Consistent olivine Mg# in cratonic mantle reflects Archean mantle melting to the exhaustion of orthopyroxene

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ABSTRACT

Shallow (garnet-free), depleted cratonic mantle, occurring as xenoliths in kimberlites and alkaline basaltic lavas, has a high Mg# (100 × Mg/(Mg + Fe) > 92) and is poor in Al and Ca compared to off-cratonic mantle. Here we compile data for many suites of shallow cratonic mantle xenoliths worldwide, and demonstrate a remarkably small range in their olivine Mg#, with an average of ~92.8. Via comparison with data for experimental melting of mantle peridotite compositions, we explain consistent olivine Mg# as the result of mantle melting and melt extraction to the point of orthopyroxene exhaustion, leaving a nearly monomineralic olivine residue.

Keywords: cratonic mantle, dunite xenoliths, residues, Archean, spinel peridotite.

INTRODUCTION

Highly depleted xenoliths from shallow cratonic mantle (recording equilibration pressures less than ~2 GPa) are nearly all depleted harzburgites or dunites, characterized by low modal clinopyroxene (<10 wt%), olivine Mg# >92, and, where available, Archean Re depletion ages (e.g., Boyd et al., 1997; Bernstein et al., 1998; Pearson et al., 2003). In addition to these features, most samples in the well-known cratonic xenolith suites from Kaapvaal, southern Africa, and Udachnaya, Siberia, have between 20% and 50% modal orthopyroxene (Boyd, 1989; Menzies, 1990; Boyd et al., 1997).

It has long been suggested that high-Mg# peridotites of cratonic mantle were residues of mantle melting (e.g., O'Hara et al., 1975; Boyd and Mertzman, 1987; Takahashi, 1990). A subset of relatively orthopyroxene-poor Kaapvaal harzburgite xenoliths may thus reflect some 30% decompression melting at 4–5 GPa (Herzberg, 2004). For the majority of Kaapvaal peridotites, however, their high modal orthopyroxene contents render them difficult to relate directly to melt extraction processes (e.g., Kesson and Ringwood, 1989; Boyd, 1989; Kelemen et al., 1998). Accordingly, orthopyroxene-rich (>20%), high-Mg# peridotites have been linked to crystal fractionation processes in an Archean magma ocean (Herzberg, 1987, 1993; Arndt et al., 2002), metamorphic differentiation (Boyd, 1989; Takahashi, 1990), residues from melt extraction at high pressures (>8 GPa; Herzberg, 1993), or a two-stage process in which dunitic or orthopyroxene-poor harzburgite residues from high degrees of melt extraction underwent subsequent SiO_2 addition, perhaps via reaction with SiO_2-rich melts originating from subduction zones (Kesson and Ringwood, 1989; Ringwood, 1990; Rudnick et al., 1994; Kelemen et al., 1998; Walter, 2003; Pearson et al., 2003; Lee et al., 2003).

While the orthopyroxene-rich nature of high-Mg# peridotite xenoliths from southern African and Siberian cratons was long considered typical of shallow cratonic mantle, over the past decade high-Mg# peridotite xenoliths with low modal orthopyroxene (<20%) have been reported from the Tanzanian, Greenland, and Slave cratons (Rudnick et al., 1994; Bernstein et al., 1998, 2006; Kopylova and Russell, 2000; Bizzarro and Stevenson, 2003). The composition of such orthopyroxene-poor, high-Mg# peridotite is broadly consistent with an origin as a shallow residue from ~40% polybaric decompression melting in the Archean (Bernstein et al., 1998, 2006; Hanghøj et al., 2000). This observed presence of orthopyroxene-poor residues in xenolith suites indicates that such a protolith exists, and lends credence to the two-stage model, involving SiO_2 addition to this protolith to form the orthopyroxene-rich peridotites common in Kaapvaal.

In this paper, we further constrain the genesis of the orthopyroxene-poor xenolith compositions. Using a new, worldwide compilation, we show that modal and major element composition of shallow cratonic mantle peridotite, particularly the narrow range of olivine Mg#, corresponds to the experimentally determined point at which orthopyroxene is exhausted during mantle melting. Thus, we propose that most or all highly depleted cratonic mantle peridotites originated as dunite residues after ~40% melt extraction, and have since undergone variable amounts of refertilization to produce observed cratonic mantle dunites and harzburgites with olivine Mg# of 92–93 or higher, and lherzolites with olivine Mg# <91.

REFRACTORY PERIDOTITE IN SHALLOW CRATONIC LITHOSPHERIC MANTLE

Peridotites from oceanic basins and from ophiolites display a positive correlation of modal olivine and olivine Mg# as shown by the fields of Phanerozoic and Proterozoic peridotites in Figure 1A. These characteristics result from progressive melt extraction from a mantle residue during polybaric decompression melting, e.g., beneath mid-ocean ridges (e.g., Dick, 1989; Boyd, 1989).

In Figure 1A, the filled symbols illustrate the compositional range of xenoliths from the Kaapvaal, Tanzania, Siberia, Slave, and Wyoming cratons. Virtually all have abundant orthopyroxene, and correspondingly contain <80% modal olivine. Most samples in the orthopyroxene-poor suites from Greenland (open symbols in Fig. 1A) have >80% modal olivine.

With the possible exception of some Kaapvaal harzburgite xenoliths with up to 25 vol% orthopyroxene that could be restites from decompression melting over a narrow pressure interval (4–5 GPa; Herzberg, 2004), a viable model for the formation of orthopyroxene-rich peridotite in cratonic mantle sees these to be the product of interaction between an orthopyroxene-poor, dunitic protolith and silica-rich melts or fluids, perhaps from subducting slabs (e.g., Kelemen et al., 1998). The effect of silica addition is given by the gray arrow in Figure 1A. Such a process is indicated by the ubiquitous enrichment of incompatible trace elements in high-Mg# peridotite xenoliths from Kaapvaal (e.g., Boyd et al., 1999; Simon et al., 2003). The dunitic protoliths are envisaged to have formed as low-pressure residues of large degree, polybaric decompression melting, and melt extraction. Such protoliths are exemplified by the Greenland xenolith suites (Fig. 1) that consist of high-Mg# dunite (Ubekendt Ejland; Bernstein et al., 2006) and orthopyroxene-poor harzburgites (Wiedemann Fjord; Bernstein et al., 1998).

Four lines of reasoning support the view that the orthopyroxene-poor protoliths, prior to SiO_2 addition, were relatively low-pressure restites. First, polybaric decompression melting due to mantle upwelling must generally have proceeded to shallow depths throughout geologic time. The most depleted residues are produced at the shallowest depths in such processes. While the presence of thick lithospheric plates can, in principle, restrict melting to relatively high pressure, it is difficult to explain why the most depleted Archean peridotites should have been restricted to high-pressure melt extraction beneath thick plates.

Second, using mass balance arguments, Bernstein et al. (1998) determined the composition of the melt extracted from primitive mantle peridotite in order to produce the Wiedemann Fjord xenolith compositions as residues. This melt composition is similar to experimental partial melts of peridotite at 2.5–3.5 GPa, and quite different from experimental partial melts at higher pressure.

Geology, May 2007; v. 35; no. 5; p. 459–462; doi: 10.1130/G23336A.1; 3 figures; Data Repository item 2007107.

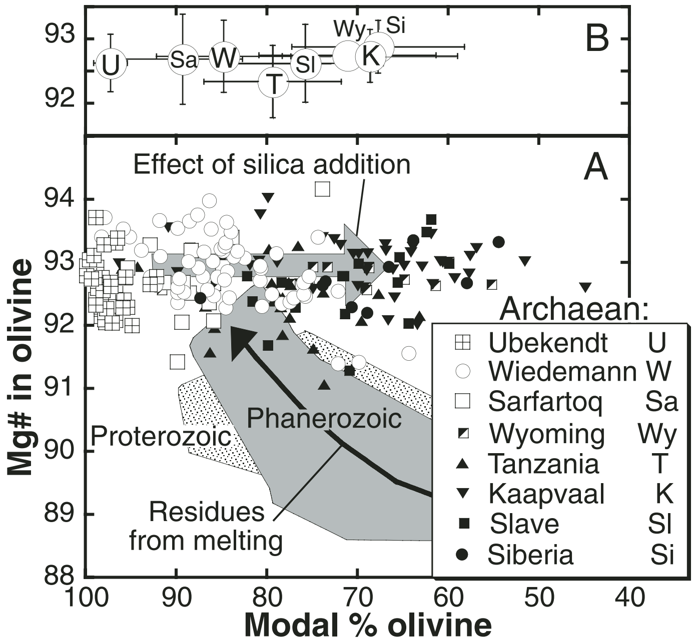

Figure 1. A: Mg# ($100 \times \mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe})$) in olivine versus modal olivine for lithospheric mantle peridotite. The fields labeled Proterozoic and Phanerozoic represent mantle peridotite of a given age (Boyd, 1989; Menzies, 1990), and the schematic melting curve is from Boyd (1989). Suites of garnet-free spinel peridotite xenoliths in the legend are from volcanics hosted in Archean crust and—where measured—record ancient Re depletion. Some suites (Kaapvaal, Siberia, Wyoming, Slave) have high orthopyroxene contents and correspondingly low average (<80%) modal olivine. Other suites, including all three from Greenland (Ubekendt, Wiedemann, and Sarfartoq), have high modal olivine (>80%). B: Same parameters but averaged over the individual xenolith suites. Error bars are 1σ. Labels refer to legend in A. Data sources can be found in the GSA Data Repository.[1]

Third, by modeling the positive correlation of heavy rare earth element (HREE) and CaO concentrations in a worldwide compilation of depleted cratonic xenoliths, Kelemen et al. (1998, Fig. 7 therein) showed that high-Mg# xenoliths from both orthopyroxene-poor and -rich suites reflect polybaric melting at a relatively low average pressure, with exhaustion of garnet before clinopyroxene. Likewise, Canil (2004) demonstrated that correlations between transition metals Al and Yb for a large data set of garnet-bearing and -free peridotite xenoliths require final melt extraction at pressures <3 GPa. Many high-Mg# cratonic peridotites do currently contain garnet and thus record equilibration pressures >3 GPa. However, the work of Kesson and Ringwood (1989), Kelemen et al. (1998), and Canil (2004) conclude that this garnet must be metamorphic in origin and that high-Mg# garnet peridotite must have been transported to greater depth subsequent to their origin as shallow residues.

Fourth, the origin of peridotitic (U-type) diamond is linked to the presence of high-Mg#, cratonic mantle peridotites. The high Cr# ($100 \times \mathrm{Cr}/(\mathrm{Cr} + \mathrm{Al})$) of garnet and spinel inclusions in peridotitic diamonds reflects melt depletion at low pressures (e.g., Stachel et al., 1998). Indeed, in the rare cases where olivine and spinel are found as two-phase inclusions in diamond, their compositions plot in the same field as olivine-spinel pairs from the Ubekendt Ejland xenolith suite (Fig. 2). This suggests that the peridotite host to U-type diamonds originated as a low-pressure residue similar to dunites from Ubekendt Ejland.

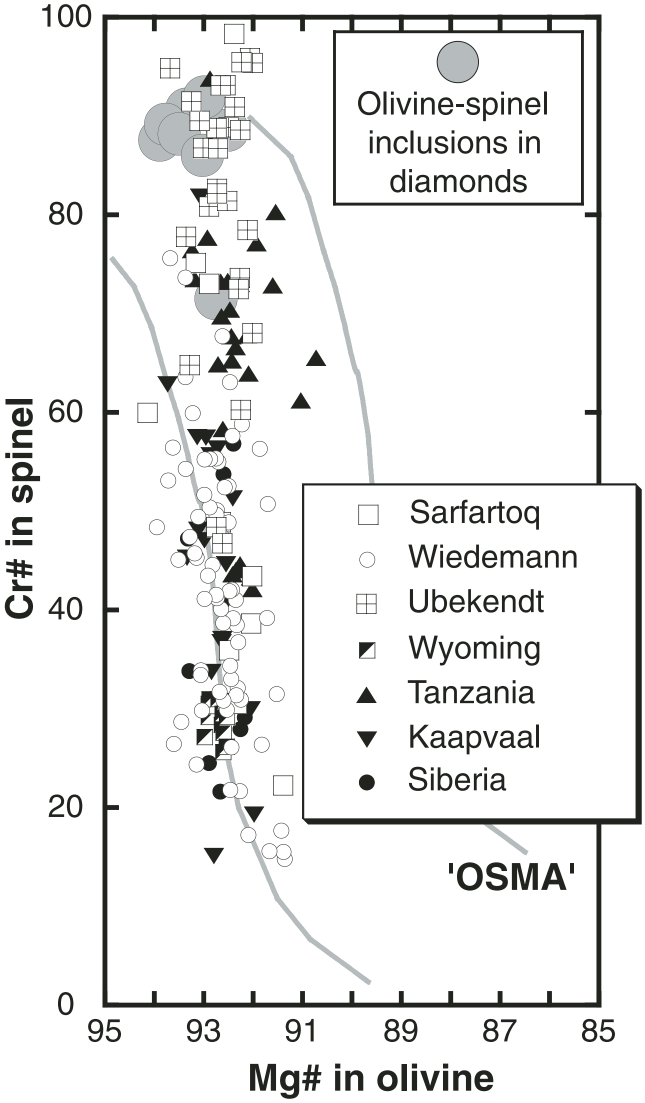

Figure 2. Cr# ($100 \times \mathrm{Cr}/(\mathrm{Cr} + \mathrm{Al})$) in spinel versus Mg# in coexisting olivine for shallow xenolith suites. Olivine-spinel inclusions in diamonds, representing trapped peridotite (Stachel et al., 1998), are chemically indistinguishable from Ubekendt dunite xenoliths (inclusion data sources can be found in the GSA Data Repository; see footnote 1). OSMA—olivine-spinel mantle array (Arai, 1994).

CONSISTENT Mg# OF 92.6 TO 92.9 FOR OLIVINE IN CRATONIC UPPER MANTLE

An intriguing aspect of Figures 1B and 2 is the small range in composition of average olivine from the individual xenolith suites. The average Mg# in olivine is Ubekendt 92.6, Wiedemann 92.7, Sarfartoq (West Greenland) 92.7, Tanzania 92.4, Slave 92.6, Wyoming 92.8, Kaapvaal 92.9, and Siberia 92.7. In addition to the xenolith suites illustrated in Figure 1, olivine in spinel peridotite xenoliths from Mengyin, North China craton, has an average Mg# of 92.5 (Zheng et al., 2001). Although comprehensive data sets on spinel peridotites from cratons are still scarce, this consistency of average olivine Mg# in spinel peridotite xenolith suites appears to be a common feature of the cratonic lithospheric mantle. For a compilation of global suites of cratonic, coarse, Mg-rich, "low-temperature" peridotites (mostly harzburgites), Pearson et al. (2003) found an average olivine Mg# of 92.8. This compilation includes both spinel and garnet peridotites, and the observation is substantiated by indirect estimates of olivine Mg#

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[1] GSA Data Repository item 2007107, data sources, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

from garnet chemistry, as obtained from garnet concentrates in kimberlites (Gaul et al., 2000). Such studies demonstrate that in the shallowest cratonic, garnet-bearing peridotites, calculated average olivine compositions approach an Mg# of 93.0 (±0.5). This holds for upper mantle beneath Western Australia, Siberia, Kaapvaal, Slave and Superior provinces (Canada and United States), and West Greenland (Gaul et al., 2000; Griffin et al., 2004). Additionally, in five populations of peridotitic diamonds from Siberian kimberlites, olivine inclusions have an average olivine Mg# of 92.8 (Sobolev et al., 2004), consistent with the hypothesis that peridotitic diamonds formed in ultradepleted hosts (Stachel et al., 1998).

The surprisingly consistent average olivine composition (Mg# ≈ 92.8) for the shallow portion of cratonic mantle peridotite and for diamond inclusions suggests that a common process determined this value. A simple mass balance showed that the depleted Wiedemann xenolith suite could form by extraction of ~40% melt from a pyrolite mantle, leaving a residue with olivine Mg# of 92.7 (Bernstein et al., 1998). This model is consistent with data from melting experiments on mantle peridotite compositions, showing a positive correlation between degree of melting and residual olivine Mg# (Fig. 3). Our value for the Wiedemann xenoliths, with 40% melting and olivine Mg# of 92.7, falls in the middle of the experimental data array.

40% MELTING WITH EXHAUSTION OF RESIDUAL ORTHOPYROXENE

In the melting experiments, residual orthopyroxene is exhausted at 40%–50% melting, with residual olivine Mg# between 92.8 and 93.5 (Fig. 3). The interval for orthopyroxene exhaustion is much more tightly constrained—40%–42% melting with olivine Mg# from 92.8 to 93.0—if one excludes experiments with more than 45% melting at 6–7 GPa from Walter (1998) (filled squares marked “6” and “7” in Fig. 3). We prefer this tighter constraint, since we believe that high degrees of melting at high pressure are unlikely in the origin of cratonic upper mantle peridotites, as explained above. An additional constraint on the composition of residual olivine after extensive melt extraction is provided by a detailed study of a harzburgite-dunite transition in the Iwanaidake peridotite, Japan (Kubo, 2002). Here, olivine Mg# was found to attain a value of 92.8 at the point when orthopyroxene is exhausted.

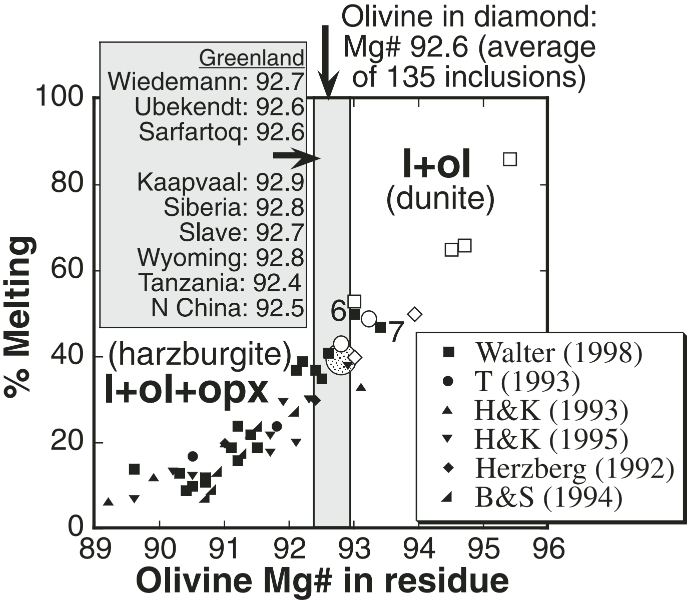

Figure 3. Degree of melting in experiments related to Mg# of residual olivine. Filled symbols refer to residual olivine and orthopyroxene (+ clinopyroxene/garnet at <30% melting), leaving a harzburgite residue (filled squares marked “6” and “7” are for experiments at 6 and 7 GPa; see text). Open symbols refer to residual olivine only, leaving a dunite residue. Stippled circle is degree of melting as calculated for Wiedemann xenoliths with average olivine Mg# of 92.7 (Bernstein et al., 1998). Bracket at Mg# of 92.4–92.9 is composition of average olivine from cratonic xenolith suites. Data sources for xenoliths and diamond inclusions can be found in the GSA Data Repository (see footnote 1). l—liquid; ol—olivine; opx—orthopyroxene.

The high average olivine Mg# of ~92.8 found in shallow cratonic lithospheric mantle worldwide, and in peridotitic diamond inclusions, is thus consistent with the origin as residues of mantle melting *at the point of orthopyroxene exhaustion*. If the melt extraction process was efficient (“near-fractional”), orthopyroxene exhaustion would cause an increase in solidus temperature of the residue by several hundred °C, and hence no further melting could occur, without either fluxing the residue at very high temperature or increasing the temperature dramatically. Thus, the olivine Mg# generally cannot increase via igneous processes after orthopyroxene exhaustion. We believe this is the best explanation for the very limited variation in olivine Mg# in shallow, cratonic mantle xenoliths worldwide. This conclusion has broad geodynamic implications.

GEODYNAMIC IMPLICATIONS

Hypotheses regarding Archean mantle processes include (1) melting in plumes at elevated pressure (8–5 GPa; e.g., Pearson et al., 1995; Griffin et al., 2003), (2) massive melting during periodic mantle overturn (Davies, 1995; Griffin et al., 2003), (3) crystal sorting processes in a magma ocean, through recycling of residues or through accumulation of high-pressure residues in an ascending plume (Arndt et al., 2002), (4) H_2O-fluxed melting in Archean subduction zones (Parman et al., 1997; Griffin et al., 2003), and (5) polybaric melting during adiabatic upwelling to low pressure, either in mantle plumes or beneath spreading centers (Kesson and Ringwood, 1989; Bernstein et al., 1998; Kelemen et al., 1998; Walter, 2003; Herzberg, 2004). The intimate relationship between cratonic crust and depleted mantle requires the elimination of Fe-rich residues left from crust formation (Arndt et al., 2002), perhaps through delamination (Arndt and Goldstein, 1989; Jull and Kelemen, 2001).

Present-day melting processes at mid-ocean ridges are best described as polybaric decompression melting during adiabatic mantle upwelling with continuous, near-fractional melt extraction (e.g., Johnson et al., 1990). The consistent olivine Mg# of ~92.8 in shallow cratonic mantle, suggesting mantle melting to the point of orthopyroxene exhaustion, suggests that depleted cratonic upper mantle formed via polybaric decompression melting, because near-fractional melt extraction is required to produce residues with such a small range in average olivine Mg#. In such a process, melting would effectively end at the point of orthopyroxene exhaustion. If, instead, melt remained present in residual peridotites, one would expect a continuous range of olivine Mg# extending to values much higher than 93.0, as in the experimental melting data. Thus, we feel it is unlikely that refractory continental upper mantle originated via processes in a magma ocean, and instead formed by decompression melting.

An origin for the orthopyroxene-poor, refractory xenoliths from Greenland through hydrous melting above Archean suprasubduction zones is possible, but because olivine-spinel chemistry of orthopyroxene-poor cratonic mantle differs from that of highly depleted, Phanerozoic, subduction-related peridotites (Bernstein et al., 2006), we favor the hypothesis that the formation of cratonic upper mantle residues was largely anhydrous as expected in a ridge or plume environment. We envisage that melting in the Archean mantle initiated at ~6 GPa and extended to pressures less than ~2 GPa (Bernstein et al., 1998; Kelemen et al., 1998; Walter, 2003; Canil, 2004; Herzberg, 2004).

ACKNOWLEDGMENTS

Carlsberg Foundation grant 04-0271 is gratefully acknowledged by Bernstein. Constructive reviews from C. Herzberg, S. O’Reilly, N. Arndt, D. Canil, T. Stachel, and G. Pearson are much appreciated. National Science Foundation grants OCE-9416631, OCE-0242233, EAR-9910899, and EAR-0337677 supported Kelemen and Hanghøj.

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Manuscript received 6 September 2006
Revised manuscript received 5 January 2007
Manuscript accepted 10 January 2007

Printed in USA