

Melting residues of fertile peridotite and the origin of cratonic lithosphere

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Abstract—Experimentally determined melt compositions from fertile, 'pyrolitic' peridotite are used to predict the major element compositions of melt extraction residues as a function of pressure, degree of melting, and melting process (*i.e.*, isobaric batch and polybaric near-fractional melt extraction). Low-temperature cratonic peridotite xenolith compositions from southern Africa, Siberia, and Tanzania are compared with model residue trends in order to constrain the role of melt extraction in their origin. The SiO₂ contents of about 80% of the xenoliths from southern Africa, and about 30% from Siberia cannot be reconciled directly with melt extraction from pyrolitic mantle. However, nearly all xenoliths from Tanzania have major oxide compositions which are explicable in terms of melt extraction from pyrolite. Two generalized models are considered to account for SiO₂ enrichment in southern African and Siberian xenoliths: (1) melt extraction and metamorphic unmixing, and (2) melt extraction and secondary addition of silica by opx crystallization.

Within the context of the melt extraction—metamorphic unmixing model, the average SiO₂ content of Siberian and Tanzanian low-temperature xenoliths can be produced by melt extraction from pyrolite, and average oxide compositions from the two cratons indicate about 35 to 45% melt extraction at average pressures of 2 to >5 GPa. In contrast, the average SiO₂ content of the southern African xenoliths is significantly higher than any residue from pyrolite, requiring that the mantle prior to melt extraction was significantly enriched in SiO₂ relative to pyrolite, a feature distinguishing it from other known depleted lithosphere.

Within the context of the melt extraction—opx-addition model, the xenolith data from all three cratons are generally consistent with primary extraction of about 40% melt at an average pressure of 3 to 4 GPa, leaving a harzburgitic residue. Subsequent to primary melt extraction, significant amounts of opx were added to the Siberian and southern African lithospheres, whereas addition of opx was not an important process within the Tanzanian lithosphere. Primary melt extraction of 40–50% melt at average pressures of 3 to 4 GPa can also explain the observed compositions of depleted lithosphere from Greenland and Papua New Guinea. Conversely, typical oceanic lithosphere, 'off-craton' continental lithosphere, and high-temperature cratonic peridotite have compositions indicating lower degrees (10–30%) and lower average pressures of melt extraction (1–2 GPa).

INTRODUCTION

THE PERIDOTITIC lithosphere beneath oceanic and continental crust has chemical characteristics indicating its derivation by melt extraction from a more fertile, probably lherzolithic, protolith (*e.g.*, DICK and FISHER, 1984; BOYD, 1989). For example, abyssal peridotites dredged from oceanic rift valleys and fracture zones are pieces of the uppermost oceanic lithosphere, and these have a mineralogy and geochemistry that is consistent with melt depletion at shallow levels (DICK and FISHER, 1984; DICK, 1989; BONATTI and MICHAEL, 1989; BOYD, 1989; JOHNSON *et al.*, 1990; WALTER, 1998), although secondary crystallization processes at depth may have obscured the primary mineralogy in some cases (NIU *et al.*, 1997).

The case for subcontinental lithosphere is less clear. Peridotite xenoliths excavated from the shallow upper mantle, primarily by alkalic and kimberlitic magmas, show a wide range of mineralogy and chemistry (*e.g.*, BOYD, 1989). Generally speaking, xenoliths sampled from beneath continental crust that is off-craton have an "oceanic" affinity, and by analogy with abyssal peridotites, they may be residues of relatively shallow melting processes (BOYD, 1999).

Whereas, xenoliths derived from stable cratonic lithosphere have a more ambiguous origin. These include both coarse-grained low-temperature (< ~1100°C) xenoliths and sheared high-temperature (> ~1100°C) xenoliths. High-temperature xenoliths from southern Africa and Siberia have major element characteristics consistent with melting at moderate pressures (2 to 3 GPa; see WALTER, 1998), although major and trace element data from some xenoliths indicate extensive metasomatism (*e.g.*, GRIFFIN *et al.*, 1989; SMITH *et al.*, 1993).

Low-temperature cratonic xenoliths have been shown to have general chemical characteristics indicative of high degrees of melt extraction; for example, very high Mg#s (~92–94) and extreme depletions in CaO and Al₂O₃ (*e.g.*, BOYD and MERTZMAN, 1987; TAKAHASHI, 1990; BOYD *et al.*, 1997). However, some unusual chemical features, most notably high-SiO₂ and in some cases anti-correlated FeO and SiO₂, are difficult to reconcile directly with partial melting processes (*e.g.*, BOYD, 1989; KELEMEN *et al.*, 1992; CANIL, 1992; HERZBERG, 1993; BOYD *et al.*, 1997; WALTER, 1998). Presently the role of melt extrac-

tion in the origin of cratonic lithosphere is poorly constrained.

In order to understand the nature of the melting events that produced the 'depleted' lithosphere, it is essential to have a quantitative knowledge of the melting behavior of fertile peridotite. Here, I use recently published data for melting of fertile peridotite over a pressure range of 1 to 7 GPa (HIROSE and KUSHIRO, 1993; WALTER, 1998) to predict the major element chemistry of melts and their residues as a function of pressure, degree of melt depletion, and melting process. The residue trends are then compared with low-temperature cratonic peridotite compositions from three cratons in order to evaluate the role of melt extraction in their origin.

EXPERIMENTAL DATA

HIROSE and KUSHIRO (1993) presented phase equilibrium data for batch melting of a fertile lherzolite, KLB-1, from 1 to 3 GPa, and WALTER (1998) presented data for melting of a chemically very similar fertile lherzolite, KR4003, from 3 to 7 GPa. In both of these studies, the degree of melting in the experiments was estimated, either from the K_2O content of the melt (HIROSE and KUSHIRO, 1993) or by mass balance of phase compositions (WALTER, 1998). Data from these studies are used here in a first-order, numerically convenient

approach for describing melt composition from fertile mantle as a function of pressure and degree of melting.

Second-degree polynomial expressions are used to describe the abundances of SiO_2 , Al_2O_3 , FeO and MgO in melts as a function of pressure (1–7 GPa) and degree of melting (0–100%). The form of these functions is not ideally suited for describing the complexity of melt compositions over such a wide range in pressure and degree of melting. In order to combat this problem, expressions were determined over discrete pressure regions using a combination of multiple linear regression to the data and force fitting of equations to predetermined boundary conditions. Regression regions, coefficients and uncertainties are given in Table 1, and plots of oxides versus melt percent, contoured for pressure, are shown in Fig. 1. Overall, the parameterizations describe the data reasonably well, typically reproducing the data to better than 5% relative (about a factor of two times microprobe precision). Data from the 3 to 7 GPa region are typically fit most precisely, while the regressions are most inaccurate at reproducing SiO_2 and Al_2O_3 at low pressures and low degrees of melting (<10%). However, such melts are not important in the models presented here, so this inaccuracy is inconsequential.

In detail these parameterizations do not provide an entirely accurate description of melting of fertile lherzolite, and they are no substitute for comprehensive phase equilibrium data or a rigorous thermodynamically based description of melting such as the MELTS algorithm (GHIORSO and SACK, 1995). However, in the absence of a more idealistic description of melting over such a wide pressure range, the

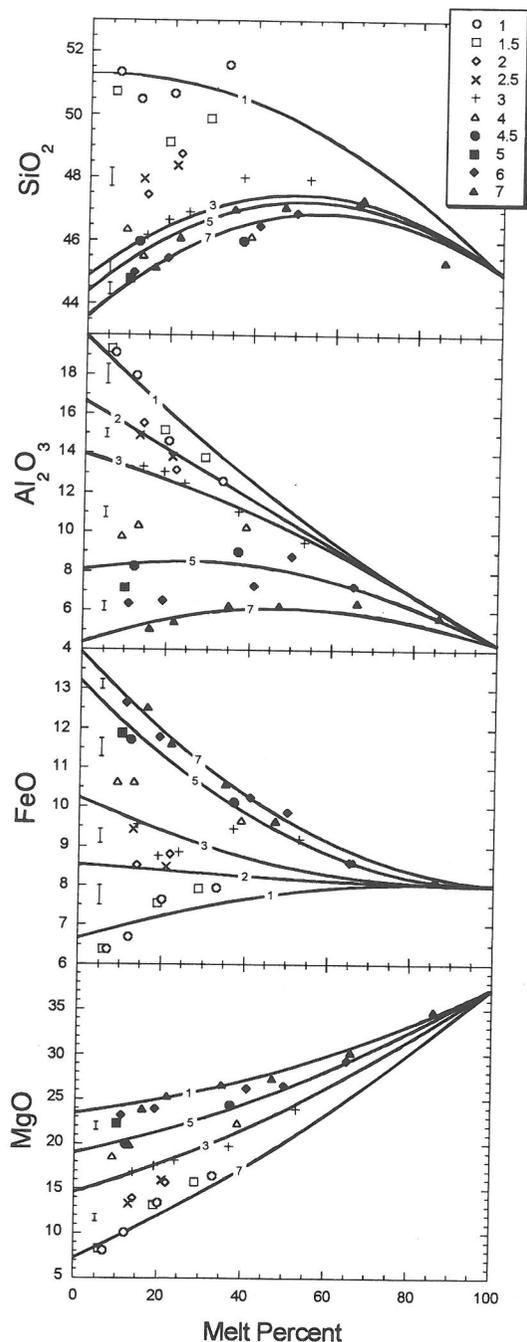
Table 1. Regression coefficients and uncertainties for polynomials that describe melt compositions from pyrolite as a function of pressure (1–7 GPa) and degree of melting (0 to 100%).

Oxide	P (GPa) ¹	n ²	α^3	β	χ	δ	ϵ	ϕ	MAD ⁴	MPD ⁵
SiO ₂	5–7	12	47.70	0.0879	-0.0010	0.0040	-0.8461	0.0375	0.36	0.8
	3–5	10	46.60	0.0889	-0.0010	0.0038	-0.5440	0.0210	0.48	1.0
	1–3	11	54.24	-0.0257	-0.0007	0.0338	-2.966	-0.0140	0.60	1.2
Al ₂ O ₃	5–7	12	17.31	-0.0592	-0.0007	0.0184	-1.845	0.0003	0.54	7.8
	3–5	10	23.55	-0.1253	-0.0005	0.0284	-3.608	0.1113	0.45	4.7
	2–3	4	6.01	-0.1664	-0.00006	0.0250	10.52	-2.590	0.42	2.9
	1–2	7	17.44	-0.2201	0.0004	0.0229	4.919	-2.467	0.85	5.5
FeO	5–7	12	9.784	-0.0885	0.0005	-0.0033	0.9128	-0.0458	0.19	1.8
	3–5	10	5.801	-0.0027	0.0003	-0.0164	1.572	-0.0282	0.38	4.0
	2–3	4	6.115	0.0270	0.00003	-0.0177	1.045	0.0806	0.34	3.8
	1–2	7	6.587	0.0519	-0.0002	-0.0181	-0.7211	0.7799	0.44	6.3
MgO	3–7	22	7.420	0.2105	0.0008	-0.0225	2.417	-0.0167	0.67	2.9
	1–3	11	3.605	0.2532	0.0009	-0.0367	3.637	-0.0006	0.78	6.6

1 The pressure region within which a given regression is applicable; 2 Number of experimental data used in regression. Other values used in the regressions were the system bulk composition (i.e. at 100% melting) and boundary values from other regression regions (i.e. the 5 GPa fitted curve for the 5 to 7 GPa region would be used as a boundary constraint for the 3 to 5 GPa regression, etc.);

3 Regression coefficients for a polynomial expression of the form: oxide (weight %) = $\alpha + \beta D + \chi D^2 + \delta DP + \epsilon P + \phi P^2$, where D is degree of melting in weight % and P is pressure in GPa; 4 Mean absolute deviation between calculated values and experimental data within the regression region;

5 Mean percentage (in weight %) deviation between calculated values and experimental data within the regression region.



expressions do provide a good characterization of the experimental data, and provide a convenient way to model complex melting processes in the upper mantle.

MELTING PROCESS

The dynamics of melting in craton forming events is ambiguous and several melting styles could have been important. Depending on physical properties such as the viscosity and density of both melt and residue, the melting process can range from isobaric or polybaric batch melt segregation, such as might occur in regions dominated by buoyant mantle upwelling, to more complex melting such as polybaric near-fractional melt segregation which might occur as a consequence of porous flow of melt in a region of passively upwelling mantle (see TURCOTTE and MORGAN, 1992). For example, melt segregation processes at modern mid-ocean ridges are the most well studied and best understood of all melting regions, yet even there the relative importance of melt and residue buoyancy is not well constrained. However, polybaric near-fractional melting can apparently account for many chemical features of MORBs and their residues (*e.g.*, KLEIN and LANGMUIR, 1987; MCKENZIE and BICKLE, 1988; JOHNSON *et al.*, 1990; NIU and BATIZA, 1991; LANGMUIR *et al.*, 1992; KINZLER and GROVE, 1993).

Neither the details of mantle flow nor the types of melt extracted (*e.g.*, basalt, komatiite) to form stable cratonic lithosphere are known in any detail, so a variety of melting models should be explored. The parameter space encompassing all perturbations of the possible melting styles is formidable so, for simplicity, the melting styles considered here are limited to isobaric batch and polybaric near-fractional melt extraction as specified below. These melt extraction models can be considered as extreme cases, and other melting styles such as polybaric batch or dynamic melt extraction should produce residue compositions which are intermediate to these endmembers but with their own distinctive trends. Indeed, the compositional data from cratonic peridotites show too much scatter to be hopeful of identifying a distinct melting style. Rather, the objective here is to compare the oxide trends of a variety of melt extraction residues with the compositional data from cratonic peridotites in order to determine to what degree the observed data is explicable in terms of melt extraction from

FIG. 1. Variation of major element oxides as a function of melt percent (weight %) in experimental batch melts of fertile peridotite [data from 1 to 2.5 GPa from HIROSE and KUSHIRO (1993) and from 3 to 7 GPa are from WALTER (1998)]. Second-degree polynomial expressions are used to describe the oxide variations as a function of melt percent and pressure. Regression regions, coefficients for polynomial expressions, and uncertainties are given in Table 1. The solid lines are contours of pressure in GPa. Error bars

show the mean average deviation between the polynomial expressions and experimental data. The SiO_2 content in the melt from experiment number 30.10 (3 GPa, 1580°C) in WALTER (1998) is believed to have been in error. A redetermination of the SiO_2 content gave 48.0%, and this value is used here.

pyrolitic mantle (hereafter, fertile upper mantle with about 45% SiO₂, 4% Al₂O₃, 8% FeO and 38% MgO, all in weight %, is referred to as pyrolite).

Polybaric near fractional melting model

Strictly speaking, one cannot use isobaric batch melting experiments on any single nine-component fertile peridotite composition to precisely model polybaric near-fractional melting because, during such a melting process, the bulk composition becomes progressively depleted throughout the melting interval and phase relations of fertile peridotite no longer apply. However, experimental isobaric batch melts can be used if the compositions of melts as a function of pressure and total degree of melt extraction are relatively insensitive to bulk composition. This assumption is implicit in the polybaric near-fractional melting models presented here. Such models have been developed previously to model polybaric near-fractional melting of spinel lherzolite (KLEIN and LANGMUIR, 1987; MCKENZIE and BICKLE, 1988; NIU and BATIZA, 1991; LANGMUIR *et al.*, 1992). More sophisticated and accurate models for melting of spinel lherzolite are now available (*e.g.*, KINZLER and GROVE, 1992, 1993; WALTER and PRESNALL, 1994; KINZLER, 1997), but comparisons among these models show that the earlier models were successful in describing the relative differences between polybaric near-fractional melting and isobaric batch melting.

Here, polybaric near-fractional melting is modeled as depicted in Fig. 2. As a simplified approach to fractional melting, it is assumed that in an upwelling "column" of mantle material, 1% melt is extracted for each 0.1 GPa of decompression above the initial pressure at which the lherzolite solidus is intersected. A melt productivity value of 1% melt per 0.1 GPa has been shown to be generally applicable for melting of spinel lherzolite (AHERN and TURCOTTE, 1979; MCKENZIE and BICKLE, 1988; YANG *et al.*, 1998), although in detail a constant degree of melt productivity with pressure is unlikely (ASIMOW *et al.*, 1997).

An example of the melting model is as follows: if the solidus is intersected at 5.1 GPa, then 1% melt is extracted at 5 GPa, another 1% at 4.9 GPa, and so forth. The *melt compositions* for these increments are determined at each pressure from the fertile starting composition; for example, a 1% batch melt composition at 5 GPa, a 2% batch melt at 4.9 GPa, and so forth. The aggregate melt composition is the sum of all melts from the column. As mentioned above, a shortcoming of this approach is the assumption that incremental depletion of the bulk composition does not effect the melt composition of subsequent melt

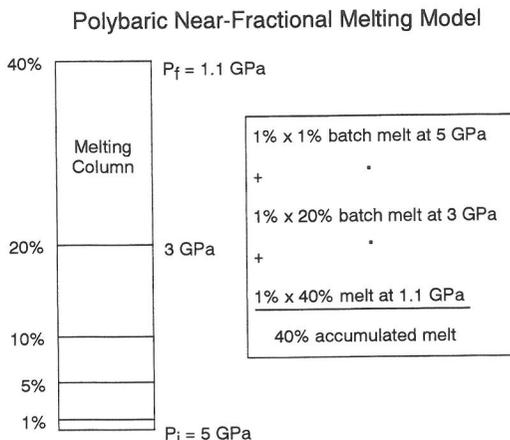


FIG. 2. Schematic illustration of the approach used to model polybaric near-fractional melting of fertile peridotite using the expressions from Table 1. The assumptions of the model are: 1) decompression melting in an upwelling column of mantle, 2) one percent melt extracted for each 0.1 GPa of decompression, and 3) the extracted melt composition at each pressure is the same as a batch melt at that pressure for the total aggregate degree of melting. The composition of the aggregate melt from the melting column is the sum of all the incremental melt extractions. For any element, *c*, the aggregate melt composition, *C_t*, is given by:

$$C_t = \sum_{j=0}^{(P_i - P_f)} c_{P_i - j}^{j+1} / (P_i - P_f) + 1$$

where *P_i* is the initial pressure of melt extraction and *P_f* is the final pressure of melt extraction (where *P* is in units of 0.1 GPa).

increments. In detail this cannot be the case for melting in a system with multiple solid-solutions, but the magnitude of this effect may not be severe, as in the case for melting of spinel lherzolite, and the general differences between polybaric near-fractional melting and isobaric batch melting can be revealed in these models.

Table 2 gives melt and residue compositions for polybaric near-fractional melting of fertile mantle. Five different models are listed comprising melting between 1 and 7 GPa, with variable initial and final pressures of melting varying within this pressure range. There are two competing factors governing melt composition in a melting zone (assuming a constant initial source composition): extent of melting and pressure of melting (see Fig. 1). For a given degree of batch melting, an increase in pressure leads to a decrease in SiO₂ and Al₂O₃, and an increase in FeO and MgO. Whereas, at a given pressure, increased melting leads to an increase in MgO, an increase in FeO at low pressures (< ~2 GPa) but a decrease at high pressures, and a more complex be-

Table 2. Melt and residue compositions (weight %) in polybaric near-fractional melting models

P Range ¹	7 - 1.1		5 - 1.1		3 - 1.1		7 - 3.1		7 - 5.1	
Ave P ²	4		3		2		5		6	
Melt % ³	60		40		20		40		20	
	Melt	Residue								
SiO ₂	46.8	43.7	47.2	44.0	48.3	44.2	46.0	44.5	45.0	45.0
Al ₂ O ₃	9.0	0.6	11.8	0.6	15.6	1.7	8.2	2.4	6.5	3.8
FeO	10.3	5.9	9.8	7.1	8.5	7.9	11.2	6.3	12.6	7.0
MgO	22.1	50.0	17.9	46.9	13.2	42.7	21.9	45.0	22.4	40.7
Mg# ⁴	79.3	93.8	76.5	92.2	73.5	90.6	77.7	92.7	76.0	91.2

¹ pressure range in GPa; ² average pressure; ³ aggregate melt percent; ⁴ Mg# = (Mg/Mg+Fe) in moles, all Fe is Fe²⁺

havior for SiO₂ and Al₂O₃. At lower pressures both oxides decrease with increased melting, whereas at higher pressures both oxides go through maximums which depend on the stability of orthopyroxene and garnet (see WALTER, 1998).

Figure 3 shows oxide variation diagrams for isobaric batch and polybaric near-fractional melt extraction. Generally speaking, the magmaphile behavior of FeO, SiO₂ and Al₂O₃ causes these oxides to decrease in residues with increase in degree of melt extraction. Exceptions to this magmaphile behavior are that SiO₂ is nominally compatible in residues at low degrees of melting (*e.g.*, <5–10%) at pressures greater than about 3 GPa, FeO is compatible in residues at pressures less than about 2 GPa, and Al₂O₃ becomes compatible in residues at low degrees of melting around 7 GPa. This compatible tendency for Al₂O₃ is expected to increase with pressure as garnet increases in proportion in the residue (WALTER, 1998). MgO is compatible in residues at all conditions and so increases with melt extraction. Because MgO is more compatible at lower pressures than at high pressures, it increases in residues at a higher rate at low pressures.

A method for deducing differences between batch and polybaric near-fractional melting residues is to compare the residue from a polybaric near-fractional melting zone with an isobaric batch residue produced by the same total degree of melt extraction and at the average pressure of melting in the zone. For example, the total melt extracted and average pressure of melting for the melting zone extending from 5 to 1.1 GPa are 40% and 3 GPa, respectively. The isobaric batch residue corresponding to these conditions is shown on Fig. 3 as an open circle. The Residue of polybaric near-fractional melt extraction has higher SiO₂ and Al₂O₃, but lower FeO and MgO than the 'equivalent' batch melt extraction residue. This is as expected considering the effect of pressure on these oxides in partial melts (Fig. 1).

In the next section these melt extraction 'grids',

which distinguish clearly between the combined effects of pressure and degree of melt extraction on the compositions of residues, are used to help deduce the role of melt extraction in the origin of cratonic peridotite.

CRATONIC PERIDOTITE DATA

Coarse-grained low-temperature cratonic peridotite xenoliths, hereafter referred to as cratonic peridotites, have been collected from many Archean cratons, but the most complete data sets are from the Kaapvaal Craton in southern Africa, Udachnaya in the Siberian Craton, and from the Tanzanian Craton. The reader is referred to the many papers describing these xenoliths for detailed information (*e.g.*, COX *et al.*, 1973; BOYD and NIXON, 1978; CARSWELL *et al.*, 1979; DANCHIN, 1979; BOYD, 1984; BOYD and MERTZMAN, 1987; BOYD *et al.*, 1997; LEE and RUDNICK, 1999). Here, I use the bulk low-temperature peridotite compositions as referred to in BOYD and MERTZMAN (1987) for southern African peridotites, the data of BOYD *et al.* (1997) for Siberian peridotites, and the data of LEE and RUDNICK (1999) for Tanzanian peridotites.

Cratonic peridotites are uniquely characterized by high Mg#, typically 92 to 94, and a wide range in modal proportions of olivine:opx. For example, opx typically ranges from 20 to 50% in the mode, and the olivine content of some xenoliths is lower than in fertile peridotites even though they are highly depleted in magmatic components such as CaO and Al₂O₃. Experimental data have been used previously to show that many of the opx-rich xenoliths apparently are too silica-rich to have been the residues of partial melting of nominally anhydrous model fertile upper mantle compositions such as pyrolite (*e.g.*, KELEMEN *et al.*, 1992; CANIL, 1992; HERZBERG, 1993; BOYD *et al.*, 1997; WALTER, 1998). The crux of the issue, as will be discussed below, is that nearly all experimental melts of pyrolite in the range of 1 atm.

to >7 GPa, have SiO_2 contents greater than the bulk composition, thereby driving the residues to lower SiO_2 contents.¹

An ongoing and lively debate has emerged concerning the origin of the orthopyroxene-rich (*i.e.*, silica-rich) nature of many cratonic peridotite xenoliths (*e.g.*, BOYD and MERTZMAN, 1987; BOYD *et al.*, 1997; CANIL, 1991, 1992; COX *et al.*, 1987; GRIFFIN *et al.*, 1998; HERZBERG, 1993, this volume; KELEMEN *et al.*, 1992, 1998; KESSON and RINGWOOD, 1989; RUDNICK *et al.*, 1994; WALTER, 1998). Two general models are presently the most competitive and will be treated here. They are: (1) *Melt extraction—metamorphic unmixing*: In this model, cratonic lithosphere is formed by melt extraction from a fertile source peridotite. Subsequently, metamorphic differentiation unmixes the residue, resulting in opx and olivine-enriched segregations (*e.g.*, BOYD and MERTZMAN, 1987; BOYD *et al.*, 1997). (2) *Melt extraction—orthopyroxene addition*: In this model cratonic lithosphere is formed by high-degree melt extraction from a fertile source peridotite leaving a harzburgitic to dunitic residue. Subsequent to or concurrent with melt extraction, SiO_2 is added to the lithosphere by orthopyroxene (opx) crystallization. Here, I will consider two separate SiO_2 addition models, cumulate mixing and melt-mantle reaction. In the cumulate mixing model, olivine and opx cumulates crystallize during or subsequent to the primary melting event(s) from high degree melts at high-pressures. The cumulates are enriched in opx so the net result is enrichment of residues in silica and a wide range in olivine:opx (see HERZBERG, 1993 and this volume). In the melt-mantle reaction model, depleted lithosphere is formed by melt extraction from a fertile source peridotite. Subsequently, Si-enriched melts, derived perhaps from low-degree melting of slab

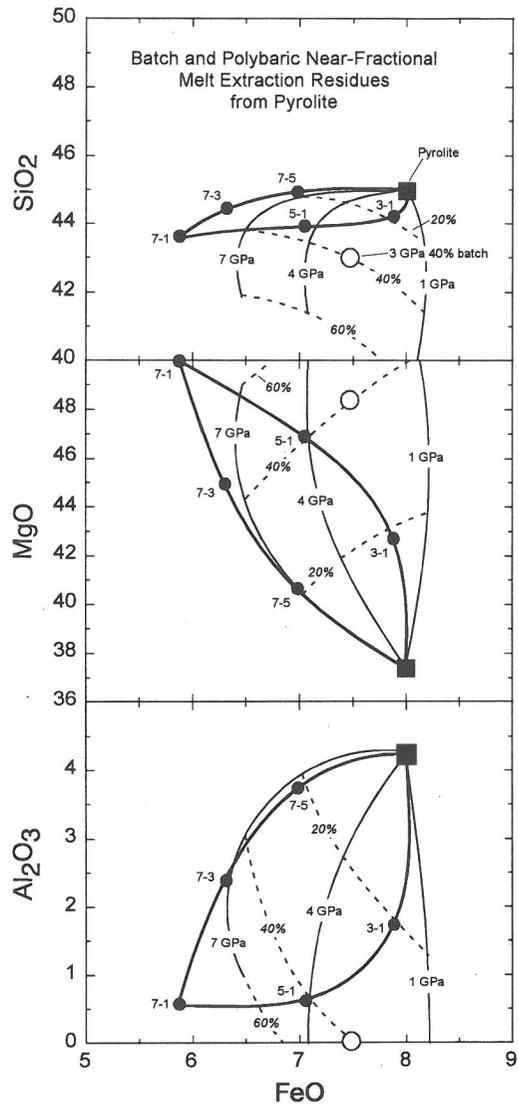


FIG. 3. Oxide variation diagrams (weight %) for residues of model batch and polybaric near-fractional melt extraction. Thin solid lines are isobaric batch melt extraction contours and dashed lines give percent batch melt extraction. The filled circles connected by thick solid contours are residues of polybaric near-fractional melt extraction and are labeled according to the pressure range of melt extraction (see Table 2). The large open circles show the composition of a residue of 40% batch melt extraction at 3 GPa, conditions which are equivalent to the total degree and average pressure of melt extraction in a polybaric-near fractional melting column extending from 5 to 1.1 GPa.

¹ It should be noted that the effects of H_2O on partial melt compositions from peridotite at high pressures are not well known. Recent data from GAETTANI and GROVE (1998) show that, at least up to 2 GPa, hydrous melts from peridotite are poorer in SiO_2 than are anhydrous melts, although on an anhydrous basis they are actually richer in SiO_2 . OHTANI *et al.* (1996) have produced experimental melts from pyrolite at 6.5 GPa with about 4 to 5% H_2O . These melts have SiO_2 contents that are higher than the bulk composition (44.7% SiO_2) and which are undistinguishable from melts of nominally anhydrous pyrolite at similar pressures (WALTER, 1998). KAWAMOTO and HOLLOWAY (1997) have shown that H_2O -saturated melts from peridotite can have very low SiO_2 contents (~33 to 44 wt.%) at high pressures (5–11 GPa), but such melts have very large amounts of H_2O (~40–60%). For an estimate of mantle H_2O content of 100–1000 ppm, such melts could only form at extremely small degrees of melting, and so are not considered important to the generation of highly depleted lithosphere.

materials in Archean subduction zones, percolate through and react with the surrounding peridotite, crystallizing opx as they cool and enriching the lithosphere in SiO_2 (KELEMEN *et al.*, 1992; KELEMEN *et al.*, 1998).

Southern Africa

Figure 4 shows xenolith data from southern Africa plotted relative to melt extraction trends. About 80% of the xenoliths have higher SiO_2 contents than model residues, and they cannot be reconciled with melt extraction from pyrolite. Even the average SiO_2 content would require a source significantly enriched in SiO_2 relative to pyrolite (HERZBERG, 1993; WALTER, 1998). Further, the generally negative

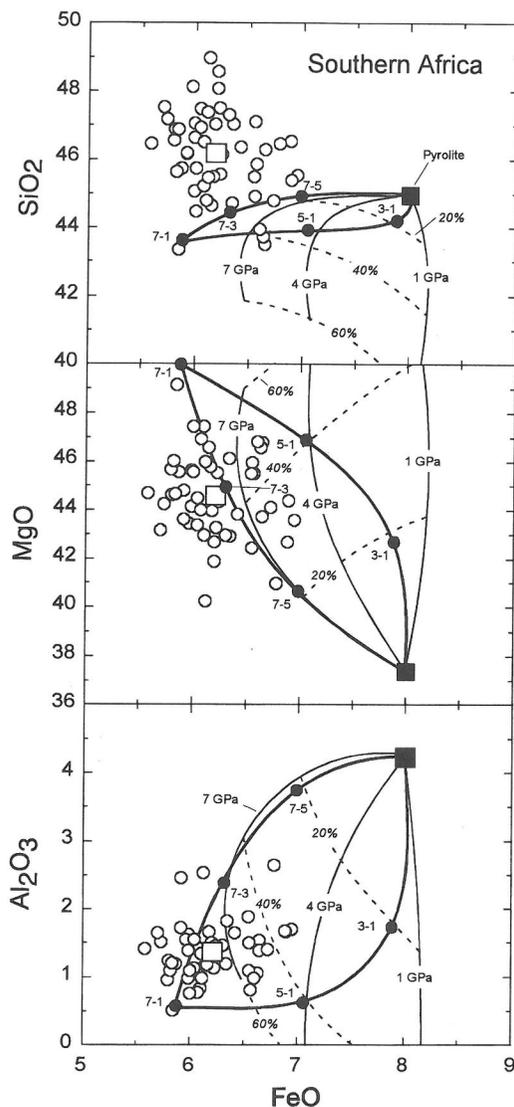


FIG. 4. Oxide variation diagrams (weight %) showing low-temperature cratonic peridotite xenolith data from the southern Africa Kaapvaal craton relative to the melt extraction trends from Fig. 3. Data are as referred to in BOYD and MERTZMAN (1987). The large open square shows the average xenolith composition.

correlation between SiO_2 and FeO is not easily reconciled with melt extraction. Indeed, for the most SiO_2 -enriched portion of the data to be produced by melt extraction it seems that a source with considerably more SiO_2 than pyrolite would be necessary, a source with perhaps as much as 48% SiO_2 or more. Thus, no melt extraction scenario seems adequate to account for the observed SiO_2 content of the xenoliths.

If the FeO, MgO and Al_2O_3 contents are primary, then they indicate very high degrees and pressures of melt extraction (WALTER, 1998). For example, the average composition indicates about 45% isobaric melt extraction at >7 GPa, or about 40% polybaric fractional melt extraction at an average pressure of 5 GPa.

The high SiO_2 contents of the xenoliths makes melt extraction alone an improbable cause for the observed data, and whatever mechanism enriched the lithosphere in SiO_2 may have changed other oxides as well. Assuming that the observed SiO_2 -enrichment is a consequence of opx addition, this would have caused an increase in SiO_2 and Al_2O_3 and a decrease in MgO and FeO. In this case, the very high pressures of melt extraction indicated by the data would in part be an artifact of opx enrichment. This will be discussed in detail below.

Siberia

Figure 5 shows xenolith data from Siberia plotted relative to melt extraction trends. About 30% of the xenoliths have SiO_2 -contents that are too high to be generated by melt extraction from pyrolite. However, the average SiO_2 -content can be achieved by about 40% melt extraction from pyrolite, either at about 7 GPa for batch extraction or at an average pressure of 3 to 4 GPa for polybaric near-fractional extraction. There is a distinct negative correlation between SiO_2 and FeO, a feature pointed out by BOYD *et al.* (1997) who noted that such a trend is contrary to upper mantle melting trends. Indeed, Figure 4 shows that the only way this trend can be reconciled with a melt extraction mechanism is for a series of residues to be generated by essentially a constant degree of melting but over a very wide range of pressures, a process that is difficult to conceive of given the thermodynamics of melting (*i.e.*, the effect of the different dP/dT slopes between the mantle solidus and adiabat).

The FeO, MgO and Al_2O_3 contents of Siberian xenoliths indicate a significant amount of melt extraction at high pressure; about 45% batch melt extraction at 6 GPa (WALTER, 1998) or polybaric melt extraction at an average pressure of about 4 GPa. As

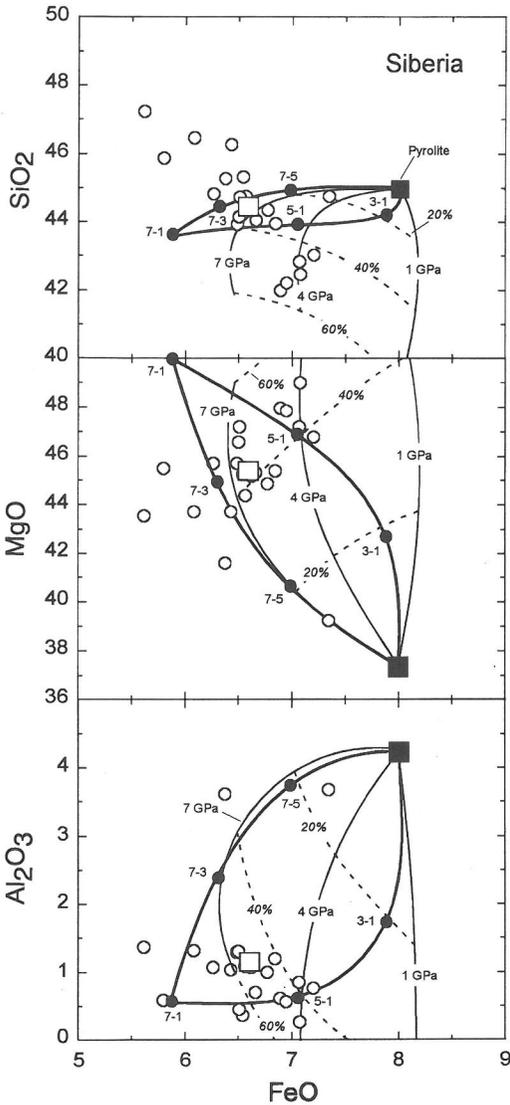


FIG. 5. Oxide variation diagrams (weight %) showing low-temperature cratonic peridotite xenolith data from the Siberian craton relative to the melt extraction trends from Fig. 3. Data are from BOYD *et al.* (1997). The large open square shows the average xenolith composition.

in the southern African case, the high SiO₂ contents indicate a secondary enrichment process which may have perturbed these oxide systematics so these estimates should be taken with caution.

Tanzania

Figure 6 shows xenolith data from Tanzania plotted relative to melt extraction trends. Most of the Tanzanian data have oxide contents which can be

reconciled with melt extraction. The xenoliths have a wide range in SiO₂ and FeO contents, but show no apparent trend. Nearly all the data fall below the polybaric near-fractional melting residues of pyrolite, but are generally consistent with isobaric melt extraction in the range of about 1 to 7 GPa and 20 to 60% melt extraction. The average SiO₂ content is lower than both southern African and Siberian lithosphere, and is consistent with about 45% batch melt extraction at 3 to 4 GPa, and lies close to a polybaric

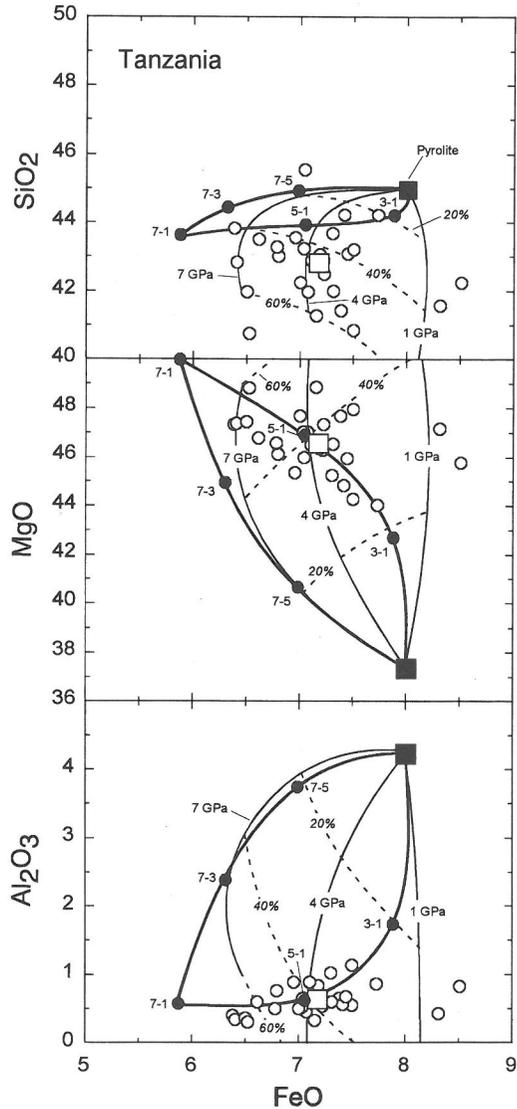


FIG. 6. Oxide variation diagrams (weight %) showing low-temperature cratonic peridotite xenolith data from the Tanzanian craton relative to the melt extraction trends from Fig. 3. Data are from LEE and RUDNICK (1999). The large square shows the average.

near-fractional residue indicating 40% melt extraction at an average pressure of 3 GPa.

In contrast to the southern African or Siberian peridotites, the Tanzanian peridotites show an overall positive correlation between MgO and FeO, a feature that is consistent with melt extraction. The average FeO content is considerably higher than in the other two cratons, indicating lower average pressures of melt extraction. In combination, the average MgO, FeO and Al_2O_3 contents indicate about 40–45% melt extraction, either batch extraction at 3 to 4 GPa, or polybaric extraction at an average pressure of about 3 GPa.

Comparison with depleted lithosphere from other locations

Figure 7 shows the average compositions of both low and high temperature peridotites from the three Archean cratons discussed above, as well as examples of depleted lithosphere from other localities including: 'off-craton' sub-continental lithosphere from the Thumb, SW U.S.A. (EHRENBERG, 1982) and W. Kettle River, British Columbia (XUE *et al.*, 1990), possible Archean lithosphere from East Greenland (BERNSTEIN *et al.*, 1998), highly depleted ophiolitic lithosphere from Papua New Guinea (JAQUES and CHAPPELL, 1980) and abyssal peridotite from four locations along the SW Indian Ocean (*i.e.*, MORB residues; DICK, 1989).

The abyssal peridotite data lie along a low-pressure melt extraction trajectory for all oxides, and are generally explained by about 15 to 25% melt extraction from pyrolytic mantle at average pressures of about 1 GPa; this low pressure melt extraction trend is often referred to as the 'oceanic trend' (see BOYD, 1989). 'Off-craton' sub-continental lithosphere and high-temperature peridotites from Archean cratons also have compositions indicating relatively low pressure melt extraction, typically 10–30% melt extraction in the range of 1 to 2 GPa (BOYD, 1999; WALTER, 1998). Note especially that even though the most depleted of these average peridotites have MgO contents similar to low-temperature cratonic peridotites, the FeO contents of the residues are significantly higher (*i.e.*, lower Mg#s), a direct consequence of melt extraction at low pressures.

The average compositions of low-temperature xenoliths from the three Archean cratons, as well as from Greenland and Papua New Guinea, indicate overall higher-degrees and higher-pressures of melt extraction. The average compositions from Tanzania, Greenland and Papua New Guinea can generally be interpreted as following along a melt extraction tra-

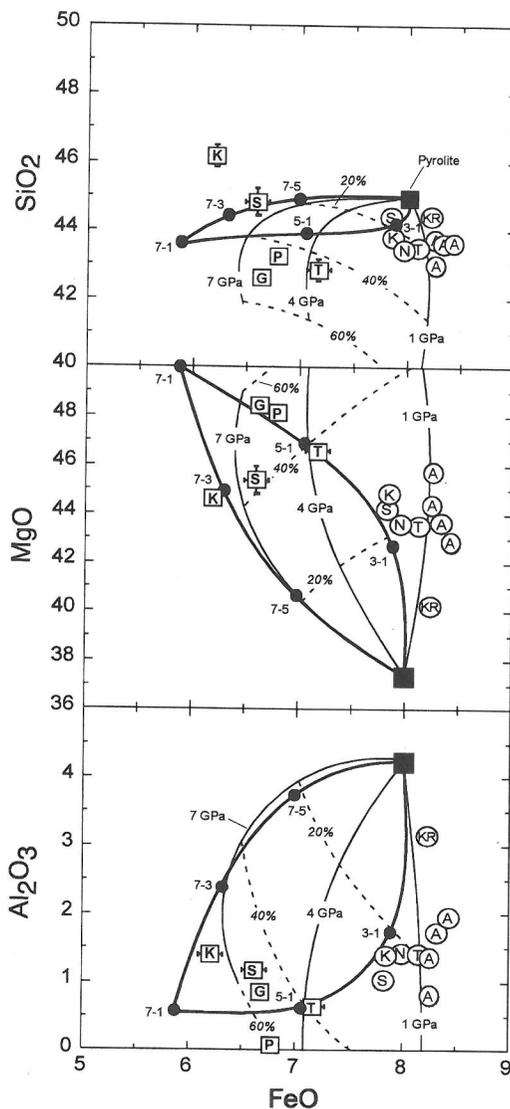


FIG. 7. Oxide versus MgO (weight %) variation diagrams showing average lithosphere compositions relative to the melt extraction trends from Fig. 3. Open squares show low-temperature cratonic peridotites from the Kaapvaal (K), Siberian (S) and Tanzanian (T) cratons (error bars showing one standard error of the mean), as well as depleted lithosphere compositions from Papua New Guinea (P) (JAQUES and CHAPPELL, 1980) and East Greenland (G) (BERNSTEIN *et al.* (1998). Open circles show high-temperature cratonic peridotite compositions from Kaapvaal (K), Siberia (S) and Tanzania (T), average coarse-grained xenolith composition from the Thumb, Navajo Volcanic Field, U.S.A. (N) (EHRENBERG, 1982), average composition of xenoliths from W. Kettle River, British Columbia (KR) (XUE *et al.*, 1990), and average abyssal peridotite compositions from four regions along the SW Indian Ridge (A) (DICK, 1989).

jectory comprising about 35 to 60% batch melt extraction at 3.5 to 6 GPa, or 40 to 50% polybaric near-fractional melt extraction at average pressures of about 3 to 4 GPa (although the average SiO_2 contents from all these locations lie below the polybaric near-fractional melt extraction trends of the models presented here). BERNSTEIN *et al.* (1998) came to a similar conclusion for the Greenland data, predicting about 40% melt extraction at an average pressure of 3 GPa.

In terms of their SiO_2 and FeO contents, the average compositions from southern Africa, and to a lesser extent, Siberia, provide a contrast to the general high-pressure melt extraction trajectory exhibited by data from the other locations. One could postulate that a compositional vector cutting across this 'typical' high-pressure melt extraction trajectory extends from about the location of the average Tanzanian composition through the Siberian and Kaapvaal average compositions. This hypothesis is supported by Figs. 4 and 5 which show that the xenolith SiO_2 vs. FeO trends from both these locations require an alternative explanation to melt extraction. As mentioned previously, secondary addition of opx is one mechanism which could possibly produce the correct compositional vector, and below this possibility is explored in more detail.

ORIGIN OF ORTHOPYROXENE ENRICHMENT IN MELTING RESIDUES

There are two commonly invoked mechanisms to produce variable olivine:opx ratios and opx-enrichment in xenoliths: metamorphic unmixing and opx crystallization. Experimental olivine and orthopyroxene compositions that coexist with mafic-ultramafic melts at 3 and 7 GPa are shown on Fig. 8 (WALTER, 1998). These compositions are considered as candidates for the types of opx and olivine compositions which might be residual from melt extraction at high-temperatures and pressures (unmixing), might crystallize from high-pressure high-degree melts (during early stages of crystal cumulation), or that might crystallize during melt-mantle reaction. Also shown are fields occupied by xenolith data from the three cratons. It can be seen from this diagram that the negative trend of SiO_2 versus FeO observed in the data from Siberia, and to a lesser extent in the data from southern Africa, is consistent with mixing or unmixing of olivine and/or opx, whereas it cannot easily be explained by melt extraction (BOYD *et al.*, 1997). The generally negative correlation between MgO and FeO in the data from Siberia, and the overall high MgO and Al_2O_3 and low FeO exhibited in both southern African and Siberian data, are con-

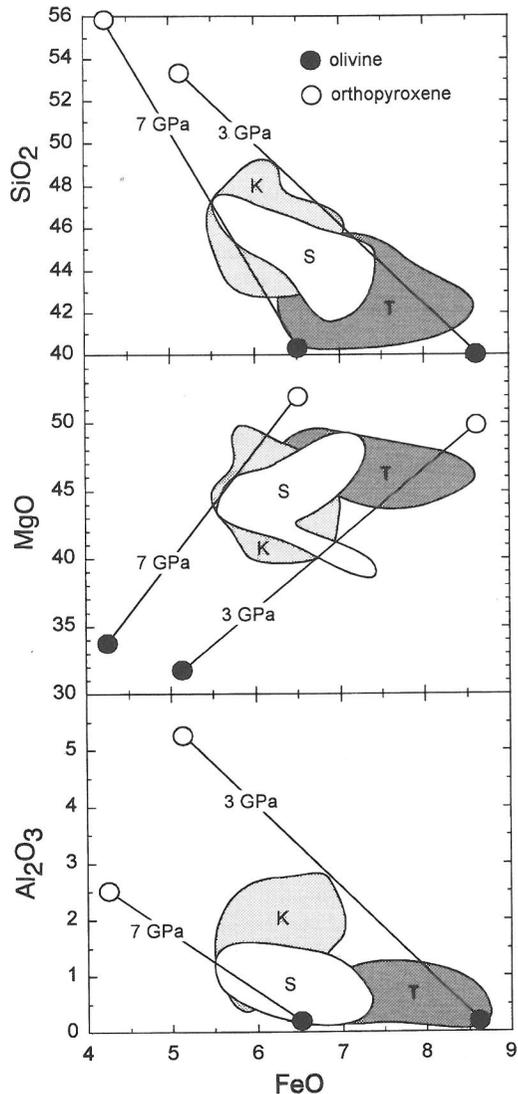


FIG. 8. Oxide variation diagrams (weight %) showing the fields occupied by low-temperature cratonic peridotites from the southern African Kaapvaal (K), Siberian (S) and Tanzanian (T) cratons. Also shown are experimental olivine and orthopyroxene compositions in equilibrium with mafic-ultramafic melts at 3 and 7 GPa (WALTER, 1998). Two anomalous data points with Al_2O_3 of $\sim 3.7\%$ were omitted from the field of Siberian data for clarity.

sistent with an opx-enrichment mechanism. In contrast, the Tanzanian data do not indicate a significant role for opx addition.

The major oxide systematics shown on Fig. 8 cannot be used to discriminate clearly among the three presently most competitive models; melt extraction + unmixing, melt extraction + cumulate mixing, and melt extraction + mantle-melt reaction, because all these processes can effectively produce

the same results. Some general characteristics and consequences of each of the mixing/unmixing models are now briefly considered.

Melt extraction—metamorphic unmixing

This model has been considered extensively by BOYD *et al.* (1997), and can be formulated as follows. Depleted mantle is formed from melt extraction events which leave a harzburgitic residue. Subsequently, and when the residue is still hot, plastic flow of the mantle caused by regional tectonic stresses results in metamorphic differentiation and sorting of olivine and opx. Eventually, cooling and recrystallization makes the residual mantle material rigid and resistant to flow, and its FeO-depleted composition makes the material buoyant with respect to surrounding undepleted mantle; stable cratonic lithosphere is formed. Sampling of the lithosphere in the form of xenoliths exhumed in volcanic eruptions occurs at a scale that is smaller than the scale of metamorphic sorting, and a wide range in olivine:opx ratios are observed.

Within the context of this model, the average composition from each craton can be used to establish the average amount of melt extraction from the mantle, assuming a homogeneous initial source composition in each region and sufficient sampling. The error bars on the average compositions from each craton shown on Fig. 8 give one standard error about the mean, a measure of the robustness of the averages. There are clear distinctions between the SiO₂ and FeO contents among the three Archean cratons, and MgO may be distinct as well, especially between southern Africa and Tanzania. Melt extraction from a pyrolitic source can reproduce both the average Siberian and Tanzanian xenolith compositions, but cannot account for the average southern African SiO₂ content (see Figs. 4–6 and the discussion above). Thus, a key feature of the unmixing model is that the southern African mantle prior to melt extraction was enriched in SiO₂ relative to pyrolite, and relative to the source regions from other known depleted lithosphere. Further, in this model the low average FeO contents at southern Africa and Siberia would be a primary feature, requiring very high pressures of melt extraction (*e.g.*, 5 to >7 GPa) or low FeO source regions relative to pyrolite.

Melt extraction—opx addition

In the two models discussed below, the characteristic feature is that SiO₂ has been added to the lithosphere as a consequence of opx crystallization. The amount of opx added to any particular xenolith rel-

ative to its initial composition after melt extraction can be variable, or even zero. A first-order assumption is that the composition of a depleted residue after melt extraction but before addition of opx lies near the SiO₂ and Al₂O₃ poor, and MgO and FeO rich portions of the xenolith data. For the southern African and Siberian data, such a composition would have about 43% SiO₂, 7% FeO, 47% MgO and 0.5% Al₂O₃. This composition is similar to the average compositions from Tanzania, Papua New Guinea and Greenland as shown on Fig. 7, and can be generated by about 40% batch melt extraction at 4 GPa, or 40% polybaric near-fractional melt extraction at an average pressure of about 3 GPa. This estimate is generally consistent with recent estimates for the amount of melt extraction before opx-addition in the models of HERZBERG (this volume) and KELEMEN *et al.* (1998). At these conditions, the residues would be primarily harzburgite, a feature that is consistent with the observation of KELEMEN *et al.* (1998) that the combined CaO-Yb systematics of nearly all depleted lithospheric xenoliths are inconsistent with significant amounts of garnet remaining in the residue.

Cumulate mixing. HERZBERG (1993, this volume) has promoted the cumulate hypothesis for opx-addition. An appealing aspect of this model is that phase equilibrium data show that opx would be enriched in the near-liquidus assemblage of high-pressure, high degree ultramafic melts (WALTER, 1998; HERZBERG and ZHANG, 1998). Because high pressure melts are dense (AGEE and WALKER, 1993) melt extraction might be impeded, permitting cooling, crystallization and cumulate addition of material with high opx:olivine ratios to the previously depleted lithosphere. This would cause residue compositions to move along compositional vectors approximated by the mixing lines on Fig. 8.

One consequence of this model is that during fractional crystallization, the derivative liquid and crystallizing minerals would change composition, with both the Mg# and SiO₂ content of the melt decreasing as crystallization proceeds. However, the relatively constant and high Mg#s of cratonic peridotite (about 92–94) do not permit crystallization of large amounts of material from a single batch of continuously differentiating melt; small amounts of crystallization from a continuously replenished supply of primary melt are needed. Therefore, as noted by BOYD *et al.* (1997) and KELEMEN *et al.* (1998), a volume of liquid equal to or even greater than the volume of cratonic lithosphere would be needed, for example, to crystallize enough opx to enrich the entire southern African lithosphere in SiO₂.

Melt-mantle reaction. KELEMEN and HART (1996) and KELEMEN *et al.* (1998) have recently discovered a positive correlation between Ni in olivine and modal opx, both in a global xenolith data set and, most strikingly, in xenoliths from the Premier kimberlite, southern Africa. In their model, KELEMEN *et al.* (1998) suggest that siliceous partial melts, perhaps derived by melting of hot-slabs in Archean subduction zones, percolate through the depleted lithosphere. Reaction of these melts with the surrounding mantle results in dissolution of olivine and crystallization of opx, thereby decreasing modal olivine and increasing modal opx in the rock. Because olivine is the primary reservoir for Ni in the mantle, this process increases the Ni content in the remaining olivine coincident with an increase in modal opx. Their numerical modeling shows that this process can account for the slope of the observed positive correlation between Ni in olivine and modal opx. This model is also attractive because the hybrid melts are roughly tonalitic in composition, which may help to explain the tonalitic bulk composition of the continental crust.

However, the observed positive correlation between Ni in olivine and opx can also be a natural consequence of cooling high temperature mantle materials with variable olivine:opx ratios, such as might be produced by cumulate mixing or metamorphic unmixing. At high temperatures, Ni is enriched in opx relative to low temperatures (BEATTIE *et al.*, 1991). Thus, during cooling Ni will diffuse out of opx and into olivine, and more Ni will diffuse into olivine in high opx:olivine mixtures than in low opx:olivine mixtures, producing a positive correlation between Ni in olivine and modal opx. KELEMEN *et al.* (1998) have empirically derived a relation for the change in D_{ol}/D_{opx} (Ni) with temperature, and their models indicate that a geologically unreasonable cooling interval of 1800 to 10°C would be required to produce the slope of the observed trend. A more geologically reasonable, yet still extreme cooling interval of 1800–800°C is still not nearly sufficient to produce the observed slope. On this basis, they concluded that the melt-mantle reaction model can best reproduce the observed correlation between Ni in olivine and modal opx.

A GENERAL MODEL FOR THE ORIGIN OF CRATONIC LITHOSPHERE

A general model for the origin of highly depleted or cratonic lithosphere is illustrated on Fig. 9. First, depleted, harzburgitic lithosphere is produced by primary melt extraction from a pyrolitic mantle composition of, on average, about 40 to 50% melt at an

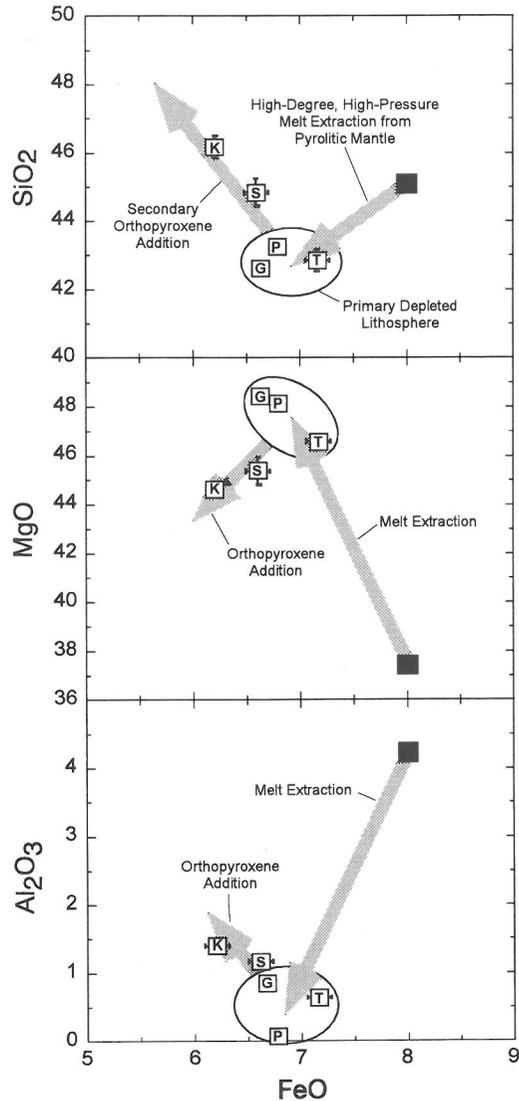


FIG. 9. Oxide variation diagrams (weight %) showing a general model for the origin of cratonic lithosphere. Symbols are as in Fig. 7. Primary melt extraction from pyrolitic mantle (solid square) of about 40 to 50% melt at an average pressure of 3 to 4 Gpa produces a residue with a composition that lies within a field exemplified by the average compositions from Tanzania, Greenland and Papua New Guinea. Subsequent addition of opx to the Siberian and southern African lithosphere has caused enrichment in SiO_2 and Al_2O_3 , and depletion in MgO and FeO.

average pressure of 3 to 4 GPa. The average compositions from the Tanzanian craton, Greenland, and Papua New Guinea closely approximate such a residue. In the case of the Siberian and southern African lithosphere, subsequent addition of opx has moved the average composition of the lithosphere along a compositional vector as shown on Fig. 9. This could

have occurred as a consequence of cumulate mixing, melt-mantle reaction, or both, but presently the arguments of KELEMEN *et al.* (1998) make melt-mantle reaction the most probable process.

This general model of primary melt extraction followed by opx-addition is preferred to a model of primary melt extraction followed by metamorphic unmixing because, (1) data from all cratons can be reconciled with melt extraction from an initially pyrolytic upper mantle, (2) an analogous record of primary melt extraction is evident in the data from Tanzania, Papua New Guinea and Greenland, and (3) high-temperature unmixing followed by cooling apparently cannot account for the slope of the observed correlation between Ni in olivine and modal opx in Premier xenoliths (KELEMEN *et al.*, 1998). It should be noted, however, that because the sampling size of many xenoliths may be small relative to the scale of any pre-existing opx and olivine segregations, some of the variation in ol:opx ratios in xenoliths from all localities may be due to sampling bias.

CONCLUSIONS

On the basis of the experimentally determined compositions of melt extraction residues from fertile, nominally anhydrous pyrolytic peridotite, the following statements can be made regarding the primary melt extraction event(s) that formed the depleted lithosphere of the southern African, Siberian and Tanzanian cratons:

(1) the SiO₂ contents of about 80% of the xenoliths from southern Africa cannot be generated directly by melt extraction, but require addition of SiO₂ by a secondary mechanism. If primary, the average xenolith FeO, MgO and Al₂O₃ contents are consistent with a considerable amount of melt extraction at high pressures, indicating about 45% isobaric melt extraction at >7 GPa, or about 40% polybaric near-fractional melt extraction at an average pressure of 4 to 5 GPa.

(2) the SiO₂ contents of about 30% of the xenoliths from Siberia cannot be generated directly by melt extraction and require addition of SiO₂ by a secondary mechanism. However, the average SiO₂-content can be achieved by about 40% melt extraction from pyrolite, either at about 7 GPa for batch extraction or at an average pressure of 3 to 4 GPa for polybaric near-fractional extraction. There is a distinct negative correlation between SiO₂ and FeO that cannot be easily reconciled with a melt extraction mechanism. If primary, the xenolith FeO, MgO and Al₂O₃ contents indicate about 45% batch melt extraction at 6 GPa or polybaric melt extraction at an average pressure of about 4 GPa.

(3) nearly all of the Tanzanian xenoliths have oxide contents which can be reconciled with melt extraction. The SiO₂ contents of most xenoliths lie below the trends for polybaric near-fractional melt extraction for pyrolite, but are generally consistent with isobaric melt extraction in the range of about 1 to 7 GPa and 20 to 60% melt extraction. The average SiO₂ content can be generated by about 45% batch melt extraction at 3 to 4 GPa, and lies close to a polybaric near-fractional residue indicating 40% melt extraction at an average pressure of 3 GPa. The xenoliths show an overall positive correlation between MgO and FeO, a feature that is consistent with melt extraction. The combined MgO, FeO and Al₂O₃ contents indicate about 40–45% melt extraction, either batch extraction at 3 to 4 GPa, or polybaric extraction at an average pressure of about 3 GPa.

(4) melt extraction residues from average oceanic, 'off-craton' subcontinental lithosphere, and high-temperature cratonic lithosphere typically indicate about 10 to 30% melt extraction at low pressures (1 to 2 GPa). In contrast, average low-temperature cratonic peridotites as well as average lithosphere from Greenland and Papua New Guinea indicate high-degrees of melt extraction (40 to 50%) at higher pressures (3 to >5 GPa).

(5) the oxide compositions of low-temperature xenolith data from all cratons, but especially southern Africa and Siberia, are generally explicable in terms of a combination of melt extraction followed by metamorphic unmixing of olivine and opx. Within the context of this model, average compositions from the three cratons record about 35–45% melt extraction, batch or polybaric near-fractional. The proto southern African lithosphere would have been significantly enriched in SiO₂ relative to pyrolite, a feature distinguishing it from other known depleted lithosphere. The low average FeO contents, especially from southern Africa and Siberia would reflect either high average pressures of melt extraction (~5 to >7 GPa), or low FeO in the source relative to pyrolite.

(6) the oxide compositions of xenolith data from the three cratons, but especially southern Africa and Siberia, are explicable in terms of a combination of high-degree melt extraction followed by addition of SiO₂ by opx crystallization, either in the form of opx-enriched cumulates or by reaction of the mantle with siliceous melts. A model that is generally consistent with the xenolith data is primary extraction of about 40 to 50% melt from a pyrolytic source at average pressures of about 3 to 4 GPa. Within the context of this model, Tanzanian lithosphere has little or no opx addition, whereas Siberian lithosphere, and especially southern African lithosphere experienced moderate to substantial amounts of opx enrichment.

The recent work of KELEMEN *et al.* (1998) indicates that the observed positive correlation between Ni in olivine and modal opx in global peridotite data sets and in data from Premier, southern Africa, may be best explained in terms of mantle-melt reaction.

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