids to reach the crust

The integration of geophysical data with geochemical data has proven powerful in revealing the nature of the deep crust and lithospheric mantle. Coupled with the mantle domains with vertically resolved spatial rock type distribution, we are able to define discrete lithospheric mantle regions and discontinuities (vertical and horizontal).

We have integrated the petrological and geochemical information with long-wavelength geophysical (gravity, magnetic and heat flow) data as well as detailed seismic tomography to extend our lithosphere mapping from the vertical "virtual drill-holes" of the mantle sampling sites to regional scales. A productive approach has been the use of detailed analysis of the Effective Elastic Thickness (T*e*) of the lithosphere to test the relationships of these domains to lithospheric strength and lithosphere composition. T*e* assessment involves inversion of gravity and topographic data and results in the delineation of regions of different lithospheric strength that are interpreted as reflecting relative rheological domains. Combining the T*e* with detailed stratigraphic and tectonic analyses of crustal history has led to an understanding of the evolution of lithosphere domains.

Detailed T*e* analysis across the Slave Craton (Canada) and Siberia, areas of importance in diamond exploration, has shown that kimberlites occur at features identified as gradients in lithosphere strength and that the kimberlites avoid strong cratonic core regions. In the Slave Craton, the observed T*e* gradient coincides with the expression of a major crustal suture zone that dips to the east near the surface. The combination of geochemical information from the mantle-derived samples and the T*e* results indicate that this suture dips sharply at depth to be near vertical in the lithospheric mantle. This provides an empirical link between this major lithosphere structure, clearly imaged in the T*e*, and the zone of kimberlite emplacement. An analogous relationship between Te gradient and kimberlite emplacement is seen in the Siberian lithosphere (Poudjom Djomani et al, 2001b). We consider that T*e* gradients can identify fundamental zones of weakness or lithospheric discontinuities that have important consequences as pathways to focus the transfer of mantle fluids (including magmas) to the overlying crust and therefore have considerable significance in large-scale exploration targeting for economic deposits related to mantle fluids such as kimberlites and Ni deposits related to magmatic processes.

6 The North China Craton – a case history of lithosphere change

The North China craton provides a cogent example of significant lithosphere change crucial to exploration for diamond-bearing kimberlites in that region. In the eastern Sino-Korean craton, eruptions of Ordovician kimberlites provide mantle samples (xenoliths and disaggregated minerals) that show the mantle at that time was thick, cool, diamondiferous and typically Archean in composition (Fig. 3); it probably had survived for at least 2 Ga (Griffin et al., 1998b). Tertiary lamprophyres and basalts that erupted through the same terranes about 400 Ma later, sampled only a thin (<120 km), hot and fertile lithosphere. Within those 400 Ma, rifting with associated asthenospheric upwelling has disaggregated and thinned the Archean lithospheric root as revealed in detailed tomography as well as by the mantle xenolith sampling. One important consequence of understanding the nature and timing of such lithospheric change is that the common concept that diamond-prospective regions require a deep, ancient lithospheric root. This does not exist today in north China although kimberlites erupted before the lithosphere thinning may be diamondiferous.

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