One view on the genesis of cratonic mantle peridotites

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Mantle peridotite xenoliths from Archean cratons generally have high molar Mg/(Mg+Fe), or Mg#. The best known suites, from the Kaapvaal and Siberian cratons, have high modal orthopyroxene (Opx) [1-3]. These high Opx harzburgites are probably not residues of partial melting of proposed primitive mantle source compositions [4-6]. Less well known cratonic xenolith suites from North America and Greenland include high Mg# peridotites with much lower modal Opx [7-9]. Such low Opx compositions could be residual from high degrees of polybaric, decompression melting, ending in the spinel lherzolite stability field at pressures of 30 to 20 kb [9]. Our research group has recently presented additional evidence that suggests that the great majority of both spinel- and garnet-bearing xenoliths are also residues of polybaric melting that ended at pressures < 30 kb [6]. Where such rocks currently record equilibration temperatures > 30 kb, this must result from tectonic transport of peridotites to greater depth after melting. In the kimberlite conference paper, two main issues will be addressed: (1) origin of Opx-rich cratonic mantle compositions, and (2) assembly of a thick continental tectosphere via tectonic thickening of relatively shallow residues of partial melting.

Orthopyroxene enrichment

Proposed scenarios for producing the high Mg#, high Opx compositions include metamorphic differentiation of high pressure residues [1], mixtures of residual peridotites and high pressure igneous cumulates from ultramafic magmas [10], and addition of SiO2 to low Opx peridotites via melt/rock reaction [4, 6, 11-15]. Our recent paper [6] focuses on a positive correlation between Ni contents of olivine and modal proportions of Opx in mantle xenoliths [15, 16], and uses this correlation to constrain the processes that produced high Mg#, high Opx cratonic mantle compositions. The observed correlation is not produced by partial melting or metamorphic differentiation. On more qualitative grounds, we suggest that Opx-enrichment is not due to the formation of very high pressure, igneous cumulates. We show that the observed correlation between Ni in olivine and modal Opx certainly can be produced by reaction between SiO2-rich liquids (e.g., small degree melts of subducted eclogite) and previously depleted, low Opx peridotites.

In agreement with previous investigators [4, 11-14], we proposed a two step process. First, high Mg#, low Opx peridotites were created by large degrees of polybaric melting ending at pressures < 30 kb. Later, the depleted residues were enriched in Opx by interaction with SiO2-rich melts generated mainly by anatexis of eclogitic metabasalt and metasediment in a subduction zone. Magmas modified by such a process could have formed a major component of the continental crust [13, 17, 18]. Thus, this hypothesis provides a genetic link between cratonic upper mantle and continental crust.

How can this hypothesis be further constrained and tested? Our recent work [6] used a somewhat new, simple method of calculating the results of melt/rock interaction in the mantle, which predicts not only the modal proportions and Ni contents olivine, Opx, and melt, but also the resulting major element composition of the melt. For example, predicted melt compositions after reaction between depleted harzburgite and a silicic partial melt of eclogite have 53 to 60% SiO2, depending on temperature. Some of these could be metastable with respect to an olivine-undersaturated, more silica rich melt composition and an olivine-free solid assemblage. Looking beyond the model results, the paper presented at the kimberlite conference will discuss the controversial issue of possible and impossible SiO2 contents in alkali- and volatile-rich, olivine + Opx saturated melts at 10 to 30 kb.

The kimberlite conference paper will also present details of the modeling method, explore further constraints that could be added, and develope other applications of the technique. In particular, we will explore whether mafic melt/peridotite interaction can produce Opx-rich harzburgites under some circumstances, as suggested in an earlier paper by our group [4].

Another possible test of the proposed role of partial melts of subducted eclogite in creation of Opx-rich, high Mg# cratonic peridotites, using currently available data, is to examine trace element contents of xenoliths. This is fraught with peril, because it is evident in many cases that open system processes have modified the trace element budget of cratonic peridotites with little or no effect on the major elements. However, we can make the prediction that - if eclogite melts have been involved in Opx-enrichment, then no Opx-rich, high Mg# harzburgites should be light rare earth depleted. This prediction is based on the following reasoning: light rare earth depletion in mantle peridotites results mainly from melt extraction processes. We believe that melt extraction has not formed Opx-rich harzburgites. Prior to Opx-enrichment residues are Opx-poor and light rare earth depleted. Anatexis of eclogitic metabasalts or metasediments produces light rare earth enriched, silicic liquids. If these silicic melts react with mantle peridotite, the solid product will be light rare earth enriched. Initially, reaction between eclogite melts and peridotite will also produce Opx-enriched solid products. After eclogite melts become saturated with mantle olivine, the Opx-enrichment will generally cease, but the modified melts will retain a light rare earth element enriched character, and this can be passed on via cryptic metasomatism to additional mantle peridotites. Thus we expect to find Opx-poor harzburgites with rare earth element patterns ranging from light rare earth depleted to light rare earth enriched, but Opx-rich harzburgites should invariably be light rare earth enriched.

A survey of mantle peridotite xenoliths worldwide, using the database of McDonough & Frey [19] shows that this prediction is roughly correct. However, trace element data are scarce for cratonic peridotites with Mg#'s greater than 91. We are making an ion probe study of a variety of cratonic mantle xenolith suites in an effort to improve the database for such rocks. We are focusing on analyses of orthopyroxene cores, because these seem least affected by late metasomatic events, including interaction with host magma during xenolith transport. Preliminary data show that Opx-poor xenoliths from Greenland have strongly light rare earth depleted orthopyroxene, whereas orthopyroxene cores in Opx-rich xenoliths from the Premier kimberlite in the Kaapvaal craton are flat to light rare earth enriched. Thus, no samples analyzed to date are both Opx-rich and light rare earth depleted. This study is ongoing, and results to date will be presented at the kimberlite conference.

In the future, there are obvious avenues of investigation to address the problem of Opx-enrichment. For example, stable isotope measurements (e.g., $^{18}O/^{16}O$, $^{6}Li/^{7}Li$) will provide strong constraints on the provenance of the melts or fluids responsible for Opx-enrichment in cratonic peridotites.

Formation of a thick, high Mg# root from shallow residues

The hypothesis that high Mg# cratonic peridotites in general resulted from polybaric partial melting processes with minimum pressures of melting less than 30 kb, if correct, has many important geodynamic implications. Currently, some high Mg# samples record pressures exceeding 50 kb, and so if these were shallow residues they must have been tectonically thickened. One question that arises is, when did the thickening occur? Possible constraints bearing on this issue are the proposed Archean ages of diamond inclusions [20, 21], on the one hand, and the proposed Phanerozoic ages of the diamonds themselves [22, 23]. It is also relevant to consider the origin of magmas emplaced within cratons. If the magmas that fed, e.g., the Bushveld Complex in the Kaapvaal craton were produced by ordinary polybaric partial melting processes, then they must have been formed at mean pressures less than 50 kb. Such decompression melting would be impossible where the convecting, adiabatically decompressing mantle is overlain by a cold cratonic "lid" extending to depths greater than 150 km. Though the nature of the Bushveld primary magma is uncertain, there is little indication that it was produced at mean pressures greater than 50 kb. Thus, the presence of the Bushveld, and similar intrusions in other cratons, suggests that cratonic mantle roots composed of cold, high Mg# peridotites had not attained their current thickness at 2 Ga.

Jordan (e.g., [24, 25]) has proposed that high Mg# continental upper mantle has been isolated from the convecting mantle over geologic time because it is neutrally buoyant with respect to the convecting mantle. This is so, he has proposed, because the density increase in cratonic roots due to conductive cooling is offset by the lower density of high Mg# peridotites compared to the convecting mantle with an Mg# of ca. 87 to 89. We believe this to be qualitatively correct, but in our collaboration with Joe Boyd and other xenolith experts, we have noticed that cratonic mantle Mg#Õs are higher than required for neutral buoyancy along a conductive, continental geotherm [Boyd, this volume]. Thus, the available evidence suggests that cratonic mantle peridotites are generally positively buoyant with respect to the convecting mantle. Such a situation might originate if density sorting of residual peridotites occurred at shallow depths, e.g. in the thermal boundary layer of an oceanic plate with a thickness of 70 to 125 km. Under these circumstances, only the most depleted, shallowest residues would be retained in the plate. After tectonic thickening, these would form a cold, positively buoyant root extending to great depths.

Preservation of shallow residues would also be enhanced by their high viscosity. Hirth & Kohlstedt [26] summarized data on the pressure dependence of the olivine/liquid distribution coefficient for H, and used these data to show that H would be dramatically depleted in the residues of partial melting at pressures less than 30 kb. This in turn results in a viscosity increase of one to two orders of magnitude in the "dry" residue compared to the asthenospheric peridotite compositions at the same temperature with their original H concentration. At higher pressure, higher olivine/liquid distribution coefficients for H dictate that residues will not suffer substantial H depletion during partial melting, and thus these residues will retain a low viscosity, not much higher than the source composition at the same temperature.

A caveat to this discussion of viscosity is the question of reintroduction of H into the cratonic mantle during metasomatic processes, particularly above subduction zones. The presence of hydrous phases in many xenoliths might suggest that this process has been important, but it is uncertain whether the H content of such xenoliths is truly representative of the cratonic mantle at large. A recent paper by Rudnick et al. [27] argues that the K contents of Kaapvaal mantle xenoliths are too high to account for low continental heat flow, and therefore that the K contents of the xenoliths reflect local metasomatism rather than the composition of the entire cratonic mantle. If so, this is probably true of H as well. There is little information on the H content of nominally "anhydrous" cratonic mantle xenoliths, but such data will be valuable in addressing this question.

References cited

1 F.R. Boyd, Compositional distinction between oceanic and cratonic lithosphere, 96, 15-26, 1989.
2 M.A. Menzies, Archaean, Proterozoic, and Phanerozoic lithospheres, in: Continental Mantle, M.A. Menzies, ed., pp. 67-86, Clarendon Press, Oxford, 1990.
3 F.R. Boyd, N.P. Pokhilenko, D.G. Pearson, S.A. Mertzman, N.V. Sobolev and L.W. Finger, Composition of the Siberian cratonic mantle: Evidence from Udachnaya peridotite xenoliths, Contrib. Mineral. Petrol. 128, 228-246, 1997.
4 P.B. Kelemen, H.J.B. Dick and J.E. Quick, Formation of harzburgite by pervasive melt/rock reaction in the upper mantle, Nature 358, 635-641, 1992.
5 M.J. Walter, Melting of garnet peridotite and the origin of komatiite and depleted lithosphere, J. Petrol. in press, 1997.
6 P.B. Kelemen, S.R. Hart and S. Bernstein, Silica enrichment in the continental upper mantle via melt/rock reaction, Earth Planet. Sci. Lett. submitted, 1998.
7 J.G. Larsen, Mantle-derived dunite and lherzolite nodules from Ubekendt Ejland, west Greenland Tertiary province, Min. Mag. 46, 329-336, 1982.
8 F.R. Boyd and D. Canil, Peridotite xenoliths from the Slave craton, Northwest Territories, 7th Annual Goldschmidt Conference Abstracts, LPI Contribution No. 921, 34, 1997.
9 S. Bernstein, P.B. Kelemen and C.K. Brooks, Depleted spinel harzburgite xenoliths in Tertiary dykes from East Greenland: Restites from high degree melting, Earth Planet. Sci. Lett. in press, 1997.
10 C.T. Herzberg, Lithosphere peridotites of the Kaapvaal craton, Earth Planet. Sci. Lett. 120, 13-29, 1993.
11 A.E. Ringwood, The petrological evolution of island arc systems, J. Geol. Soc. Lond. 130, 183-204, 1974.
12 S.E. Kesson and A.E. Ringwood, Slab-mantle interactions 2. The formation of diamonds, Chem. Geol. 78, 97-118, 1989.
13 P.B. Kelemen, N. Shimizu and T. Dunn, Relative depletion of niobium in some arc magmas and the continental crust: partitioning of K, Nb, La and Ce during melt/rock reaction in the upper mantle, Earth and Planetary Science Letters 120, 111-134, 1993.
14 R.L. Rudnick, W.F. McDonough and A. Orpin, Northern Tanzanian peridotite xenoliths: A comparison with Kapvaal peridotites and inferences on metasomatic interactions, in: Kimberlites, Related Rocks and Mantle Xenoliths, Vol. 1, Proceedings 5th Int. Kimberlite Conf., H.O.A. Meyer and O. Leonardos, eds., CRPM, Brasilia, 1994.
15 P.B. Kelemen and S.R. Hart, Silica enrichment in the continental lithosphere via melt/rock reaction, V.M. Goldschmidt Conference Abstracts, J. Conference Abstracts 1, 308, 1996.
16 F.R. Boyd, Correlation of orthopyroxene abundance with the Ni content of coexisting olivine in cratonic peridotites, EOS 78, F746, 1997.
17 C. Sen and T. Dunn, Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: Implications for the origin of adakites, Contrib. Mineral. Petrol.117, 394-409, 1994.
18 P.B. Kelemen, Genesis of high Mg# andesites and the continental crust, Contrib. Mineral. Petrol. 120,1-19, 1995.
19 W. McDonough and F. Frey, Rare earth elements of upper mantle rocks, in: Geochemistry and Mineralogy of Rare Earth Elements, Rev. Mineralogy 21, B.R. Lipin and G.R. McKay, eds., pp. 99-145, Min. Soc. Amer., Washington, D.C., 1989.
20 S.H. Richardson, J.J. Gurney, A.J. Erlank and J.W. Harris, Origin of diamonds in old enriched mantle, Nature 310, 198-202, 1984.
21 S.H. Richardson, J.W. Harris and J.J. Gurney, Three generations of diamonds from old continental mantle, Nature 366, 256-258, 1993.
22 N. Shimizu and N.V. Sobolev, Young peridotitic diamonds from the Mir kimberlite, Nature 375, 394, 1995.
23 N. Shimizu, N.V. Sobolev and E.S. Yefimova, Chemical heterogeneities of inclusion garnets and juvenile character of peridotitic diamonds from Siberia, Russian Geol. & Geophys. 38, 356-372, 1997.
24 T.H. Jordan, The continental tectosphere, Rev. Geophys. Space Phys. 13, 1-12, 1975.
25 T.H. Jordan, Structure and formation of the continental tectosphere, J. Petrol. Special Lithosphere Issue(Special Lithosphere Issue), 11-37, 1988.
26 G. Hirth and D.L. Kohlstedt, Water in the oceanic upper mantle: Implications for rheology, melt extraction and the evolution of the lithosphere, Earth Planet. Sci. Lett. 144, 93-108, 1996.
27 R.L. Rudnick, W.F. McDonough and R.J. O'Connell, Thermal structure, thickness and composition of continental lithosphere, Chemical Geology, Special Issue, in press.