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Cratonic mantle roots, remnants of a more chondritic Archean mantle?

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Abstract

The Earth's continents are cored by Archean cratons underlain by seismically fast mantle roots descending to depths of 200^+ km that appear to be both more refractory and colder than the surrounding asthenospheric mantle. Low-temperature mantle xenoliths from kimberlite pipes indicate that the shallow parts of these cratonic mantle roots are dominated by refractory harzburgites that are very old (3^+ Ga). A fundamental mass balance problem arises, however, when attempts are made to relate Archean high-Mg lavas to a refractory restite equivalent to the refractory lithospheric mantle roots beneath Archean cratons. The majority of high-Mg Archean magmas are too low in Al and high in Si to leave behind a refractory residue with the composition of the harzburgite xenoliths that constitute the Archean mantle roots beneath continental cratons, if a Pyrolitic primitive mantle source is assumed. The problem is particularly acute for 3^+ Ga Al-depleted komatiites and the Si-rich harzburgites of the Kaapvaal and Slave cratons, but remains for cratonic harzburgites that are not anomalously rich in orthopyroxene and many Al-undepleted komatiites. This problem would disappear if fertile Archean mantle was richer in Fe and Si, more similar in composition to chondritic meteorites than the present Pyrolitic upper mantle of the Earth. Accepting the possibility that the Earth's convecting upper mantle has become poorer in Fe and Si over geologic time not only provides a simpler way of relating Archean high-Mg lavas to the lithospheric mantle roots that underlie Archean cratons, but could lead to new models for the nature Archean magmatism and the lower mantle sources of modern hot-spot volcanism.

Keywords: Archean; Craton; Lithosphere; Mantle; Root; Chondrite

1. Introduction

Jordan (1988) was the first to recognize that the Earth's continents are cored by Archean cratons underlain by seismically fast mantle roots descending to depths of 200^+ km that are both colder than the surrounding asthenospheric mantle and very old. He proposed that their long-term stability might reflect their relatively refractory chemical composition, which renders them buoyant with respect to the asthenospheric mantle. Comparisons of mantle xenolith suites in kimberlites from Archean cratonic terranes with mantle xenoliths from off-craton alkaline basalts in Proterozoic or younger terranes have confirmed that cratonic mantle roots have higher Mg numbers [Mg/(Mg + Fe)] and are low in Al, which controls the abundance of garnet, the densest major phase in the lithospheric mantle (Boyd, 1989). The refractory nature of the lithospheric mantle roots beneath Archean cratons, however, raises new problems in terms of their relationship to komatiitic magmas and the nature of the

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Earth's fertile mantle in the Archean. This paper uses a comparison of the compositional differences between the Proterozoic lithospheric mantle beneath the Canadian Cordillera and the adjacent Archean mantle roots beneath the Slave and Churchill Provinces of the North American craton, as well as other Archean cratons on one hand and the compositional arrays of Archean and Tertiary high-Mg lavas on the other, to argue that a serious mass balance problem exists in the Earth whose resolution may be hindered by current Pyrolitic models for the Earth's primitive mantle. High-Mg Archean magmas, such as komatiites and ferropicrites, are too low in Al and high in Si to leave behind a refractory residue with the composition of the harzburgite xenoliths that constitute the mantle roots beneath Archean cratons, if a Pyrolitic primitive mantle source is assumed. This paper demonstrates that the problem would be resolved if early Archean fertile mantle had a composition closer to that of chondritic meteorites, as opposed to the Pyrolitic composition of the present upper mantle. This would require that the chemical composition of the Earth's upper mantle has changed since the Hadean. Forsaking conventional geodynamic wisdom that the composition of the Earth's mantle has been in a steady state since the Hadean, and accepting the possibility that the Earth's convecting upper mantle has become poorer in Fe and Si since then, not only provides a simple way of relating Archean high-Mg lavas to Archean cratonic mantle roots, but would have important implications for mantle processes both in the Archean and today.

2. Data

2.1. Cordilleran versus cratonic mantle xenoliths

Mantle xenoliths from 16 recent off-craton alkaline volcanic suites along the Canadian Cordillera (Fig. 1) range from depleted harzburgites, similar to those along mid-ocean ridges, to fertile lherzolites (Figs. 2 and 3) that approach the estimated composition of

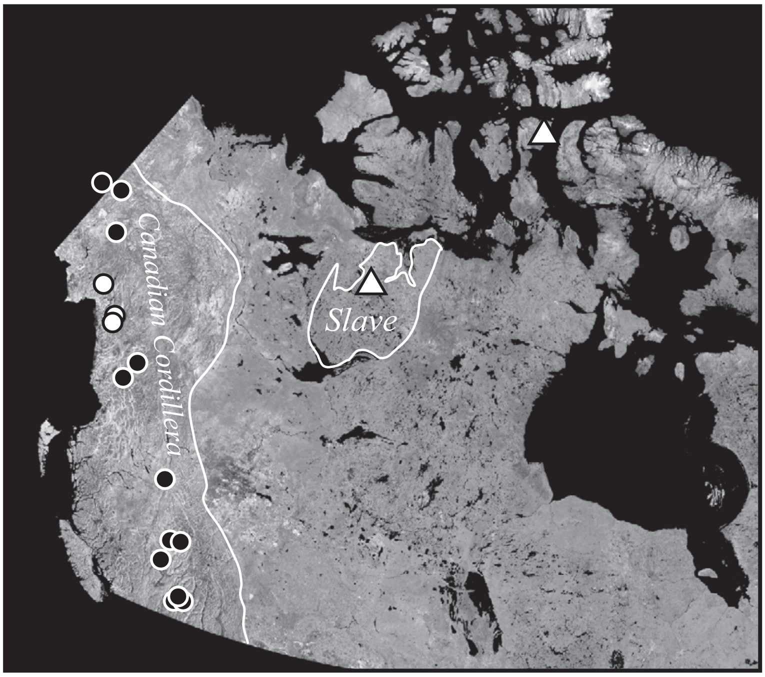

Fig. 1. Radar mosaic map of northwestern Canada showing the locations of mantle xenolith localities hosted by recent alkaline basalts along the Canadian Cordillera, the Jericho kimberlite pipe in the Slave Province, and the Nikos kimberlite pipe of Somerset Island. Symbols: bimodal Cordilleran xenolith suites—white circles, unimodal Cordilleran xenolith suites—black circles, Jericho pipe and Nikos pipes—white triangles.

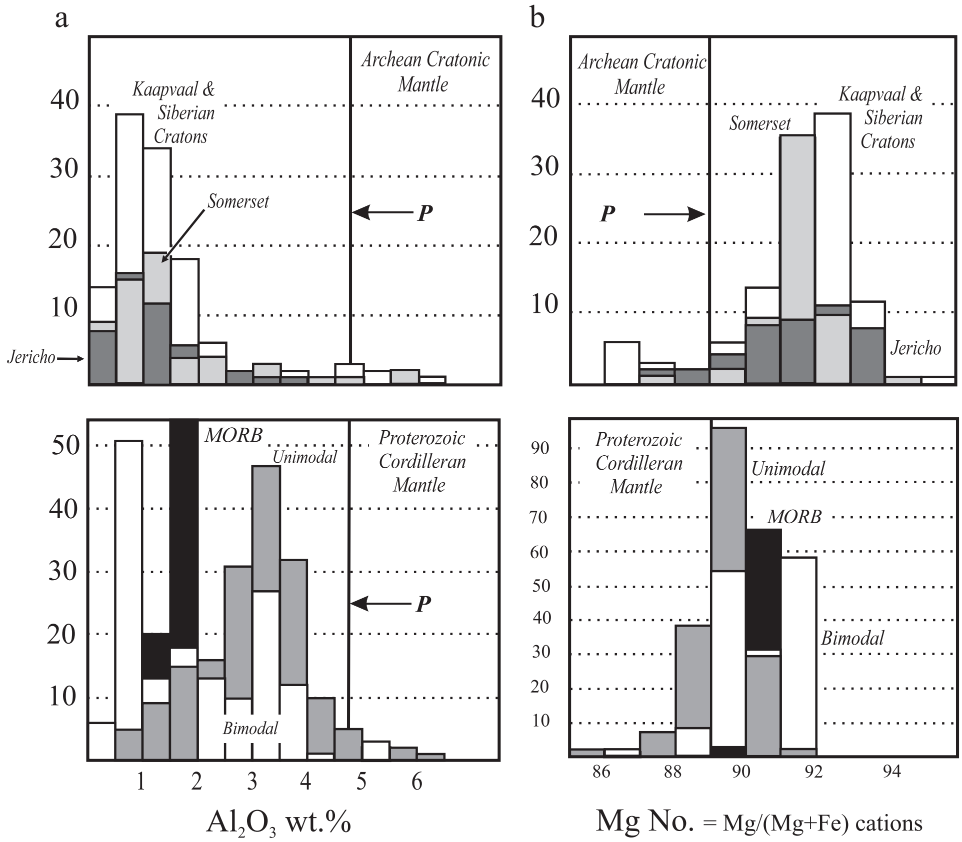

Fig. 2. Histograms of (a) Al_2O_3 content and (b) whole-rock Mg number (Mg/Mg + Fe) of kimberlite-hosted cratonic mantle xenolith suites from the Canadian shield, and other cratons, Proterozoic Canadian Cordilleran mantle xenolith suites hosted in recent alkaline basalts, and MORB peridotites dredged from the MARK region of the mid-Atlantic Ridge. Fields: MARK region peridotites—black, Kaapvaal and Siberian craton xenolith suites—white, Somerset Island xenolith suite—light gray, Jericho xenolith suite—dark gray, Cordilleran bimodal xenolith suites—white, Cordilleran unimodal xenolith suites—gray, Primitive mantle—*P* (data sources: Boyd, 1987; Boyd et al., 1997; Carswell et al., 1979; Casey, 1997; Chesley et al., 1999; Cox et al., 1987; Danchin, 1979; Francis, 1987; Kopylova and Russell, 2000; Lee and Rudnick, 1999; Nixon and Boyd, 1973; Schmidberger and Francis, 1999; Shi et al., 1998; Peslier et al., 2002).

primitive mantle (McDonough and Sun, 1995). Most of these mantle xenolith suites exhibit unimodal populations with a prominent mode corresponding to relatively fertile spinel lherzolite, with 3.3 wt.% Al_2O_3 and an Mg number of 0.893 (Table 1), which is interpreted to represent the prevalent lithospheric mantle beneath the Canadian Cordillera (Shi et al., 1998). Os model ages for these Cordilleran spinel lherzolite xenoliths (Peslier et al., 2000a,b, 2002) indicate that the lithospheric mantle along the western margin to the North American craton stabilized in the mid-Proterozoic (~ 1.5 Ga), in agreement with a recent compilation of Os isotopic results (Meisel et al., 2001) from a variety of off-craton basalt-hosted mantle xenoliths that has demonstrated the Proterozoic age of lithospheric mantle peripheral to many of the Earth's continental cratons.

Three Cordilleran xenolith sites clustered near the Yukon–British Columbia border (Fig. 1) are characterized by bimodal populations (Fig. 2), with one mode corresponding to the fertile spinel lherzolite observed in the 13 other Cordilleran xenolith suites, while the other mode corresponds to relatively refractory spinel harzburgite (Shi et al., 1998), with lower Al contents (~ 0.8 wt.%) and higher Mg numbers (0.912) (Fig. 2 and Table 1). The spinel harzburgite xenoliths of both the bimodal and unimodal suites are more refractory in composition than harzburgites that dominate the

Table 1
Average composition and normative mineralogy of mantle xenoliths

	Kaapvaal	Siberia	Tanzania	Slave	Somerset	MORB	Cordillera harzburgite	Cordillera lherzolite	Primitive mantle
Number	55	19	29	30	16	79	70	158	–
Major elements in wt.% oxide:									
SiO_2	46.20	44.56	43.63	44.82	43.55	44.69	43.76	44.60	45.62
TiO_2	0.09	0.04	0.11	0.05	0.05	0.02	0.03	0.11	0.22
Al_2O_3	1.31	0.89	0.65	0.95	1.87	1.45	0.78	3.28	4.73
Cr_2O_3	0.31	0.00	0.00	0.42	0.51	0.42	0.41	0.40	0.37
MgO	44.03	46.14	47.51	45.30	44.45	43.98	45.86	39.53	36.37
FeO	6.49	7.23	7.36	6.95	7.61	8.42	7.92	8.46	8.18
MnO	0.11	0.13	0.13	0.11	0.12	0.13	0.13	0.14	0.14
NiO	0.28	0.00	0.00	0.30	0.33	0.32	0.34	0.28	0.24
CaO	0.93	0.82	0.43	0.78	1.32	0.51	0.64	2.95	3.75
Na_2O	0.11	0.07	0.07	0.18	0.10	0.04	0.10	0.22	0.35
K_2O	0.15	0.12	0.10	0.14	0.08	0.02	0.02	0.05	0.03
LOI	2.81	11.32	0.00	2.75	3.73	11.72	0.21	0.21	0.10
Mg number	0.924	0.919	0.920	0.921	0.912	0.903	0.912	0.893	0.888
Calculated mode in the garnet stability field in oxygen units:									
Cpx	3.0	3.1	1.6	3.9	4.8	0.0	1.9	12.7	16.4
Opx	29.5	18.7	14.5	20.6	12.9	24.3	16.3	14.8	19.2
Oliv	62.4	74.7	81.3	71.7	74.0	68.5	77.5	59.8	47.3
Garn	5.2	3.4	2.7	3.9	8.3	7.2	4.4	12.8	17.2

Average composition and normative mineralogy of low-temperature mantle xenoliths in kimberlites from the Kaapvaal, Siberian, Tanzanian, and Slave cratons, as well as those from Somerset Island, MORB peridotites dredged from the MARK region of the mid-Atlantic ridge, the harzburgite, and lherzolite modes of Canadian Cordilleran mantle xenolith suites, and a recent estimate of the composition of primitive mantle composition (O'Neill and Palme, 1998). The modes were calculated in the garnet stability field at a temperature of 1200 °C (data sources as in Fig. 3).

dredge hauls from the MARK region (Casey, 1997) of the mid-Atlantic ridge ($Al_2O_3 \sim 1.5$ wt.% and Mg number ~ 0.90). The array from fertile lherzolite to depleted harzburgite that characterizes all the Cordilleran mantle xenolith suites, and the majority of the Earth's off-craton mantle xenolith suites hosted by alkaline basalts, is equivalent to the "oceanic" trend of Boyd (1989) and is well modeled (Fig. 3) as a series of residues produced by progressive melting (0–25%) of a Pyrolitic primitive mantle source (Francis, 1987; Shi et al., 1998). The anomalous abundance of harzburgites in the three xenolith suites near the Yukon–northern British Columbia border overlie a teleseismic S wave slowness anomaly (Frederiksen et al., 1998) in the underlying asthenospheric mantle, and has been proposed to reflect melting due the ingress of volatiles and heat into the overlying lithospheric mantle (Shi et al., 1998).

Peridotite mantle xenolith suites from the Jericho pipe (Fig. 1) in the northern Slave Province (Kopylova and Russell, 2000) are dominated by garnet harzburgites with low Al contents (~ 1 wt.% Al_2O_3), similar to those of Cordilleran harzburgites (Fig. 2 and Table 1), but with distinctly higher Mg numbers (0.92), and olivine forsterite (Fo) contents, as do the garnet harzburgites in kimberlites from other Archean cratons, such as those of the Kaapvaal, Siberian, and Tanzanian cratons. The Nikos kimberlite xenoliths from Somerset Island (Schmidberger and Francis, 1999) are also dominated by garnet harzburgites, but they are relatively less refractory ($Al_2O_3 \sim 1.9$ wt.%, Mg number ~ 0.91) than those of the Jericho pipe in the Slave Province and the harzburgites of the adjacent Canadian Cordillera. The relatively more refractory nature of cratonic mantle xenoliths is particularly characteristic of the low-temperature mantle xenoliths, which preserve equilibration pressures that are shallower than the "kink" that commonly characterizes cratonic paleogeotherms defined by kimberlite-hosted mantle xenoliths, and

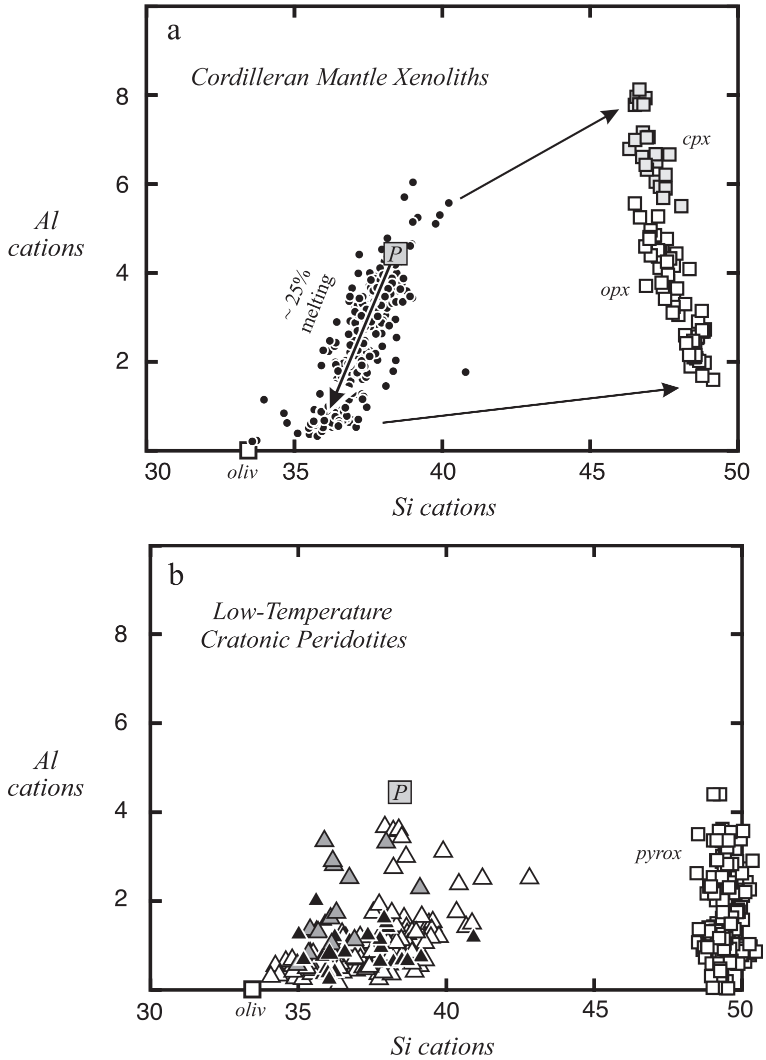

Fig. 3. Al versus Si in cation units showing the whole-rock compositions of (a) Canadian Cordilleran mantle xenoliths and (b) low-temperature cratonic mantle xenoliths in kimberlites. Symbols: Cordilleran mantle xenoliths—black circles; low-temperature cratonic mantle xenoliths: Jericho—black triangles, Somerset Island—gray triangles, Kaapvaal, Siberian, and Tanzanian cratons—open triangles (data sources as in Fig. 2).

thus sample the shallowest upper mantle beneath the cratons. Rather than defining a trend towards a Pyrolitic primitive mantle in Al–Si space, low-temperature cratonic harzburgites trend from those with Si contents similar to the spinel harzburgites associated with mid-ocean ridges and those of the Canadian Cordillera towards anomalously Si-rich compositions (Fig. 3). A few harzburgites dredged from mid-ocean ridges do have high Si contents, but they are characterized by low Mg numbers (<0.89) and are probably cumulates. In contrast, all low temperature cratonic harzburgites, regardless of Si content, have higher Mg numbers than harzburgites with similarly low Al contents from the Canadian Cordillera or mid-ocean ridges.

Richardson (Richardson et al., 1984) first demonstrated that garnet inclusions in South African diamonds yielded a 3.5-Ga Nd isochron, indicating an Archean age for the Kaapvaal craton mantle roots. More recently, a number of Os isotopic studies have demonstrated the likely 3^{+}-Ga age of low-temperature garnet peridotites in kimberlites from the Kaapvaal, Siberian, and Slave cratons (Chesley et al., 1999; Irvine et al., 1999; Pearson et al., 1995a,b), and have established the antiquity of the shallow portions of cratonic mantle roots in general. Most recently, a 2.8-Ga whole-rock Lu–Hf isochron obtained on low-temperature garnet harzburgites from the Nikos pipe has confirmed the validity of the Archean Os-depletion ages (Schmidberger et al., 2002).

The contrast between Proterozoic Cordilleran mantle xenoliths and Archean low-temperature harzburgites from cratonic kimberlites is particularly striking when their normative mineralogy is calculated at similar conditions of pressure and temperature (Fig. 4). While the Proterozoic Cordilleran mantle xenoliths range from depleted harzburgites to fertile lherzolites similar to primitive mantle in composition, Archean low-temperature cratonic mantle xenoliths trend from depleted harzburgites towards increasing orthopyroxene, with little increase in clinopyroxene or garnet, and no evident trend towards the composition of primitive mantle (Fig. 4). This trend towards increasing orthopyroxene is most clearly developed in the low temperature harzburgites of the Kaapvaal, Siberia, and Slave cratons, whereas low temperature harzburgites of Somerset Island and the Tanzanian and Greenland cratons have relatively low Si contents, similar to the harzburgites of the Canadian Cordillera or mid-ocean ridges.

2.2. Tertiary versus Archean high-Mg lavas

In addition to the generally higher Mg contents of Archean komatiites (Arndt et al., 1997; Herzberg and O'Hara, 1997), there are systematic differences between Phanerozoic and Archean high-Mg lavas. The array of Archean high-Mg lavas, including both komatiites and ferropicrites, appears to be shifted to higher Fe contents and lower Al/Si ratios than Tertiary high-Mg lavas (Figs. 5 and 6). Some would attribute these differences solely to higher mantle temperatures in the Archean, and thus higher pressures and degrees of partial melting that yielded liquids with both higher Mg and Fe contents compared to Tertiary picrites. This explanation does not, however, account for the systematic mismatch between Fe and incompatible minor or trace elements (e.g. Ti and Zr) when comparing Archean and Tertiary high-Mg lavas. For example, although Archean Al-undepleted komatiites have Fe contents and Al/Si ratios similar to those of modern Hawaiian picrites, their low Ti and Zr contents are more

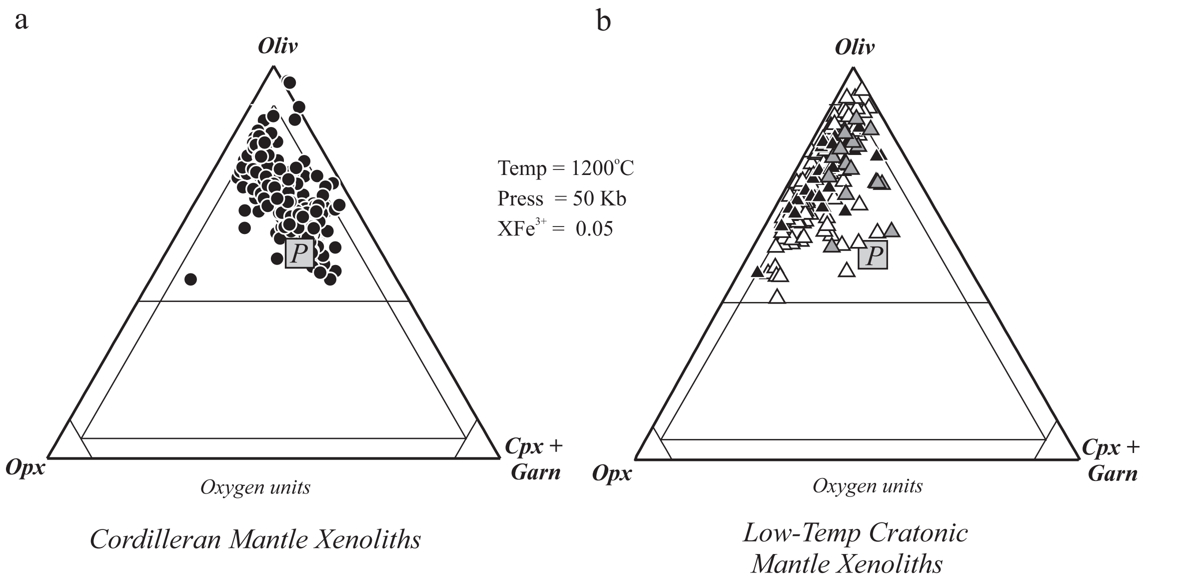

Fig. 4. Calculated modes in the garnet stability field for (a) Cordilleran mantle xenoliths and (b) low temperature cratonic mantle xenoliths (symbols and data sources as in Fig. 3).

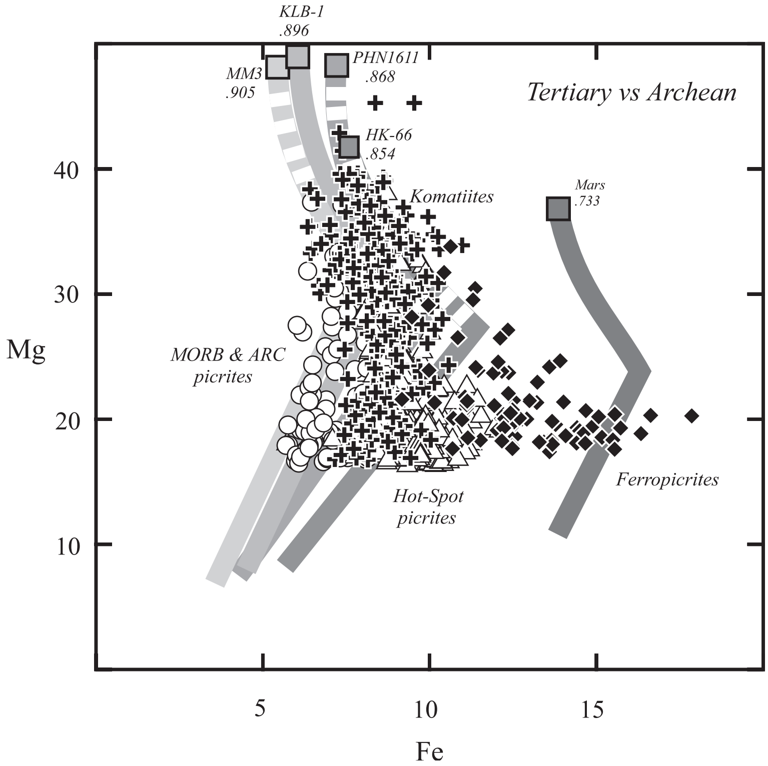

Fig. 5. Mg versus Fe in cation units for high-Mg (12^{+} wt.% MgO) Tertiary and Archean lavas along with the spectra of experimental melts produced from a variety of model mantle compositions. Symbols: Tertiary MORB and Arc picrites—open circles, Tertiary hot-spot picrites—open triangles, Archean komatiites—black crosses, Archean ferropicrites—black diamonds, model mantle compositions MM3, KLB-1, PHN1611, HK-66, and Mars—shaded squares, with their corresponding spectra of experimental partial melts indicated by the shaded paths (data sources: Berka and Holloway, 1994; Francis et al., 1999; Hirose and Kushiro, 1993; Kushiro, 1998; Takahashi, 1986; Takahashi et al., 1994; Walter, 1998).

typical of relatively Fe-poor MORB picrites (Fig. 7a,b). In contrast, Archean ferropicrites that are similar to Hawaiian picrites and mildly alkaline ankaramites in terms of Ti and Zr have systematically higher Fe (Fig. 7a,b) and lower Al/Si ratios (Fig. 6) than both Tertiary hotspot picrites and rarer Phanerozoic ferropicrites (Gibson et al., 2000). Furthermore, although Al-depleted komatiites have been documented together with Al-undepleted komatiites in the late Archean (Cattell and Arndt, 1987), there appears to be a general temporal evolution in the composition of komatiitic lavas, from the Al-depleted (Al/Ti ~ 10) komatiites that characterize 3^{+} Ga greenstone belts to Al-undepleted (Al/Ti ~ 20) komatiites that characterize circa 2.6–2.9 Ga greenstone belts to the Al-rich Mesozoic komatiites of Gorgona Island, which exhibit Al–Si systematics similar to those of modern MORB (Fig. 8a).

3. Discussion

A fundamental mass balance problem arises when attempts are made to relate high-Mg Archean lavas to a refractory restite equivalent to the low-temperature garnet harzburgites of lithospheric mantle roots beneath Archean cratons (Herzberg, 1993). If a Pyrolitic primitive mantle source is assumed, the majority of high-Mg Archean magmas are too low in Al and high in Si to leave behind a refractory residue with the composition of the harzburgite xenoliths that constitute the Archean mantle roots beneath continental cratons (Fig. 6). This problem is particularly acute for 3^{+} Ga Al-depleted komatiites and the Si-rich harzburgites of the Kaapvaal, Siberian, and Slave cratons. A number of proposals have been made to explain the orthopyroxene-rich nature

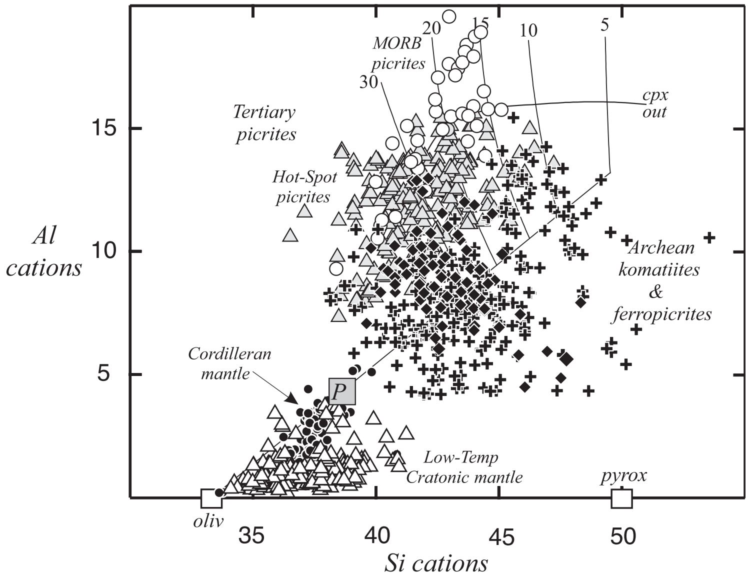

Fig. 6. Al versus Si in cation units for high-Mg (12^+ wt.% MgO) Tertiary and Archean lavas, along with Cordilleran and low-temperature cratonic mantle xenoliths, and a grid indicating the pressures in kilobars of experimental partial melts of primitive mantle. Symbols as in Figs. 3 and 5, except hot-spot picrites—gray triangles (data sources as in Figs. 3 and 5).

of some low-temperature harzburgite xenoliths in cratonic kimberlites:

(1) Prograde metamorphism of a residual MORB peridotite protolith that had been relatively enriched in silica during serpentinization of the oceanic lithosphere by the preferential leaching of other cations such as Ca (Helmstaedt and Schulze, 1989; Schulze, 1986). Actual analyses of serpentinized MORB peridotites with Mg numbers greater than 0.89, however, are not anomalous in Si (Fig. 8b), but resemble those of mantle harzburgites found in alkaline basalts.
(2) Floatation of residual harzburgite on top of komatiitic melts followed by metamorphic differentiation into orthopyroxene-rich and orthopyroxene-poor layers and cooling (Boyd, 1989).
(3) Tectonic mixing of orthopyroxene-rich cumulates derived from komatiitic melt or a high Si terrestrial magma ocean (Boyd, 1989; Herzberg, 1993).
(4) Reaction of residual harzburgite with fluids or siliceous melts rising from underlying subduction zones, as a result of which olivine is converted to orthopyroxene (Kelemen et al., 1999).

Although each of these proposals has some merit, with the exception of Herzberg (1993), most have interpreted the origin of the orthopyroxene enrichment in terms of the action of a secondary process, following the generation of komatiitic magmas from a Pyrolitic mantle source. The unstated assumption is that the Earth's asthenospheric mantle has been in a compositional steady state since the Hadean, with the composition of fertile mantle having always been approximately that of primitive mantle Pyrolite (McDonough and Sun, 1995; O'Neill and Palme, 1998). With the recent recognition that cratonic mantle xenoliths from Tanzania (Chesley et al., 1999), Greenland (Bernstein et al., 1998), and Somerset Island (Schmidberger and Francis, 1999) are not enriched in orthopyroxene compared to oceanic lithospheric mantle, interest in the Si-enrichment of cratonic mantle roots has waned. It is important to realize, however, that the mass balance problem in relating komatiites to cratonic mantle roots persists even for Archean mantle restites with the relatively Si-poor compositions of younger harzburgites in alkaline basalt suites and beneath mid-ocean ridges. The derivation of liquid compositions ranging from Al-depleted to Al-undepleted Archean komatiites from a

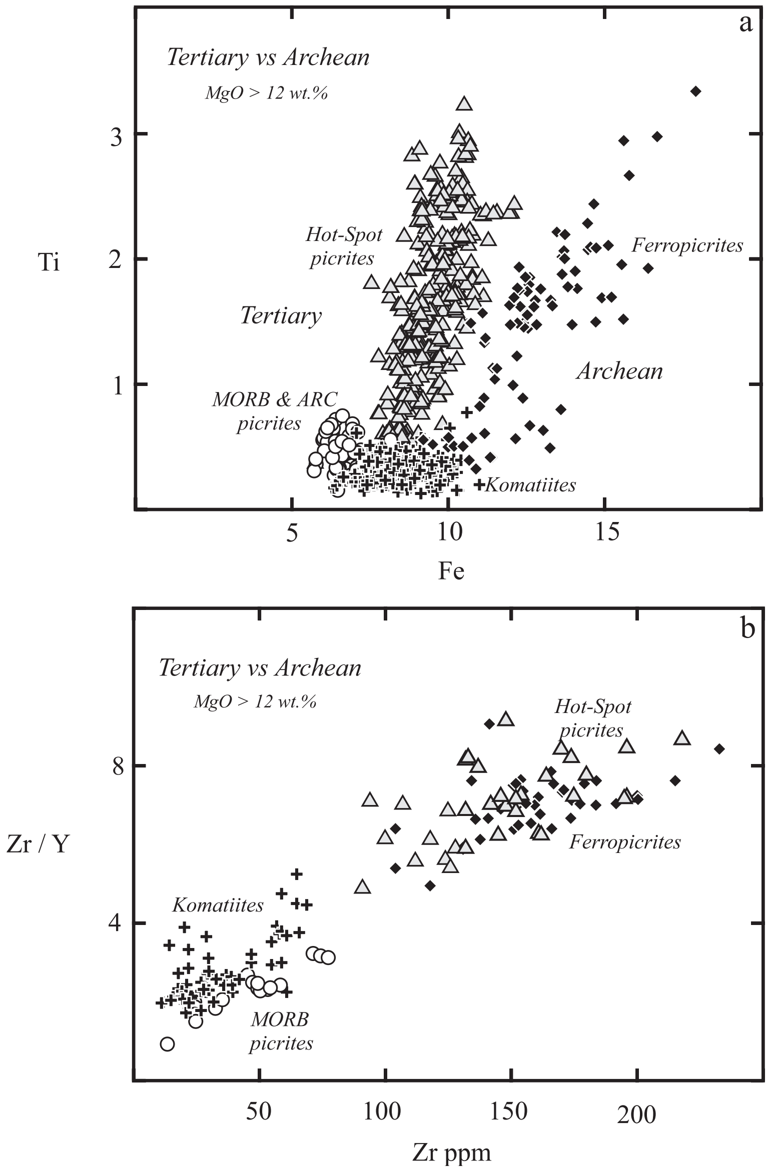

Fig. 7. (a) Fe versus Ti in cation units and (b) Zr versus Zr/Y in ppm for high-Mg (12^{+} wt.% MgO) Tertiary and Archean lavas. Symbols as in Fig. 6 (data sources as in Fig. 5).

primitive mantle source would leave refractory residues that range in composition from garnetiferrous dunite to dunite (Fig. 6). Neither of these two lithologies are well represented in cratonic mantle xenolith populations. Only komatiites with Al contents significantly above the extension of line joining olivine to primitive mantle in a plot of Al versus Si (Fig. 8) are capable of leaving a refractory residue with significant orthopyroxene. The fact that a number of experimenters have obtained komatiitic partial melts from model Pyrolitic primitive mantle sources (Walter, 1998) does not invalidate the foregoing argument. The phase rule requires that the partial melt of any peridotite will have a similar major element composition at similar

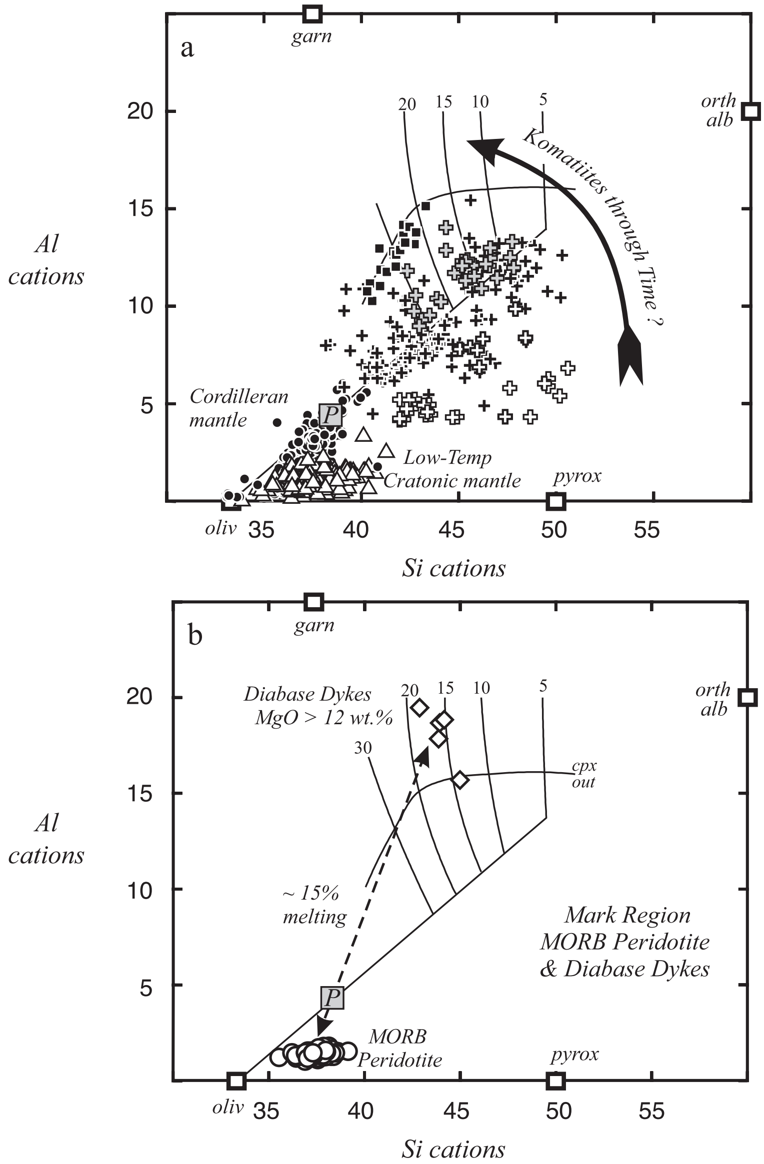

Fig. 8. Al versus Si in cation units for (a) komatiites through time and (b) dredged peridotites and picritic dykes that cut them from the MARK region of the mid-Atlantic ridge. Symbols: 3^{+} Ga komatiites—open crosses, 2.6–2.9 Ga komatiites—black crosses, 1.0–2.5 Ga komatiites—gray crosses, Mesozoic Gorgona komatiites—black squares, MARK region MORB peridotites—open circles, and picritic dykes—open diamonds. Other symbols as in Fig. 3 (data sources: Casey, 1997, others as in Fig. 5).

P–T conditions, it is rather the composition of the refractory restite that is sensitive to the original source composition. Furthermore, experimental melts of primitive mantle compositions that have pyroxene in their coexisting refractory restite have relatively high Al/Si ratios, and pyroxene is absent in the restites of experimental melts that approach the lower Al/Si ratios typical of most Archean komatiites (Walter, 1998). A more complex explanation for the low Al/Si ratios of Al-depleted komatiites involving a derivation from a mantle source that had been depleted with respect to primitive mantle by a previous melting event(s) makes their relatively high Fe contents even more difficult to rationalize.

The concept of a primitive mantle composition has its underpinnings in the approach of Pyrolite models for mantle source regions of basaltic magmas to the intersection of the compositional array of basalt-hosted mantle xenoliths and the extrapolation of the array of chondritic meteorites in Al/Si, Ca/Si, and Mg/Si spaces (Fig. 9) (Jagoutz et al., 1979). The presently accepted major element composition of fertile Pyrolite mantle (McDonough and Sun, 1995) is essentially that of the most Al-rich spinel lherzolite xenoliths hosted by off-craton alkaline basalts. Estimates for the major element composition of Earth's primitive mantle are essentially indistinguishable from fertile Pyrolite, in that they are obtained by a small correction (~ 1%) for what is thought to have been extracted to form the continental crust (O'Neill and Palme, 1998). Pyrolitic mantle sources appear to work well in Phanerozoic volcanic suites, as can be seen in Fig. 8b where a Pyrolite source can relate picritic MORB dykes to the residual MORB harzburgite they cut by ~ 15% partial melting (Casey, 1997). Archean komatiites that could coexist with olivine of Fo 92.5–94 composition, however, cannot be linked to the harzburgites of cratonic mantle roots with a line that passes through the composition of primitive mantle, but such a join does pass through the compositions of chondritic meteorites in Mg/Si versus Al/Si space (Fig. 9). This suggests that Archean komatiitic magmas could be simply related to the lithospheric mantle roots beneath Archean cratons if they were derived from mantle sources that were more chondritic in terms of Mg/Si than the presently accepted composition for fertile Pyrolitic mantle. This interpretation would require that the Earth's fertile convecting upper mantle has evolved since the Hadean to its present Pyrolite composition. Further support for such a possibility can be found in the compositions of chondritic meteorites. The intersection between the compositional

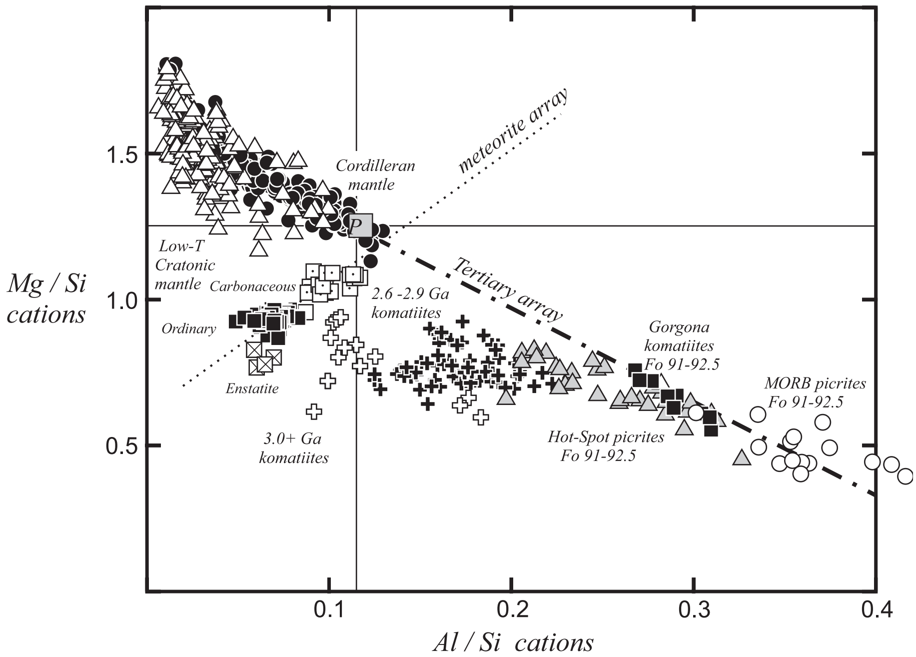

Fig. 9. Mg/Si versus Al/Si for low-temperature cratonic mantle xenoliths in kimberlites, off-craton basalt-hosted mantle xenoliths from the Canadian Cordillera, along with the compositions of chondritic meteorites, high-Mg MORB picrites, and Tertiary hot-spot picrites that would coexist with an olivine of Fo 91–92.5 composition, and komatiites that would coexist with an olivine of Fo 92.5–94 composition. Symbols: carbonaceous chondrites—squares with dots, ordinary chondrites—black squares, enstatite chondrites—crossed squares. Other symbols as in Figs. 3, 6, and 8 (data sources: Jarosewich, 1990, others as in Figs. 3 and 5).

arrays of chondritic meteorites and mantle xenoliths is also evident a simple plot of Fe versus Mg (Fig. 10), in which the silicate portions of the chondritic meteorites form a linear array trending directing away from Fe. Here, however, the point of intersection with the mantle array is further from the composition of primitive mantle than in Al/Si or Ca/Si versus Mg/Si space. When corrected to an Mg number (~ 0.86) that would make them approximately collinear with the compositions of Archean komatiites that would coexist with olivine of Fo 92.5–94 composition and the compositions of low-temperature cratonic mantle xenoliths in Mg–Fe space (Fig. 10) by mathematically removing additional FeO, both the carbonaceous and the ordinary chondrite meteorites fall to more Si-rich compositions than primitive mantle, and would provide much more suitable sources with which to link komatiitic magmas and refractory cratonic mantle xenoliths in Si–Al space (Fig. 11). A mantle with a composition of the Mg number 86-normalized silicate portions of the chondritic meteorites would melt at the same pseudo-invariant point as a Pyrolitic mantle, with the initial liquid coexisting with olivine, orthopyroxene, clinopyroxene, and a pressure-dependent aluminous phase, but at a slightly lower solidus temperature (~ 20°) because of its lower Mg number

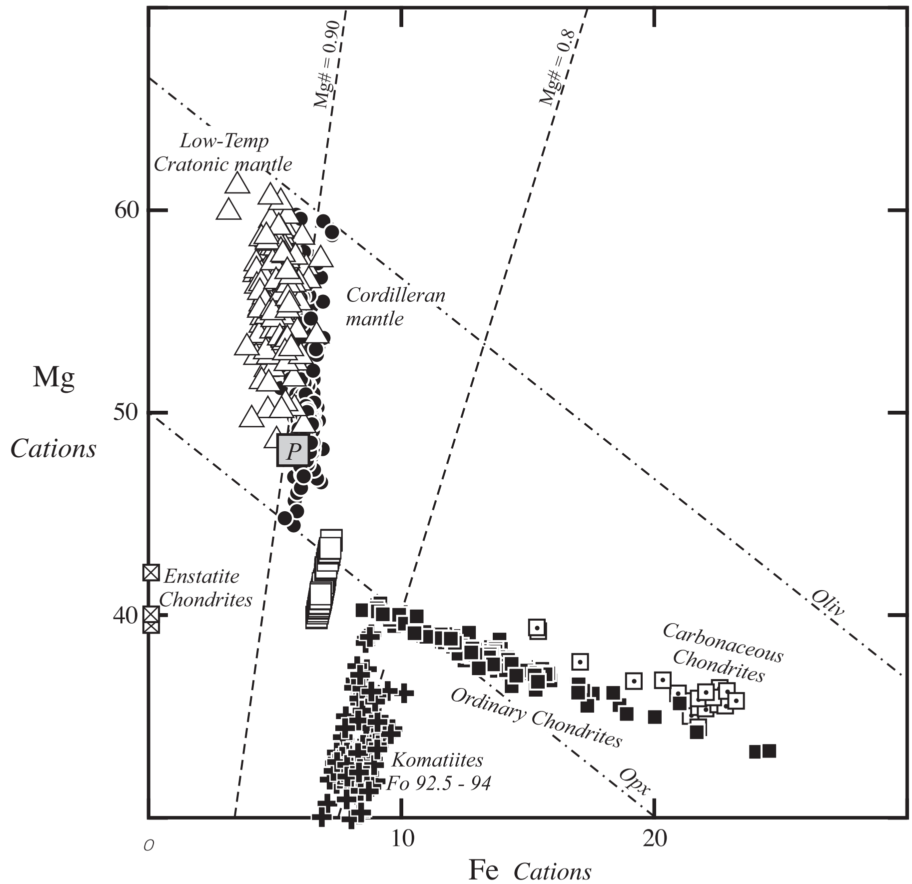

Fig. 10. Mg versus Fe in cation units for low-temperature cratonic mantle xenoliths in kimberlites, off-craton basalt-hosted mantle xenoliths from the Canadian Cordillera, the silicate portions of chondritic meteorites, the silicate portions of chondritic meteorites normalized to an Mg number of 0.86 by the removal of FeO, and komatiites that would coexist with an olivine of Fo 92.5–94 composition. Symbols: Mg number 0.86 normalized meteorites—open squares, komatiites that would coexist with an olivine of Fo 92.5–93 composition—black crosses. Other symbols as in Figs. 3 and 8 (data sources as in Figs. 3, 5, and 9).

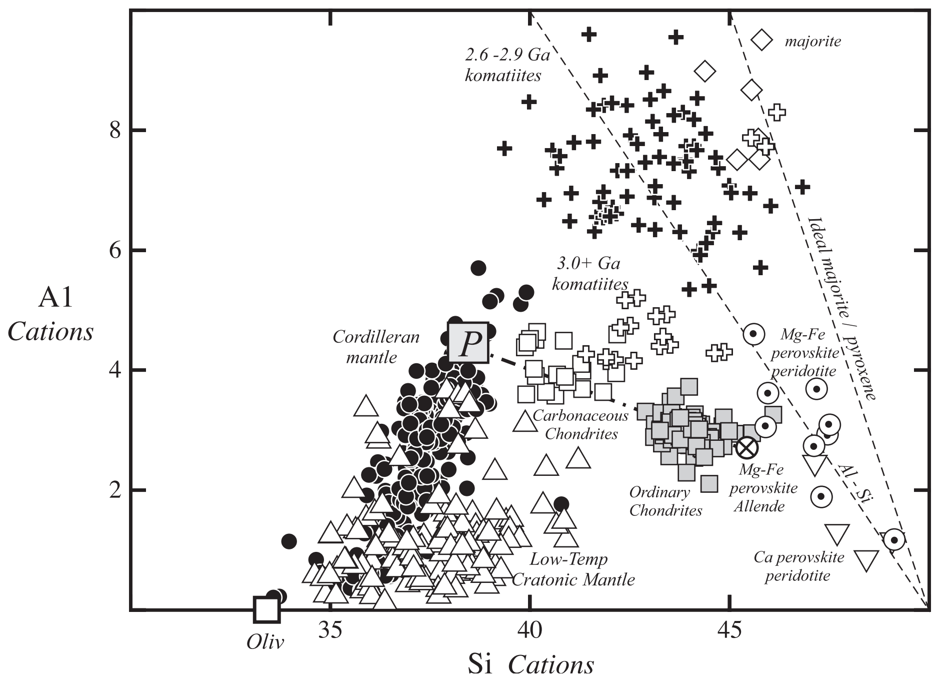

Fig. 11. Al versus Si in cation units for low-temperature cratonic mantle xenoliths in kimberlites, off-craton basalt-hosted mantle xenoliths from the Canadian Cordillera, chondritic meteorites normalized to an Mg number of 0.86, as well as the compositions of experimentally determined higher pressure phases in mantle peridotite. Symbols: carbonaceous chondrites—open squares, ordinary chondrites—shaded squares, Mg–Fe perovskite—dotted circles, Ca perovskite—inverted triangles, majorite—open diamonds. Other symbols as in Figs. 3 and 9 (data sources: Collerson et al., 2000; Wood, 2000, others as in Figs. 3, 5, and 9).

(Hirschmann, 2000). The removal of this pseudo-invariant melt will, however, leave residues with higher orthopyroxene contents than off-cratonic harzburgites, and the extent of melting at any given temperature will be greater than that for a Pyrolitic source, leading to higher Mg numbers in the residue. These are exactly the characteristics of many low-temperature cratonic mantle xenoliths.

The high Mg/Si ratio of the Earth's upper mantle compared to chondritic meteorites has been a persistent cosmochemical enigma (O'Neill and Palme, 1998). Either bulk silicate Earth is not chondritic or the composition of the Earth's mantle has changed, and a Si-rich reservoir must exist within the Earth to balance the observed high Mg/Si ratio of the Earth's upper mantle. The two most likely candidates for such a reservoir are the recently hypothesized "abyssal layer" (Kellogg et al., 1999) in the lower mantle and the Earth's liquid outer core. The approximate alignment of primitive mantle, chondritic meteorites, and mantle perovskites suggests that the fractionation of Mg–Fe perovskite might be a mechanism to produce the proposed change in the composition of the mantle. The lever rule in Al–Si space is consistent with modern Pyrolite mantle being derived by ~ 20–30% fractionation of Mg–Fe perovskite from the composition of carbonaceous chondrites (Fig. 11), after the loss of metal, sulfide, and/or magnesiowustite to raise their Mg number to 0.86.

The fact that experimental perovskites have higher Mg number than their peridotite hosts (Wood, 2000), however, would require that magnesiowustite segregation accompany perovskite fractionation in order to prevent a decrease in Mg number. Numerous authors have discussed the possibility of perovskite fractionation from a magma ocean in the early Hadean, shortly after accretion, to explain the high Mg/Si ratio of the Earth's present upper mantle. This explanation has run into difficulty because experimental data on perovskite/melt element partitioning suggests that extensive fractionation of Mg–Fe perovskite in a magma ocean should change the Ca/Al, Al/Ti, and Sc/Sm ratios of the residual liquid (McFarlane et al., 1994; Kato et al., 1988), but the values of these ratios in the present Pyrolitic upper mantle are similar to those of chondrites. Furthermore, the lower melting temperature of carbonaceous chondrite with respect to primitive mantle means that it would be impossible to generate Pyrolitic primitive mantle by fractionating Mg–Fe perovskite from a chondritic magma ocean.

What is new in this paper, however, is the proposal that the present Mg/Si ratio of the mantle has developed since the Hadean, long after an early Hadean magma ocean would have solidified. Geophysicists are presently divided on the seismic evidence for the existence of a lower mantle "abyssal" layer (Kellogg et al., 1999) that is both denser and hotter than the convecting upper mantle. Many proponents of an abyssal layer in the lower mantle assume that it represents primitive undepleted mantle, and is thus relatively enriched in incompatible elements, heat producing elements, and primordial noble gases (Kellogg et al., 1999) compared to the asthenospheric upper mantle we observe today. Could the abyssal layer, however, represent an Mg–Fe perovskite enriched separate removed from the upper mantle to produce the latter's present Pyrolitic composition? The similarity of komatiitic Ca/Al ratios, as well as ratios of refractory lithophile incompatible elements in general, to those of chondrites and modern picrites, indicates that the Ca- and Al-rich perovskites and majorites that have been reported (Collerson et al., 2000; Wood, 2000) have not been preferentially removed from the upper mantle. If it is assumed that the higher Ca and Al contents of the present Pyrolite upper mantle reflect the preferential loss of Mg–Fe perovskite to a dense "abyssal" layer in the lower mantle (assuming a bulk silicate Earth that resembles carbonaceous chondrites), then the minimum mass of the lower layer must also be on the order of 20%, assuming it contained little Ca or Al. Given the low incompatible trace element contents of Mg–Fe perovskites compared to Ca–Al perovskites, the general absolute enrichment in incompatible elements in Pyrolite over carbonaceous chondrites (~ 1.2) (McDonough and Sun, 1995) is also consistent with a mantle reservoir poor in incompatible trace elements constituting 20% of the mantle. The major problem with an "abyssal" layer reservoir model, however, is that following the solidification of a possible early Hadean magma ocean, there is no obvious mechanism that will preferentially sequester Mg–Fe perovskite and magnesiowustite in a lower mantle "abyssal" layer since the Hadean.

The presence of metallic silicon in highly reducing enstatite chondrites (O'Neill et al., 1998), the suprachondritic $^{186}Os/^{188}Os$ ratios of Hawaiian picrites (Brandon et al., 1998), and the observation of metal-silicate reactions in high pressure experiments (Ito et al., 1995) suggest that both Si and Fe may be transferred between Earth's lower mantle and outer liquid core by reactions in the D″ layer of the type:

$$(Mg_x, Fe_{1-x})SiO_{3Pv} + 3(1-x)Fe_{metal} \rightarrow xMgSiO_{3Pv} + (1-x)SiFe_{3metal} + (1-x)FeO_{metal}$$

Such a reaction may provide a mechanism for depleting the mantle in its Fe-perovskite component over time. The dissolution of ~ 5–6 wt.% each of Si and FeO into the Earth's core by such a reaction mechanism in the D″ layer could have produced the difference between the Mg/Si ratios of the chondritic meteorites and Pyrolitic primitive mantle (O'Neill et al., 1998) and the increase in the mantle Mg number since the Hadean (Francis et al., 1999). The fact that the present upper mantle has relatively high and unfractionated highly siderophile trace element contents (e.g. platinum group elements) does not invalidate this possibility because current estimates for the partitioning of siderophile elements into FeO (Ohtani et al., 1997) indicate that the loss of FeO to the core might have a negligible effect on the siderophile element abundances of the remaining mantle.

Perhaps the best estimate for the starting composition of the Earth's silicate mantle is obtained after the manner of Larimer and Anders (1970) (O'Neill and Palme, 1998), in which the co-variation of Ni/Mg with Fe/Mg in the chondritic meteorites can be interpreted to indicate that bulk silicate Earth had an Mg number of ~ 0.80 at the end of the Hadean (Fig. 12), a value that corresponds closely with the lowest Mg numbers of the silicate portions of ordinary chondrites (Fig. 10). The compositions of Archean komatiites suggest that the Mg number of the fertile mantle had increased to ~ 0.86 by the early Archean,

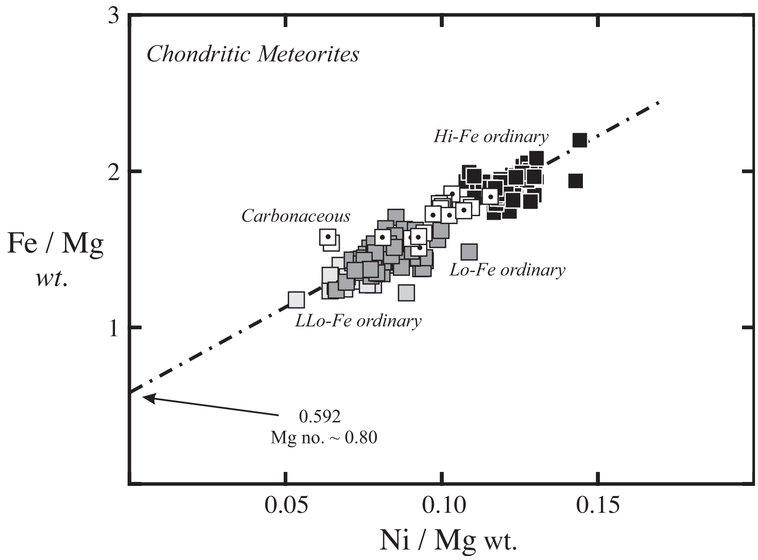

Fig. 12. Fe/Mg versus Ni/Mg in weight units for chondritic meteorites. Symbols: high-Fe chondrites—black squares, low-Fe chondrites—gray squares, very low-Fe chondrites—open squares, carbonaceous chondrites—dotted squares (data source as in Fig. 9).

but since then there appears to have been a further decrease in Si and increase in Al, Ca, and Mg numbers to the present Pyrolitic mantle values (Mg number ~ 0.89). The increase in the Al content of komatiitic magmas from the early Archean through to the Mesozoic (Fig. 8b) would, in this scenario, reflect the increase in Al and decrease in Si of the fertile upper mantle caused by the preferential loss of Fe perovskite and FeO to the core. The lever rule would require that Al-depleted 3^{+} Ga komatiites represent very large degrees of partial melting (70–80%), which are more easily reconciled with magma ocean-type models, rather than mantle plume models (Fig. 11). The estimated degree of partial melting in Al–Si space falls to ~ 50% for Al-undepleted komatiites of the late Archean and 30–40% for the Mesozoic komatiites of Gorgona (Fig. 11).

Although the exact mechanism(s) that has produced the proposed decrease in the Fe and Si contents of fertile mantle since the Hadean remains to be established, one of the most intriguing aspects of this proposal lies in its implications for the origin of the distinctive chemical character of the picritic magmas of ocean island basalt (OIB) suites, which are enriched in Fe and Si, and depleted in Al compared to MORB picrites (Fig. 6) (Francis, 1995). If MORB and Hawaiian primitive magmas were derived from the same mantle source, then the lower Al content of Hawaiian picrites would require that they represent a greater degree of partial melting. Yet, the fractionated trace element profiles of Hawaiian picrites suggest smaller degrees of partial melting of the source that gave rise to MORB, leaving a significant proportion of garnet in the residue. This paradox, combined with the absence of coexisting olivine and garnet on the liquidus of Hawaiian picrites at any pressure (Eggins, 1992), requires that the major element composition of Hawaiian mantle source(s) differs from that of the convecting upper mantle that produces MORB. The enrichments in Fe and Si contents that characterize Hawaiian, and OIB picrites in general, mimic the characteristics of Archean high-Mg magmas, and these are exactly the two elements that the proposed model requires to be sequestered in the lower mantle or outer core.

The most fertile mantle xenoliths in off-craton alkaline volcanic suites, those that constrain the presently accepted composition of fertile Pyrolite mantle, have Os isotopic compositions that are similar to those of the majority of modern MORB samples that have appreciable Os contents ($^{187}Os/^{188}Os$ ~ 0.13) (Meisel et al., 2001). This, in combination with their common light rare-earth depleted character (Roden et al., 1984) and the complementarity of MORB picrites and the array of Proterozoic mantle xenoliths, suggests that fertile lherzolite xenoliths may represent actual fragments of the convecting upper mantle source for MORB, trapped and preserved along the margins of continental cratons. The consistent Proterozoic model ages obtained for such fertile lherzolite xenoliths would imply that the Pyrolitic convecting upper mantle that produces modern MORB is a Proterozoic or younger feature of the Earth.

4. Conclusions

The mass balance problem that results when Archean komatiitic magmas are related to cratonic mantle roots may reflect current assumptions about the composition of fertile mantle sources in the Archean. The low Al/Si ratios of komatiites may indicate a more chondritic composition for the Earth's early Archean mantle. The presently accepted major element composition of primitive mantle is based on Proterozoic mantle xenoliths. The compatible major element, trace element, and Os isotopic compositions of fertile Proterozoic mantle xenoliths and MORB suggest that the present Pyrolitic convecting upper mantle that produces MORB may be a Proterozoic or younger feature of the Earth. According to this view, the depleted mantle roots beneath continental cratons would represent the refractory relicts of a Si- and Fe-rich early Archean mantle. Forsaking conventional geodynamic wisdom that the Earth has been in a compositional steady state since the Hadean, and accepting the possibility that the Earth's convecting upper mantle has become poorer in Fe and Si over geologic time, not only provides a simpler way of relating Archean high-Mg lavas to the lithospheric mantle roots that underlie Archean cratons, but could also lead to new models for the nature Archean magmatism and the lower mantle sources of modern hot-spot volcanism.

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