Tectonic Aspects of the Kimberlite - Diamond - Upper-Mantle-Sample Connection: Does a coherent Model evolve?

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The renaissance in kimberlite and upper-mantle studies, for which the 1IKC held in Cape Town, in September of 1973, provided the first major international forum, led to two important conceptual changes affecting virtually all aspects of our understanding of upper mantle processes, including diamond and kimberlite formation. The first concerns the relationship of diamonds to kimberlites, with a conversion from the phenocrystal to xenocrystal school of thought set in motion by studies of Kramers et al. (1979), and gathering momentum after Richardson et al. (1984) showed that peridotitic diamonds from the Mesozoic Finsch and Kimberley-group kimberlites had been stored in the upper mantle since Archean times prior to reaching the surface via the kimberlites. The second change began with the proposal that xenoliths of so-called mantle eclogites from what was then believed to be kimberlitic diatremes of the Colorado Plateau are metamorphosed basic rocks (Helmstaedt and Anderson, 1969; Helmstaedt et al., 1972) that may represent samples of oceanic lithosphere subducted under the west coast of North America (Helmstaedt and Doig, 1973, 1975). At the time of the 1IKC, all mantle eclogites from kimberlites were interpreted as high-pressure crystallization products from partial melts of mantle peridotite that showed various sub-solidus textural adjustments predating kimberlite eruption (e.g., Lappin and Dawson, 1975). The proposal that the subduction hypothesis may also apply to the diamondiferous upper mantle sample from kimberlites (e.g., Sharp, 1974; Helmstaedt, 1978), did not gain wider acceptance until various geochemical and isotopic supporting evidence, mainly pertaining to the eclogitic component, was accumulated in the late 1980s (for a review, see McCandless and Gurney, 1997). A subduction origin was also attributed to certain peridotite xenoliths, including their diamonds (Schulze, 1986; see review by Boyd, 1989a), but much disagreement remains regarding these rock types.

The restriction of richly diamondiferous kimberlites to the Archean parts of cratons, as well as the Archean isotopic signatures obtained from diamond inclusions, suggest a major episode of diamond formation in the Archean and long-term storage of diamonds in subcratonal lithospheric roots. Petrological models, based initially on southern African xenolith and diamond inclusion suites (e.g., Boyd and Gurney, 1986; Haggerty, 1986; Gurney, 1990) suggest a highly depleted, peridotitic diamond source with lenses of eclogitic rocks at depths between 150 to 200 km and temperatures not exceeding 1200°C. They are compatible with seismological and geothermal data suggesting that the lithosphere under older continental regions is of greater than average thickness (Jordan, 1978) and characterized by higher shear wave velocities (e.g., Grand, 1987), implying cooler temperatures relative to the adjacent asthenosphere. However, many problems remain about the correlation between geophysicists' and geochemists' views of the lithosphere (Anderson, 1995).

The origin of lithospheric roots is a problem of Archean tectonics and hinges on an explanation for their highly depleted, and thus refractory and gravitationally stable nature.
Two endmember hypotheses proposed are (1) the harzburgites formed essentially *in situ* as residue

after melt extraction from normal mantle peridotite, of either komatiites or more voluminous basalts (e.g., Bickle, 1986; Boyd, 1989b), and (2) the depleted roots are the result of tectonic underplating by imbricated slabs of oceanic lithosphere (e.g., Helmstaedt and Schulze, 1989; Abbott, 1991).

By using knowledge representation techniques, we will show that the subduction hypothesis has a greater "explanatory cohesion", especially as it is compatible with more recent views on Archean surface geology, in particular the formation of granitoid rocks of the trondhjemite-tonalite-granodiorite (TTG) suites, which are volumetrically dominant in Archean cratons and form the oldest preserved Archean crust. These TTG suites are believed to have formed by 15-30% melting of a mafic, garnet-bearing precursor (subducted ocean floor rocks that are metamorphosed to garnet ampbibolites and low-temperature eclogites), with the voluminous complementary residue being transformed into high-temperature eclogites (e.g., Rapp et al., 1991; Rudnick, 1995) that either sank into the deeper mantle or became part of the lithosphere under the evolving Archean cratons. Trace element data from eclogitic inclusions in diamonds from eclogite xenoliths in kimberlites of the Siberian craton are consistent with eclogite formation in equilibrium with a tonalitic melt (Ireland et al., 1994). Diamond formation under Archean cratons may thus be related to subduction of Archean (and post-Archean?) oceanic lithosphere (see also Schulze, 1986), scraped-off remnants of which may be preserved in some greenstone belts. It may be speculated that thicker and thus cooler lithosphere formed where early continental crust was repeatedly underplated, thus increasing the diamond potential of Archean cratons under or near the early Archean (>3Ga) continental nuclei.

Until recently, all petrological and geochemical probing of the subcontinental lithosphere was done without a geometric framework. The P-T history of xenoliths was used to infer the depth of origin at the time of kimberlite formation and formed the basis for establishing "paleogeotherms" and what has been generally referred to as "upper-mantle stratigraphy". Geophysical methods, including seismic refraction, tomography based on teleseismic studies, and magnetotelluric (MT) studies, lacked the resolution to infer internal structure of the roots other than providing the general orientation of velocity and conductivity anisotropies.

Seismic reflection studies, in particular the Abitibi-Grenville, Trans-Hudson Orogen and SNORCLE transects of the Canadian LITHOPROBE program have provided images of deep-crustal and upper-mantle structures in Archean and Paleoproterozoic terrains of the Canadian Shield that have helped to close the observational gap and are thus of relevance to the debate about the origin of lithospheric roots. For example, in the Superior Province, beneath the Abitibi-Opatica Plutonic Belt boundary, a zone of north-dipping seismic reflectors, extending from the base of the crust into the upper mantle to depths of about 70 km, has been interpreted as a remnant of Archean subducted oceanic crust (Calvert et al., 1995). The northerly imbrication of the Abitibi crust and the mantle suture image are compatible with earlier models of southward prograding tectonic accretion of the Superior Province.

The most spectacular seismic reflection profile to date is SNORCLE Corridor 1, crossing the western part of the southern Slave Province and the Proterozoic terranes between the Slave Province and the eastern margin of the Cordillera. The profile, the closest yet to a diamondiferous lithospheric root, will be presented at the conference, together with a 3D model illustrating the spatial relationship between the section and the kimberlite pipes of the Slave Province. It shows clear evidence for eastward imbrication of the Moho under the Archean Slave Province as well as numerous shallowdipping reflectors to a depth of approximately 110 km which allow inferences about the geometry of accretion under the Slave Province and adjacent Proterozoic orogens.

The SNORCLE profile clearly establishes that the lithosphere beneath Archean cratons grows by lateral accretion, as envisaged in earlier models, and that underplating of the Archean lithosphere continues in the Proterozoic, as suggested by several workers to explain the coexistence of old P-type with younger E-type diamonds in single kimberlite pipes (e.g., Gurney, 1990; Abbott, 1991). Information gleaned from the profile also requires the re-evaluation of many practices of upper-mantle petrologists, especially that of modelling the upper mantle in terms of traditional paleogeotherm-based upper-mantle stratigraphy. Efforts must be made to interpret the nature of the seismic reflectors. Are all of them eclogite layers or, more likely, are some of them fossil mylonite zones, samples of which are known to us as the much-debated sheared nodules? If so, the hallowed notion that all "deep" and "hot" nodules are quenched from their stability field when plucked by the kimberlite may have to be abandoned.

The notion of disequilibrium may also help to solve numerous puzzles connected with diamond storage in the lithosphere. Whereas the structural complexity of the lithosphere explains the enormous variations in diamond populations within individual and adjacent kimberlite pipes, it also begs the question, why such differences survive. For example, why should highly strained diamonds not be annealed, if they are stored in their stability field for billions of years? Using the experience from recent studies on ultra-high-pressure metamorphic rocks, we speculate that diamonds may become structurally trapped outside their stability field as the result of fault motions within the lithosphere. They may also be preserved outside their stability field in Archean lithosphere that has isostatically rebounded after an obducted Proterozoic orogen has been eroded.

Geophysical studies will ultimately provide a geometric framework of the subcontinental lithosphere against which kinematic and dynamic upper-mantle models may be tested. As has been shown by studies of ultra-high-pressure metamorphic rocks, in which diamonds may be transported to the surface by tectonic movements, upper-mantle models cannot be realistic unless tested for coherence with surface-tectonic models. For the formation of the diamondiferous upper-mantle sample in cratonic roots, this requires tests against modern models of Archean plate tectonics. Models for the preservation and destruction of the cratonic roots and kimberlite formation must take into account the overprint on old lithosphere by post-Archean plate and plume interactions.

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