

The Lithospheric Mantle beneath Continental Margins: Melting and Melt–Rock Reaction in Canadian Cordillera Xenoliths

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Seven alkali basalt centers in the southern Canadian Cordillera contain mantle xenolith suites that comprise spinel Cr-diopside peridotites, spinel augite-bearing wehrlites and orthopyroxene-poor lherzolites, and minor pyroxenites. The Cr-diopside peridotites appear to be residues of the extraction of Mg-rich basalts by up to 15% partial melting (median 5–10%) of a pyrolite-like source in the spinel stability field. The xenoliths are similar to other mantle xenolith suites derived from beneath convergent continental margins, but are less depleted, less oxidized, and have lower spinel mg-number than peridotites found in fore-arc settings. Their dominant high field strength element depleted character, however, is typical of arc lavas, and may suggest that fluids or melts circulating through the Canadian Cordillera lithosphere were subduction related. Modeling using MELTS is consistent with the augite-bearing xenoliths being formed by interaction between crystallizing alkaline melts and peridotite. Assimilation–fractional crystallization modeling suggests that the trace element patterns of liquids in equilibrium with the augite xenoliths may represent the initial melts that reacted with the peridotite. Moreover, the compositions of these melts are similar to those of some glasses observed in the mantle xenoliths. Melt–rock interaction may thus be a viable mechanism for the formation of Si- and alkali-rich glass in peridotites.

KEY WORDS: Canadian Cordillera; mantle xenolith; peridotite; wehrlite; melt–rock reaction

INTRODUCTION

Spinel peridotite xenoliths occur in many alkali basalt centers of the Canadian Cordillera, a Phanerozoic convergent orogen bordering the western edge of the Canadian craton. The Cordillera formed during the late Jurassic and Cretaceous through the successive accretion of tectonic terranes of various lithologies (mainly arc related) to the stable margin of ancestral North America (e.g. Monger *et al.*, 1982; Gabrielse & Yorath, 1991). However, the nature of the lithospheric mantle beneath these terranes and its tectonic origin are poorly constrained. Moreover, the southern part of this continental margin is bordered by an active subduction zone (Gabrielse *et al.*, 1991), and thus the lithosphere may have been modified by subduction-related melts or fluids. The mantle xenoliths thus represent samples of the lithospheric mantle at the transition between cratonic continental lithosphere and oceanic mantle. The major element composition of the mantle lithosphere is of interest as a potential source of magmas and also because it may react with magmas migrating through it on their way to the surface.

The petrochemical and isotopic characteristics of xenolith suites from the northern Canadian Cordillera have been well documented (Foster *et al.*, 1966; Nicholls *et al.*, 1982; Francis, 1987; Carignan *et al.*, 1996; Shi *et al.*, 1998; Edwards & Russell, 2000; Peslier *et al.*, 2000a, 2000b), whereas the petrological characteristics of the

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southern Cordillera xenoliths have been described for a number of individual suites involving geothermobarometry studies (Fiesinger & Nicholls, 1977; Fujii & Scarfe, 1982; Ross, 1983; Brearley & Scarfe, 1984; Brearley *et al.*, 1984; Canil *et al.*, 1987; Canil & Scarfe, 1989), determination of oxidation states (Canil *et al.*, 1990), Rb–Sr (Sun *et al.*, 1991), Sm–Nd (Xue *et al.*, 1990), and Re–Os (Peslier *et al.*, 2000a, 2000b) isotope systematics, and trace element abundances of whole-rock and minerals (Sun & Kerrich, 1995). Before this study, however, little information has been available on the bulk major element compositions of the xenoliths and thus the chemical composition of the lithosphere. This paper presents an integrated study of the petrochemical characteristics of all southern Canadian Cordillera xenolith suites, with a systematic comparison with xenolith suites from the northern Canadian Cordillera. The origin of both Cr-diopside- and augite-bearing xenoliths in the Canadian Cordillera is addressed, using simple melting and crystallization models, as well as the MELTS program (Ghiorso *et al.*, 1995; Asimow & Ghiorso, 1998), to reproduce the compositional variation of the xenolith suites and to constrain the compositions of melts in equilibrium with them. A comparison with mantle peridotites from other tectonic settings is used to constrain the processes of formation of the entire Canadian Cordillera mantle lithosphere.

SAMPLE LOCALITIES, ROCK TYPES AND TEXTURES

A total of 175 mantle xenoliths were sampled at seven volcanic centers in the southern Canadian Cordillera: Summit Lake (SL), Kostal Lake (KL), Big Timothy (BT), Rayfield River (RR), West Kettle River (KR), Lassie Lake (LL) and Lightning Peak (LP) (Fig. 1, Table 1). The host lavas range in composition from alkali olivine basalts (AOB) to olivine nephelinites (OI-NEPH; Table 1), with eruption ages ranging from mid-Tertiary (SL) to recent (KL; Table 1). The xenoliths occur as inclusions in lava flows (SL, BT, RR, KR, LL and LP) or as bombs in cinder cones (KL). The number of xenoliths collected from each suite varies between five and 54 (Table 1) and reflects, in part, the extent of previous sampling at these localities. Alteration of the xenoliths is minor at most sites, except at BT where about one-third of the xenoliths show pervasive replacement of olivine by iddingsite. Our sampling at this site was biased towards the fresh samples. The dominant xenoliths in all suites are spinel lherzolites, consisting of olivine, orthopyroxene (opx), clinopyroxene (cpx), and spinel in decreasing proportions (Fig. 2). These represent the dominant lithology of the lithospheric mantle beneath both the southern and northern Canadian Cordillera (Francis, 1987; Shi *et al.*, 1998). Spinel

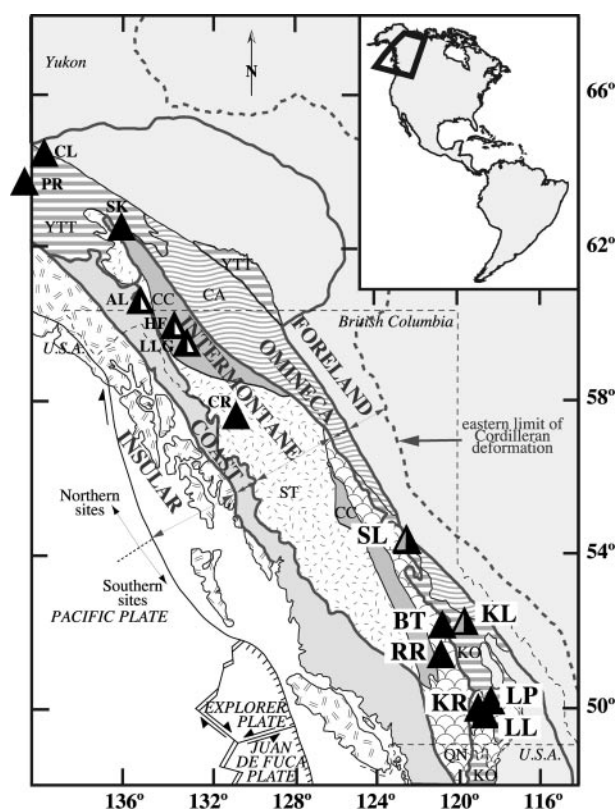


Fig. 1. Map of the Canadian Cordillera, showing the xenolith sites and a simplified sketch of the tectonic terranes accreted to the stable margin of North America. Black triangles are xenolith locations with a majority of lherzolites, black and white triangles with an equal amount of lherzolites and harzburgites (bimodal suites), black and gray triangles with lherzolites and augite-bearing xenoliths (wehrlites mainly). Southern Cordillera xenolith sites: SL, Summit Lake; KL, Kostal Lake; BT, Big Timothy; RR, Rayfield River; KR, West Kettle River; LL, Lassie Lake; LP, Lightning Peak. Northern Cordillera xenolith sites (Francis, 1987; Shi *et al.*, 1998): CL, Clinton; PR, Prindle; SK, Selkirk; AL, Alligator Lake; HF, Hirschfield; LLG, Llangorse; CR, Castle Rock. Insular, Coast, Intermontane and Foreland are the names of the belts dividing the Canadian Cordillera. Tectonic terrane names: YTT, Yukon Tanana; KO, Kootenay terrane; CA, Cassiar; QN, Quesnellia; CC, Cache Creek; ST, Stikine (Gabrielse *et al.*, 1991). Oceanic plate boundaries are from Riddihough & Hyndman (1991).

typically makes up <5% of all samples. Xenoliths from LP contain traces (<5%) of amphibole. Although phlogopite has been reported at KL (Canil & Scarfe, 1989), it is present in only one of our samples.

Most of the peridotites belong to the Type I (Cr-diopside peridotite) of Frey & Prinz (1978). Among these, rare harzburgites were found at RR and KL and a few dunites at KL. The textures of the Type I xenoliths are mainly protogranular (Mercier & Nicolas, 1975) at LP, RR, KL and SL, but the xenoliths from SL and RR are finer grained (olivine and opx <1 mm) than those from LP and KL (1–2 mm). The textures of the BT xenoliths range from protogranular to equigranular, but most are

Table 1: Location of xenolith sites, number of xenoliths sampled, and age and whole-rock analyses of host basalts

Location:	Big Timothy (BT)	Kostal Lake (KL)	Lassie Lake (LL)	Lightning Peak (LP)	Rayfield River (RR)	Summit Lake (SL)	West Kettle River (KR)
Latitude:	52°5'N	52°10'N	49°36'N	49°53'N	51°20'N	54°31'N	49°47'N
Longitude:	119°55'W	119°57'W	118°10'W	118°32'W	121°7'W	122°38'W	119°4'W
No. of xenoliths:	34	54	5	24	13	33	10
Basalt sample:	BT-1	KL-1	LL-1	LP-3	RR-1	SL-1	KR-4
Basalt type:	OI-NEPH	Basanite	Basanite	OI-NEPH	AOB	Basanite	Basanite
Age:	0.4 ± 0.04 Ma (1)	7750 BP (2)	4.8 ± 0.2 Ma (1)	2.5 ± 0.1 Ma (3)	6–10 Ma (4)	26 Ma (4)	1.2 Ma (1)
SiO ₂	41.54	44.29	45.87	41.81	47.07	46.83	43.07
TiO ₂	3.22	2.68	2.64	3.05	2.40	1.63	3.19
Al ₂ O ₃	13.11	13.68	14.61	11.83	15.58	16.97	14.19
Fe ₂ O ₃	15.21	13.81	12.55	14.17	13.30	9.49	13.36
MnO	0.25	0.18	0.18	0.20	0.18	0.16	0.19
MgO	6.99	9.84	9.55	14.17	7.73	7.85	8.63
CaO	9.66	9.55	8.59	8.52	8.39	9.44	9.73
Na ₂ O	4.90	3.70	3.15	3.89	3.77	3.08	3.79
K ₂ O	2.96	1.58	1.85	1.90	1.31	3.37	1.63
P ₂ O ₅	1.43	0.60	0.49	0.80	0.65	0.64	0.89
Ba	1309	800	630	819	437	4792	722
Co	35	50	45	71	42	34	46
Cr	123	361	337	672	279	188	218
Ni	133	232	394	517	159	127	154
Sc	222	19	16	18	13	29	20
LOI	0.00	0.00	0.71	0.00	0.29	0.27	1.62
Total	99.44	100.07	100.35	100.58	100.77	100.26	100.41

OI-NEPH, olivine nephelinite; AOB, alkali olivine basalt [terminology of Francis & Ludden (1990)]. Ages from: (1) K–Ar method (Sun *et al.*, 1991); (2) Metcalfe (1987); (3) K–Ar method by B. N. Church (Brearley *et al.*, 1984); (4) Bevier (1983). All data in wt % but Ba, Co, Cr, Ni and Sc in ppm. LOI, loss on ignition.

protogranular and very coarse grained (2 mm). Porphyroclastic to equigranular textures are found in LL and KR xenoliths, the latter site having moderately coarse-grained xenoliths (1 mm). Kink-banding in olivine is common in all samples. Spinels in the protogranular xenoliths are large, with rounded boundaries, and are associated with opx, whereas those in the equigranular xenoliths are small and interstitial. Clinopyroxene occurs as much smaller grains than olivine and opx.

Augite-bearing wehrlites are abundant at KL (about 50% of the xenoliths sampled) and SL (about 25% of the whole suite); these two xenolith sites are located closest to the boundary of cratonic North America (Figs 1 and 2). Seven augite-bearing lherzolites, which are opx poor compared with the Cr-diopside lherzolites (Fig. 2), were found at SL and one at KL. All these augite xenoliths

exhibit cumulate textures, similar to those commonly observed in the Type II xenoliths of Frey & Prinz (1978), characterized by olivine grains or olivine aggregates enclosed in poikilitic augites. The wehrlites are very coarse grained at KL (2–3 mm), but finer grained at SL (<1 mm). A few pyroxenites (<60% olivine) were found at BT, KL, KR and SL, and composite xenoliths are sometimes present at BT, SL and KL (Fig. 2).

ANALYTICAL TECHNIQUES

Whole-rock samples of the xenoliths and their host basalts were crushed in an aluminum mortar and fused with lithium tetraborate. Whole-rock major elements and the trace elements Ba, Sc, Co, Ni and Cr were analyzed by

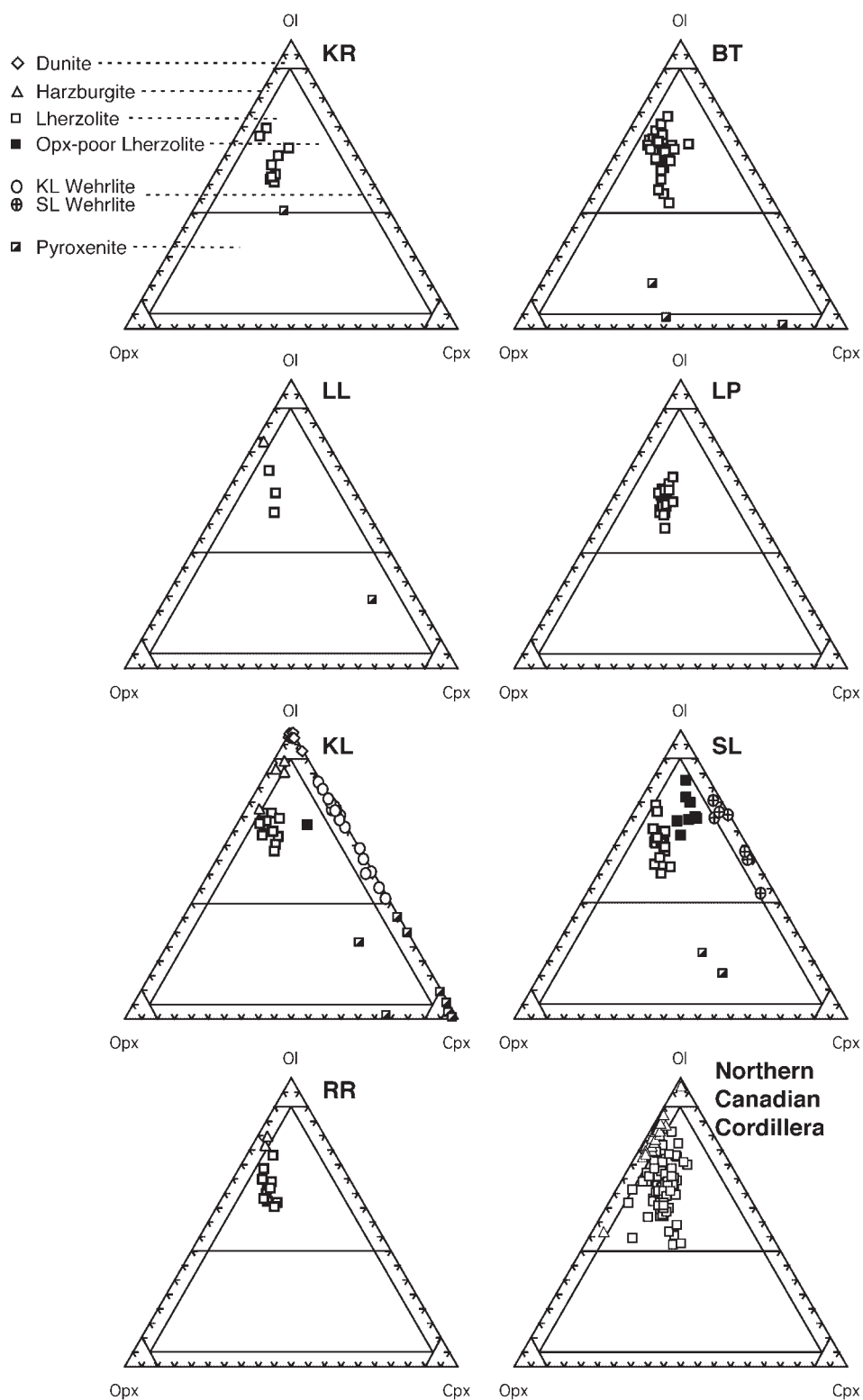


Fig. 2. Modal composition of the xenolith suites. The modal compositions were determined by calculating the normative mineralogy of spinel peridotites from their whole-rock composition and distributing the elements among olivine, opx, cpx and spinel. The following equations in molar units were used: $\text{Cpx} = X = (\text{Ca} + \text{Na} + \text{K})$; $\text{Sp} = Y^{3+}/2 = \text{Cr}/2 + (\text{Al} + 2\text{Ti} - \text{Na})/2$; $\text{Opx}^* = Y/2 = [(\text{Mg} + \text{Fe} + \text{Mn}) - \text{Sp} - \text{cpx}]/2$; $\text{Si}^* = \text{Si} - 2\text{Cpx} - 2\text{Opx} + \text{Ti}$; $\text{Ol} = -\text{Si}^*$; $\text{Opx} = \text{Opx}^* - \text{Ol}$. Conversion to cation units and normalization to 100% gives the modal proportion.

Table 2: Representative whole-rock analyses of peridotite mantle xenoliths from the southern Canadian Cordillera

	KLX-67	RRX-21	KLX-47	KLX-70	BTX-16	BTX-23	BTX-26	KRX-14
	Fe-rich dunite	Harzburgite	Harzburgite	Lherzolite	Lherzolite	Lherzolite	Lherzolite	Lherzolite
Cpx	0.69	3.10	4.49	11.60	12.02	10.66	18.36	15.35
Opx	1.34	16.88	22.86	18.22	25.71	21.34	31.50	23.37
Olivine	97.04	78.72	71.13	68.41	59.58	65.78	46.44	58.35
Spinel	0.94	1.30	1.52	1.78	2.68	2.22	3.71	2.93
SiO ₂	39.890	42.660	43.730	43.400	44.320	43.720	44.960	43.870
TiO ₂	0.019	0.020	0.015	0.146	0.070	0.040	0.120	0.170
Al ₂ O ₃	0.300	0.940	1.260	1.850	3.050	2.140	4.560	3.450
FeO _t	10.100	8.670	7.950	8.670	8.150	8.190	7.660	8.780
MnO	0.139	0.130	0.130	0.139	0.130	0.140	0.130	0.140
MgO	47.790	45.430	44.370	41.650	40.460	41.880	36.670	38.860
CaO	0.120	0.640	0.940	2.280	2.430	2.240	3.640	3.050
Na ₂ O				0.200	0.140	0.010	0.260	0.210
K ₂ O	0.030	0.010	0.010	0.020	0.020	0.010	0.050	0.200
P ₂ O ₅	0.016	0.000	0.010	0.021			0.010	0.020
NiO	0.410	0.320	0.330	0.310	0.290	0.310	0.260	0.280
Cr ₂ O ₃	0.382	0.340	0.399	0.421	0.410	0.490	0.500	0.360
Ba					10			32
Co	163	132	120	117	104	119	102	110
Sc			30		17		86	18
LOI								0.27
Total	100.15	100.03	99.52	100.01	100.34	100.02	99.14	100.59
mg-no.	0.894	0.903	0.909	0.895	0.899	0.901	0.895	0.887
T°C Wells	989	874		983	908	964	978	958
T°C Ca Opx	985	889	985	945	927	1271	961	936

X-ray fluorescence spectrometry (XRF) with a Philips PW 1400 system in the Earth and Planetary Sciences Department of McGill University. Representative analyses are given in Tables 1 and 2 and the complete dataset is given in an Electronic Appendix that may be downloaded from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>. The analytical precision (in wt %) is <0.6% for all major elements, calculated from 20 replicates on one fused disc.

The major element compositions of minerals were analyzed using a JEOL 8700 Super-probe at McGill University, with an accelerating voltage of 20 kV, a beam current of 20 nA and a beam diameter of 5 µm. All elements were measured with 20 s counting time on peaks and 10 s on background, except for Ni, for which counting times were 50 s and 25 s, respectively. Representative analyses are given in Tables 3–6 and the complete dataset is given in the Electronic Appendix. Trace element abundances in whole-rock samples were

determined by inductively coupled plasma mass spectrometry (ICP-MS; Perkin Elmer SCIEX ELAN) analysis of solutions at the CRPG (Nancy, France), after pre-concentration on True Spec resin columns. These solutions were prepared by mixing 300 mg of sample with lithium tetraborate, melting the mix at 980°C, and dissolving the resulting glass bead into concentrated nitric acid overnight. Representative analyses are given in Table 7 and the complete dataset is given in the Electronic Appendix. Reproducibility is better than 0.1 ppm for most elements, as can be seen in two replicates of sample BTX-26 in Table 7.

MINERALOGY

Olivines from the Cr-diopside peridotites are homogeneous in composition within individual grains and thin sections (Table 3). These olivines have Fo contents

Table 2: continued

	KRX-8	LPX-18	RRX-18	SLX-4	KLX-11	SLX-24	SLX-39	SLX-14
	Lherzolite	Lherzolite	Lherzolite	Lherzolite	Wehrlite	Wehrlite	Wehrlite	Opx-poor lherz
Cpx	18.64	14.11	16.56	9.70	45.74	40.44	21.21	18.80
Opx	28.33	18.89	26.53	24.52	2.10	2.38	2.32	10.51
Olivine	49.13	64.88	53.69	63.58	49.12	52.91	74.06	68.06
Spinel	3.90	2.12	3.22	2.21	3.04	4.26	2.41	2.64
SiO ₂	44.690	43.560	44.490	43.770	43.640	42.610	41.050	42.230
TiO ₂	0.160	0.120	0.086	0.053	0.480	0.324	0.178	0.150
Al ₂ O ₃	4.770	3.060	3.730	2.100	3.540	5.340	2.330	2.810
FeO _i	8.170	8.750	8.100	9.360	11.640	8.240	12.090	10.230
MnO	0.130	0.140	0.132	0.155	0.170	0.143	0.193	0.170
MgO	37.040	40.110	38.340	40.780	29.890	33.010	38.070	38.840
CaO	3.770	2.490	3.350	2.030	9.060	7.990	4.230	3.760
Na ₂ O	0.190	0.610	0.170		0.330	0.340	0.140	0.170
K ₂ O	0.090	0.200	0.010	0.050	0.030	0.080	0.040	0.130
P ₂ O ₅	0.010	0.010	0.003	0.003	0.020	0.021	0.065	0.010
NiO	0.260	0.280	0.270	0.310	0.110	0.230	0.230	0.270
Cr ₂ O ₃	0.380	0.290	0.523	0.357	0.250	0.356	0.339	0.410
Ba	102				53	44	31	24
Co	12	113	105	117	129	105	122	111
Sc	0.03		10		23	29	15	13
LOI	0.03		0.120	0.190		0.55	0.06	0.09
Total	99.66	100.55	100.18	100.13	100.46	100.12	100.33	100.37
mg-no.	0.890	0.891	0.894	0.886	0.821	0.877	0.849	0.871
T°C Wells		900	906	1038	1057	1028		
T°C Ca Opx		918	936	1068	1074	1055		

The complete dataset is available for downloading from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>. Mode data in % (calculation details in caption of Fig. 2). Silicate oxides in wt %, Ba, Co and Sc in ppm.

ranging from 87.5 to 91.5, which roughly correlates with the modal proportion of olivine (Fig. 3). The olivines of the Cr-diopside harzburgites and dunites, however, do not have systematically higher Fo contents than the lherzolites (89.5–91.5). Orthopyroxenes are generally homogeneous in composition, but exsolution lamellae of cpx are present in large opx crystals in xenoliths from BT and RR. Lherzolite opx and cpx are typically enstatite and Cr-diopside, respectively (Tables 4 and 5). The CaO content of opx and the FeO content of cpx in SL lherzolites are, however, higher than those of the opx and cpx in lherzolites from the other suites. Spinel has homogeneous compositions within individual xenoliths, with *mg*-number $[Mg/(Mg + Fe^{2+})]$ ranging from 0.70 to 0.85 (Table 6).

Olivine grains in the augite xenoliths are homogeneous in composition within individual samples. The Fo contents of olivine in the wehrlites range from 82.5 to 84.5 at KL and from 85 and 90.5 at SL and those of the opx-poor lherzolites at SL from 87 to 90 (Table 3). The

wehrlite olivine has Fo contents that correlate positively with the olivine modal proportion at KL, but negatively at SL (Fig. 3). The cpx in the wehrlites and opx-poor lherzolites is a black augite, distinctly more Fe rich than the emerald green cpx of the Cr-diopside peridotites (Table 5). One harzburgite at KL also has augitic cpx. Exsolution lamellae of opx are occasionally observed in the augites.

GEO THERMOMETRY

Equilibration temperatures were calculated using the geothermometer of Wells (1977), which is based on the exchange of Fe^{2+} and Mg^{2+} between cpx and opx (T_{Fe-Mg}), and that of Brey & Köhler (1990), which is based on the exchange of Ca between opx and cpx ($T_{Ca \text{ in opx}}$) but is pressure dependent. As no geobarometer exists for spinel peridotites, the pressure is constrained only by the spinel stability field (10–20 kbar; Green & Hibberson, 1970;

Table 3: Representative olivine and amphibole analyses

	KLX-67	RRX-21	KLX-47	KLX-70	BTX-16	BTX-23	BTX-26	KRX-14
SiO ₂	39.96	40.82	41.12	40.88	40.95	41.02	40.88	40.36
TiO ₂	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01
FeO _t	9.92	8.81	8.39	9.03	9.27	8.93	9.50	10.09
MnO	0.10	0.12	0.11	0.13	0.13	0.13	0.13	0.15
MgO	48.55	49.61	49.79	49.35	49.35	49.63	49.31	48.06
CaO	0.06	0.04	0.05	0.05	0.04	0.04	0.06	0.09
Na ₂ O	0.01	0.00	0.02	0.01	0.00	0.00	0.01	0.01
NiO	0.33	0.31	0.33	0.30	0.30	0.30	0.29	0.29
Cr ₂ O ₃	0.01	0.01	0.07	0.01	0.01	0.00	0.00	0.02
Total	98.97	99.73	99.90	99.78	100.05	100.07	100.20	99.07
mg-no.	0.8972	0.9094	0.9137	0.9069	0.9047	0.9083	0.9025	0.8947

	LPX-18	RRX-18	SLX-4	KLX-11	SLX-24	SLX-39	SLX-14	LPX-18 Amph
SiO ₂	40.78	40.54	40.26	38.98	40.28	39.50	39.79	47.13
TiO ₂	0.00	0.00	0.00	0.00	0.01	0.01	0.01	2.03
Al ₂ O ₃	0.00	0.00	0.03	0.03	0.02	0.01	0.03	7.71
FeO _t	10.11	9.64	10.23	16.13	10.78	14.11	12.55	3.05
MnO	0.15	0.14	0.15	0.20	0.17	0.21	0.14	0.06
MgO	48.30	48.91	48.83	44.54	48.40	45.69	46.70	14.20
CaO	0.06	0.04	0.10	0.10	0.13	0.20	0.16	23.33
Na ₂ O	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.58
K ₂ O								0.01
P ₂ O ₅								0.03
NiO	0.28	0.30	0.30	0.16	0.23	0.20	0.30	0.05
Cr ₂ O ₃	0.00	0.01	0.01	0.00	0.02	0.01	0.00	1.40
Total	99.69	99.58	99.92	100.15	100.04	99.95	99.69	99.56
mg-no.	0.8949	0.9004	0.8948	0.8311	0.8889	0.8523	0.8690	

Amphiboles are Ti-pargasites. Silicate oxides in wt %. The complete dataset is available for downloading from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>. Each mineral composition represents the average of three spot analyses on different grains.

O'Neill, 1981). The best match between $T_{\text{Ca in opx}}$ and $T_{\text{Fe-Mg}}$ for the Canadian Cordilleran xenoliths is obtained using a pressure of 10 kbar in the calculation of $T_{\text{Ca in opx}}$ (Table 2). One sample (BTX-23) falls off the 1:1 correlation between the two geothermometers probably because the microprobe spots may have partly overlapped cpx exsolution lamellae, resulting in higher Ca contents and thus high $T_{\text{Ca in opx}}$. For many of the wehrlites, the use of these thermometers is not possible because opx is absent.

Most of the calculated temperatures range between 900°C and 1000°C (Table 2), which is consistent with previous studies at RR (Canil *et al.*, 1987), KR (Fujii & Scarfe, 1982), LP (Brearley *et al.*, 1984) and KL (Canil

& Scarfe, 1989). SL Cr-diopside lherzolites record temperatures significantly higher than 1000°C, even higher than those for most other suites in the Canadian Cordillera. This suggests that the geotherm is steeper beneath SL than elsewhere (Brearley & Scarfe, 1984), that the xenoliths originated from a deeper source region (Brearley & Scarfe, 1984) or that a magmatic intrusion heated the SL mantle lithosphere. Some harzburgites in the northern Canadian Cordillera record similarly high temperatures, ~100°C hotter than those for associated lherzolites (Shi *et al.*, 1998). The augite xenoliths yield higher temperatures than all Cr-diopside xenoliths except those of SL (Table 2), which indicates either that these rocks originated at greater depth than the Cr-diopside lherzolites or that

Table 4: Representative orthopyroxene analyses

	KLX-67	RRX-21	KLX-47	KLX-70	BTX-16	BTX-23
SiO ₂	55.71	55.24	56.28	54.74	55.11	54.68
TiO ₂	0.02	0.03	0.01	0.08	0.07	0.06
Al ₂ O ₃	1.25	2.64	2.94	3.50	4.48	4.71
FeO _t	6.46	5.80	5.53	5.96	6.26	5.58
MnO	0.09	0.13	0.13	0.14	0.12	0.13
MgO	33.92	34.79	33.89	34.05	33.48	32.13
CaO	0.84	0.53	0.85	0.70	0.65	2.26
Na ₂ O	0.07	0.06	0.13	0.11	0.08	0.16
K ₂ O	0.00	0.00	0.01	0.00	0.00	0.01
P ₂ O ₅	0.02	0.00	0.02	0.01	0.00	0.01
NiO	0.07	0.08	0.07	0.10	0.07	0.08
Cr ₂ O ₃	0.38	0.44	0.60	0.49	0.36	0.69
Total	98.84	99.74	100.44	99.87	100.68	100.48
<i>mg</i> -no.	0.9034	0.9144	0.9162	0.9106	0.9051	0.9113
Cr/(Cr + Al)	0.170	0.100	0.121	0.086	0.051	0.090

	BTX-26	KRX-14	LPX-18	RRX-18	SLX-4	KLX-11
SiO ₂	54.87	54.29	54.82	54.25	53.71	52.07
TiO ₂	0.11	0.10	0.06	0.08	0.07	0.41
Al ₂ O ₃	5.16	4.51	4.23	4.12	4.91	6.12
FeO _t	6.18	6.52	6.53	6.43	6.74	10.54
MnO	0.13	0.15	0.16	0.15	0.13	0.19
MgO	32.99	33.32	33.75	33.59	32.84	29.36
CaO	0.77	0.68	0.64	0.67	1.16	1.16
Na ₂ O	0.12	0.13	0.07	0.06	0.10	0.12
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00
P ₂ O ₅	0.01	0.00	0.00	0.00	0.00	0.01
NiO	0.09	0.09	0.08	0.08	0.09	0.06
Cr ₂ O ₃	0.36	0.30	0.28	0.33	0.56	0.15
Total	100.78	100.08	100.60	99.77	100.32	100.20
<i>mg</i> -no.	0.9049	0.9011	0.9021	0.9031	0.8968	0.8324
Cr/(Cr + Al)	0.044	0.043	0.042	0.051	0.071	0.016

Silicate oxides in wt %. The complete dataset is available for downloading from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>. Each mineral composition represents the average of three spot analyses on different grains.

they record higher magmatic temperatures whereas the Cr-diopside suites record lower temperatures of metamorphic origin.

WHOLE-ROCK GEOCHEMISTRY

The spectrum of Cr-diopside peridotite xenoliths varies from Al-rich lherzolites to Al-poor lherzolites, harzburgites and dunites. The *mg*-number varies from 88 to 91 and Al₂O₃ from 1.4 to 4.8 wt % in the lherzolites

(Fig. 4). Four of the seven dunites sampled at KL have high *mg*-number (>89) and equigranular textures, and thus appear to belong to the Cr-diopside peridotite group. Three of these Cr-diopside dunites are enriched in FeO compared with most other Cr-diopside peridotites (Fig. 5), and thus their *mg*-number (89) is not higher than that of the most depleted lherzolites. The range of Al₂O₃ contents in the Cr-diopside peridotites varies from site to site, from relatively low-Al lherzolites at KL to relatively high-Al lherzolites at LP and KR (Fig. 4). The overall range in Al₂O₃ of all southern Canadian Cordillera

Table 5: Representative clinopyroxene analyses

	KLX-67	RRX-21	KLX-70	BTX-16	BTX-23	BTX-26	KRX-14
SiO ₂	52.77	52.15	50.09	52.46	52.20	52.10	51.71
TiO ₂	0.15	0.18	1.21	0.37	0.18	0.45	0.51
Al ₂ O ₃	3.43	4.45	6.60	6.95	6.00	7.21	6.81
FeO _t	2.93	2.28	2.85	2.44	2.50	2.81	3.05
MnO	0.05	0.07	0.08	0.08	0.08	0.09	0.09
MgO	16.66	15.84	15.70	14.90	15.56	15.25	15.27
CaO	20.39	21.02	19.78	20.58	20.84	19.76	19.69
Na ₂ O	1.31	1.62	1.54	1.82	1.41	1.78	1.86
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P ₂ O ₅	0.44	0.01	0.04	0.01	0.01	0.01	0.02
NiO	0.02	0.04	0.04	0.03	0.04	0.04	0.04
Cr ₂ O ₃	1.59	1.41	1.26	0.88	1.26	0.76	0.68
Total	99.75	99.06	99.18	100.52	100.08	100.25	99.73
<i>mg</i> -no.	0.9102	0.9254	0.9075	0.9158	0.9172	0.9064	0.8993
Cr/(Cr + Al)	0.2378	0.1747	0.1138	0.0784	0.1235	0.0664	0.0627

	LPX-18	RRX-18	SLX-4	KLX-11	SLX-24	SLX-39	SLX-14
SiO ₂	51.90	50.84	51.09	49.06	49.97	50.43	50.17
TiO ₂	0.30	0.42	0.31	0.89	0.63	0.63	0.66
Al ₂ O ₃	5.46	6.36	5.83	6.90	7.31	6.57	6.67
FeO _t	2.72	2.67	3.40	6.01	3.83	4.71	4.14
MnO	0.09	0.08	0.09	0.13	0.12	0.12	0.14
MgO	15.79	15.27	16.50	15.38	15.91	15.33	15.71
CaO	21.67	20.65	19.96	19.18	19.82	19.85	20.02
Na ₂ O	1.20	1.58	1.12	0.86	1.16	1.09	1.13
K ₂ O	0.00	0.00	0.01	0.00	0.00	0.01	0.01
P ₂ O ₅	0.01	0.02	0.02	0.03	0.02	0.46	0.42
NiO	0.03	0.04	0.04	0.03	0.04	0.04	0.02
Cr ₂ O ₃	0.69	0.76	1.08	0.75	0.46	0.77	0.71
Total	99.87	98.66	99.44	99.21	99.25	100.01	99.80
<i>mg</i> -no.	0.9119	0.9106	0.8964	0.8201	0.8809	0.8531	0.8713
Cr/(Cr + Al)	0.0777	0.0739	0.1105	0.0677	0.0402	0.0728	0.0664

Silicate oxides in wt %. The complete dataset is available for downloading from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>. Each mineral composition represents the average of three spot analyses on different grains.

xenoliths is similar to that of the suites from the northern Canadian Cordillera (prominent mode at 3.25, Fig. 4; Shi *et al.*, 1998).

The augite wehrlites have lower *mg*-number (from 79 to 85 at KL, and from 80.5 to 88 at SL) than the Cr-diopside peridotites. The low *mg*-number (<85) and the cumulate texture of three of the seven dunites sampled at KL indicate that they are part of the augite xenolith group. The opx-poor augite-bearing lherzolites have intermediate compositions between the Cr-diopside peridotites and the augite wehrlites in terms of major (Fig.

6) and trace (Fig. 7) elements, and their *mg*-number varies from 84 to 89. The augite xenoliths at SL (wehrlites, opx-poor lherzolites) have lower Fe, and higher Al contents at similar MgO contents than those at KL (Fig. 6).

Rare earth element (REE) patterns in the lherzolites vary from light rare earth element (LREE) depleted, through flat, to LREE enriched (Fig. 7). Harzburgites from RR have LREE-depleted patterns, whereas those from KL and LL have steep LREE-enriched patterns. The levels of middle to heavy rare earth elements (MREE to HREE) in the lherzolites generally correlate positively

Table 6: Representative spinel analyses

	KLX-67	RRX-21	KLX-47	KLX-70	BTX-16	BTX-23	BTX-26
SiO ₂	0.04	0.00	0.03	0.00	0.00	0.00	0.01
TiO ₂	0.16	0.09	0.01	0.26	0.06	0.07	0.11
Al ₂ O ₃	16.41	41.47	36.78	48.19	56.69	49.19	58.42
FeO _t	19.60	12.00	13.22	11.62	10.47	11.50	10.07
MnO	0.11	0.15	0.19	0.14	0.11	0.12	0.10
MgO	12.77	18.59	17.61	20.07	21.20	20.18	21.67
CaO	0.02	0.00	0.04	0.01	0.00	0.00	0.00
Na ₂ O	0.01	0.00	0.01	0.00	0.00	0.00	0.00
NiO	0.14	0.22	0.24	0.30	0.37	0.30	0.39
Cr ₂ O ₃	49.87	27.65	31.96	19.80	10.84	17.78	8.87
Total	99.13	100.18	100.10	100.38	99.75	99.14	99.63
Fe ³⁺	0.127	0.047	0.063	0.060	0.051	0.069	0.051
Fe ²⁺	0.393	0.230	0.248	0.199	0.175	0.188	0.164
mg-no.	0.5373	0.7342	0.7037	0.7548	0.7831	0.7578	0.7933
cr-no.	0.6707	0.3090	0.3681	0.2160	0.1137	0.1951	0.0924

	KRX-14	LPX-18	RRX-18	KLX-11	SLX-24	SLX-39	SLX-14
SiO ₂	0.01	0.00	0.00	0.02	0.02	0.05	0.04
TiO ₂	0.26	0.07	0.07	0.24	0.27	0.35	0.25
Al ₂ O ₃	57.33	58.59	58.16	60.15	61.71	50.77	52.71
FeO _t	11.50	10.34	10.40	16.53	9.76	17.68	14.26
MnO	0.10	0.11	0.11	0.12	0.11	0.10	0.16
MgO	21.23	21.32	20.91	19.15	21.61	18.03	18.84
CaO	0.00	0.01	0.00	0.01	0.01	0.00	0.00
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.01	0.01
NiO	0.37	0.35	0.34	0.21	0.31	0.27	0.29
Cr ₂ O ₃	9.52	9.53	9.84	3.81	6.39	12.08	11.99
Total	100.34	100.32	99.84	100.23	100.19	99.35	98.54
Fe ³⁺	0.063	0.041	0.033	0.091	0.023	0.119	0.074
Fe ²⁺	0.184	0.180	0.190	0.265	0.183	0.278	0.244
mg-no.	0.7670	0.7861	0.7818	0.6737	0.7978	0.6451	0.7020
cr-no.	0.1002	0.0984	0.1019	0.0407	0.0649	0.1376	0.1324

Silicate oxides in wt %. The complete dataset is available for downloading from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>. Each mineral composition represents the average of three spot analyses on different grains.

with Al₂O₃, but a broad negative correlation exists between La/Yb ratio and Al₂O₃ content (Fig. 8). Rubidium and Ba are enriched compared with the HREE in all xenoliths when compared with primitive mantle. Overall, the majority of the lherzolites analyzed (13 of a total of 17 samples) exhibit pronounced negative Zr and Hf anomalies, commonly coupled with a negative Ti anomaly (10 of a total of 17 samples). Zr and Hf broadly correlate with Al₂O₃ content in most Cr-diopside lherzolites, but not with La/Yb ratios (Fig. 9). Most Ta and Nb analyses were discarded because they were too close

to the detection limit (<0.1 times primitive mantle; Sun & McDonough, 1989). Finally, the Cr-diopside lherzolites and harzburgites that plot above the Zr and Hf vs Al₂O₃ correlations are systematically LREE enriched (Figs 8 and 9).

REE patterns in the SL augite xenoliths are characterized by LREE enrichment, relatively flat MREE to HREE, and negative HFSE anomalies (Fig. 7). SL opx-poor lherzolites have trace elements patterns that mimic those of the SL augite xenolith suites, but with systematically lower contents (Fig. 7). KL augite xenoliths,

Table 7: Trace element content of bulk-rock (ppm) mantle xenoliths

Sample no.: Rock type:	RRX-21 Harz	KLX-47 Harz	BTX-16 Lherz	BTX-23 Lherz	BTX-26 Lherz	BTX-26 (2) Lherz	KRX-14 Lherz	LPX-18 Lherz	SLX-4 Lherz	KLX-11 Wehr	SLX-39 Wehr
La	0.01	0.39	0.04	0.23	0.09	0.11	1.46	3.11	0.06	1.41	4.39
Ce	0.02	0.89	0.08	0.47	0.31	0.36	2.37	8.94	0.18	3.92	10.15
Pr		0.11	0.02	0.05	0.07	0.06	0.43	1.16	0.03	0.66	1.30
Nd		0.45	0.18	0.27	0.50	0.45	1.81	5.05	0.20	3.31	5.54
Sm	0.01	0.09	0.09	0.07	0.26	0.22	0.42	1.00	0.09	1.03	1.03
Eu	0.01	0.02	0.05	0.03	0.11	0.10	0.17	0.29	0.04	0.38	0.32
Gd	0.03	0.09	0.22	0.11	0.43	0.42	0.48	0.71	0.13	1.23	1.02
Tb	0.00	0.01	0.05	0.02	0.09	0.08	0.09	0.12	0.03	0.19	0.16
Dy	0.05	0.06	0.32	0.18	0.64	0.59	0.59	0.72	0.20	1.09	0.88
Ho	0.01	0.01	0.07	0.04	0.14	0.13	0.13	0.15	0.05	0.20	0.18
Er	0.03	0.04	0.25	0.12	0.41	0.38	0.35	0.46	0.15	0.47	0.49
Tm	0.01	0.01	0.04	0.02	0.07	0.06	0.06	0.07	0.03	0.06	0.08
Yb	0.05	0.05	0.26	0.14	0.43	0.43	0.34	0.47	0.18	0.40	0.46
Lu	0.01	0.01	0.04	0.02	0.07	0.06	0.06	0.08	0.03	0.05	0.08
Sc	7.60			11.16	16.60						
Ti	108	90	420	240	749		995	719	318	2854	1067
Ba	1.46	1.92	2.69	16.62	2.30	2.44	17.36	24.92	3.38	8.72	23.35
Co	103	98	87	98	81	88	88	91	105	97	101
Cr	2597	2563	2736	2885	3062	3301	2271	2551	2547	1666	2227
Cs	0.06	0.00	0.02	0.21	0.11	0.04	0.02	0.03	0.03		0.04
Cu	8.89	3.70	19.24	5.00	19.44	20.99	8.65	19.53	17.39	26.09	25.61
Ga	1.39	1.03	2.73	2.02	3.87	4.17	4.47	3.95	1.98	5.86	3.09
Hf	0.01	0.07	0.06	0.04	0.13	0.13	0.25	0.24	0.05	0.65	0.33
Mo	0.41	0.25	0.24	0.29	0.28	0.27	0.26	0.25	0.22	0.13	0.17
Nb		0.18		0.08	0.04	0.03	1.51	2.09	0.03	0.91	1.29
Ni	2164	2163	1680	1944	1546	1742	1641	1963	2103	775	1597
Rb	0.32	0.18	0.45	0.80	0.90	0.62	3.59	3.05	0.58	0.54	0.75
Sb	0.06	0.03	0.06	0.04	0.01	0.04	0.03	0.02	0.01	0.03	0.04
Sn	0.11	0.07	0.10	0.08	0.09	0.15	0.14	0.16	0.02	0.31	0.16
Sr	0.53	4.59	2.84	8.14	10.32	11.61	99.27	70.05	3.89	43.88	32.29
Ta		0.02		0.01			0.09	0.07		0.08	0.13
Th		0.13	0.01	0.02			0.09	0.03		0.09	0.28
V	26.20	29.58	65.16	53.32	89.12	94.74	71.65	73.32	52.85	165.66	73.64
W	0.04	0.07	0.02	0.02	0.05	0.24	0.03	0.01			
Y	0.26	0.34	2.23	1.10	3.90	4.01	3.43	4.15	1.44	5.60	5.12
Zn	40.76	40.80	43.47	51.40	42.82	47.53	49.92	41.13	44.96	62.21	55.28
Zr	0.33	3.46	1.82	1.20	3.91	4.22	9.24	9.37	1.53	18.00	12.59
Ge	0.77	0.68	0.78	0.82	0.91	0.81	0.96	0.78	0.68	1.01	0.70

The complete dataset is available for downloading from the *Journal of Petrology* website at <http://www.petrology.oupjournals.org>.

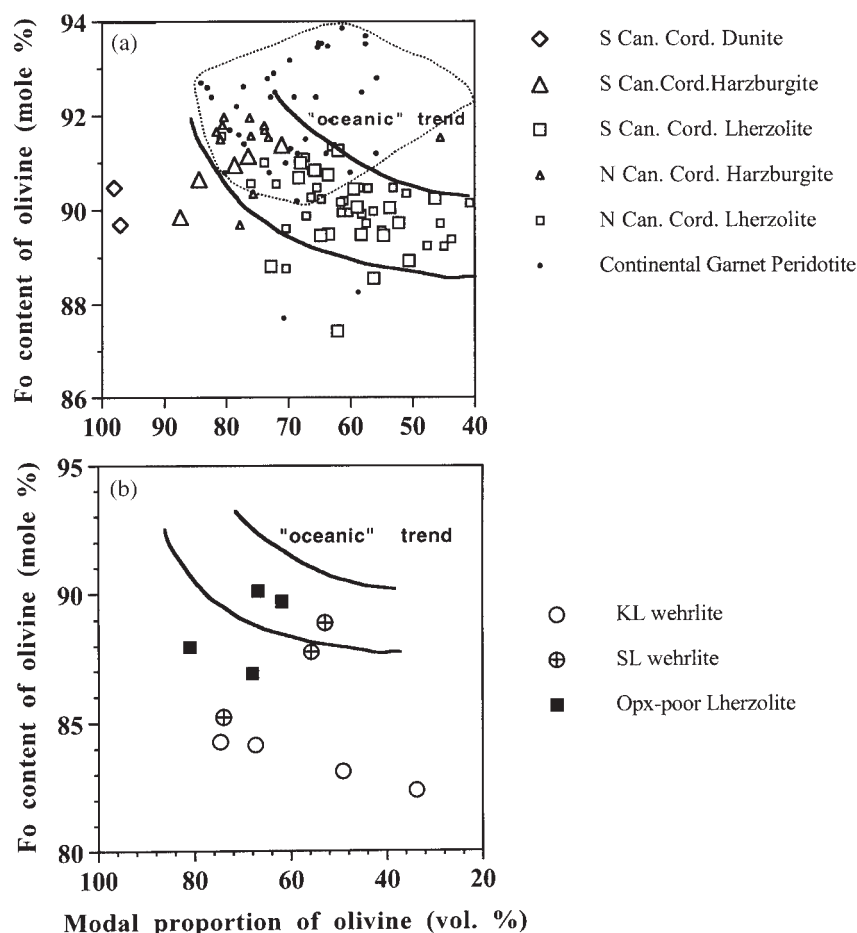


Fig. 3. Forsterite content vs the modal proportion of olivine in xenoliths from the Canadian Cordillera. (a) Cr-diopside suites. The two black lines limit the 'oceanic trend' of Boyd (1989) based on abyssal and ophiolite data, and between which most of the spinel peridotites plot. Dotted line that surrounds small black circles defines the field for garnet peridotites from cratonic areas [see below and also fig. 2 of Boyd (1989)]. Northern Canadian Cordillera data are from Shi *et al.* (1998). Spinel peridotites from around the world: Australia (Griffin *et al.*, 1984; O'Reilly & Griffin, 1988; Stolz & Davies, 1988; Chen *et al.*, 1989); Africa (Dupuy *et al.*, 1986); Asia (Song & Frey, 1989; Ionov & Wood, 1992; Ionov *et al.*, 1995); Europe (Dupuy *et al.*, 1987); North America (Frey & Prinz, 1978; Boyd, 1981; Roden *et al.*, 1988; Galer & O'Nions, 1989; Brandon & Draper 1996; Bernstein *et al.*, 1998). Garnet peridotites from South Africa (Boyd, 1981, 1987; Nixon *et al.*, 1981; Nixon, 1987; Boyd *et al.*, 1993) and Siberia (Boyd *et al.*, 1997). (b) Augite xenolith suites compared with the Cr-diopside suites (black lines).

on the other hand, are systematically depleted in HREE compared with MREE, and show a characteristic convex-upwards pattern (Fig. 7). KL augite xenoliths exhibit negative Hf, Zr and Nb anomalies, but no Ti anomaly (Fig. 7). Most trace elements correlate positively with Al_2O_3 content, but not with La/Yb ratio in the KL augite xenolith suite (Hf and Zr shown in Fig. 9).

DISCUSSION

The Cr-diopside xenolith suites

Processes responsible for the Cr-diopside suite compositional range

Correlations between MgO and other major elements (Fig. 5) can be interpreted as reflecting various degrees

of extraction of a basaltic melt from the most fertile composition (lowest MgO) leaving the more depleted (higher MgO) compositions as solid residues. In a diagram in which a compatible element (e.g. Ni) is plotted against a relatively incompatible element (e.g. Yb) (Fig. 10), progressive melting of a fertile composition should produce a series of residual compositions with a relatively larger variation in incompatible elements compared with that for compatible elements (Francis, 1987). In the melting model presented here, the source composition (KRX-13) is taken as one of the most fertile of our samples, which resembles primitive mantle compositions (Ringwood, 1975; Hart & Zindler, 1986; Fig. 10 and Table 2), and whose flat to LREE-depleted trace element pattern indicates no metasomatic disturbance (Fig. 7).

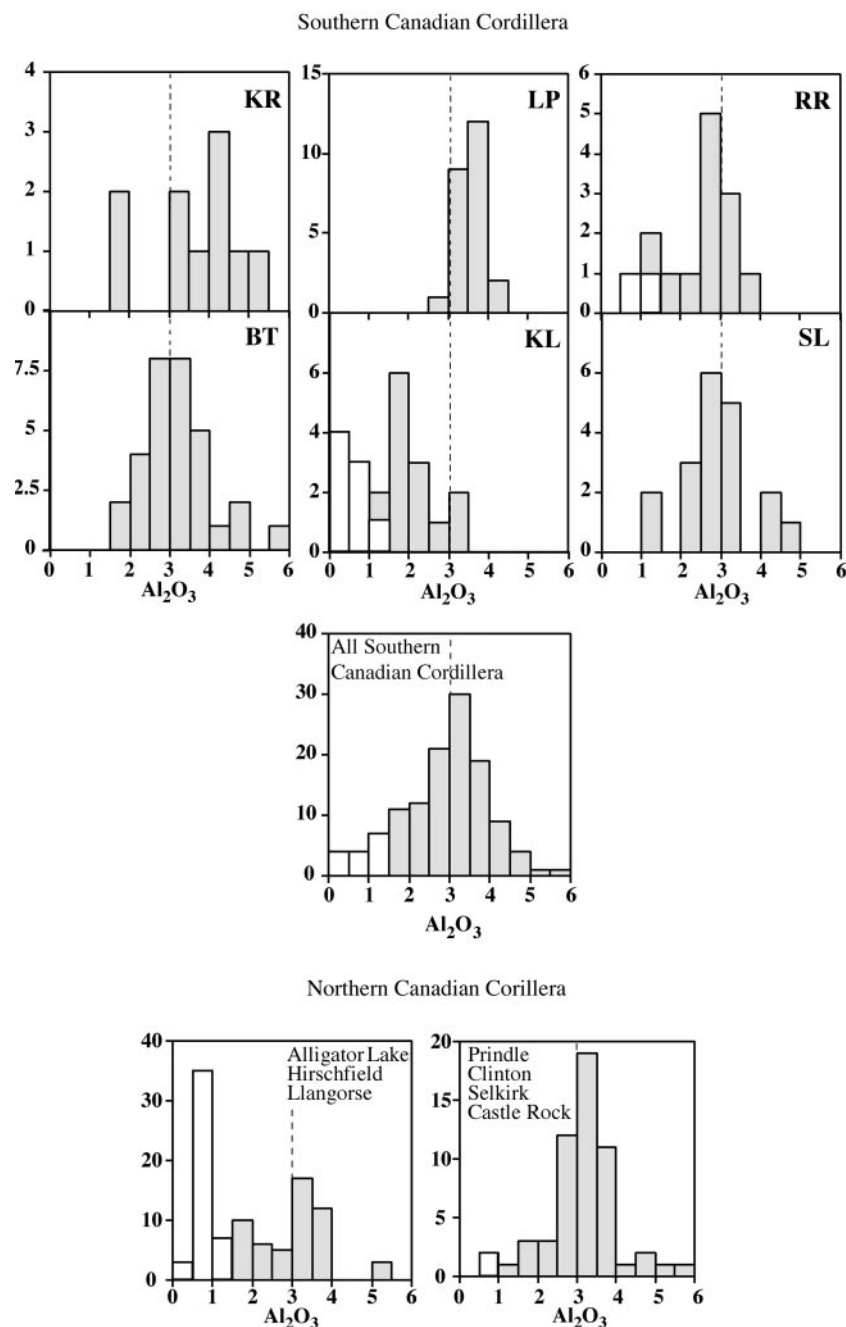


Fig. 4. Histograms of Al_2O_3 contents (wt %) for Cr-diopside peridotites from the Canadian Cordillera. Lherzolites are in gray and harzburgites (and dunites in the case of KL) in white. Data for the northern Canadian Cordillera from Francis (1987) and Shi *et al.* (1998). Dotted line is a reference line at 3 wt %. LL is not shown, as only four samples were available.

Both equilibrium and fractional melting trends (Shaw, 1979) can reasonably reproduce the range of lherzolite Ni and Yb compositions (Fig. 10). Using partition coefficients $D_{\text{Yb}} = 0.1$ and $D_{\text{Ni}} = 3.7$ (see Fig. 10 caption for detailed D estimation), 15% fractional melting is sufficient to reproduce the entire lherzolite trend, whereas equilibrium models require 35% melting. The use of a set of higher

partition coefficients for Ni and Yb ($D_{\text{Yb}} = 0.14$, $D_{\text{Ni}} = 13$) does not change these amounts of melting significantly for either model. Similarly, the harzburgites could be the residue of 25% (fractional) to 50% (equilibrium) melting and the low-Fe dunite of 35% (fractional) to 60% (equilibrium) melting, using the lower set of partition coefficients for Ni and Yb. At first glance, the compositional

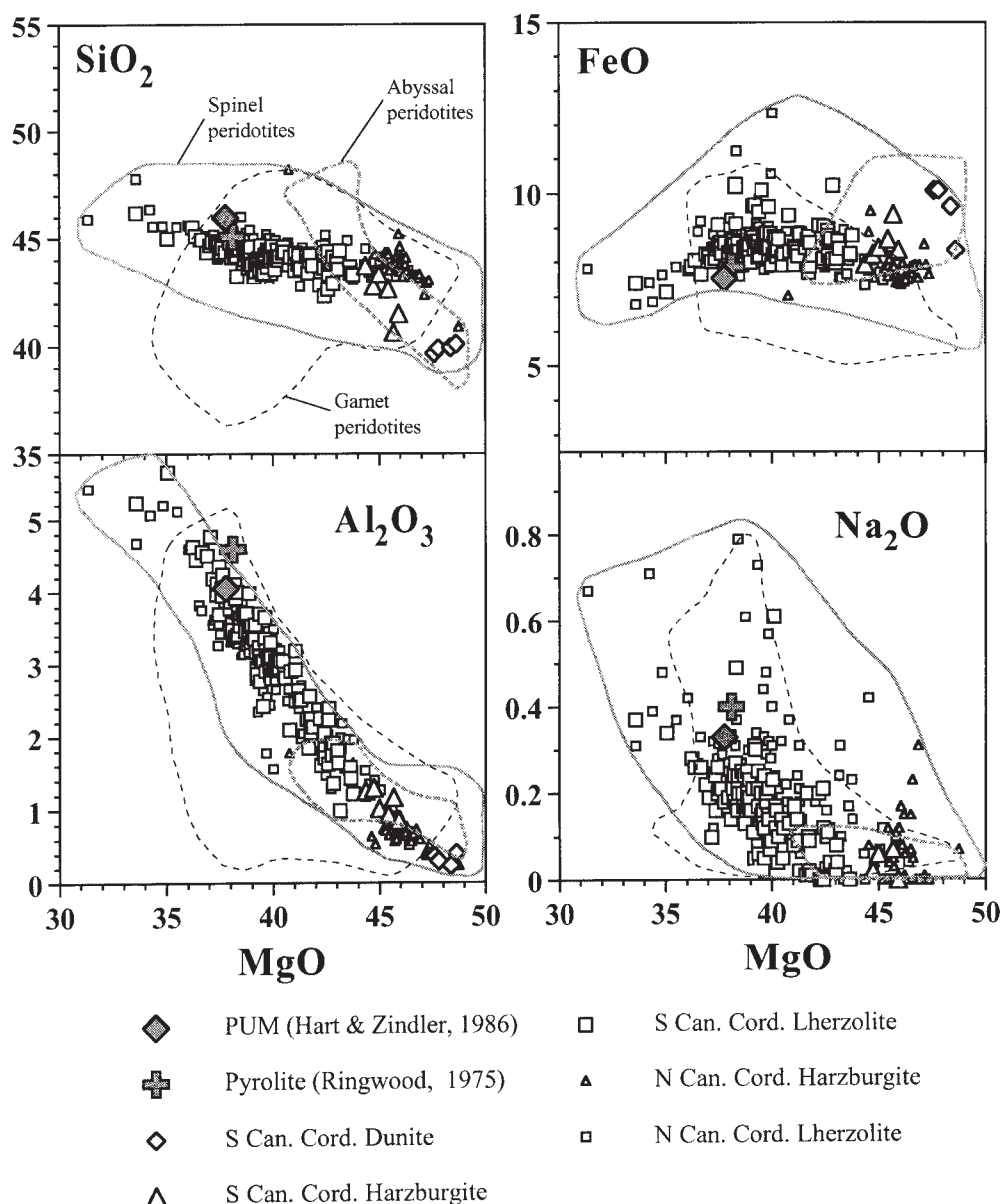


Fig. 5. Whole-rock compositions of the Cr-diopside suites from the southern Canadian Cordillera compared with those of the northern Canadian Cordillera and other peridotites from around the world. Gray continuous line indicates spinel peridotites from around the world; fine black dashed line, garnet peridotites from around the world; bold gray dotted line, abyssal peridotites. References for spinel and garnet peridotites as in Fig. 3. Abyssal peridotites are ODP core samples from the Atlantic (Karson *et al.*, 1997; Brandon *et al.*, 2000) and Pacific (Mével *et al.*, 1996; Rehkämper *et al.*, 1999) oceans. PUM, primitive upper mantle (Hart & Zindler, 1986)

range of the Cr-diopside peridotites can thus be interpreted as the residues of melting of a source with a composition equivalent to fertile lherzolite KRX-13. The fact that the LP xenoliths have a very narrow range of relatively fertile compositions, whereas the KL xenoliths range from fertile lherzolites to depleted dunites (Figs 2 and 4) indicates that the extent of melting differed at each xenolith locality.

Calculation of melt compositions in equilibrium with the Cr-diopside peridotites

The compositions of melts extracted from the Cr-diopside peridotites were estimated using a simple mass balance calculation. With a knowledge of the average Fo content of olivine in a residual xenolith and the olivine–liquid Fe/Mg equilibrium constant (K_D of 0.33 at 15 kbar and

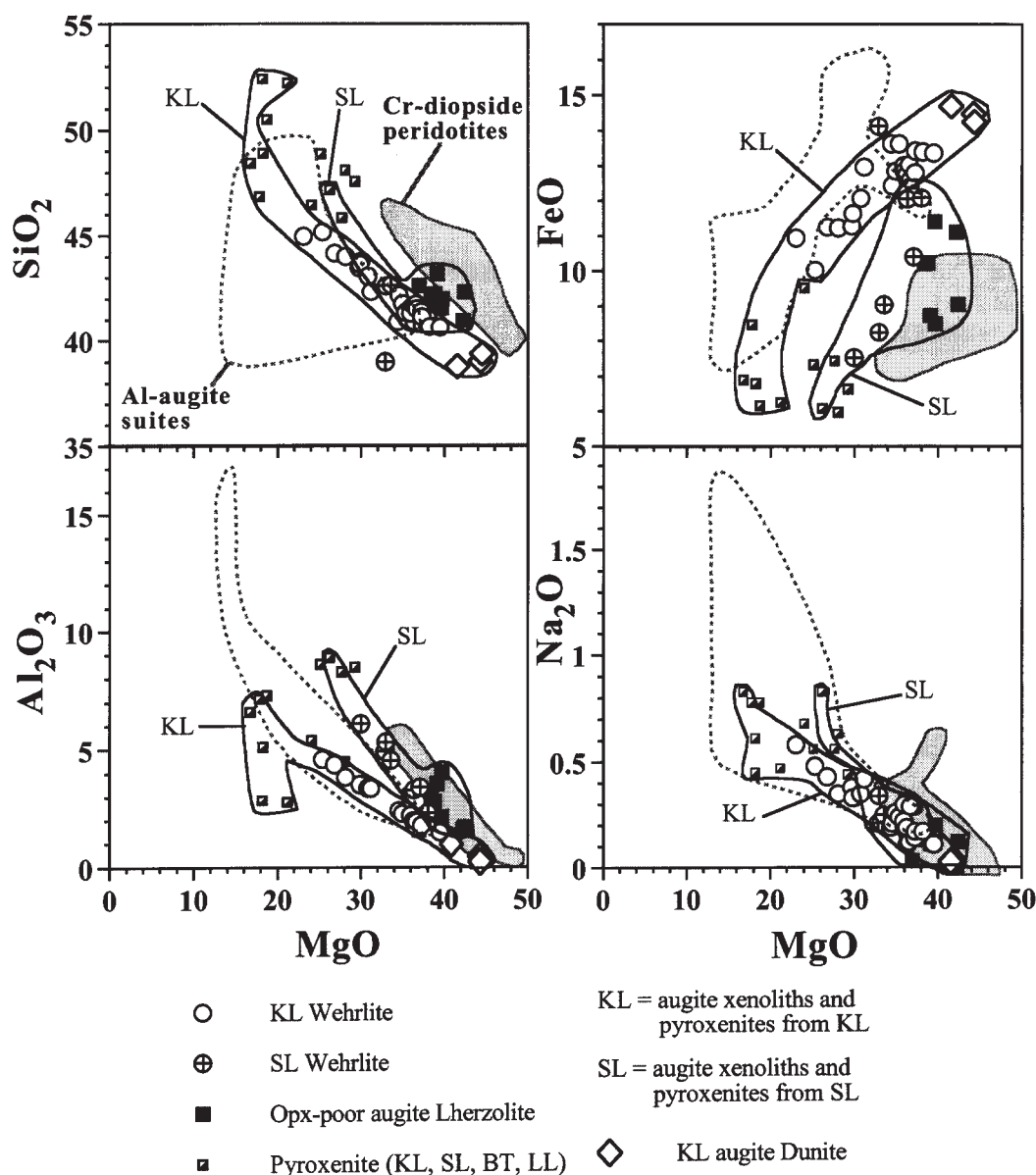


Fig. 6. Whole-rock composition of the augite xenolith suites and of the pyroxenites compared with that of the Cr-diopside peridotites from the southern Canadian Cordillera (gray field) and the Al-augite suites taken from the literature (dashed gray line). Al-augite suites from the literature (Frey & Prinz, 1978; Irving, 1980; Griffin *et al.*, 1984, 1988; Aoki, 1987; Gamble & Kyle, 1987; Hunter & Upton, 1987; Kepezhinskas *et al.*, 1995).

1150°C; Ulmer, 1989), the degree of fusion can be estimated from the MgO and FeO contents of any chosen source and residue composition (Francis, 1987). Once the degree of fusion (F) is determined, the compositions of melts in equilibrium with the residue (Table 8 and Fig. 11) can be calculated by solving mass balance equations for each element [$FE_{\text{liquid}} + (1 - F)E_{\text{residue}} = E_{\text{source}}$, where E is the concentration of one element (Francis, 1987)].

The composition of fertile lherzolite KRX-13 (Table 2) was used as a source. The average composition of all depleted lherzolites and the average composition of the Cr-diopside harzburgites were used as residues. The two resulting liquids (liquid L with lherzolite residue and liquid H with harzburgite residue) correspond to 20% and 25% partial melting, respectively, and are both Mg-rich basalts in composition (Table 8). The dominant composition of southern Canadian Cordillera lherzolites

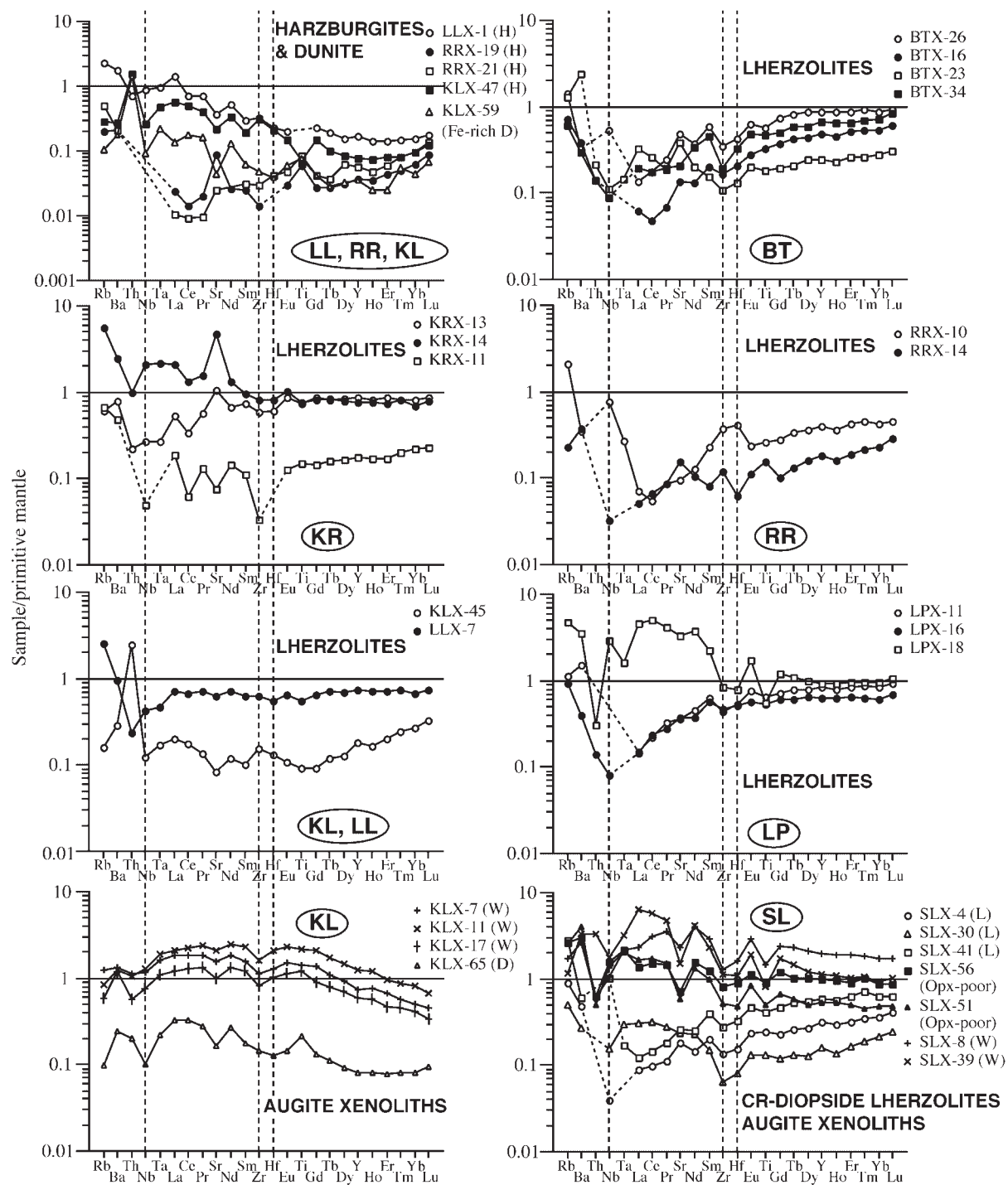


Fig. 7. Primitive-mantle-normalized (Sun & McDonough, 1989) whole-rock extended trace-element diagrams for the southern Canadian Cordillera xenoliths. D, dunite; H, harzburgite; L, lherzolite; W, wehrlite; Opx-poor, opx-poor lherzolite.

(Al_2O_3 at 3–3.5 wt %; Fig. 4) results from 5–10% melting (Fig. 10). The composition of the liquid produced by that amount of melting (L2 in Table 8) was calculated

using KRX-13 as a source and the average composition of lherzolites with Al_2O_3 contents between 3 and 3.5 wt % as a residue. Liquid L2 is a Mg-rich basalt as well (Table

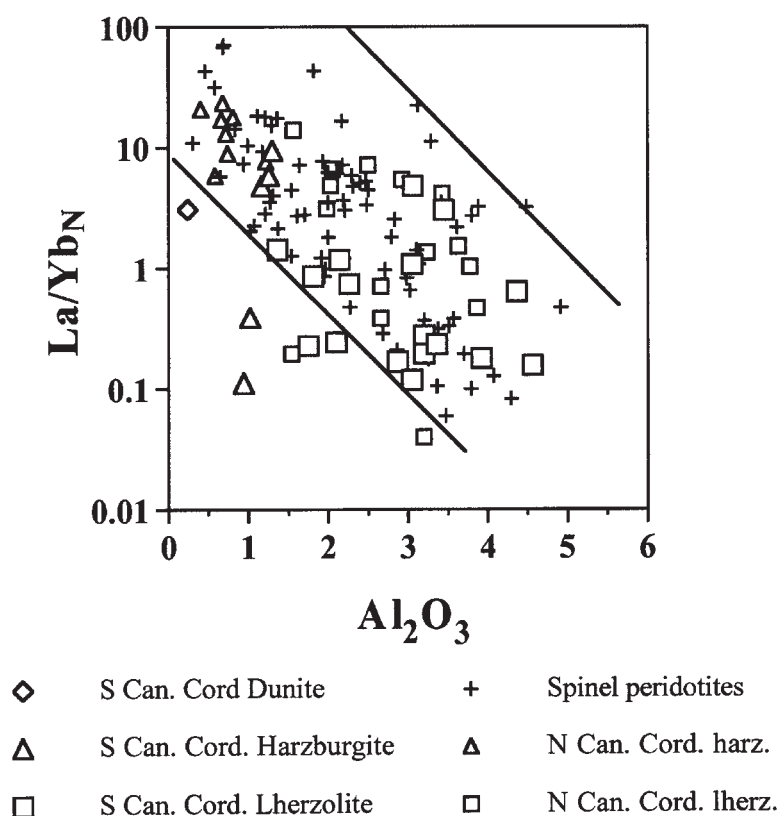


Fig. 8. Chondrite-normalized La/Yb ratio (Sun & McDonough, 1989) vs Al_2O_3 (wt %) of the Cr-diopside peridotites from the Canadian Cordillera, compared with the other spinel peridotites from around the world. The negative correlation between La/Yb ratio vs Al_2O_3 contents characteristic of spinel peridotites worldwide is highlighted by two black lines. References are the same as for Fig. 5.

8). These calculated liquids do not resemble the Mg-rich alkali basalts from the northern Canadian Cordillera (which are too Ca poor; Eiché *et al.*, 1987), Cretaceous Carmacks ankaramites from the Canadian Cordillera (which are too Si rich; Johnston *et al.*, 1996) or komatiites (which are too Al poor and Fe rich; Fig. 11).

The compositions of the calculated liquids can be recalculated for comparison with experimental melts obtained by fusion of KLB-1, a fertile lherzolite from Kilbourne Hole (Hirose & Kushiro, 1993). Melt L', which composition was calculated from a lherzolite residue, resembles experimental melts generated by 13–19% melting at 15–25 kbar under dry conditions, and leaving olivine, opx and cpx in the residue. Melt H', which composition was calculated from a harzburgite residue, resembles 10 kbar experimental melts that have olivine and opx in the residue (Hirose & Kushiro, 1993; Fig. 11 and Table 8). The estimated degree of fusion for melt L' (14%) also corresponds to that of the most similar 25 kbar experimental melt (13%), but the degree of fusion calculated for melt H' (17%) is lower than that of the closest experimental liquid (20%).

Trace element variations

Most Cr-diopside xenoliths from the southern Canadian Cordillera have relatively high primitive-mantle-normalized Rb and Ba contents compared with HREE, and two of them (KRX-14 and RRX-19) exhibit a positive anomaly in Sr (Fig. 7). These characteristics may reflect alteration processes because Rb and Ba are relatively mobile during surface weathering (Pearce, 1983). However, no obvious alteration features were noted in the thin sections.

The HREE and MREE abundances of the Cr-diopside peridotites correlate with indices of fusion such as MgO or Al_2O_3 in the southern Canadian Cordillera xenoliths. Moreover, the ratio of Tb/Yb has been used in peridotites to distinguish between melting in the spinel and garnet facies (Bodinier *et al.*, 1988), because HREE such as Yb are strongly partitioned into garnet during melting. The Tb/Yb ratio of residual peridotite will decrease rapidly during the first 10% of fusion in the garnet stability field, whereas this ratio will be less affected in the spinel stability field (Fig. 12; Bodinier *et al.*, 1988; McDonough &

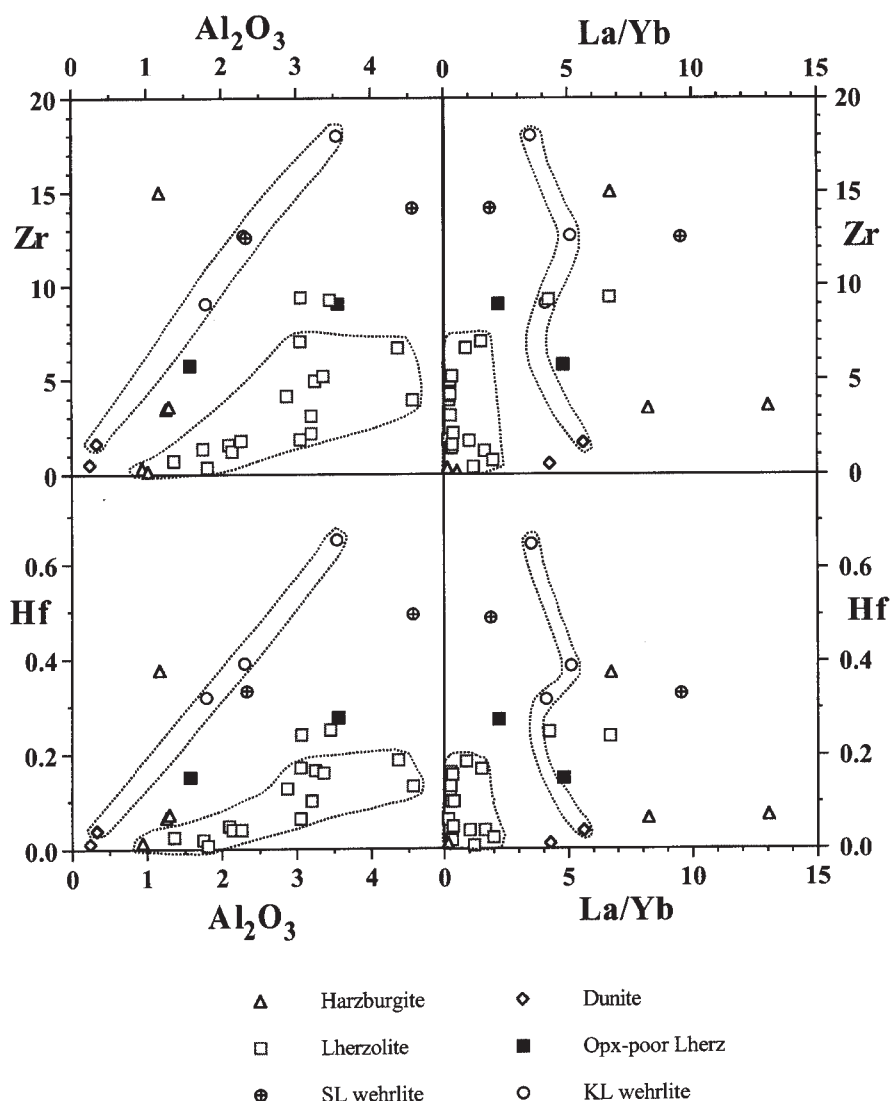


Fig. 9. Zr and Hf contents (ppm) of the southern Canadian Cordillera xenoliths vs Al_2O_3 content (wt %) and La/Yb ratio. Dotted lines highlight the positive correlations in the Al_2O_3 diagrams shown by most harzburgite and lherzolites, and the same samples in the La/Yb diagrams for Cr-diopside peridotites and the KL wehrlite suite. The dunite and one harzburgite (Zr 15 ppm, Hf 0.38 ppm) not included in the dotted lines are Fe rich. The other peridotites that do not fall on the broad correlation are harzburgites LLX-1 and KLX-47, and lherzolites LPX-18 and KRX-14, and are the peridotites that underwent the strongest metasomatism as exemplified by their high La/Yb ratios compared with other peridotites.

Frey, 1990). Most of the lherzolites from the Canadian Cordillera appear to follow the melting trend for the spinel stability field.

The majority of the Cr-diopside lherzolites have depleted LREE patterns (Fig. 7), probably the result of melting with loss of the incompatible elements to the melt (e.g. BT, RR, 2 SL lherzolites). These lherzolites generally have MREE/HREE slightly less than unity, consistent with the increasing compatibility of the MREE relative to HREE. Other samples, however, have MREE/HREE about unity, which may reflect low degrees of

melting that depleted the samples in the most incompatible REE, but did not affect the more compatible elements such as MREE and HREE (e.g. LP, LL and 2 KR). A low degree of melting is consistent with the relatively fertile compositions of these particular samples (Al_2O_3 of 3–4 wt %).

The Canadian Cordillera xenoliths also display a negative correlation between La/Yb_N and Al_2O_3 , which is characteristic of spinel xenoliths in general (Fig. 8; McDonough & Frey, 1990). In particular, the steep REE patterns of most Cr-diopside harzburgites and dunites

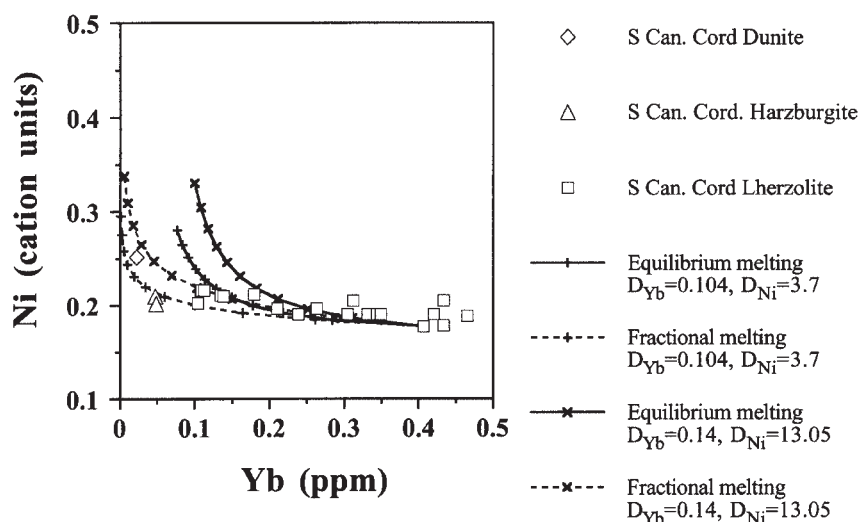


Fig. 10. Ni (cation units) vs ppm Yb to compare the model melting results with the Cr-diopside peridotite data from the southern Canadian Cordillera. Trace element equilibrium and fractional melting equations are from Shaw (1979). Source composition is sample KRX-13 [KRX-13 composition is close to primitive mantle values (Ringwood, 1975; Hart & Zindler, 1986) and its trace element pattern does not show any disturbance by metasomatism; see Fig. 7]. Distribution coefficients between whole-rock and liquid (D) were calculated assuming a peridotite composed of 60% olivine, 25% orthopyroxene and 15% clinopyroxene and with the following mineral partition coefficients (Green, 1994): $D_{\text{Ni}} \text{ Ol} = 5\text{--}20$; $D_{\text{Ni}} \text{ Opx} = 1.5\text{--}3$; $D_{\text{Ni}} \text{ Cpx} = 2$; $D_{\text{Yb}} \text{ Ol} = 0.02\text{--}0.04$; $D_{\text{Yb}} \text{ Opx} = 0.2\text{--}0.3$; $D_{\text{Yb}} \text{ Cpx} = 0.2\text{--}0.8$. Increments on model curves are for 5% melting.

are typical of depleted spinel peridotites (Bedini *et al.*, 1997; Shi *et al.*, 1998; see also Fig. 7). There is little consensus on this common paradox, i.e. that the most depleted peridotites in terms of major elements are the most enriched in incompatible trace elements. It could be caused by the physical properties of the peridotites, if olivine-poor rocks are significantly less permeable to metasomatic melts than olivine-rich ones (Toramaru & Fujii, 1986), resulting in enhanced REE migration in olivine-rich rocks (McKenzie, 1984; Takazawa *et al.*, 1992). Harzburgites from RR, however, have very depleted REE patterns, consistent with partial melting. The BT lherzolites are selectively enriched in LREE and their chemistry is consistent with a chromatographic metasomatic process (Takazawa *et al.*, 1992), in which an enriched melt percolates through an LREE-depleted peridotite, and first affects La (e.g. BTX-16), then Ce (e.g. BTX-34) and then Nd (e.g. BTX-23), i.e. in order of increasing partition coefficient. In particular, the xenoliths that plot above the Tb/Yb vs Al_2O_3 trend (Fig. 12) may have suffered sufficient metasomatism to have disturbed the MREE. The KR lherzolites show a systematic negative Ce anomaly. Ce anomalies in mantle rocks could be due to metasomatism by oxidized melts or fluids derived from subducting slab (Ionov *et al.*, 1995, and references therein). This feature is not seen in the two other xenolith sites close to KR (LP and LL) however. Although the three LP lherzolites analyzed for trace elements contain amphibole, only one shows the strong

LREE enrichment typical of hydrous lherzolites (McDonough & Frey, 1990).

Almost all of the southern Canadian Cordillera xenoliths (Sun & Kerrich, 1995; this study) have negative HFSE anomalies, with varying enrichment in LREE. Some of the anomalies may be the result of analytical problems attending measurement of elements at or near detection limit. This is probably the case for the sawtooth profile of KRX-11, and the very low Nb contents of RRX-14, LPX-16 and SLX-4 (Fig. 7). In a study of southern Canadian Cordillera xenoliths (KR, BT, LL and Jacque Lake sites), Sun & Kerrich (1995) related the size of the HFSE anomalies to the modal proportions of minerals. Indeed, a significant proportion of the HFSE resides in opx as well as in cpx in peridotites (Eggins *et al.*, 1998). The Zr and Hf contents of the Cr-diopside lherzolites show a broad correlation with Al_2O_3 , suggesting that these elements were mainly controlled by melting processes (Fig. 9). Enrichment in LREE coupled with negative anomalies in Ti, Zr and Hf in peridotites has been attributed to carbonate metasomatism (Hauri *et al.*, 1993; Rudnick *et al.*, 1993), which may thus be responsible for the trace element characteristics of BT, KR and LP xenoliths (Fig. 7). Arc lavas are also characterized by such HFSE depletions (e.g. Davidson, 1996), however, and the metasomatic fluids that have affected the southern Canadian Cordillera mantle may thus have originated from the subduction of the Pacific plate under

Table 8: Composition of computed melts extracted from *Cr*-diopside peridotites

	Residue	Liq L	Residue	Liq H	Residue	Liq L2	Residue	Liq L'	Residue	Liq H'	Hirose & Kushiro (1993)			
Co:		KRX-13		KRX-13		KRX-13		KLB-1		KLB-1 = Co	Run 16	Run 19	Run 23	Run 25
Residue:	KLX-61	KLX-61	Harz av.	Harz av.	Lherz av.*	Lherz av.*	KLX-61	KLX-61	Harz av.	Harz av.		Ol Opx	Ol Opx	Ol Opx
Phases:												Cpx	Cpx	Cpx
Fo:	90.61		91.16		89.87		90.61		91.16		89.1	91	90.6	90.5
F% melt:	21.64		25.35		7.85		13.76		17.43			20	18.9	12.6
														16.6
SiO ₂	43.95	47.42	43.13	49.32	44.13	51.39	43.95	45.49	43.13	49.08	44.48	50.67	49.13	47.97
TiO ₂	0.01	0.71	0.02	0.58	0.11	0.75	0.01	1.05	0.02	0.80	0.16	0.42	0.6	0.83
Al ₂ O ₃	1.75	13.83	1.13	13.90	3.22	17.84	1.75	14.35	1.13	14.71	3.59	14.61	15.18	14.88
FeO _t	7.97	10.38	8.32	9.02	8.42	9.32	7.97	8.48	8.32	6.83	8.10	7.64	7.54	9.43
MnO	0.13	0.18	0.13	0.17	0.14	0.14	0.13	0.05	0.13	0.07	0.12	0.13	0.14	0
MgO	43.00	17.35	44.89	15.52	39.46	13.82	43	14.85	44.89	11.95	39.22	13.39	13.11	13.36
CaO	1.67	9.82	0.78	11.25	2.88	9.93	1.67	13.79	0.78	15.50	3.44	11.17	12.28	10.23
Na ₂ O	0.02	0.85	0.04	0.67	0.18	0.44	0.02	1.95	0.04	1.48	0.30	1.5	1.58	2.37
K ₂ O	0.00	0.09	0.03	0.01	0.07	-0.57	0	0.14	0.03	0.00	0.02	0.19	0.08	0.82
P ₂ O ₅	0.00	0.04	0.01	0.01	0.01	0.01		0.20	0.01	0.12				
NiO	0.32	0.04	0.33	0.05	0.29	-0.09		-0.18	0.33	-0.14				
Cr ₂ O ₃	0.39	0.53	0.46	0.30	0.55	-1.12	0.40	-0.18	0.46	-0.40	0.31	0.28	0.36	0.11
Total	99.21	101.24	99.79	100.81	99.46	101.85	98.89	100.00	99.79	100.00	99.74	100.00	100.00	100.00

Co, initial composition. Source compositions: fertile lherzolite KRX-13 (this study) and KLB-1 (Hirose & Kushiro, 1993). Residue compositions: fertile lherzolite KLX-61, average composition of Cr-diopside harzburgites (Harz av.), and average composition of lherzolites in which the Al₂O₃ content is 3–3.5 (Lherz av.*). Experimental melts used in Fig. 11, their starting compositions and the experimental conditions (Hirose & Kushiro, 1993). Phases, residual phases.

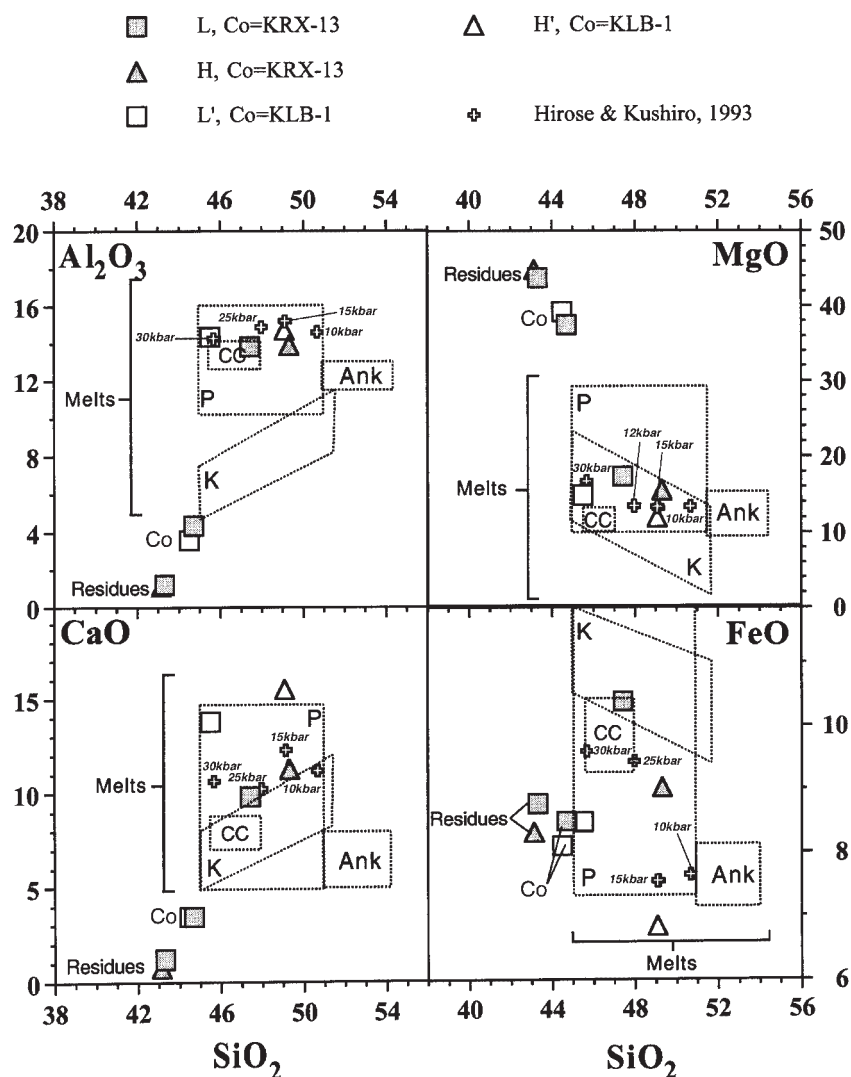


Fig. 11. Calculated melt compositions (Al₂O₃, MgO, CaO, FeO vs SiO₂) generated from the southern Canadian Cordillera xenolith compositions compared with experimental data and primitive lava fields. Co, initial composition (KRX-13 or KLB-1). Squares, melting (melt L) to generate lherzolite KLB-61 as a residue. Triangles, melting (melt H) to generate the average composition of Cr-diopside harzburgites as a residue. Crosses, experimental melts under anhydrous conditions at 10, 15, 25 and 30 kbar (Hirose & Kushiro, 1993). (See Table 8 for details on the experimental conditions.) Fields indicate the range and compositions of primitive lavas: P, picrites [references given by Francis (1995)]; K, komatiites [references given by Bernstein *et al.* (1998)]; CC, primitive lavas from the Canadian Cordillera (Eiché *et al.*, 1987); ANK, ankaramites from the Canadian Cordillera (Johnston *et al.*, 1996).

this region, which has been taking place for more than 40 Myr (Gabrielse *et al.*, 1991).

Comparison with other peridotites

Northern Canadian Cordillera xenoliths. All suites from the northern Canadian Cordillera are relatively fertile in composition, with many of the lherzolites having Al₂O₃ contents higher than 3 wt % (Fig. 4). The most fertile suite is that of Fort Selkirk, with Al₂O₃ contents up to 6 wt % (Francis, 1987). Similarities in Al₂O₃ and cpx contents (Fig. 2) between north and south are interpreted

to reflect similar degrees of partial melting in the mantle lithosphere under the entire Canadian Cordillera. The results of the melting-model trends calculated for the southern Canadian Cordillera (harzburgites produced by 25% fractional melting) are in agreement with published values of up to 20–25% melting for northern Canadian Cordillera xenoliths (Francis, 1987; Shi *et al.*, 1998). Finally, the Fe-rich Cr-diopside dunites of the southern Canadian Cordillera are similar to another rare type of Fe-rich harzburgite found in the northern Canadian Cordillera (Fig. 5), which Francis (1987) interpreted to

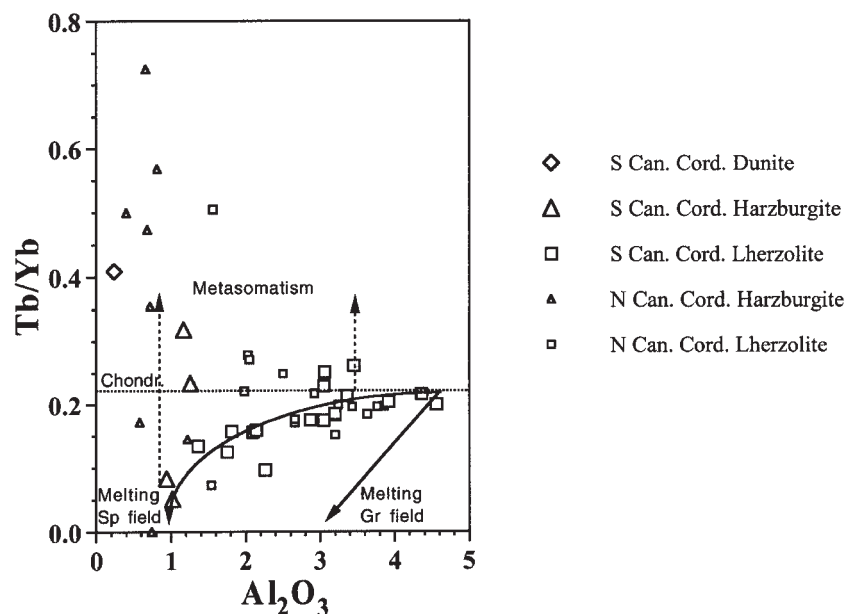


Fig. 12. Tb/Yb vs Al_2O_3 (wt %) in Canadian Cordillera xenoliths. Arrows indicate trends for melting in the spinel and garnet stability field (Bodinier *et al.*, 1988; McDonough & Frey, 1990), and for metasomatism. Northern Canadian Cordillera data are unpublished data (L. Shi & D. Francis, 1998).

have suffered interaction with an alkaline melt at depth. By analogy with reactions observed between host lava and xenoliths, such a reaction is likely to preferentially enrich a spinel peridotite in Fe, and deplete it in Al and Si, resulting in a more olivine-rich peridotite by the consumption of pyroxene and spinel (Francis, 1987). The addition of olivine by migrating melts would lower the Fo content of the olivine in these Fe-rich dunites (Niu & Hékinian, 1997; Fig. 3a). This is consistent with their high Ni content (0.25–0.32) compared with that of the majority of the Cr-diopside peridotites (0.2 cation units on average, Fig. 10), as olivine is the mineral in which most of the Ni of a peridotite resides.

Three of the northern xenolith suites (Llangorse, Alligator Lake and Hirshfield) are, however, bimodal; they are characterized by high proportions of both harzburgites and lherzolites (Fig. 4; Francis, 1987; Shi *et al.*, 1998). Harzburgites from the northern Canadian Cordillera are richer in SiO_2 and Na_2O but poorer in FeO than those of the southern Cordilleran harzburgites (Francis, 1987; Fig. 5). They may result from recent metasomatism-induced melting, linked to an underlying region of anomalously hot mantle that has been detected teleseismically (Frederiksen *et al.*, 1998; Shi *et al.*, 1998).

In summary, the lithospheric mantle throughout the Canadian Cordillera appears relatively homogeneous in composition, dominated by relatively fertile lherzolite with 3 wt % Al_2O_3 , representing the residue of 5–10% melting of a pyrolite-like source. Rare harzburgites in

the south represent the extreme end-member reflecting up to 25% melting of pyrolite. The abundant harzburgites of the bimodal northern suites exhibit the effect of more extensive metasomatism and melting of the lherzolites (Shi *et al.*, 1998; Peslier *et al.*, 2000b).

Comparison with peridotites from other tectonic settings. Spinel peridotite xenoliths hosted in alkali basalts are found mainly at the edge of cratons in terranes formed after the Precambrian, such as SE Australia, part of the western USA, and Sikhote-Alin at the southeastern edge of Siberia. The Canadian Cordillera lherzolites have whole-rock major element compositions similar to those of other continental spinel peridotite xenoliths (Fig. 5). In particular, the tectonic setting of the Sikhote-Alin region resembles that of the Canadian Cordillera, as it formed by the accretion of terranes to the edge of a craton, and was bordered by a subduction zone during the Mesozoic (Canil *et al.*, 1990; Ionov & Wood, 1992; Ionov *et al.*, 1995). The southern Canadian Cordillera lherzolites are very similar to those of Sikhote-Alin in terms of their major and trace element composition, and reduced oxygen fugacities (Ionov & Wood, 1992; Ionov *et al.*, 1995). The characteristics of the Canadian Cordillera lherzolites are, thus, not unique, and appears to be typical of the lithospheric mantle beneath young orogenic belts bordering cratons.

Although the Canadian Cordillera lherzolites are clearly different from continental garnet peridotite xenoliths found in kimberlites in cratonic environments (Fig.

5; e.g. Boyd, 1989; Kelemen *et al.*, 1992), a comparison with oceanic peridotites is instructive, as Canadian Cordillera xenoliths plot along the 'oceanic trend' formed by abyssal and ophiolitic peridotites in a modal olivine vs Fo content diagram (Fig. 3). Both abyssal peridotites and Cr-diopside xenoliths from the Canadian Cordillera plot within the Olivine–Spinel Mantle Array ('OSMA') representing the locus of most spinel xenoliths (oceanic and continental) and orogenic massifs and ophiolites (Fig. 13a; Dick & Bullen, 1984; Arai, 1994). However, abyssal peridotites have a narrower range of whole-rock compositions and are typically more depleted than the Canadian Cordillera peridotites (Figs 5 and 13c and d). Moreover, abyssal peridotites typically have clinopyroxene REE patterns strongly depleted in LREE (Johnson *et al.*, 1990), whereas the REE patterns of the Canadian Cordillera lherzolites range from depleted to enriched types (Fig. 7).

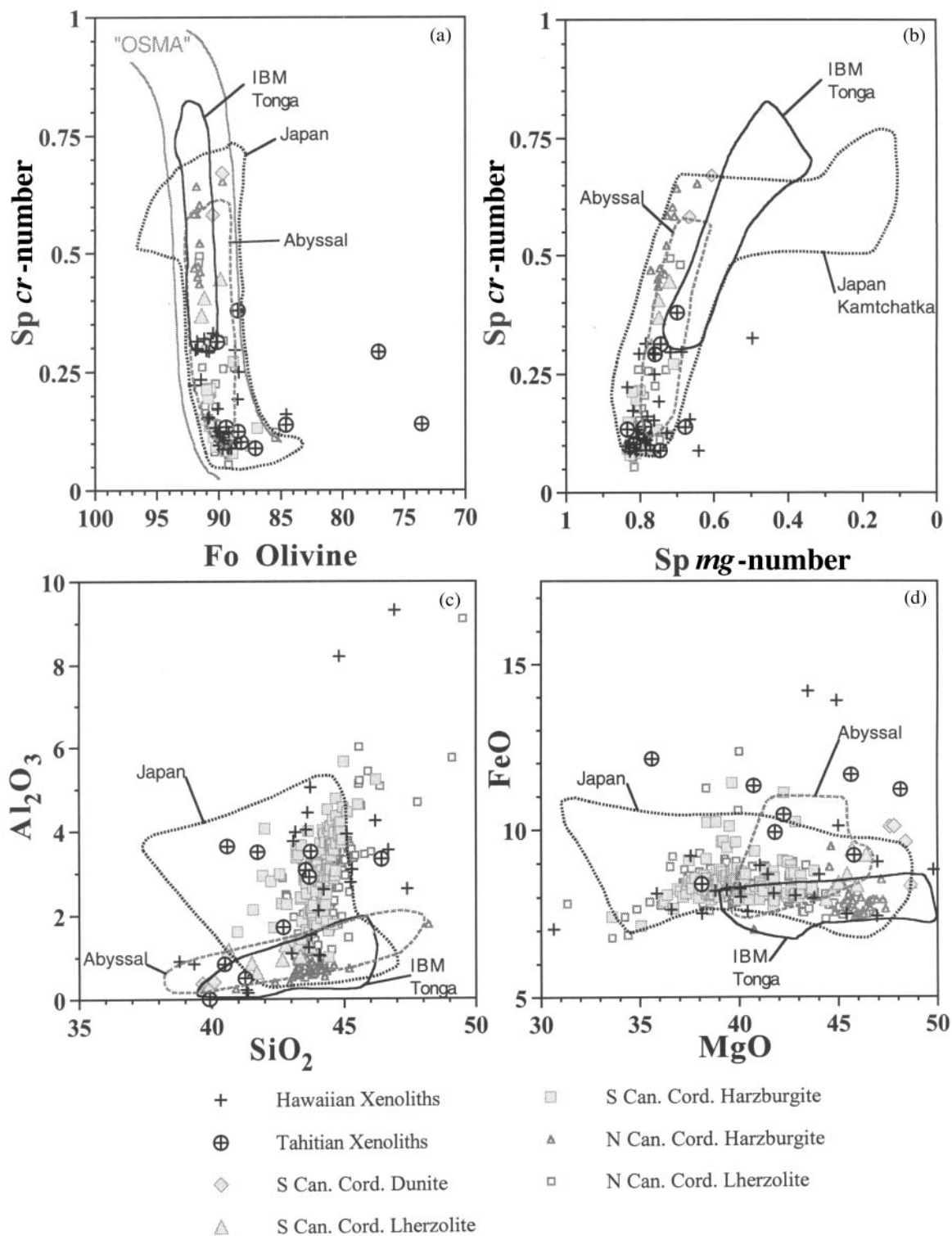
Mantle xenoliths entrained in OIB lavas at Hawaii and Tahiti are samples of the Pacific oceanic lithospheric mantle. Tahitian xenoliths are, however, poorer in SiO₂ and richer in FeO, and their olivines have lower Fo contents than those from Hawaii and the Canadian Cordillera. The low olivine Fo contents of most Tahitian xenoliths compared with the 'OSMA' trend (Dick & Bullen, 1984; Arai, 1994) may argue against these xenoliths being representative of typical Pacific oceanic mantle. Hawaiian xenoliths, which may represent intraplate oceanic lithosphere, have low spinel *cr*-number compared with abyssal peridotites, but overlap the Canadian Cordillera lherzolite range in all diagrams (Fig. 13).

Canadian Cordillera lherzolites have lower spinel *cr*-number, spinel *mg*-number and MgO contents, and higher FeO and Al₂O₃ than peridotites in fore-arc settings (Solomon islands, Izu–Bonin–Marianas and Tonga trenches, and part of Japan and Kamchatka). Fore-arc peridotites are typically very depleted (high MgO, low FeO, low Al₂O₃) and have spinel *mg*-number even higher than those of the depleted harzburgites from the Canadian Cordillera (Fig. 13). The Canadian Cordillera peridotites are, however, similar to those of back-arc setting peridotites, such as are found in parts of Japan and Kamchatka (Fig. 13). The southern Canadian Cordilleran xenoliths have equilibrated at lower oxygen fugacities (Canil *et al.*, 1990) compared with arc peridotites, which typically exhibit high oxygen fugacities (Wood & Virgo, 1989; Wood *et al.*, 1990; Brandon & Draper, 1996; Parkinson & Pearce, 1998). If any arc-like metasomatized mantle is present in the Canadian Cordillera, only harzburgites may be possible candidates despite their slightly low spinel *mg*-number (Peslier *et al.*, 2000b).

The augite xenolith suites

The augite xenolith suites comprise mainly wehrlite, minor amounts of dunite at KL and opx-poor lherzolites at SL and KL (Fig. 2). Among other criteria, the low forsterite contents of olivine in the majority of the augite xenoliths (Fig. 3b) and the positive correlations between whole-rock FeO and MgO (Fig. 6) exclude partial melting as a formation mechanism for these rocks. Crystallization from basaltic melt is consistent with the low Fo content of olivine (Fig. 3b) in the augite xenolith suites compared with that of the Cr-diopside suite. The fact that almost all analyzed trace elements (Table 7) show positive correlations with Al₂O₃ in the KL augite xenolith suites (Zr and Hf shown in Fig. 9) is also expected for a crystallization process during which these elements are incompatible in ol and cpx. A cumulate origin has been suggested for the origin of Al-augite suites (e.g. Frey & Prinz, 1978) and the pyroxenite layers found in peridotite orogenic massifs (e.g. Bodinier *et al.*, 1987; Becker, 1996). Crystallization, however, produces a series of cumulates with comparatively large variations in compatible element concentrations (e.g. Ni) compared with those of incompatible elements (e.g. Yb) (Francis, 1987). Simple crystallization is thus not compatible with the wide range in Yb contents of the KL augite xenoliths (from 0.04 to 0.4 ppm whereas Ni varies from 2230 to 775 ppm) and with the small range in Ni content of the SL augite xenoliths (from 1916 to 1477 ppm whereas Yb varies from 0.24 to 0.86 ppm).

Kelemen (1990) proposed that melt–peridotite reaction could produce discordant dunite and olivine-rich wehrlite veins in the upper mantle. Figure 14 details a reaction path for a system comprising crystallizing melt and peridotite at constant temperature and pressure. A basaltic melt may ascend slowly enough into the upper mantle that thermal equilibration occurs before melt–rock reaction. In this case, the reaction occurs isothermally, which may be a realistic approximation. The peridotite (L1 in Fig. 14a) is assumed to lie both on the SiO₂-rich side of a line between the olivine apex and the initial liquid composition, and with more olivine than the compositions along the isotherm that runs through the initial liquid composition. Reaction between a basaltic liquid crystallizing olivine with lower *mg*-number and peridotite containing olivine of higher *mg*-number increases *mg*-number in the resulting melt (Kelemen, 1990). A basaltic partial melt ascending through the lithospheric mantle fractionates olivine. Experiments have shown that in the uppermost part of the lithospheric mantle this liquid will tend towards saturation in olivine and cpx, but will be undersaturated in opx (Kelemen, 1990, and references therein). Therefore, the initial liquid shown in Fig. 14 is on the olivine–cpx cotectic. Increase in *mg*-number of the melt resulting from reaction with peridotite shifts the



olivine–cpx cotectic towards the olivine apex (Fig. 14b, Kelemen, 1990). Accompanying assimilation of peridotite shifts the composition of the melt towards the olivine

apex, requiring crystallization of increased amounts of olivine for the liquid to remain on the cotectic and isothermal. This can be modeled as a series of small

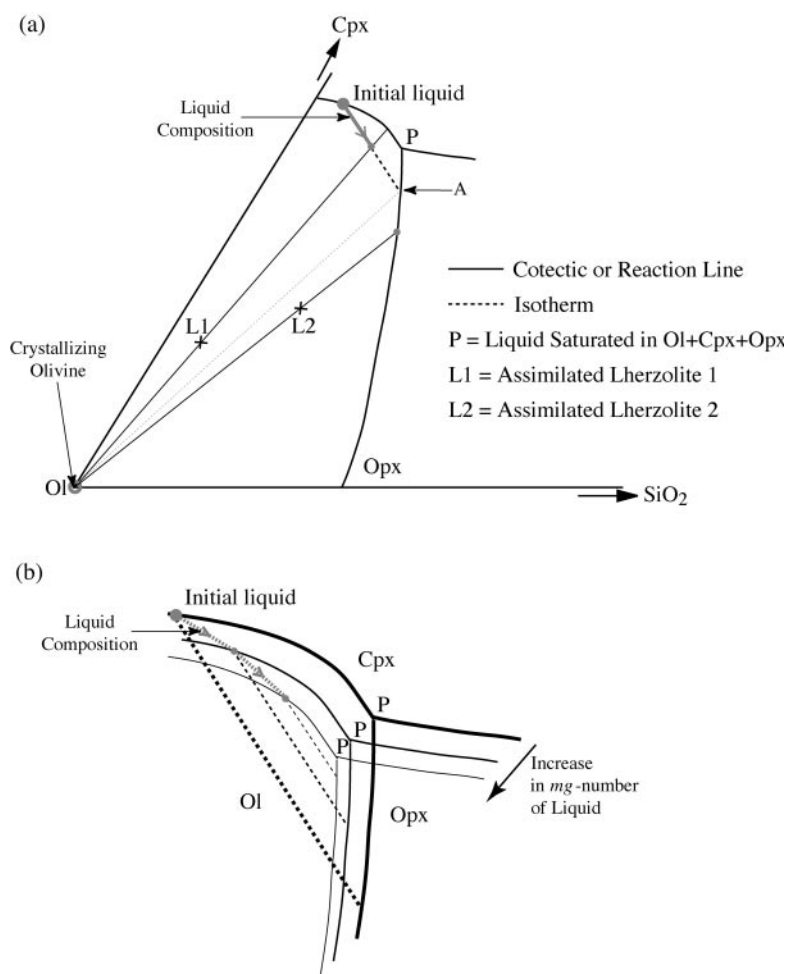


Fig. 14. (a) Schematic portion of the Olivine–Cpx–SiO₂ phase diagram projected from the plagioclase composition (after Kelemen, 1990). In gray are solid and liquid compositions resulting from the crystallization of a melt assimilating its peridotitic wall-rock. L1 and L2 are compositions of lherzolite being assimilated. Point A is the intersection of the line joining the olivine apex and the point of intersection of the isotherm with the opx–olivine cotectic. (b) Enhanced view of the peritectic region of the Olivine–Cpx–SiO₂ phase diagram showing the effect of increasing liquid *mg*-number on the cotectic and isotherm locations, and on the composition of the crystallizing liquid dissolving peridotite. This figure shows the effect on a crystallizing liquid of reaction with peridotite after Kelemen (1990). (See text for detailed explanations.)

increments in which the liquid moves into the olivine primary phase field, crystallizing olivine only, then moves back to the olivine–cpx cotectic, crystallizing olivine and cpx (Kelemen, 1990). The melt composition shifts along the ‘moving’ cotectic during the reaction (Fig. 14a). The

crystallizing phases are thus olivine and cpx, but with a larger proportion of olivine than that which fractional crystallization alone would produce (Kelemen, 1990). When the composition of the peridotite (L1 in Fig 14a) is located to the left of a line joining the olivine apex

Fig. 13 (opposite). Comparison of the Canadian Cordillera peridotites with oceanic peridotites. Sp *cr*-number is Cr/(Cr + Al) of spinel; Sp *mg*-number is Mg/(Mg + Fe²⁺) in spinel with Fe²⁺ calculated using the structural formula AB₂O₄ for spinel (Table 5); Fo Olivine, forsterite content (mol %) of olivine calculated as Mg/(Mg + Fe), Fe being all Fe²⁺. The continuous gray lines delimit the ‘OSMA’ (Olivine–Spinel Mantle Array) trend (Arai, 1994). Bold gray dashed line, abyssal peridotites (Arai, 1994; Mével *et al.*, 1996; Karson *et al.*, 1997; Niu *et al.*, 1997; Rehkämper *et al.*, 1999; Brandon *et al.*, 2000). Black dotted line, back-arc to fore-arc peridotites from Japan, and (b), from Japan and Kamchatka (Aoki & Shiba, 1973; Arai, 1980, 1991; Takahashi, 1980; Aoki, 1987; Ozawa, 1988, 1994; Kepezhinskas *et al.*, 1993, 1995; Umino & Yoshizawa, 1996) and fig. 4d of Arai (1994). Black continuous line, arc peridotites from Izu–Bonin–Marianas (IBM) and Tonga (Bloomer & Fisher, 1987; Neal, 1988; Maury *et al.*, 1992; Parkinson & Pearce, 1998). Other data sources: mantle xenoliths from Hawaii (Jackson & Wright, 1970; Goto & Yokoyama, 1988; Sen, 1988); mantle xenoliths from Tahiti (Tracy, 1980); Canadian Cordillera Cr-diopside peridotites (Francis, 1987; Shi *et al.*, 1998; this study).

and the point of intersection of the isotherm with the opx–olivine cotectic (point A in Fig. 14a), only olivine and cpx are able to crystallize. The presence of opx-poor lherzolites requires additional explanation. For liquid–peridotite reaction to produce opx, the composition of the assimilated peridotite has to be located to the right of the line Olivine–A (peridotite L2 in Fig. 14a; Kelemen, 1990). In this case, the bulk composition shifts rapidly away from the olivine–cpx join. The melt, following the reasoning above, stays on the olivine–cpx cotectic but may attain saturation in opx at P (Fig. 14a) and produce an opx-bearing assemblage.

If the peridotite wall-rock is colder than the melt, the energy required to dissolve the peridotite, as well as the heat dissipated in the cold peridotite wall-rock, will result in a drop in temperature of the melt, thereby inducing crystallization (Kelemen, 1990). This cooling results in the rate of crystallization being higher than that of peridotite assimilation, i.e. the mass crystallized exceeds the mass assimilated. Moreover, the enthalpies of fusion of the peridotite phases at any given temperature are smaller than those of the newly crystallized assemblage (Kelemen, 1990). Consequently, if the enthalpy is held constant, the reaction path along the shifting olivine–cpx cotectic towards P (Fig. 14) results in a drop in the temperature of the system (Kelemen, 1990).

This melt–rock reaction hypothesis can be tested using the MELTS program (Ghiorso & Sack, 1995; Asimow & Ghiorso, 1998), which calculates the composition of interacting silicate solids and liquids based on thermodynamics. The model tested here is that of a melt undergoing fractional crystallization while assimilating small amounts of KL or SL peridotite. Both models were run under constant pressure and enthalpy. A mass of 100 g of initial melt undergoing fractional crystallization assimilates peridotite in steps of 1 g. Peridotite compositions were taken as a typical KL lherzolite (Al_2O_3 of 1.75 wt %) and a typical SL lherzolite (Al_2O_3 of 3 wt %; Fig. 4, Table 9). A realistic composition for the starting melt is first determined by calculating the Fe/Mg ratio of melts in equilibrium with the augite xenoliths. At KL, this ratio is about 0.6 using the equation $\text{Fe}_{\text{melt}}/\text{Mg}_{\text{melt}} = (\text{Fe}_{\text{Ol}}/\text{Mg}_{\text{Ol}})/K_D$ with $K_D = 0.33$ at 15 kbar and 1150°C (Ulmer, 1989). Calculated liquids in equilibrium with KL augite xenoliths are also characterized by strong LREE enrichment (La/Yb of 31–45; see Fig. 16b, below). Fe/Mg ratios (0.3 and 0.5) and trace element patterns of melts in equilibrium with the SL augite xenoliths are similar to those of KL (see Fig. 16c), with slightly stronger enrichments in lithophile elements at SL (La/Yb from 16 to 83). Fe/Mg of around 0.6 and La/Yb >30 are found in some alkaline lavas of the Canadian Cordillera (Francis & Ludden, 1995). Various alkaline magma compositions were investigated, and the interaction of those

with >42 wt % SiO_2 and peridotite results in the crystallization of opx first, then olivine, and finally cpx. This could be the way the rare Canadian Cordillera pyroxenites formed. However, as our MELTS modeling and experimental data show (Shaw *et al.*, 1998), reaction of a more silica-poor melt with peridotite crystallizes cpx before opx, thereby producing wehrlites. The alkaline lava used in both models presented in Table 9 is HF-11, an olivine nephelinite from the northern Canadian Cordillera with 40.3 wt % SiO_2 (Francis & Ludden, 1995). When the starting temperature of the melt is its liquidus temperature and the pressure 15 kbar, the first olivine to crystallize has a Fo content of 86 (model 2 for SL augite xenoliths). To achieve the Fo content of 81–85 of the KL wehrlites (model 1), the pressure and the starting temperature of the melt have to be lowered. At 10 kbar the liquidus temperature of HF-11 is 1388°C. A low Fo content is achieved when the temperature of the melt HF-11 is 1310°C, at which temperature only olivine is on the liquidus.

Model 1 (KL augite xenoliths) resulted in the crystallization of olivine + cpx as soon as peridotite starts to react with the melt at 1286°C, and olivine + cpx + opx when the total mass of peridotite assimilated equals the starting mass of liquid at 1230°C (Fig. 15, Table 9). Addition of 23 g of peridotite to the 100 g melt is necessary to reproduce the olivine and cpx compositions of the KL augite xenoliths (Table 9). The positive correlation between Fo content and olivine content observed in the KL augite suite (Fig. 3b) is consistent with the modeling in most of its olivine + cpx interval (Fig. 15). In model 2 (SL augite xenoliths), the first mineral to crystallize is also olivine, then cpx, and opx. With an initial temperature of the melt at the liquidus temperature, the Fo content increases from 85 to 86 while the modal proportion of olivine decreases, which is in agreement to what is observed in the SL wehrlites (Figs 3b and 15). The compositions of the first cpx and opx to crystallize in the model are similar to what is observed in SL wehrlites and opx-poor lherzolites (Table 9). The augite xenolith suites thus appear to be the result of the interaction of a Si-undersaturated alkaline melt, such as an olivine nephelinite, with peridotite at depth.

One more aspect of melt–rock reaction as a viable mechanism for the origin of the augite xenoliths needs to be addressed; that is, if that model can explain the trace element patterns of the augite xenoliths and the calculated liquids in equilibrium with them (Figs 7 and 16). To test if melt–rock reaction can produce the trace element patterns of the KL augite xenoliths, an AFC model (DePaolo, 1981) was used with melt HF-11 and peridotite KLX-45 as starting compositions (Fig. 16a). Using the same parameters as produced by the melt–rock reaction using the MELTS program, i.e. mass assimilated/mass crystallized ratio (Ma/Mc) of 0.8 and

Table 9: continued

Model 2													
Total <i>Mc</i> (g):	0	<1	39	118	179	314							
Total <i>Ma</i> added (g):	0	6	42	99	145	254							
Mass liquid (g):	100	104	102	80	65	41							
<i>T</i> system (°C):	1465	1430	1369	1346	1320	1235							
<i>P</i> (kbar):	15	15	15	15	15	15							
Fo Olivine:		86	85	85.3	86	90							
Phase (wt %):	Melt	Ci	Melt	1st Cpx	Melt	Cpx	1st Opx	Melt	Cpx	Opx	SLX-39Cpx	SLX-56Cpx	SLX-56Opx
SiO ₂	40.28	41.15	43.35	51.78	44.65	50.62	46.74	50.08	53.68	52.24	49.86	53.72	50.43
TiO ₂	2.33	2.24	2.31	0.79	2.58	1.23	2.67	1.55	0.83	1.25	1.79	1.07	0.63
Al ₂ O ₃	11.48	11.17	12.25	4.91	14.97	6.12	17.13	6.79	4.66	18.97	7.46	5	6.57
FeO	13.4	13.27	11.67	4.44	10.54	5.49	8.58	6.69	8.15	3.36	5.59	6.59	4.71
MnO	0.23	0.22	0.14		0.07		0.03			0			
MgO	10.85	12.67	10.34	17.17	8.31	17.03	6.53	17.98	31.13	3.35	16.25	32.54	15.33
CaO	10.96	10.7	11.49	20.55	8.84	19.04	6.53	16.38	1.56	3.14	17.96	1.07	19.85
Na ₂ O	5.09	4.89	5.08	0.45	6.37	0.62	7.67	0.79	0.12	11.68	1.35	0.17	1.09
K ₂ O	1.84	1.76	1.81		2.3		2.81			4.46			
P ₂ O ₅	1.47	1.41	1.07		0.83		0.66			0.42			
H ₂ O	0.51	0.49	0.5		0.64		0.78			1.24			
<i>mg-no.</i>	59.07	62.99	61.21		58.43		57.57			63.99			

Fo, forsterite; Fa, fayalite; Clinoens., clinoenstatite; Al-Buffo., aluminobuffonite; Heden., hedenbergite; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Sp, spinel; *Mc*, mass crystallized; *Ma*, mass peridotite assimilated; *W*, wehrlite; *mg-number* = 100Mg/(Mg + Fe²⁺ total); 1st Cpx, first cpx to crystallize during modeling; 1st Opx, first opx to crystallize during modeling. Initial melt composition (*Ci*) is that of olivine nephelinite HF-11 (Francis & Ludden, 1995). Silica-undersaturated melts like HF-11 precipitate clinopyroxene before orthopyroxene when reacting with peridotite, thereby producing wehrlites similar to those of SL and KL. If a more silica-rich melt had been chosen, orthopyroxene would crystallize before clinopyroxene, and produce pyroxenites. Assimilant compositions are KLX Iherzolite (model 1) and SLX Iherzolite (model 2). Both models were run under constant pressure and enthalpy. Every step involves melt reacting with 1 g peridotite and fractionation of the crystallized phases. Only a few representative steps are shown here. The initial mass of the melt was set at 100 g and slowly decreases as the melt reacts with peridotite. A mass of 400 g of peridotite was set as an upper limit for the models. In model 1, olivine precipitates before any peridotite is added because the temperature of the initial melt was set below its liquidus temperature (1388°C at 10 kbar). An initial temperature below the liquidus of the melt was necessary with this melt-rock reaction modeling to achieve the low forsterite content of KL augite xenoliths (Fo = 82.4–84.3). The modeling results in falling system temperatures because the melt is much warmer than the peridotite, and enthalpy is conserved. Compositions of augite xenolith minerals are also shown to emphasize that this MELTS melt-rock reaction model produces mineral compositions that reasonably match those of natural samples. Models 1 and 2 start to reproduce augite wehrlite compositions with only a total of 23 and 42 g of peridotite, respectively, having reacted with a total of 100 g of melt. In model 2, orthopyroxene crystallizes after a total of 145 g of peridotite has been reacting with the melt, thereby producing compositions similar to those of SL opx-poor augite xenoliths.

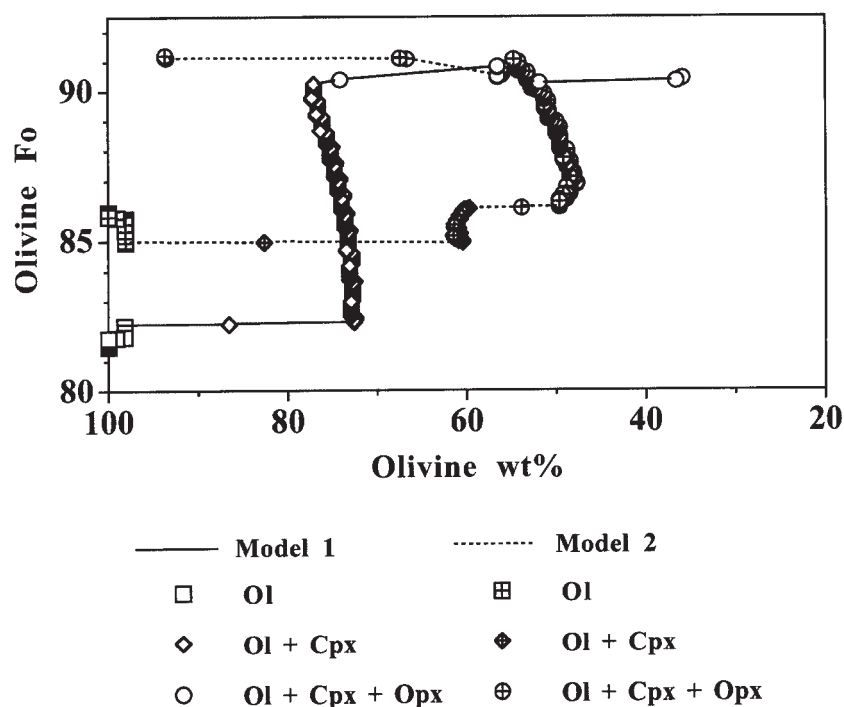


Fig. 15. Results of alkaline melt-peridotite reactions calculated with the MELTS program (Ghiorso & Sack, 1995; Asimow & Ghiorso, 1998) presented as the Fo content (mol %) of crystallized olivine vs the weight percent of olivine crystallized at each step of the program (per 1 g of peridotite assimilated). Each symbol represents a step. Crystallized phases are fractionated at each step. Details of models are presented in Table 9. The modeling is presented here until the end run of the MELTS program where a total of 400 g of peridotite has been assimilated by a total of 100 g of melt (a clearly unrealistic situation). The composition of the augite xenolith suites, however, can be reproduced with only a total of 23–42 g (wehrlites) to 145 g (opx-poor lherzolites) peridotite added.

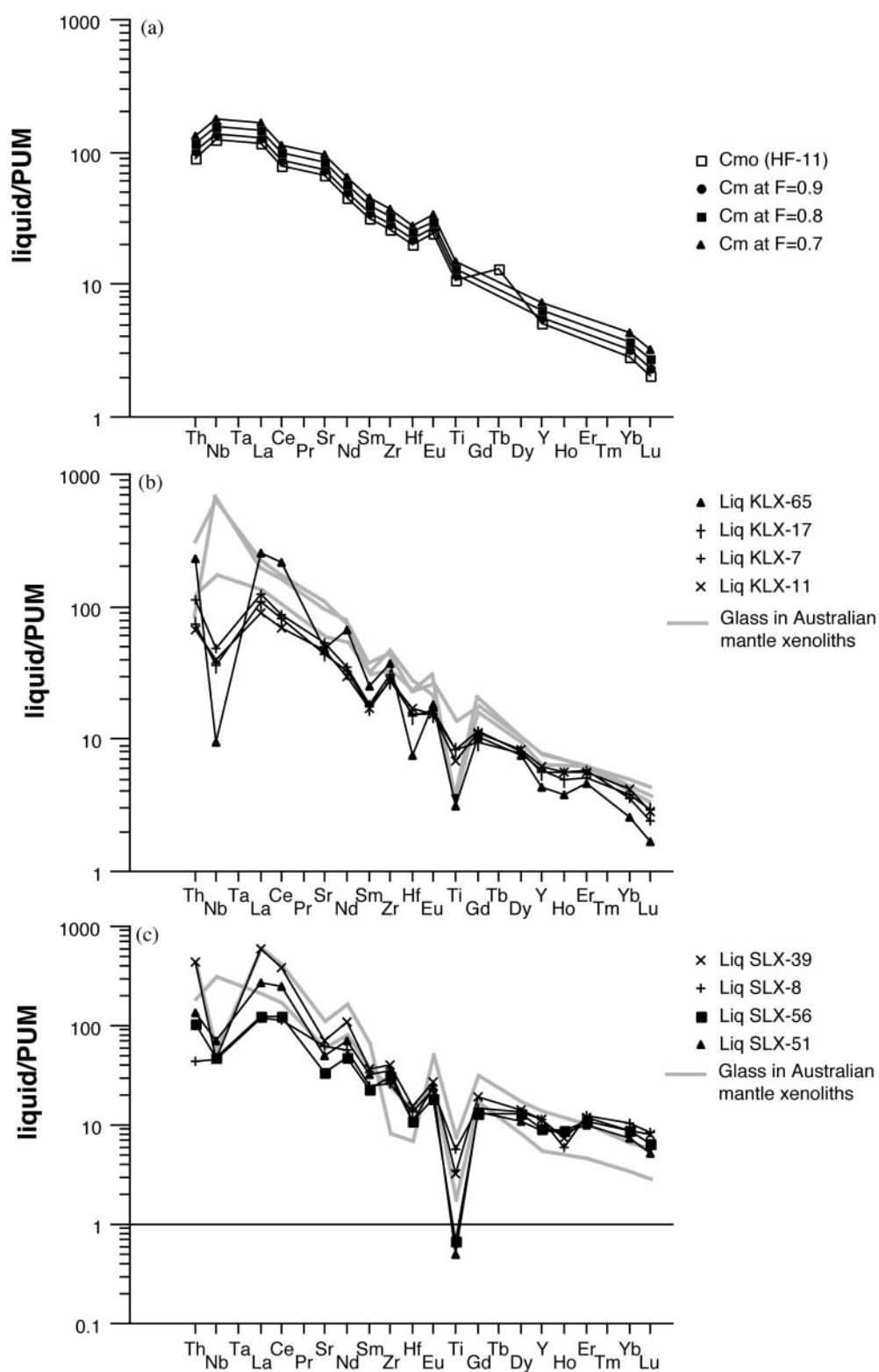
mass melt/initial mass melt (Mm/Mmo) of 0.9–0.7, does not change the trace element pattern of the AFC melt produced compared with the pattern of the original melt, but merely shifts it to slightly higher concentrations (Fig. 16a). Different initial melts, phase proportions in the crystallized assemblage, or partition coefficients do not change that observation. In other words, the calculated trace element patterns of liquids in equilibrium with the augite xenoliths are representative of those of the initial melts that produced them by interaction with peridotite (Fig. 16b and c). Melts in equilibrium with the augite xenoliths have steep LREE-enriched patterns, and Nb, Hf and Ti depletions, and KL ones have HREE-depleted patterns (Fig. 16b and c). Melt-rock reaction between Si-undersaturated alkaline melt and peridotite thus appears to be the best explanation for the major and trace element composition of the augite xenoliths.

Inferences from melt-rock reaction processes in the Canadian Cordillera mantle lithosphere

Augite xenoliths in KL and SL can both be explained by the reaction of alkaline melts with their peridotitic wall-rock. Differences in composition at the two sites are probably due to the different compositions of the magmas,

different temperatures of these melts, and different peridotite compositions, Cr-diopside xenoliths being overall more depleted at KL than at SL (Fig. 4). The mantle lithosphere beneath SL and KL would then be characterized by Cr-diopside peridotite crosscut by veins of discordant dunite, wehrlite, pyroxenite and opx-poor lherzolites. Augite xenoliths are present only at SL and KL, the two xenolith sites located the closest to the craton. It might be speculated that the transition region between the Canadian Cordillera orogen and the craton favors the circulation of melts, perhaps through ductile shear zones in the mantle. Alternatively, thickening of the lithosphere towards the craton may tend to favor the trapping of melts in the mantle, instead of their reaching the surface as exemplified in the many alkaline centers throughout the Canadian Cordillera (e.g. Francis & Ludden, 1995; Abraham *et al.*, 2001).

The MELTS modeling of the interaction of peridotite with Si-undersaturated melts produces melt compositions that are very rich in Al and alkalis (Table 9). The composition of these melts resembles that of glass in mantle xenoliths, which is typically rich in SiO_2 (45–75 wt %), Al_2O_3 (12–26 wt %) and alkalis (up to 16 wt %) (e.g. Schiano & Clocchiatti, 1994; Yaxley *et al.*, 1997).



Moreover, the trace element composition of the melts that interacted with peridotite (Fig. 16b and c) resembles some of the compositions of interstitial glass in mantle xenoliths (Yaxley & Kamenetsky, 1999), with the exception of the element Nb (Fig. 16b and c). Similarly, experimental work has shown that opx dissolution in Si-undersaturated melts can be responsible for the formation of some of the Si-rich alkaline glass commonly found in peridotites (Shaw *et al.*, 1998; Shaw, 1999). Production of wehrlite and opx-poor lherzolite by melt–rock interaction may thus be responsible for the formation of evolved melts that sometimes appear trapped as glass in mantle xenoliths.

CONCLUSION

The xenoliths found at alkali basalt volcanic centers of the southern Canadian Cordillera represent the mantle lithosphere located between the cratonic root of the Canadian continent and the Pacific oceanic lithosphere. They comprise Cr-diopside peridotites (spinel lherzolites, with minor harzburgites and dunites) and augite-bearing xenoliths (dunites, wehrlites, pyroxenites, opx-poor lherzolites). The Cr-diopside peridotites were formed by the extraction of basaltic melts in the spinel stability field, followed by cryptic metasomatism. Cr-diopside lherzolite is the dominant lithology among the xenoliths, and appears to be the result of similar degrees of melting in both the southern and northern Canadian Cordillera. No correlation between melting extent and crustal tectonics appears to exist. The composition of the Cr-diopside peridotites is similar to that of other spinel peridotites in continental areas bordering cratons and at Hawaii, but they are more fertile and less oxidized than those found in fore-arc tectonic setting. The largely HFSE-depleted character of the Cr-diopside xenoliths, however, may suggest a subduction origin for the metasomatic agents. Augite xenoliths are abundant in xenolith sites close to the craton and represent reactions between Cr-diopside peridotite and alkaline melts. The lithospheric mantle beneath the entire Canadian Cordillera is thus composed of relatively homogeneous Cr-diopside peridotite representing residues of 5–10% melting, followed by cryptic

subduction-related metasomatism. In particular, numerous depleted harzburgites are present locally in the north and are the end-result of metasomatism. Veins of crystallized alkaline melts that reacted with Cr-diopside peridotite crosscut abundantly the lithospheric mantle beneath the orogen–craton transition.

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Fig. 16 (opposite). (a) Primitive-mantle-normalized trace element patterns for nephelinite HF-11 and the melts resulting from AFC modeling (DePaolo, 1981) with HF-11 as initial liquid composition and lherzolite KLX-45 as assimilate. F , mass melt/initial melt mass (Mm/Mm_0). Modeling was run with mass assimilated/mass crystallized (Ma/Mc) of 0.8, and for a crystallizing assemblage made of 74% olivine, 24% clinopyroxene, and 2% spinel. AFC modeling with these parameters does not change the trace element pattern of the initial melt. (b) and (c) show calculated trace element patterns for liquids in equilibrium with KL (b) and SL (c) augite xenoliths (wehrlites KLX-7, KLX-17, KLX-11, SLX-39, SLX-8; dunite KLX-65; and opx-poor lherzolites SLX-56 and SLX-51), and comparison with trace element profiles of glasses found in Australian mantle xenoliths (Yaxley & Kamenetsky, 1999). With the exception of Nb, the trace element patterns of liquids in equilibrium with the augite xenoliths resemble those of glasses found in mantle xenoliths. Normalizing values of primitive mantle (PUM) are from Sun & McDonough (1989) and references therein. All calculations were made using mineral partition coefficients from Johnson (1998), except for Th (Norman, 1998).

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