

Silica enrichment in the continental upper mantle via melt/rock reaction

Peter B. Kelemen^{a,*}, Stanley R. Hart^a, Stefan Bernstein^b

^a Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

^b Danish Lithosphere Centre, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark

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Abstract

Mantle peridotite xenoliths from Archean cratons generally have high molar Mg/(Mg + Fe), or Mg#. The best known suites, from the Kapvaal and Siberian cratons, have high modal orthopyroxene (Opx). These high Opx compositions are probably not residues of partial melting. Less well known cratonic xenolith suites from Greenland and North America include high Mg# peridotites with much lower modal Opx. 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 kbar. This paper presents additional evidence that the great majority of both spinel- and garnet-bearing xenoliths are also residues of polybaric melting that ended at pressures ≤ 30 kbar. Where xenoliths record equilibration pressures > 30 kbar, this must result from tectonic transport of peridotites to greater depth after melting. Proposed mechanisms for producing the high Mg#, high Opx compositions include metamorphic differentiation of high pressure residues, mixtures of residual peridotites and high pressure igneous cumulates from ultramafic magmas, and addition of SiO₂ to low Opx peridotites via melt/rock reaction. This paper focuses on a positive correlation between Ni contents of olivine and modal proportions of Opx in mantle xenoliths, and uses this correlation to constrain the processes that produced high Mg#, high Opx cratonic mantle compositions. The observed correlation is probably not produced by partial melting, metamorphic differentiation, or formation of igneous cumulates. It can be produced by reaction between SiO₂-rich liquids (e.g., small degree melts of subducted eclogite) and previously depleted, low Opx peridotites. We propose a two step process. First, high Mg#, low Opx peridotites were created by large degrees of polybaric melting ending at pressures < 30 kbar. Later, these depleted residues were enriched in Opx by interaction with SiO₂-rich melts generated mainly by partial melting of eclogitic basalt and sediment in a subduction zone. Magmas modified by such a process could have formed a major component of the continental crust. Thus, this hypothesis provides a genetic link between cratonic upper mantle and continental crust. © 1998 Elsevier Science B.V. All rights reserved.

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* Corresponding author. Tel.: +1 508 289 2956; Fax: +1 508 457 2183; E-mail: peterk@cliff.whoi.edu

1. Introduction

1.1. *Origin and evolution of the continental upper mantle*

Constraints on the origin and evolution of the continental upper mantle are vital to understanding the genesis of continents. Jordan (e.g., [1]) noted that mantle peridotites with high Mg# (molar Mg/(Mg + Fe)) are less dense, at a given temperature, than peridotites with a lower Mg#. Samples of the mantle from beneath Archean continental cratons generally have high Mg# compared to other mantle samples. Jordan proposed that formation of residual peridotites with a high Mg# in the uppermost mantle created a long-lived, compositionally buoyant ‘tectosphere’ that stabilized nascent continental cratons.

Other workers propose that there is little compositional difference between continental upper mantle and surrounding, asthenospheric mantle. In this view, when upper mantle peridotite cools within the conductive boundary layer of a continental plate, it becomes gravitationally unstable and returns to the convecting asthenosphere (e.g., [2,3]). A viewpoint that reconciles these two hypotheses is that the nature of the uppermost mantle beneath continents has varied over time: Archean cratons may be underlain by high Mg# peridotite to depths of 200 km or more, whereas younger regions may be underlain by lower Mg# peridotite which can become convectively unstable [1]. This suggests that the processes of formation and modification of the uppermost mantle beneath continents has changed over geologic time.

Still another view is that mantle viscosity is at least as important as composition in creating stable ‘lithosphere’ (e.g., [4]). This is almost certainly the case for parts of the crust and shallow mantle at temperatures less than 700°C. However, recent workers have proposed that high viscosity ‘mantle lithosphere’ may be present at higher temperatures as well. Small amounts of partial melting will lower the H₂O content of peridotites, increasing their viscosity by more than an order of magnitude [5,6]. The amount of melting required to extract significant H₂O from peridotite is less than the amount required to create a compositionally buoyant residue. Thus, continental cratons could be stabilized by the presence of low H₂O, high viscosity ‘lithosphere’ which

remains isolated from the convecting mantle over geologic time not because it is buoyant but because it is stiff. This H₂O-depletion effect could, of course, be combined with compositional buoyancy, creating doubly-stable upper mantle in some regions.

None of the foregoing hypotheses explains why cold upper mantle is always overlain by silicic continental crust, as is observed in global compilations of heat flow and seismic data (e.g., [7–9]). Silicic crust is intrinsically buoyant and, although it would be tectonically reworked, it might generally escape permanent subduction into the convecting asthenosphere even in the absence of stable, underlying cratonic mantle. Similarly, a stiff and/or buoyant layer in the upper mantle need not necessarily be overlain by silicic crust. However, geophysical evidence shows that virtually all continental crust is underlain by a layer of shallow mantle peridotite which is cold, and therefore old and static.

Data to refine hypotheses for the formation and evolution of continental upper mantle are sparse. There has been substantial work on mantle xenoliths, carried to the Earth’s surface in intra-plate lavas; this method supplies detailed information on very small samples. Its application to larger regions requires extrapolation based on ideas about the genesis of the individual samples and the regions from which they are obtained. Another important dataset comes from geophysical observations. These provide data over broad regions, but they can be interpreted in a variety of ways, again requiring theoretical extrapolation.

In this paper, we offer a hypothesis for the origin of high Mg# cratonic upper mantle, based on mantle xenolith compositions. Our hypothesis explains how formation of the continental crust and upper mantle may be linked by common processes.

1.2. *Orthopyroxene enrichment in high Mg# peridotites*

In this paper, we focus on the fact that about 30% of continental upper mantle samples (xenoliths and exposed massifs) are enriched in Opx/olivine relative to peridotites residual from partial melting of the primitive mantle (e.g., [10,11]). This is particularly evident for ‘low temperature’ spinel and garnet peridotite xenoliths from the Kapvaal craton in South Africa, which have average normative Opx

of about 30 wt% [10]. (The Kapvaal mantle xenolith suite, and many other cratonic xenolith suites, also includes 'high temperature' peridotites; the high temperature xenoliths preserved equilibration pressures $> \sim 55$ kbar, whereas the 'low temperature' xenoliths preserve equilibration pressures $< \sim 60$ kbar). The average modal Opx in the 'low temperature' Kapvaal xenoliths is higher than the Opx mode in residues of low pressure melting of primitive or depleted mantle (as in ocean ridge peridotites, e.g., [11–15]), and about the same as the maximum attainable Opx mode in residues derived by partial melting of primitive mantle to the point of Cpx exhaustion at pressures from 25 to 140 kbar (e.g., [10,11]). Recent experimental work and related calculations [16], indicate that the average Kapvaal mode may be closer to 28% Opx, and at the same pressure and temperature the maximum Opx mode in residual peridotites is about 23%; if so, even the average Kapvaal composition is more Opx-rich than possible residues. Thus, *at least* half of all Kapvaal 'low temperature' peridotite xenoliths have Opx/Ol higher than in any possible residues of partial melting of primitive peridotite in the upper mantle.

In addition to high modal Opx, Kapvaal 'low temperature' peridotites also have a high Mg#, higher than for highly depleted abyssal peridotites. Even if the Opx mode has been modified by later processes, such a high Mg# suggests a high degree of melting at some point in the history of these samples [10]. Partial melting of mantle peridotite at relatively high pressure produces SiO₂-rich residues compared to melting at lower pressure. Thus, Boyd [10] proposed that a high degree of melting at high pressure produced the Kapvaal peridotites. Alternatively, if the high Opx content has another origin, high degrees of melting at lower pressure could also have produced the high Mg# that is observed in the Kapvaal suite. For reasons independent of the explanation for high Opx contents, we favor the hypothesis that the genesis of high Mg# in cratonic peridotites included partial melting at a pressure of ~ 30 kbar or less (Section 4.1).

Recently, Boyd et al. [17] demonstrated that 'low temperature' spinel and garnet peridotite xenoliths from the Siberian craton have Mg# and Opx contents as high as those from Kapvaal. This was consistent with the hypothesis that high Mg# and Opx contents

were intrinsically linked, perhaps by high pressures of melting. However, mantle xenoliths from central East Greenland, central West Greenland and northern North America [18,17,19–22] have high Mg#, comparable to the Kapvaal suite, but much lower Opx contents (Fig. 1). High Mg# peridotites from ophiolites in the western Pacific also have low Opx compared to Kapvaal peridotites [27,25,26]. Thus, neither high Mg# nor high modal Opx are *necessarily* linked in the formation of cratonic upper mantle.

Using experimental data from Falloon et al. [28] and Walter [16], Bernstein et al. [18] showed that the high Mg#, low Opx mantle xenoliths from East Greenland could have been produced by about 40% melting of primitive mantle peridotite at an average pressure between 20 and 30 kbar. Here, we extend this reasoning and show that formation of high Mg# residues with Opx contents of 31 wt%, such as the Kapvaal 'low temperature' xenoliths, would require similarly high degrees of melting (~ 36 wt%) (Fig. 2). In order to produce a high Opx residue with an appropriate Mg#, the liquids produced would have to have 25 to 26 wt% MgO, Mg# of 0.81 to 0.82, and 44 to 45 wt% SiO₂.

As previously noted by others (e.g., [16,40–42], no melting experiments to date produced liquid compositions which would leave a high Opx, high Mg# residue like the Kapvaal peridotite compositions. For example, the melting experiments of Walter [16] extend from 11 to 86 wt% melting at 30 to 70 kbar but they include no such liquid compositions (Fig. 2). SiO₂ contents as low as 44 to 45 wt% are observed in relatively small degree melts (13 wt% melting at 50 kbar and 11 wt% at 60 kbar), but these have low MgO contents (21 and 23%, respectively), have Mg#'s of 0.77 to 0.78, and coexist with olivine having Mg#'s of 91.2 and 90.7. Very high degree melts again approach SiO₂ concentrations as low as 45 wt%, but these have more than 30 wt% MgO and Mg#'s that are much too high.

Walter's more recent calculations [43] also suggest that polybaric melting cannot produce Kapvaal peridotite compositions as residues. Furthermore, other calculations based on recent experimental data [44,31] continue to support our hypothesis [11] that, regardless of Mg#, Opx contents higher than about 30% cannot be attained in residues of partial melting of primitive peridotite compositions at any pressure

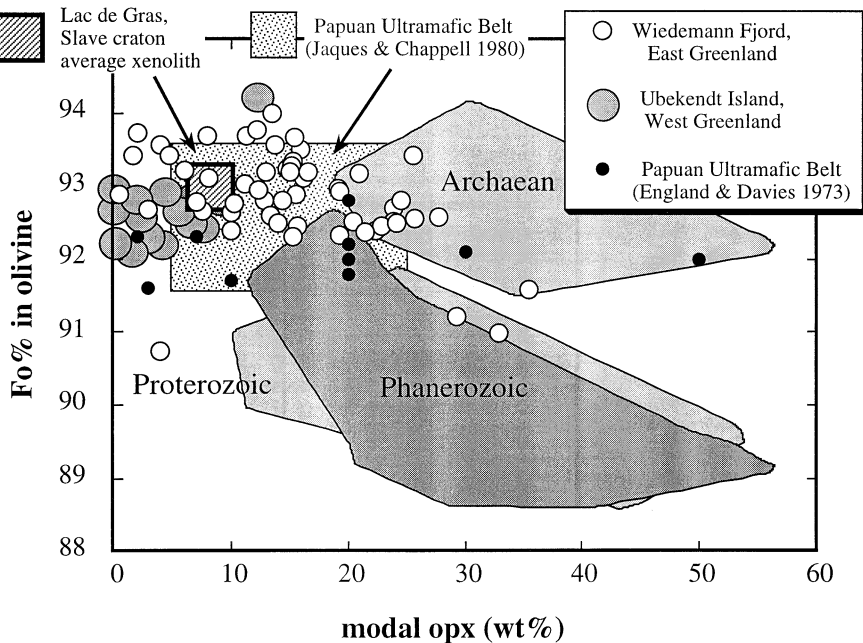


Fig. 1. Modal orthopyroxene (Opx) vs. molar Mg/(Mg + Fe), or Mg#, for olivine in mantle xenoliths. Compiled fields for xenoliths found in regions of Archean, Proterozoic and Phanerozoic crust are from Boyd [10] and Menzies [23]. Also shown are compositions of xenoliths from East Greenland [18], central West Greenland [22], and the Canadian Slave craton [24], and samples from the mantle section of the Papuan ophiolite [25,26]. All of these have olivine Mg# as high as the compiled Archean data, but much lower modal Opx (i.e., much higher modal olivine). The Canadian and Greenland xenoliths are probably derived from Archean cratonic upper mantle, suggesting that the field of Archean mantle compositions should extend to very low Opx contents.

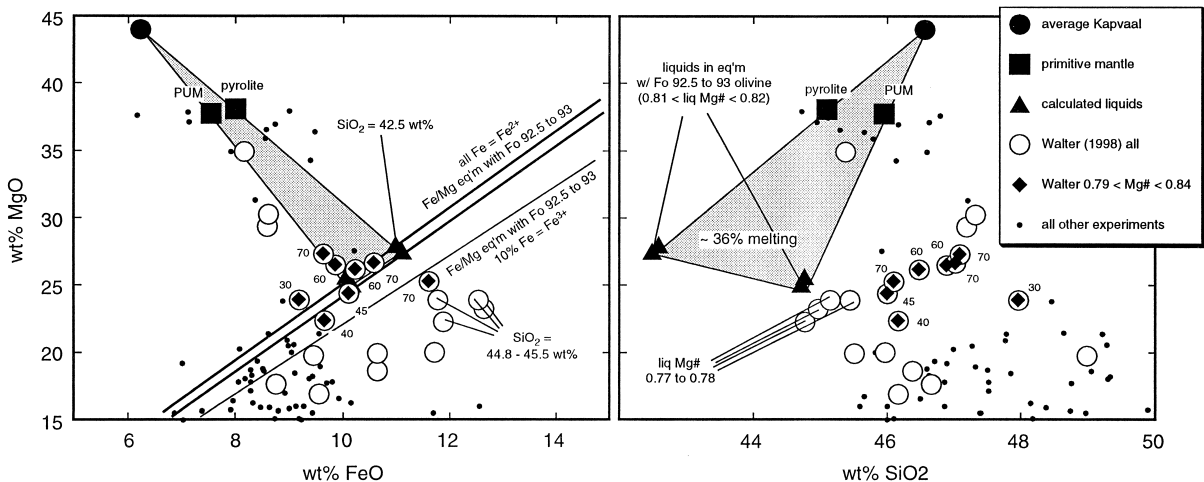


Fig. 2. Plots illustrating mass balance calculations to determine the composition of a hypothetical liquid that could be extracted from proposed primitive mantle compositions (pyrolite [29] and PUM [30]) to leave a residue with the composition of average 'low temperature' mantle xenoliths from the Kapvaal craton [10]. Shown for comparison are compositions of experimental partial melts with more than 15 wt% MgO reported to be in equilibrium with mantle peridotite [28,31–39], with special emphasis on those reported by Walter [16]. Liquid compositions from Walter's data with Mg# appropriate for equilibrium with $Fe_{92.5}$ to Fe_{93} olivine are indicated with diamond symbols, and their pressures of melting in kbar are indicated. None of the experimental liquids have compositions which satisfy the mass balance constraints, and therefore we suggest that the average Kapvaal mantle xenolith composition is probably not residual.

or degree of melting. We demonstrate this again in Section 3.1 and Fig. 7a. It could be that melting primitive peridotite at high H₂O and/or CO₂ fugacities in future experiments will produce residua with more than 30% Opx. However, to produce residual olivine with an Mg# of 92 or more, the fraction of melting must exceed 30%. In natural systems at such high melt fractions, high H₂O or CO₂ contents in the melt seem improbable. Thus, average Kapvaal and Siberian low temperature xenolith compositions are probably not residual.

There are three other proposed hypotheses to explain Opx enrichment in high Mg# continental mantle samples. (1) High degrees of melting at relatively high pressure produced a high Mg# residue with high (e.g., >25%) Opx, and then metamorphic differentiation created peridotites with higher and lower Opx from these residues (e.g., [10]). (2) High Mg# peridotites with low Opx (<25%) may have been created by a high degree of melting at low to moderate pressure, and melt/rock reaction may have subsequently added SiO₂ to create high Opx peridotites (e.g., [11,45–48]). (3) High Mg#, cratonic mantle peridotites with 30 to 50 wt% Opx are mixtures of ~50% high Mg#, low Opx residual peridotites (as in hypothesis (2)) plus ~50% high pressure igneous cumulates with 25% olivine and 75% Opx (e.g., [40–42], and Herzberg, 1997, personal communication).

In this paper, we argue that Ni concentration in olivine provides a key constraint in determining which of these processes may have been important in the genesis of high Mg#, high Opx cratonic mantle. We show that Ni in olivine shows a positive correlation with modal Opx in most cratonic xenoliths. If high Opx mantle peridotites formed solely by metamorphic differentiation, as in hypothesis (1), there should be little or no systematic relationship of phase composition with phase proportions, especially for samples with Opx > 31%. Metamorphic differentiation *combined with subsequent cooling* can produce a positive correlation of Ni in olivine with Opx mode, as we will show in Section 3.2. However, even under these circumstances, the slope of the correlation is less than the observed slope in cratonic peridotites. If high Opx mantle peridotites formed as mixtures of residues and igneous cumulates, as in hypothesis (3), one would expect a correlation between Ni and Mg#, but none is observed. Also,

small amounts of crystal fractionation are required to produce the igneous cumulate component without substantially lowering olivine Ni and Mg#. For such cumulates to comprise ~50% of the cratonic mantle, the volume of high pressure, ultramafic magma required would be similar to the volume of the cratonic mantle, and we find this implausible.

Finally, if Opx enrichment formed as a result of melt/rock reaction, as in hypothesis (2), one would expect a strong correlation of Ni in olivine with Opx mode, extending to the highest Opx proportions. In the following section of this paper, we show that Ni concentration in olivine is strongly, positively correlated with Opx proportion, even in high Opx samples, supporting hypothesis (2).

2. Correlation of Opx proportion with Ni in olivine

In Figs. 3 and 4 we illustrate co-variation of Ni in olivine, Mg#, and modal Opx in mantle samples. This is done for three different sample populations: (1) the global database compiled by McDonough and Frey [49], (2) xenoliths from the Kapvaal craton, the Siberian craton, and the Arctic western hemisphere, and (3) xenoliths from one locality, the Premier kimberlite pipe. For the Kapvaal and Siberian data, and for the Premier data in particular, we rely on data kindly supplied by Joe Boyd (personal communication). The data for populations (1), (2) and (3) are consistent, and show that Ni concentration in olivine is positively correlated with Opx proportion (Fig. 3) but not with olivine Mg# (Fig. 4).

As briefly noted by Kelemen and Hart [48], these chemical characteristics are not consistent with an origin of high Mg#, high Opx samples by high pressure partial melting, but they are a simple, predictable consequence of melt/rock reactions in which melt₁ + olivine forms melt₂ + Opx, with a net increase in the SiO₂ content of the peridotite product. Thus, these data are consistent with the hypothesis that many high Mg# peridotites from the continental upper mantle have undergone addition of SiO₂ due to melt/rock reaction. We will demonstrate this further with a quantitative model in Section 3.3.

The McDonough and Frey database does not include mineral compositions. Ni contents and Mg#

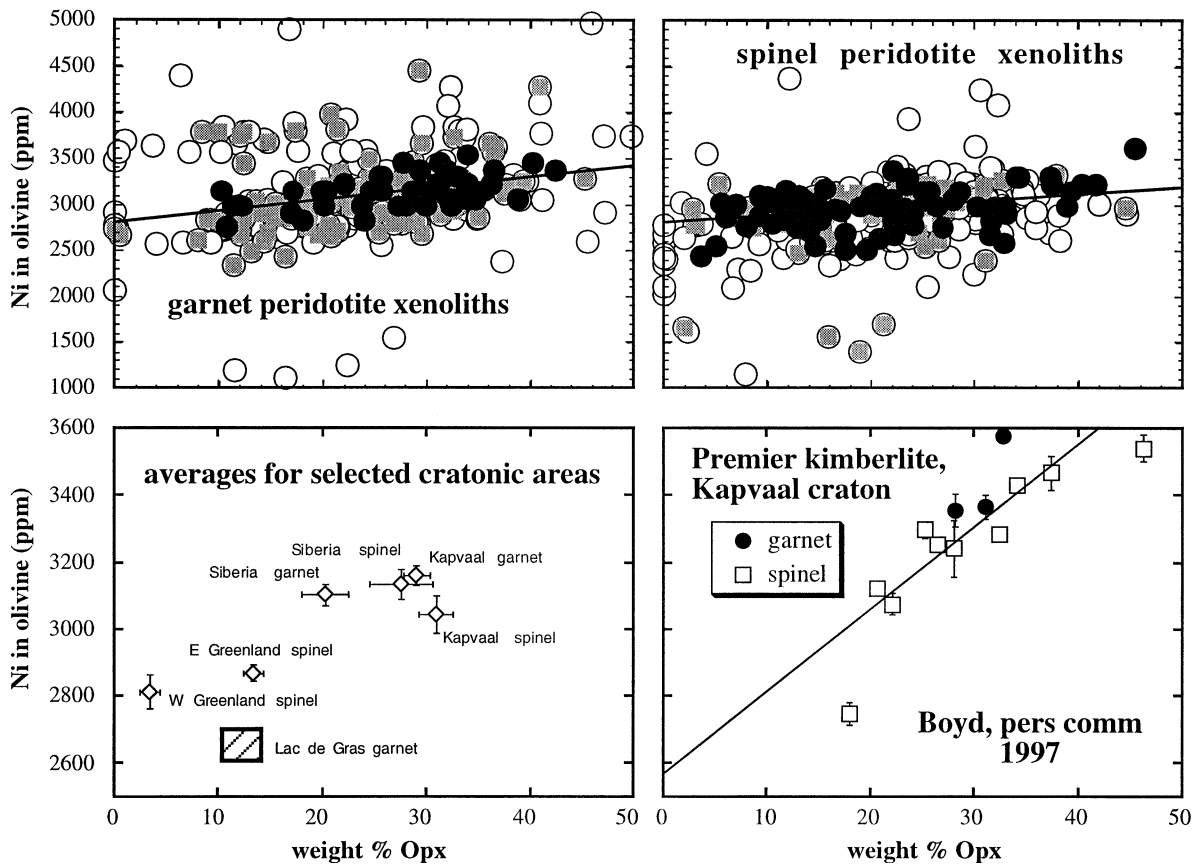


Fig. 3. Several different data sources indicate a positive correlation between Ni in olivine (ppm) and modal Opx in mantle xenoliths, on a worldwide basis, among cratonic peridotites, and within specific cratonic xenolith suites. Top, data from the worldwide peridotite database of McDonough and Frey [49], with normative mineral proportions and Ni contents of minerals calculated using the method of Kelemen et al. [11] at an assumed temperature of 1100°C, shown as open circles (all data) and grey squares (samples with <2% normative Cpx). Superimposed on these normative data are black circles representing data from 'low temperature' cratonic xenolith suites (East Greenland xenoliths (our new data and [18]), Udachnaya in Siberia [17], and Kapvaal (Boyd, pers. comm. 1996), in which Ni in olivine was measured by conventional electron microprobe methods, and Opx mode was determined either by point counting (Greenland) or mass balance using bulk and mineral compositions (Siberia, Kapvaal). Lines are linear regression fits through the electron probe data set. Bottom left, regional averages of cratonic 'low temperature' xenolith compositions, with error bars for one standard error of the mean. In addition to data in top two panels, this plot includes the average for xenoliths from Lac de Gras in the Slave craton [24] and for Ubekendt Island in West Greenland (our new data and [22]). Bottom right, high precision Ni analyses in spinel (open symbols) and garnet (filled symbols) peridotite xenoliths from the Premier kimberlite in the Kapvaal craton [50], with linear regression fit through all the data ($\text{Ni in olivine} = 2573 + 24.36 \text{ wt\% Opx}$, $r^2 = 0.84$). Error bars are for one standard deviation from the mean Ni content in olivine, based on four or more analyses per sample.

in olivine have been calculated from the bulk rock composition in the following way. First, normative mineral proportions for mantle conditions were calculated using the method of Kelemen et al. [11]. Second, the Ni concentration in the whole rock was apportioned among the mineral phases according to their normative proportions, using temperature

dependent mineral/mineral partition coefficients derived by us from the data of Bodinier et al. [51] and [52], as given in the caption for Fig. 5. This is the method Kelemen et al. [11] used to calculate REE abundances in clinopyroxene from rock compositions, and it has probably been employed by others prior to that time. Recently, a paper describing

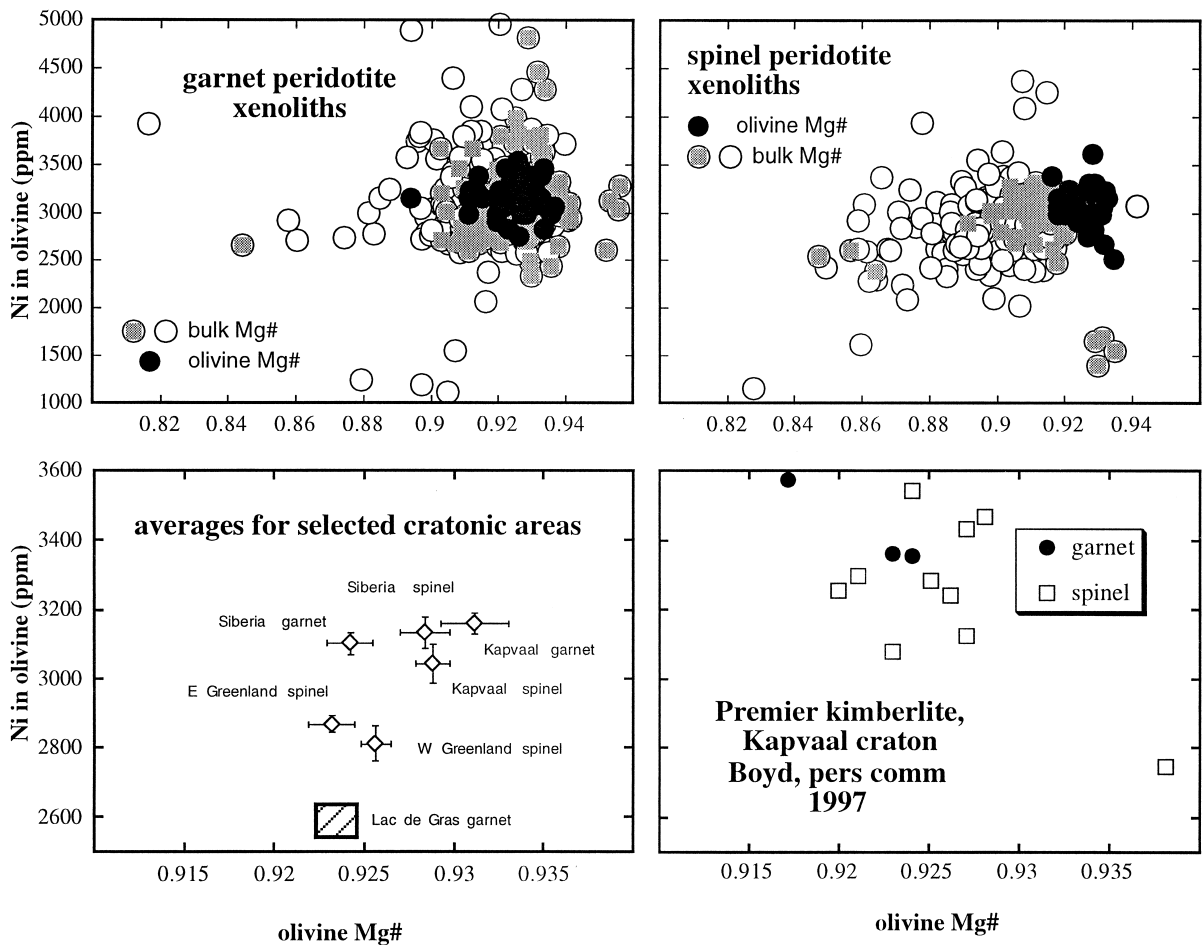


Fig. 4. Using the same data sets as in Fig. 3, it is clear that there is little or no correlation between Ni in olivine and Mg# of the bulk rock (open circles and grey squares, top two panels) or Mg# of olivine (black circles in top two panels, and all data in bottom two panels).

the algebra required for this calculation in detail was published by Bédard [53]. We chose mineral/mineral partition coefficients at 1100°C for Ni for Figs. 3 and 4.

For sample populations (2) and (3), all Ni concentrations and Mg# in olivine were determined by electron microprobe analyses. Sample population (3) was analyzed in 1997 using a special technique at the Carnegie Institution of Washington which is precise to within about ± 50 ppm. Routine electron microprobe analyses of Ni in olivine are commonly uncertain to within $\pm 10\%$ relative, and standards used for this analysis are different in different laboratories, so that the question of accuracy arises in comparing data sets, as in sample population (2).

So many analyses are represented in population (1) that this problem is probably minimized. In population (2), analyses from two different labs (Carnegie prior to 1997, Univ. Copenhagen 1996–97) are combined. From Fig. 3, it is clear that the analyses fall into distinct populations — the mean Ni in olivine from Copenhagen analyses of East Greenland samples is clearly distinct from the mean for Carnegie analyses of samples from Kapvaal, Siberia, and Arctic Canada. In order to ensure that the differences are real, and not a result of systematic inter-laboratory differences in standardization, we analyzed four Kapvaal samples at Copenhagen. Comparison of the Copenhagen values with pre-1997 Carnegie values for the same samples shows scatter (at the

$\pm 10\%$ level), but no systematic difference (average difference = 20 ppm). Therefore, we believe that the comparatively large differences between the means for Kapvaal, Siberia, Arctic Canada and East Greenland are real.

The modal proportions of minerals for xenoliths from the Kapvaal and Siberian cratons and the Grizzly kimberlite pipe in Arctic Canada were calculated using a least squares method combining the bulk rock composition and electron microprobe analyses of the minerals [17]. The modal proportions of minerals in central east and west Greenland xenoliths were determined by point counting of thin sections [18,22], and are inherently less accurate than the modes determined by least squares.

The correlation of Ni in olivine vs. modal Opx in the global data shows considerable scatter, but this is greatly reduced, and the positive correlation is enhanced, when only harzburgites are considered. Comparison of the total data set with the harzburgite alone also shows that Ni in olivine is not correlated with modal Cpx.

It should be noted that, while the correlation of olivine Ni with modal Opx in xenoliths from the Premier kimberlite pipe is striking, similar data from Joe Boyd for xenoliths from the Udachnaya pipe in Siberia show a weaker correlation, and his data for the Kimberley pipe in the Kapvaal craton show no correlation. This should not be surprising since the cratonic mantle beneath any given kimberlite pipe is likely to have a polygenetic history. Various residual peridotite compositions, formed via different degrees of partial melting, will have been juxtaposed both before and after metasomatic events affecting modal Opx. It is somewhat amazing that a xenolith suite from any kimberlite would form a coherent trend on a plot of Ni in olivine vs. modal Opx, given the apparently accidental process by which xenoliths are sampled during kimberlite transport. On the other hand, when xenoliths from a given locality do show evidence that the xenoliths are co-genetic, this cries out for an explanation. Thus, Fig. 3 illustrates that globally, in craton averages, and in some individual kimberlites, there is a correlation between Ni in olivine and modal Opx. In the following section we present quantitative models that constrain the genesis of this correlation.

3. Models of compositional variation

3.1. Partial melting

In Fig. 5 we compare the results of some simple models for formation of high Opx peridotites. Fig. 5a illustrates the results of partial melting calculations. Partial melting in the spinel lherzolite facies produces a slight positive correlation between Ni in olivine and modal Opx in the initial stages of melting, but after Cpx is exhausted the variation trend is slightly negative. In addition, this process cannot account for the formation of Opx-rich residues. (As an aside, we note that the trend of decreasing Ni in olivine over the first 20% of spinel melting seemed counter-intuitive to us; it stems from the melting reaction which produces increasing modal olivine more rapidly than increasing bulk Ni concentration).

Partial melting at ~ 30 kbar, close to the transition between garnet and spinel lherzolite stability fields, produces slight enrichment in Opx in residues up to the point at which Cpx and garnet are exhausted, where modal Opx is ~ 30 wt%, after which Opx will be progressively depleted by continued melting. Until Cpx is exhausted, Ni contents in olivine drop with increasing modal Opx; after Cpx-out, Ni in olivine is relatively constant. Thus, this melting model produces neither a correlation between Ni in olivine and modal Opx, nor $> 30\%$ modal Opx. In melting at 50 to 70 kbar and high temperature, the bulk distribution coefficient for Ni is close to 1, so bulk Ni in residues changes very little. At the same time, the modal proportion of Opx in the residue is nearly constant and modal olivine grows steadily, so that high pressure melting produces a substantial decrease in Ni in olivine at nearly constant Opx.

In summary, Fig. 5a illustrates that partial melting, at any pressure, cannot account for observed co-variation of Ni in olivine and modal Opx in cratonic peridotite xenoliths.

3.2. Metamorphic differentiation plus cooling

In Fig. 5b, we illustrate results of calculations in which metamorphic differentiation is combined with subsequent cooling. Metamorphic differentiation, by itself, will not produce substantial variation in phase compositions. However, if metamorphic dif-

ferentiation occurs at high temperature, where Opx is relatively rich in Ni, and then the rock cools, Ni must diffuse from Opx into olivine in order to maintain equilibrium. Cooling of an Opx-rich rock increases Ni in olivine more than cooling of an Opx-poor rock, giving rise to a positive correlation between modal Opx and Ni in olivine.

Fig. 5b shows that, even for a large cooling interval (metamorphic differentiation at 1800°C, with subsequent cooling to 800°C, plus complete exchange to produce an equilibrium Ni distribution between olivine and Opx), this effect is insufficient to account for the slope of the positive correlation between Ni in olivine and Opx. Therefore, we believe that metamorphic differentiation followed by cooling is an unlikely explanation for the observed correlation of Ni in olivine with modal Opx.

An additional consideration is that cooling of high temperature Opx could produce exsolved clinopyroxene and garnet, with lower Ni distribution coefficients. If so, the combined olivine/(Opx + Cpx + garnet) distribution coefficient would be lower than the olivine/Opx value used for Fig. 5b. In fact, Cpx and garnet are not abundant in Kapvaal low temperature harzburgites (average of 2% Cpx and 5% garnet; Boyd, pers. comm. 1997), so in fact this effect is likely to be small. Quantitatively, given a high temperature olivine/Opx Ni distribution coefficient of 2.3 to 2.5 (1800 to 1600°C), producing the observed slope for xenoliths from the Premier kimberlite via cooling following metamorphic differentiation requires a low temperature olivine/(Opx + Cpx + garnet) distribution coefficient > 200 (corresponding to olivine/Opx at 17°C), strikingly different from olivine/Opx of 3.8 to 7.0 at 1000 to 500°C. Since Cpx + garnet are never more abundant than Opx in these rocks (Boyd, pers. comm., 1997), a value of 200 for olivine/(Opx + Cpx + garnet) could not be attained at temperatures > 500°C.

3.3. Melt/rock reaction

In Fig. 5c, we illustrate the results of calculations in which melt/rock reaction consumes some olivine + an initial liquid to produce additional Opx + a modified liquid. We emphasize that these are a small subset of the possible models. They are illustrated to show the general effect of melt/rock reaction

which modifies the olivine/Opx ratio. Because Ni is enriched in olivine/Opx at equilibrium, reactions which consume olivine to produce Opx will decrease the size of the olivine reservoir for Ni, driving Ni concentration higher in the remaining olivine.

In the examples illustrated, a partial melt of eclogite reacts with depleted, low Opx harzburgite to produce high Opx harzburgite (+ modified melt). This could occur above a subduction zone, if subducted oceanic crust and/or sediment underwent small amounts of partial melting, and the melts migrated upward into hotter mantle peridotite (e.g., [45–47,67–70]). As predicted on qualitative grounds, our calculations show that this reaction produces increasing Ni in olivine with increasing modal Opx, and leaves the Mg# of the peridotite virtually unchanged. Because the initial liquid arises by partial melting of an olivine-free, low Ni eclogite composition, the resulting liquid is enriched in Ni by reaction, and bulk Ni in peridotite shows a slight decrease.

Note that dissolution of Opx to produce a more olivine-rich peridotite, increasing the size of the olivine reservoir at near constant bulk Ni, might also produce a positive correlation between Ni in olivine and modal Opx (not illustrated). As emphasized in several papers (e.g., [71–73]), this reaction is likely where mantle-derived melts migrate upward through peridotite along an adiabatic geothermal gradient. However, note that this process could not account for the production of peridotites with > 30% Opx. As a consequence, with additional reasons discussed in Section 4.2, we believe the main process responsible for the correlation, at least in cratonic mantle peridotites, has been increasing Opx via reactions in which olivine + SiO₂ (melt 1) = Opx (+ melt 2).

4. Discussion

Following a variety of other workers [11,45,47], we have proposed that high Mg#, high Opx cratonic peridotites originated as a result of a two stage process (Fig. 6). First, high Mg#, low Opx protoliths were created, and then these were modified by SiO₂ addition via melt/rock reaction ([48] and Section 3.3, above). In this discussion, we first review data on the possible origin of high Mg#, low Opx

protoliths (Section 4.1), and then make additional remarks on the process of SiO₂ addition (Section 4.2). Finally, we place our hypothesis in a geodynamic framework in Section 4.3.

4.1. Origin of the high Mg#, low Opx protolith: shallow residues

Our new data on xenoliths recovered from 40 Ma alkaline dikes cutting the Tertiary flood basalts in central East Greenland [18] demonstrate that high Mg#, low Opx peridotites are indeed present in the cratonic mantle. Such compositions are also found in xenoliths from cratonic North America [19–21,24], and in Tertiary alkaline dikes and lavas postdating the flood basalts in central West Greenland [22]. Our East Greenland xenoliths are mostly spinel harzburgites with high Mg# olivines (average 92.7) and low

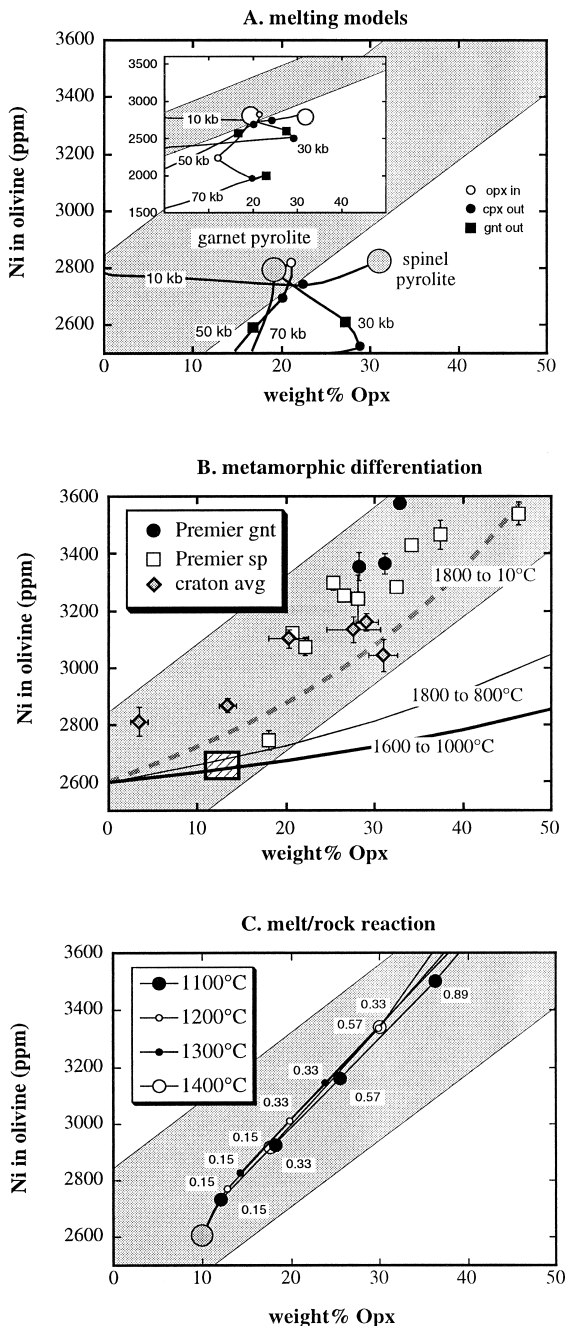


Fig. 5. Results of simple models of mantle processes in terms of variation of modal Opx and Ni in olivine. For these models, temperature dependent Ni distribution coefficients were from Hart and Davis [54], and our fits to the mineral composition data of Bodinier et al. [51] and Ryan et al. [52], yielding olivine/liquid = $\exp[-7.69 + 15,850/(TK)]$, olivine/Opx = $0.515 + 3260/T(^{\circ}\text{C})$, olivine/Cpx = $11,656/T(^{\circ}\text{C}) - 4.051$, and olivine/garnet = $\exp(5425/T \text{ K})$. In addition, we used a fixed spinel/liquid Ni distribution coefficient of 5. The olivine/Opx distribution coefficients are particularly crucial to this paper. An additional data set from Boyd (pers. comm. 1997) yields olivine/Opx ranging from 4.8 at 700°C to 2.8 at 1530°C, in good agreement with our expression which yields 5.2 at 700°C and 2.6 at 1530°C. We also modeled the concentration of a heavy rare earth element, Yb, in the residues of partial melting. Yb distribution coefficients ($D(\text{Yb})$) for Cpx were assumed to be linearly proportional to molar Wollastonite (Wo) proportions (e.g., [55]), with values of 0 at Wo = 0, and 0.52 at Wo = 0.448 [56]. $D(\text{Yb})$ values for olivine, Opx and spinel were from [46] and references therein, and $D(\text{Yb})$ for garnet was 4, from [57]. (A) Results of fractional melting models of pyrolyte at 10, 30, 50 and 70 kbar. Fractional melting models were run with mineral compositions and proportions at appropriate temperatures and pressures, and then the resulting modal proportion of Opx and Ni contents in olivine were recalculated at 1000°C. None of the melting models reproduces the observed correlation between modal Opx and Ni in olivine (grey shaded region), and in addition neither low nor 'high' pressure melting generates residual peridotites with more than 32 wt% Opx whereas the observed Opx contents extend to almost 50 wt%. At 10 kbar, the melting interval from the solidus to Cpx-out was assumed to be at an average temperature of 1300°C, and the interval from Cpx-out to Opx-out was at 1500°C. At 30 kbar, the intervals from the solidus to garnet-out, garnet-out to Cpx-out, and Cpx-out to Opx-out were at 1500, 1550, and 1600°C, respectively. At 50 kbar, the intervals from the solidus to Opx-in, Opx-in to Cpx-out, and Cpx-out to garnet-out were at 1530, 1580, and 1620°C. At 70 kbar, the intervals from the solidus to Opx-in, Opx-in to Cpx-out, Cpx-out to

modal Opx (average 13 wt%). The central Greenland and North American xenoliths have higher Mg# than mid-ocean ridge peridotites and xenoliths from continental, off-craton areas, and lower Opx than Siberian and Kapvaal craton xenoliths (Figs. 1, 3 and 4).

Equilibration temperatures for our East Greenland samples average 850°C, only slightly hotter than a conductive continental geotherm at 40 to 90 km depth, rendering it unlikely that they represent juvenile continental upper mantle created during Tertiary rifting. More likely, they are genetically related to the Archean continental crust underlying the flood basalts. The distinct bulk chemistry makes the East

Greenland xenoliths probable residues of high degrees of melting during the Archean. Melting was likely polybaric, and probably continued to pressures within the spinel lherzolite facies. Bernstein et al. [18] showed that the average composition of the East Greenland xenoliths is consistent with extraction of 40 wt% melt from primitive mantle peridotite at ~20 to 30 kbar. The melt composition produced by this process is very similar to that of Munro-type komatiites, in equilibrium with olivine with an average Mg# of ~92.5.

An alternative is that the East Greenland peridotite composition is the result of subduction-related magmatic processes involving relatively high de-

garnet-out, and garnet-out to Opx out were at 1700, 1780, 1800, and 1850°C. Normative modes in spinel and garnet facies for a pyrolite source [29] were calculated by the method of Kelemen et al. [11]. This method requires specification of the molar Wollastonite (Wo) content of Cpx and Opx. We used $Wo \text{ in Cpx} = 0.94821 - 0.000468317(T^\circ\text{C})$, fit to the experimental data of Walter [16] and Baker and Stolper [58] with $r^2 = 0.92$, and $Wo \text{ in Opx} = 0.04$ with no temperature dependence. Note that this technique correctly yields a norm for garnet pyrolite at 1650°C with a single pyroxene phase having about 17 mol% Wo. Melt modes were from Baker and Stolper [58] at 10 kbar, Walter [16] at 30 and 70 kbar, and Walter (pers. comm., 1998) at 50 kbar. Ni concentration in the source was taken to be 2080 ppm [59], but 17.6 wt% of the Ni was assumed to be bound in a sulfide phase that is retained in the solid residue (given ~200 ppm S in the primitive mantle, e.g. [60]), leaving 1714 ppm Ni to participate in the silicate melting budget. (B) Effects of metamorphic differentiation followed by cooling, with an initial Ni content of 2600 ppm in olivine. This initial value was chosen to pass through the average Ni content of olivine in garnet peridotite xenoliths from the Slave craton. Shown for comparison are measured Ni contents and wt% Opx for averages of 'low temperature' cratonic xenoliths from East Greenland, Siberia and the Kapvaal craton, and for individual samples from the Premier kimberlite in South Africa, as described in caption for Fig. 3. Metamorphic differentiation will produce rocks with a variety of modes but no significant variation in phase composition. Subsequent cooling will increase the olivine/Opx distribution coefficient for Ni. If the two phases reequilibrate, Ni will be higher in olivine in the more Opx-rich rocks. However, this effect is insufficient to explain the slope of the correlation between Ni in olivine and modal Opx observed in cratonic mantle xenoliths. (C) Models of melt/rock reaction in which a small degree melt of a basaltic composition (25.7 ppm Ni based on 3% melting of normal mid-ocean ridge basalt [59]) reacts with depleted harzburgite (90 wt% Fo₉₂, 10 wt% En₉₃, 2600 ppm Ni in olivine) to produce Opx-rich harzburgite and a modified liquid. Results of this calculation reproduce the observed correlation between modal Opx and Ni in olivine (grey shaded region). Marked points are labeled with the melt/rock ratio. To model this reaction, we solved a system of non-linear equations using an iterative, least squares minimization routine at an assumed temperature. The initial liquid composition was an experimental liquid produced by partial melting of a basaltic amphibolite at 32 kbar and 1175°C by Rapp and Watson [61]. Constraints include mass balance equations for SiO₂, MgO, FeO, and the group of all other liquid components, and temperature dependent olivine/liquid MgO and FeO expressions from Roeder and Emslie [62]. Mass fractions of all phases were required to sum to 1, as were mass fractions of all phase components. Additional assumptions were that olivine and Opx were stoichiometric and included only SiO₂, MgO and FeO, that there were no other solid phases, and that Opx Mg# = 1.01 olivine Mg#. In these calculations, residuals for all equations were < 0.31% relative. Ni was not used in the mass balance calculation. Instead, Ni was apportioned among the resulting phases using bulk Ni concentration, phase proportions, and Ni distribution coefficients. This system of equations yields phase proportions and compositions. Results of calculations at 1400 to 1100°C yield increasing (1400–1200°C) to constant (1100°C) liquid mass. In the range of product peridotite compositions from 0 to 50 wt% Opx, liquid compositions have 55 to 66 wt% SiO₂, 3.4 to 6 wt% Na₂O, and 2.5 to 4 wt% K₂O. These silica-rich, alkali-rich calculated liquid compositions are very similar to those of alkali-rich glass inclusions trapped in mantle olivine at 7 to 12 kbar (e.g., [63]), in keeping with the theory that high alkali and H₂O contents can dramatically increase the SiO₂ content of olivine + Opx saturated liquids at pressures up to at least 20 kbar [64,65]. Calculated liquids had 705 to 58 ppm Ni, with Ni contents positively correlated with both temperature and melt/rock ratio. Corresponding olivine Mg#'s ranged from 0.92 to 0.95, correlated mainly with melt/rock ratio. Calculated Ni in olivine vs. wt% Opx from this modeling approach are essentially identical to those of Kelemen and Hart [48], who used the same Ni distribution coefficients and reactants as in this study, and the trace element model of DePaolo [66], assuming a ratio of solid reactants/solid products (Ma/Mc) of 0.97, and solid products with 50 wt% Opx, 45 wt% olivine, 5% spinel, or 50 wt% Opx, 40 wt% olivine, 10 wt% garnet. We prefer the new mass balance approach because it yields values of Ni in olivine for a variety of comparatively well-constrained solid and liquid phase proportions and compositions.

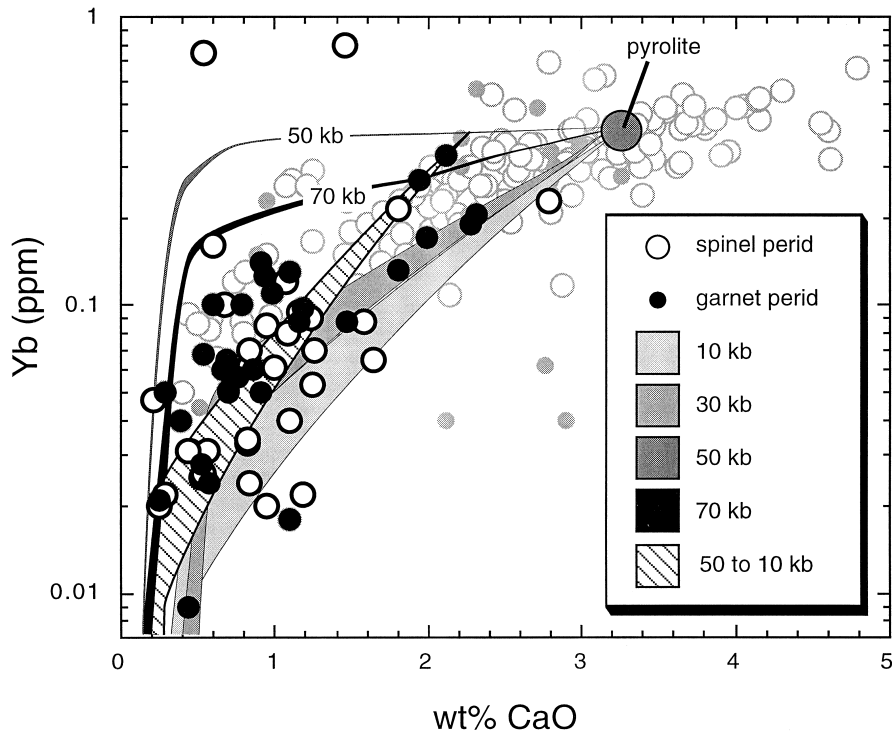


Fig. 6. Schematic illustration of the two stage process proposed to explain formation of high Mg#, high Opx cratonic mantle peridotites. High Mg#, low Opx peridotites are created by large degrees of polybaric partial melting, in a mantle plume or beneath a spreading center, at a potential temperature of $\sim 1500^{\circ}\text{C}$. These residual peridotites later react with SiO_2 -rich melts derived from small degrees of anatexis of subducted metabasalt and metasediment, leading to an increase in Opx and increasing Ni in olivine. During this process, and/or during later plate collision, the high Mg# peridotites are tectonically transported to greater depth.

degrees of melting due to high H_2O fugacity. Similar peridotites, with low Opx and olivine with $\text{Mg}\# > 92$, have been reported from ophiolites in Papua New Guinea (Fig. 1; [27,25,26]). Bernstein et al. [18] found that such compositions cannot form by simple re-melting of previously depleted oceanic peridotite (e.g., [14]), because at the appropriate Mg# the resulting melt would have more than 30% MgO and almost 50% SiO_2 . If the Papuan peridotites are not the residues of komatiite extraction, and instead formed by a magmatic process in a subduction-related arc, this must have occurred in an open system, with dissolution of Opx in migrating melt.

Conversely, the Papuan high Mg# peridotites could conceivably be the residues of komatiite extraction. Perhaps they are relict upper mantle from beneath a large, oceanic igneous province, where Storey et al. propose that komatiites have formed in the Phanerozoic [74]. Also, Sobolev and Danu-

shevsky [75] suggest that komatiitic melts are currently formed in some arcs, as a result of high degrees of melting produced by H_2O flux from subducted crust into hot, rising asthenosphere above the slab. In this view, high Mg# peridotites might indeed be residues of komatiite extraction, but this process has not been restricted to the Archean.

In any case, we propose that the East Greenland xenoliths have the composition of the depleted protolith prior to the silica addition process proposed in Section 3.3. Either komatiite extraction or a (less well constrained) subduction process could also account for the bulk composition of xenoliths from West Greenland and cratonic North America. Both would form highly depleted residues at pressures of 30 kbar or less.

Compiled geochemical data for mantle xenoliths support the view that all have a protolith formed by partial melting that ended at pressures ≤ 30 kbar. In

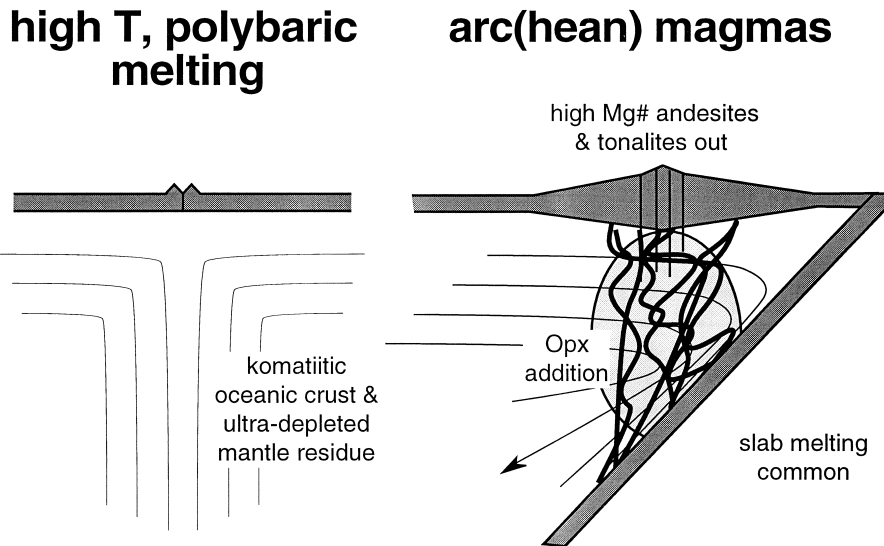


Fig. 7. Plots of CaO vs. Yb concentration in mantle xenoliths from the global database of McDonough and Frey [49]. Both spinel and garnet peridotite xenoliths show a positive correlation between CaO and Yb. Data for xenoliths with bulk rock Mg# > 0.91, mostly from the Kapvaal craton, are shown in black; all others are in grey. Also shown are calculated CaO vs. Yb from the melting models described in the caption for Fig. 5, for a pyrolite source with 2.5 times chondritic Yb (~0.4 ppm) and ~3.3 wt% CaO. In addition to fractional melting, we also modeled 'continuous melting' [76] with a residual melt porosity of 2 wt%; this yields the curves with higher Yb concentration at a given wt% CaO. Because Yb is compatible in garnet, melting with residual garnet produces little Yb variation in residues, but CaO concentration decreases with increasing degrees of melting. At lower pressure, melting of spinel peridotite depletes residues in both CaO and Yb. However, the depletion of Yb that we calculate for melting at 10 kbar is too large to fit the data. A fairly good fit is obtained using the 30 kbar melting mode of Walter [16], in which garnet is exhausted at 10% melting. In natural systems, isobaric melting is unlikely. Thus, we also made an approximate model of polybaric melting. A polybaric melting model, with 10% melting in the garnet facies (50 kbar melting model) followed by continued melting in the spinel facies (10 kbar melting mode) fits the global peridotite data very well. If the concentrations of CaO and Yb in mantle xenoliths mainly reflect the effects of partial melting processes, then the correlation between their concentrations is consistent with polybaric partial melting extending to pressures and melt fractions where residual garnet was not present. This requires melting that ended at ≤ 30 kbar. Thus garnet-bearing mantle xenoliths which currently record pressures > 30 kbar are probably shallow residues of polybaric partial melting that have been tectonically transported to greater depth. Even in garnet peridotite xenoliths recording pressures < 30 kbar, formation of garnet is probably metamorphic, and postdates partial melting. It is possible that the concentration of Yb has been affected by trace element metasomatism. If the Yb concentrations were lower, at a given CaO, after melting and prior to metasomatism, then garnet must have played an even smaller role as a residual phase.

Fig. 7, we illustrate the co-variation of Ca and Yb in the global peridotite data base of McDonough and Frey [49]. As is illustrated, the well known positive correlation between Ca and Yb is easily explained as a result of polybaric fractional melting ending in the spinel lherzolite facies. Because Yb is enriched in garnet/melt at equilibrium, melting in the presence of garnet at pressures > 30 kbar cannot explain the observed compositional variation. Melting of a garnet lherzolite at 30 kbar represents an intermediate case, because garnet is less stable near the garnet–spinel lherzolite transition, and is exhausted early during partial melting (~10% melting; [16]). In the light of the Ca vs. Yb variation, it is probable that

both spinel and garnet peridotite cratonic xenoliths have protoliths that underwent 10 to 50% polybaric melting, ending with a garnet-free residue. If the mantle source composition had Al contents similar to the primitive mantle [29,30], then garnet would not be a residual phase at ≤ 30 kbar. Based on this reasoning, few if any continental mantle xenoliths formed as residues of a melting process restricted to pressures > 30 kbar.

Many high Mg# garnet peridotite xenoliths have mineral compositions that record equilibration at pressures > 30 kbar (e.g., [77]), including the high Mg#, low Opx xenoliths from the Slave craton in Canada which record pressures up to 65 kbar [24].

If these rocks were once residues of partial melting at < 30 kbar, they must have been tectonically transported to greater depth at a later time. The hypothesis that shallow residues were transported to greater depth during formation of the cratonic upper mantle has been previously proposed (e.g., [78,79]). Polybaric melting due to adiabatic decompression of upwelling mantle produces slightly depleted residues at high pressure, and highly depleted residues at low pressure. For plausible patterns of mantle flow, the residual upper mantle formed by such processes will retain an inverse correlation between degree of depletion and depth. ‘Low temperature’ xenoliths from Kapvaal and Siberia, spinel and garnet harzburgites that equilibrated at pressures ranging from < 30 to 60 kbar, do not show systematic compositional variation with depth (e.g., [17]). This is inconsistent with their origin as variably depleted residues produced by a single decompression melting event, and consistent with tectonic stacking or thickening of highly depleted, shallow mantle residues.

The relatively low density of high Mg#, low Opx, shallow residual peridotites would have inhibited or prevented their subsequent subduction into the convecting mantle (e.g., [1]). Instead, they remained part of a thermal boundary layer in the uppermost mantle. Less depleted residues at greater depth may not have been buoyant and thus may generally have been recycled into the convecting mantle. According to Jordan ([1]), the base of the mechanical boundary layer in continental upper mantle is at about 700°C. Along a 40 mW/m² geotherm in thick, continental cratons, this corresponds to a depth of about 100 km. In ocean basins with a thinner lithosphere, the 700°C isotherm could be as shallow as 50 km. At 700°C, residual peridotites must have an Mg# of about 92 in order to be neutrally buoyant compared to oceanic peridotites at 1450°C with an Mg# of about 88 at the same depth [1]. Most ‘low temperature’ cratonic mantle xenoliths have an Mg# of 92 or more, independent of their pressure of equilibration (e.g., [17]). Thus it appears that neutral buoyancy at the base of the mechanical boundary layer — rather than over a range of depths and temperatures extending to the base of the conductive geotherm as in Jordan’s ‘isopycnic hypothesis’ — has generally constrained the Mg# of the cratonic upper mantle to values > 92. Residual peridotites that were buoyant enough to

remain isolated from the convective mantle may have been juxtaposed to form thicker cratonic roots after separation from less depleted residues with lower Mg#.

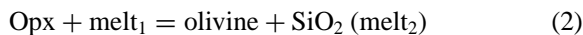
In summary, both major and trace element variation in mantle xenoliths support the view that most continental mantle peridotites underwent variable degrees of melt extraction, ending at relatively low pressure (≤30 kbar). High Mg# peridotites, typical of ‘low temperature’ mantle xenoliths from Archean cratons, underwent particularly large amounts of melting and melt extraction. In this view, all the protoliths of cratonic upper mantle would have been compositionally similar to the xenoliths from Greenland and Arctic Canada, prior to addition of SiO₂ by melt/rock reaction.

4.2. SiO₂ addition via melt/rock reaction

As discussed in Section 3.3, the observed correlation between Ni in olivine and modal Opx in continental mantle xenoliths, and in high Mg# cratonic mantle peridotites in particular, could have been produced by two distinct types of reaction:



and



Reaction (1) is likely where basaltic and/or sedimentary bulk compositions in amphibolite to eclogite facies undergo small degrees of partial melting at mantle depths (as, perhaps, in Archean subduction zones, e.g., [80]), and the resulting, silica-rich melt passes upward into mantle peridotite [45–48,67,68]. At constant temperature and pressure, this reaction would exhaust the liquid phase — and this may well have happened at various times and places. However, in general melts of subducted material will pass upward into hotter, overlying mantle. The combined effects of heating and decompression may permit the survival of such melts, which — as a result of reaction (1) — could become sufficiently poor in SiO₂ and rich in MgO to equilibrate with mantle olivine.

A scenario similar to melting of subducted material could arise if and when thick, basaltic crust cools, and the bottom is converted to a dense, eclogite assemblage. If the volume of such material is

sufficiently large, it might become gravitationally unstable and sink through the less dense upper mantle (e.g., [81–85]). During this ‘lower crustal delamination’, descending eclogites might be heated sufficiently to undergo anatexis, producing SiO₂-rich melts that would react with surrounding peridotite.

Reactions (1) and (2) also could take place where cooling, decompressing, mantle-derived magmas enter the conductive boundary layer in the uppermost mantle. Because the olivine primary phase volume expands with decreasing pressure, reaction between decompressing melts and mantle peridotite at near constant temperature tends to dissolve pyroxene and create olivine, enriching the resulting melts in SiO₂ [71–73,86]. If this process continues until magmas become saturated in Opx, then continued cooling of such melts combined with reaction will drive them along olivine–Opx co-saturation boundaries, creating Opx-rich solid products [11,68]. Finally, the cooling liquid will become saturated in olivine + Opx + Cpx (+ an aluminous phase), and could create pyroxene-rich lherzolites. These processes have been described extensively elsewhere. Because the net effect is to dissolve pyroxene at depth and precipitate pyroxene in the shallow mantle, the combination of reactions (1) and (2) creates an uppermost mantle layer which is progressively enriched in SiO₂ over time.

Reaction (2) is likely where mantle-derived melts migrate upward through peridotite along an adiabatic geothermal gradient [73]. The continental xenoliths that show a correlation between Ni in olivine and modal Opx are generally considered to be representative of ancient, static upper mantle. Therefore, it is likely that melt/rock reactions that modified these peridotites occurred within a conductive geothermal gradient. Reaction (2) may also occur over a restricted vertical interval near the base of the conductive boundary layer in the uppermost mantle. However, where melt transport is by porous flow, the thermal Peclet number must be small, and melts and solid will maintain the same temperature [87]. As a consequence, where magma fluxes are not large, the temperature of both melt and solid will closely approach the melt-free geotherm. For these reasons, reaction (2) is unlikely to be important over long vertical distances — i.e., over temperature intervals of more than about 40°C — within the conductive

layer. Furthermore, because reaction (2) produces a net increase in liquid mass (and porosity) at constant temperature [72,86] or under adiabatic conditions [73], it makes diffuse porous flow unstable, and tends to form narrow dissolution channels of focused melt flow [73,88]. For all these reasons, it seems unlikely that reaction (2) has produced pervasive compositional variation in the continental upper mantle.

In summary, it seems probable that Opx precipitation (reaction (1)) has been more important than Opx dissolution (reaction (2)) in producing the observed correlation of Ni in olivine vs. Opx mode in continental peridotites. In addition to the physical arguments in the previous paragraphs, we find evidence for this in the compositional variation of mantle samples. First, Opx precipitation reactions can account for the production of peridotites with more than 30% Opx. Second, peridotites dredged from the mid-ocean ridges, formed within adiabatically upwelling mantle, do not show a general, positive correlation between Ni in olivine and modal Opx (Henry Dick, pers. comm., 1997). Third, it is well known that cratonic mantle xenoliths are generally light rare earth element (LREE) enriched as compared to the primitive mantle, and even more so as compared to residual peridotites from the oceans (e.g., [11], Fig. 4). If reaction between partial melts of eclogites and previously depleted mantle peridotite has been common beneath cratons over geologic time, this could explain both LREE enrichment and the presence of abundant Opx [46,47].

4.3. *Geodynamics of continental genesis: a preferred model*

Our preferred hypothesis is that residual peridotites, with olivine Mg# > 92 and Opx < 20%, were commonly created as the most depleted, shallowest residues of polybaric melting in the Archean, when ambient mantle temperatures were somewhat higher than at present. While it has been argued that formation of Archean, Belingwe-type komatiites must have occurred in extraordinarily hot mantle plumes [89] with potential temperatures of ~1900°C, this does not apply to the formation of high Mg# residual peridotites such as are found in East Greenland. Formation of the East Greenland peridotites

by partial melting of primitive peridotite requires about 40% melting at an average pressure of ~ 30 kbar [18]. For 'dry' melting (H_2O -free), this requires $\sim 1550^\circ\text{C}$ at 30 kbar [16], or a potential temperature of $\sim 1500^\circ\text{C}$. At present, a potential temperature of 1500°C is thought to be unusually high in the upper mantle, restricted to thermal plumes. It is not clear to us whether the creation of depleted residues such as those in East Greenland only occurred within hot (and/or wet) 'mantle plumes' (e.g., [89]), or if the Archean mantle had an ambient potential temperature close to 1500°C so that high Mg# residues could have been produced beneath spreading centers similar to present-day mid-ocean ridges (e.g., [90]).

In some cratons, high Mg#, low Opx residues were modified by melt/rock reaction which changed olivine/Opx proportions [11,45–48,68]. For the reasons enumerated in Section 4.2, we think this occurred mainly as a result of reactions which consumed olivine and formed Opx. There are several scenarios in which this could happen. However, we prefer the idea that it resulted mainly from interaction with silicic melts derived by small amounts of partial melting of eclogite in subducting oceanic crust and sediment [45–48,68]. Partial melting of subducted material would have been enhanced if mantle temperatures and/or oceanic spreading rates were high in the Archean (e.g., [80]).

We prefer the addition of SiO_2 via melting of subducted basalt and sediment for several reasons given in Sections 1.2 and 4.2. In addition, this hypothesis provides a genetic link between Opx-rich cratonic peridotites and continental crust. It has been proposed that LREE enriched partial melts of subducted eclogite comprise an important component of continental crust [80,91,61]. Although this is a compelling argument, it is nonetheless true that average continental crust has higher Mg# than any experimental partial melts of eclogitic basalt or sediment compositions [70]. This can be explained if melts of subducted oceanic crust interacted with mantle peridotite (e.g., [47,67,68,92–94]) to produce the high Mg#, high SiO_2 composition of the continental crust [46,70]. If this is correct, there should be a complementary volume of LREE-enriched, Opx-rich mantle peridotites. Evidence summarized in this paper suggests that the complementary Opx-rich peridotites are indeed present in the cratonic upper mantle.

Subduction- and collision-related imbrication (e.g., [78,79]) or tectonic thickening of high Mg# mantle peridotites created thick cratonic roots in which the degree of melting (Mg#, bulk rock Ni) is no longer related to depth. It is not clear whether the melt/rock reaction that formed high Opx peridotites occurred before, during, or after these thickening events. Perhaps — to some degree — SiO_2 addition is a repeated, ongoing process, involving episodes of subduction-related magmatism along continental margins, followed by continental collision and thickening. However, there is some evidence that the process was generally ancient.

In addition to high Mg#, high Opx samples, sometimes termed 'low temperature' peridotites, the Kapvaal and Siberian cratonic xenolith suites include 'high temperature' peridotites (HTP), preserving pressures of equilibration > 55 kbar, relatively low Mg# (90.5 to 92), and relatively low modal Opx (20 to 30 wt%; e.g., [17]). These lie close to a conductive, continental geotherm and some have ancient Os isotope model ages (0.4 to 3.5 Ga, averaging about 2 Ga [95–97]). Since these rocks do not have obviously high modal Opx, they may have been accreted after the silica addition process which formed Opx-rich peridotites. Thus, either the formation of Opx-rich, high Mg# peridotites generally occurred before 2 Ga, or the average Os model age of HTP does not record their time of accretion beneath the high Mg#, high Opx, 'low temperature' peridotites.

To summarize, our preferred explanation for high Mg#, Opx-rich cratonic mantle samples is that they form via a two step process. First, high Mg#, Opx-poor peridotites form as shallow residues, probably as a result of high degrees of polybaric mantle melting. Later, modal Opx increases as a result of SiO_2 addition to the mantle by melt/rock reaction involving partial melts of eclogitic, subducted basalt and sediment. This is consistent with the idea that melt/rock reaction in the upper mantle above subduction zones has been intrinsic to the genesis of continental crust. In particular, reaction between silicic, small degree melts of subducted eclogite and overlying mantle peridotite could explain global features of both the cratonic upper mantle and continental crust composition, and this is our preferred hypothesis. However, other processes may also have played a role in producing Opx-rich peridotites with

high Ni in olivine. Among these might be reaction between mantle-derived liquids and conductively cooled upper mantle peridotite, and perhaps reaction between mantle peridotites and partial melts of descending eclogite derived by delamination of the continental lower crust.

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