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Re–Os constraints on harzburgite and lherzolite formation in the lithospheric mantle: A study of Northern Canadian Cordillera xenoliths

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Abstract—Osmium isotope data from lherzolite and harzburgite xenoliths of the northern Canadian Cordillera provide constraints on the genesis and age of the lithospheric mantle in a typical off-cratonic continental setting. The $^{187}Os/^{188}Os$ ratios of the lherzolites show a positive correlation with Al_2O_3 and heavy rare earth elements (HREE), which probably reflects Re/Os fractionation during various degrees of mantle melting, followed by a long period of radiogenic ingrowth. These observations are consistent with melting during the Proterozoic. Harzburgite Os isotopic ratios, however, plot above the regional correlation of the lherzolites. A positive correlation between their Os isotopic ratios and 1/Os concentrations suggests that they are the end result of the introduction of metasomatic agents with low Os contents, but high $^{187}Os/^{188}Os$ ratios, into the lithospheric mantle. These fluids or melts may have originated from a region of anomalously slow mantle detected seismically (Frederiksen et al., 1998) below harzburgite-rich xenolith localities (Shi et al., 1998). Alternatively, the radiogenic Os-bearing metasomatic agents may have been related to subduction processes along the western margin of the Canadian Cordillera, as has been previously suggested to explain the high Os isotopic ratios of xenoliths from the northern US Cordillera (Brandon et al., 1996). *Copyright © 2000 Elsevier Science Ltd*

1. INTRODUCTION

The cratonic cores of continents have been reasonably well documented by studies of peridotite xenoliths brought up by kimberlitic magmas (Walker et al., 1989; Carlson and Irving, 1994; Pearson et al., 1995a,b; Olive et al., 1997; Chesley et al., 1999). Systematic constraints are limited, however, on the age, formation mechanisms and metasomatic processes, past and present, of the lithospheric mantle underlying Phanerozoic orogenic belts surrounding the cratons (e.g., Menzies, 1983; McBride et al., 1996; Handler et al., 1997). Peridotite xenoliths found in alkali basalt centers of these regions represent this mantle lithosphere. A striking systematic feature of these peridotites is that the harzburgites are typically enriched in incompatible trace elements compared to the lherzolites, whereas the opposite would be expected if these rocks were simple melting residues (e.g., McDonough and Frey, 1989). This enrichment is attributed to metasomatism. However, the reason why depleted harzburgites are more affected by the latter than fertile lherzolites is the subject of debate, as is the relative chronology of melting and metasomatic events (Menzies, 1983; Takazawa et al., 1992; Ionov et al., 1994). The presence of bimodal suites, i.e., made up of nearly equal proportions of harzburgites and lherzolites, in the Canadian Cordillera is particularly interesting as it allows a direct comparison of these two rock types at the same location. This paper mainly focuses on the differences between harzburgites and lherzolites and their implications for subcontinental lithospheric processes in an off-cratonic, post-Archean setting.

The Re–Os system provides a powerful tool for studying the origin of harzburgites and lherzolites. Its great advantage over other isotopic systems used to study mantle rocks is that Os behaves compatibly, while Re is moderately incompatible during melting processes. Consequently, many earlier studies assumed the Os budget of a mantle rock to be nearly insensitive to percolating melts and fluids, in contrast to the budget of other isotopic systems such as Rb–Sr, Pb–Pb, and Sm–Nd (Reisberg et al., 1991; Pearson et al., 1995a,b; Wilson et al., 1996; Handler et al., 1997). In peridotites, the compatibility of Os has been used to allow calculation of minimum and model ages of melt depletion in the subcontinental lithosphere (e.g., Walker et al., 1989; Reisberg and Lorand, 1995; Burnham et al., 1998).

Nonetheless, correlations between Nd, Pb, and Os isotopes in harzburgite xenoliths from beneath present day volcanic arcs suggest that Os may be mobilized by oxidizing fluids related to subduction (Brandon et al., 1996; 1999; McInnes et al., 1999). Osmium may also have been added by asthenospheric metasomatic agents passing through the continental lithosphere in a rift environment bordering a craton (Chesley et al., 1999). The chalcophile behavior of Re and Os may induce movement of these elements together with sulfur during post-volcanic alteration of mantle xenoliths (Lorand, 1990), or during grain-boundary percolation of PGE (platinum group element)-bearing sulphidic fluids in the sub-continental mantle (Lorand, 1997; Pearson et al., 1998; Chesley et al., 1999). In this paper, the concept of systematic immobility of Os during metasomatism of peridotites is challenged again (Brandon et al., 1996; Pearson et al., 1998; Brandon et al., 1999; Chesley et al., 1999; McInnes et al., 1999).

The results presented below demonstrate that the Os isotopic

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systematics of lherzolites and harzburgites found in off-cratonic continental areas originated through different processes and at different times. These Os data show that the lherzolitic mantle lithosphere below the northern Canadian Cordillera preserves evidence for melt extraction during the Proterozoic. However, the harzburgite xenoliths from bimodal, as well as unimodal suites, record more recent metasomatic and/or melting events triggered by radiogenic Os bearing fluids or melts. The lithospheric mantle underlying Phanerozoic continental orogens is thus the result of a two-fold genesis, involving ancient melting, locally overprinted by recent metasomatism.

2. GEOLOGICAL SETTING

The Canadian Cordillera formed between 150 and 50 Ma ago by the accretion of diverse tectonic terranes to the North American protocontinent (Monger et al., 1982; Fig. 1). For the past 60 Ma, the tectonics of the Canadian Cordillera have been dominated by interactions with Pacific oceanic plates (Kula, entirely subducted, Pacific, Juan de Fuca and Explorer plates), which have been subducted beneath the margin of the northern American continental plate (Gabrielse and Yorath, 1991; Fig. 1). Late Tertiary to recent basaltic volcanism occurred throughout the Canadian Cordillera and appears to be related to zones of *trans*-tension reflecting lateral movement between these plates (Souther, 1991). A zone of anomalously slow mantle that appears to reflect a Tertiary to recent thermal event in the northern Cordillera has been discovered through teleseismic studies (Frederiksen et al., 1998). Volcanic centers above this zone contain a high proportion of cryptically metasomatized harzburgite xenoliths. In contrast xenolith suites outside this zone are dominated by lherzolites (Shi et al., 1998). These two types of mantle xenolith suites are referred to, respectively, as bimodal (comprising approximately equal proportions of lherzolites and harzburgites) and unimodal (composed almost solely of lherzolites, with only minor harzburgites; about 5%).

3. SAMPLE DESCRIPTION AND PREVIOUS STUDIES

All the xenoliths of this study were derived from mid-Tertiary to recent alkali basaltic lavas and are fresh spinel peridotites. Rhenium–Osmium analyses were performed on xenoliths from two bimodal suites; the Alligator Lake suite (17 samples) and the Llangorse suite (four samples). These two suites are located in the northern Canadian Cordillera. In addition, three harzburgite samples from unimodal suites of the southern Canadian Cordillera (Fig. 1; Rayfield River and Kostal Lake) were also analyzed. Re–Os analysis of lherzolites from other unimodal suites from the Canadian Cordillera are described elsewhere (Peslier et al., 2000a,b). All the analyzed xenoliths are Type I Cr-diopside peridotites as defined by Frey and Prinz (1978). Major and trace element compositions for Alligator Lake and Llangorse xenoliths are reported in Francis (1987) and Shi et al. (1998), respectively. Major element trends, such as negative correlations of CaO, Al_2O_3, TiO_2, SiO_2, and FeO with MgO, and a positive correlation of NiO with MgO, indicate that the xenoliths are the residues of melt extraction (Francis, 1987; Shi et al., 1998). However, as often observed in spinel Cr-diopside suites (McDonough and Frey, 1989), clinopyroxenes in the harzburgites are enriched in incompatible trace elements compared to those of the lherzolites (Shi et al., 1998), opposite to what is expected for melt extraction.

Most of the harzburgite whole rocks have steep light rare earth element enriched patterns (Ce/Yb from 16.38 to 69.08; Table 1; unpublished data from Shi and Francis), except at one unimodal suite (Rayfield River) where the two harzburgites analyzed are depleted in LREE (Ce/Yb <1; Table 1; Peslier et al., 2000a,b). Lherzolite whole rock REE patterns are quite variable, but are generally more LREE depleted than those of the harzburgites (Ce/Yb varies from 0.10 to 55.26; Table 1; unpublished data from Shi and Francis). The contrast between harzburgite and lherzolite REE patterns is more striking in the clinopyroxene data (Fig. 12 of Shi et al., 1998). The combination of the teleseismic studies conducted in the northern Canadian Cordillera (Frederiksen et al., 1998) and trace element laser ICP–MS analyses of clinopyroxenes from the bimodal suites led Shi et al. (1998) to elaborate the following model for the genesis of the harzburgites. The influx of fluids/melts from the hot anomalous zone induced melting of the overlying mantle lithosphere, represented by the lherzolites which are the dominant peridotite type in the region. The harzburgites would thus represent the residue after this melting. The fluids/melts were likely to be enriched in incompatible trace elements, and thus were also responsible for the concomitant incompatible trace element enrichment of the harzburgites. On the other hand, a Sr–Pb study of the bimodal suites (Carignan et al., 1996) concluded that some of the lherzolite and harzburgite isotopic characteristics were disturbed by a recent metasomatic event (less than 30 Ma), probably linked to subduction related fluids.

4. ANALYTICAL PROCEDURES

Samples for Os analysis were digested by the Carius tube technique, and Os was extracted by double distillation (Shirey and Walker, 1995). Typically, 1.5 g of sample powder were digested. Osmium was further purified through a microdistillation procedure (Roy-Barman, 1993). Osmium was analyzed as negative ions (Creaser et al., 1991; Volkening et al., 1991) on a Finnigan MAT 262 mass spectrometer, in peak jumping mode using an electron multiplier. Measurements of 70 standards (>40 pg yielded $^{187}Os/^{188}Os$ ratios $=0.173\,98 \pm 0.000\,40$ (2σ standard deviation of the population). Osmium total blanks were between 5 and 7 pg. Precision on the isotopic ratios of the analyzed samples is less than $\pm 0.3\%$ ($2\sigma - m$, Table 1). Reproducibility of $^{187}Os/^{188}Os$ ratios is within 1% (Table 1; Peslier et al., 2000). Osmium concentration reproducibility is between 15 and 30%, which probably reflects a nugget effect (Shirey and Walker, 1998, and references therein), i.e., heterogeneity of the sample on the scale that the aliquots were taken.

Rhenium was processed in two ways. In some cases, separate aliquots of powder were dissolved in $3HF + 1HNO_3$ and left for 3 days in an oven at 140 °C. Re was then extracted on one AG1X8 anion column following the procedure described in Reisberg et al. (1991), and then analyzed by isotope dilution on an Elan 6000 ICP–MS (bold characters in Table 1). In other cases, samples dissolved by Carius tube and spiked for both Re and Os were processed through the anion column described above, and analyzed by ICP–MS (plain characters in Table 1). Blanks were 18 ± 12 pg. The blank correction varies from 2.5

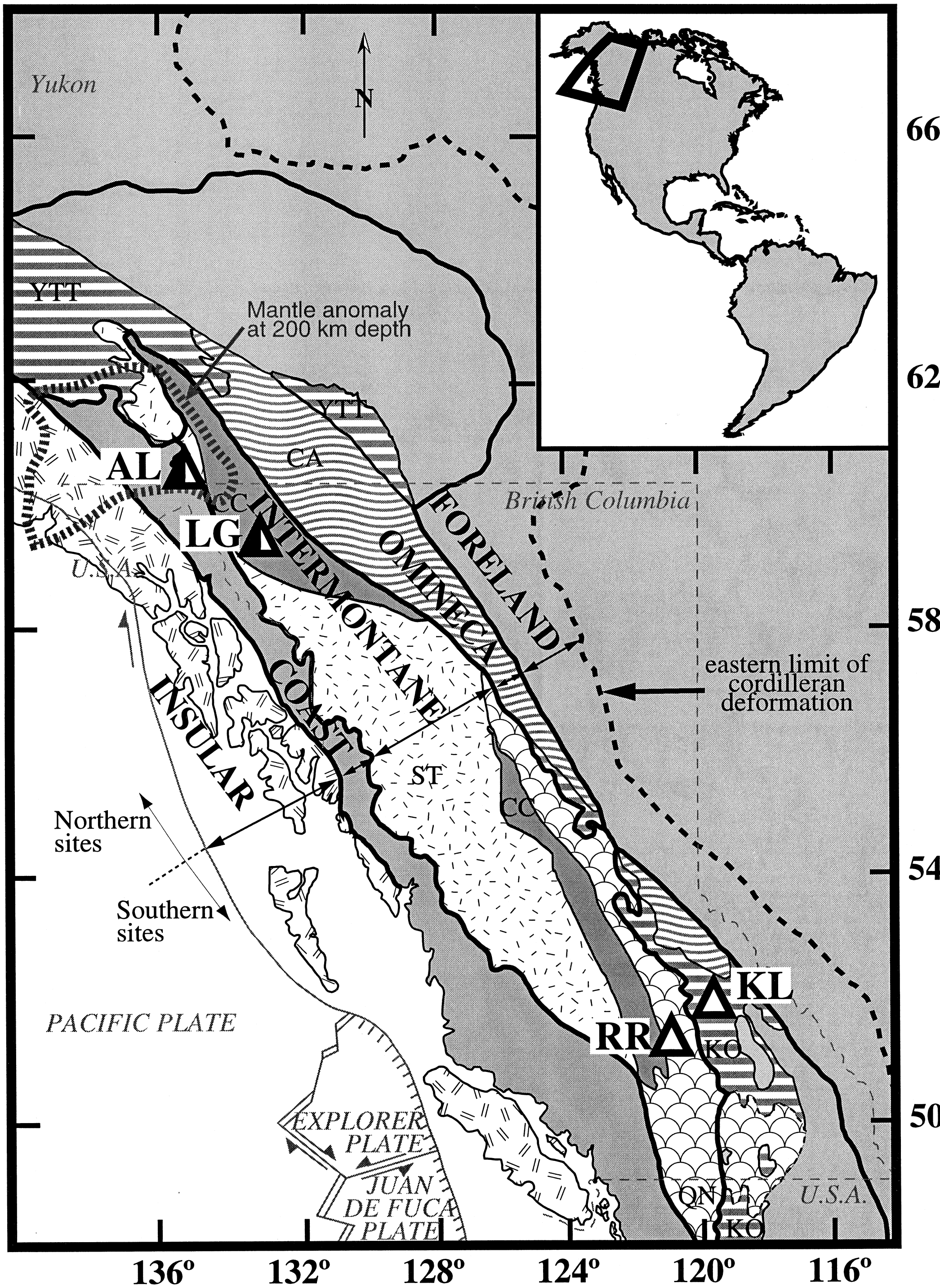

Fig. 1. Map of the Canadian Cordillera and mantle xenolith site locations. White triangles represent unimodal suites, while black and white triangles denote bimodal suites. Xenolith site name abbreviations: AL = Alligator Lake, LG = Llangorse, RR = Rayfield River, KL = Kostal Lake. Tectonic terrane name abbreviations: YTT = Yukon Tanana (=similar characteristics to the Kootenay terrane (KO) of British Columbia, Mortensen, 1992), CA = Cassiar, ON = Quesnellia, CC = Cache Creek, ST = Stikine. Oceanic plate boundaries are from Riddihough and Hyndman (1991). The approximate location of the seismic mantle anomaly at 200 km depth was drawn from Frederiksen et al. (1998) and Shi et al. (1998).

to 50 % (in the low-Re content samples, i.e., <0.02 ppb). Since many of the Re concentrations were measured on different powder splits than the corresponding Os analyses, powder heterogeneity combined with large blank correction in some

Table 1. Os isotope data from mantle xenoliths of the Canadian Cordillera. Precision on the $^{187}Os/^{188}Os$ ratios listed corresponds to $2\sigma\text{-}m$ run statistics. Uncertainties on the Lu and Al_2O_3 contents are respectively ±0.001 ppm (analytical precision calculated from 10 replicate analyses of a REE standard) and 0.03 wt. % (analytical precision calculated from 20 replicate analysis). Re contents determined on samples dissolved in HF–HNO_3 are denoted in boldface and corrected for 30 pg total blank, while those digested by the Carius Tube technique are listed in plain type and corrected for a 50 pg total blank. Os isotopic ratios were normalized to $^{192}Os/^{188}Os = 3.082\,71$. U = Unimodal suites, B = Bimodal suites, * = samples analyzed by Carignan et al. (1996). Model age calculations (T_{MA}) and minimum Re depletion age (T_{RD}) were made using a $\lambda = 1.666 \times 10^{-11}$ y^{-1} (Smoliar et al., 1996), a present primitive mantle $^{187}Os/^{188}Os$ ratio of 0.1290 and $^{187}Re/^{188}Os$ ratio of 0.428 (Meisel et al., 1996). *S* contents were analyzed by combustion followed by impulsion coulometry at the CRPG-CNRS (Nancy, France), and reproducibility ranges from 10% to 40%. Ce/Yb ratios are unnormalized.

Location name	Tectonic terrane	Sample	Rock type	[Re] (ppb)	[Os] (ppb)	$^{187}Os/^{188}Os$	$^{187}Re/^{188}Os$	T_{MA} (Ga)	T_{RD} (Ga)	*S* (ppm)	Al_2O_3 (wt.%)	Mg #	Nd (ppm)	Sm (ppm)	Yb (ppm)	Lu (ppm)	Ce/Yb
Northern Canadian Cordillera																	
Alligator Lake (B)	Coast Belt	AL-40	lherz		2.23	0.128 40 ± 25			0.08	30	3.43	89.5	0.55	0.208	0.305	0.053	5.24
		AL-42	lherz	**0.187**	1.50	0.125 68 ± 13	0.5995	<0	0.46		3.24	89.7	0.90	0.296	0.295	0.050	4.39
		AL-46	lherz		0.15	0.130 81 ± 58			<0		3.53	89.3	0.70	0.220	0.380	0.060	55.26
		AL-47	lherz		2.19	0.125 41 ± 37			0.50		2.66	89.6	0.27	0.120	0.227	0.040	1.76
		AL-70	lherz								1.56	85.3	1.82	0.478	0.103	0.013	41.21
		AL-75	lherz	**0.090**	1.06	0.125 91 ± 28	0.4088	<0	0.43		2.05	89.8	2.93	0.618	0.188	0.028	29.01
		AL-76[a]	lherz	**0.310**	1.81	0.128 30	0.8220	<0	0.10	35	3.63	88.3	0.56	0.168	0.335	0.055	11.93
		AL-86	lherz	**0.144**	0.73	0.125 31 ± 37	0.9537	<0	0.52		2.50	89.1	1.79	0.299	0.229	0.039	18.78
		AL-88[a]	lherz	**0.289**	1.53	0.131 60	0.9075	0.32	<0	58	3.77	89.5	0.53	0.206	0.365	0.066	13.20
		AL-41	harz	**0.179**	1.14	0.125 54 ± 34	0.7518	<0	0.48	38	0.62	91.3	0.51	0.076	0.019	0.004	69.08
		AL-49	harz		0.68	0.120 98 ± 34			1.11	27	0.44	90.9	0.27	0.042	0.012	0.002	50.67
		AL-52[a]	harz	**0.093**	0.78	0.127 40	0.5742	<0	0.22	27	0.58	91.2	0.34	0.063	0.029	0.004	39.16
		AL-53	harz		1.71	0.125 31 ± 24			0.52		0.72	91.2	0.50	0.085	0.031	0.005	34.24
		AL-54	harz	0.057	1.76	0.126 48 ± 49	0.1559	0.55	0.35		0.66	91.4	1.30	0.273	0.048	0.006	43.61
		AL-56	harz	**0.082**	1.02	0.127 24 ± 25	0.3849	2.40	0.25		1.22	89.9	0.36	0.055	0.062	0.011	16.38
Llangorse (B)	Cache Creek	XLG-30N	lherz	0.360	4.47	0.124 50 ± 29	0.3872	<4.5	0.63	80	3.13	90.7	0.05	0.047	0.256	0.044	0.10
		XLG-29A	lherz	**0.195**	0.51	0.122 36 ± 43	1.8416	<0	0.92	65	1.49	89.7			0.082	0.015	0.49
		XLG-12A	harz	**0.003**	0.41	0.129 57 ± 36	0.0349	<0	<0	36	0.71	91.3	0.07		0.009	0.008	19.85
		XLG-25A	harz	0.014	0.05	0.137 28 ± 76	1.3403	0.54	<0	33	0.84	91.6	0.87	0.160	0.037	0.008	49.22
Southern Canadian Cordillera																	
Rayfield River (U)	Quesnellia	RRX-19	harz	**0.045**	3.14	0.124 43 ± 30	0.0290	0.68	0.64		1.02	90.5	0.04	0.011	0.031	0.007	0.82
		RRX-21	harz	**0.019**	1.34	0.125 32 ± 21	0.0680	0.61	0.51	41	0.94	90.3		0.014	0.048	0.010	0.33
Kostal Lake (U)	Kootenay	KLX-47	harz	**0.028**	1.26	0.126 61 ± 39	0.1064	<0	0.33		1.17	89.7	0.45	0.085	0.047	0.009	18.78
Other sites[b]		KRX-11[b]	lherz	**0.011**	1.17	0.123 63 ± 21	0.0451	0.84	0.75	27	1.81	90.4					
					0.77	0.124 94 ± 43											
		BTX-26[b]	lherz	**0.054**	1.05	0.130 90 ± 58	0.2463	<0	<0	29	4.56	89.5					
				0.071	1.23	0.131 11 ± 22	0.2762										

[a] Re–Os analysis from Carignan et al. (1996).

[b] Re–Os analysis from Peslier et al. (1999b); only shown here for demonstrating the reproducibility of the Os data).

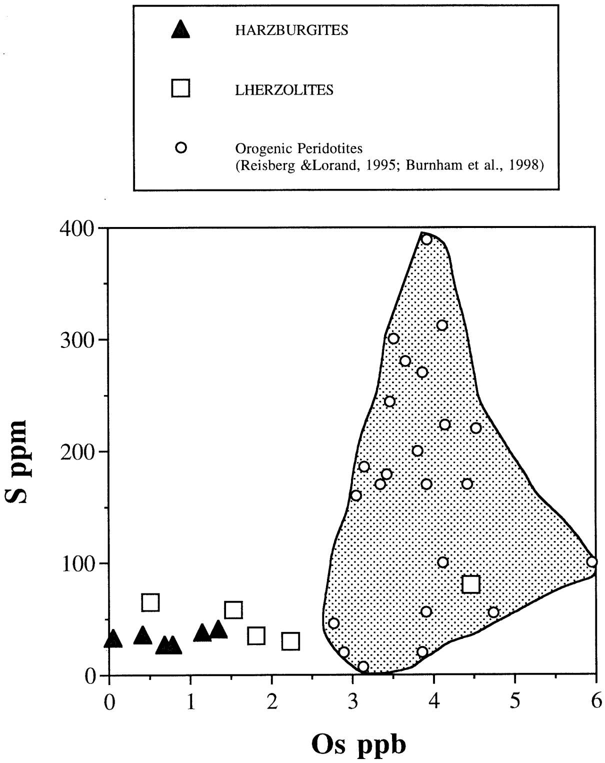

Fig. 2. S content versus Os content of Canadian Cordillera xenoliths and comparison with orogenic peridotites (Reisberg and Lorand, 1995; Burnham et al., 1998). Dotted area represents orogenic peridotite field.

cases, will introduce uncertainty on the Re/Os ratios. However, all of the lherzolites, including those analyzed by Carignan et al. (1996) at the Carnegie Institution of Washington, have similar ^{187}Re/^{188}Os ratios that are consistently higher than those of the harzburgites (see Section 6.1), suggesting that these effects on the Re concentrations are of minor importance.

5. RESULTS

Osmium and Re concentrations and ^{187}Os/^{188}Os ratios are given in Table 1, as well as three data points from the study of Carignan et al. (1996), and two samples from Peslier et al. (2000b). The two latter data are presented here only to show the reproducibility of the data, and are not used in the figures and discussion of this paper. The Os contents of all the analyzed xenoliths range from 0.05 ppb to 4.5 ppb, most being less than 2.5 ppb (Table 1). These values are comparable to those reported for other spinel peridotite xenoliths in alkali basalts (McBride et al., 1996; Handler et al., 1997), but less than the values usually found in peridotite massifs (e.g., Reisberg et al., 1991; Fig. 2). Sulfur contents (Table 1) are also lower than typical peridotite massif values, as is often the case in mantle xenoliths (Lorand, 1990). Re contents range from 0.014 to 0.310 ppb, which are typical upper mantle values, and are generally lower in the harzburgites than in the lherzolites (Fig. 3a). A broad correlation exists between Re and Al_2O_3 and HREE (heavy rare earth elements; Fig. 3a) contents.

Although no correlation is observed between ^{187}Re/^{188}Os and ^{187}Os/^{188}Os (Fig. 4), the ^{187}Os/^{188}Os ratios of the lherzolites define a good correlation with fusion indexes such as Al_2O_3 and HREE (Fig. 5). This trend is not seen in the harzburgites from either the bimodal or the unimodal suites. Despite potential variations in Os concentrations resulting from the nugget effect (see above), 1/Os correlates with ^{187}Os/^{188}Os among the harzburgites (Fig. 6). The coefficient of correlation (r^2) of the ^{187}Os/^{188}Os vs. 1/Os harzburgite correlation is 0.888 (excluding samples XLG-25A and AL-49). One of the harzburgites (XLG-25A) has a ^{187}Os/^{188}Os ratio of 0.1373, which is markedly higher than the primitive upper mantle value of 0.1290 (Meisel et al., 1996). Furthermore this sample also has the lowest Os concentration of all the xenoliths and falls below the ^{187}Os/^{188}Os vs. 1/Os harzburgite correlation (Fig. 6). Another harzburgite xenolith from the Llangorse site (XL-12A) also possesses a high Os isotopic ratio with a relatively low Os concentration, but nonetheless plots on the ^{187}Os/^{188}Os–1/Os trend of the other harzburgites. Harzburgite AL-49 also falls off the harzburgite correlation and is the only harzburgite that appears to lie on the ^{187}Os/^{188}Os–Al_2O_3 correlation line de-

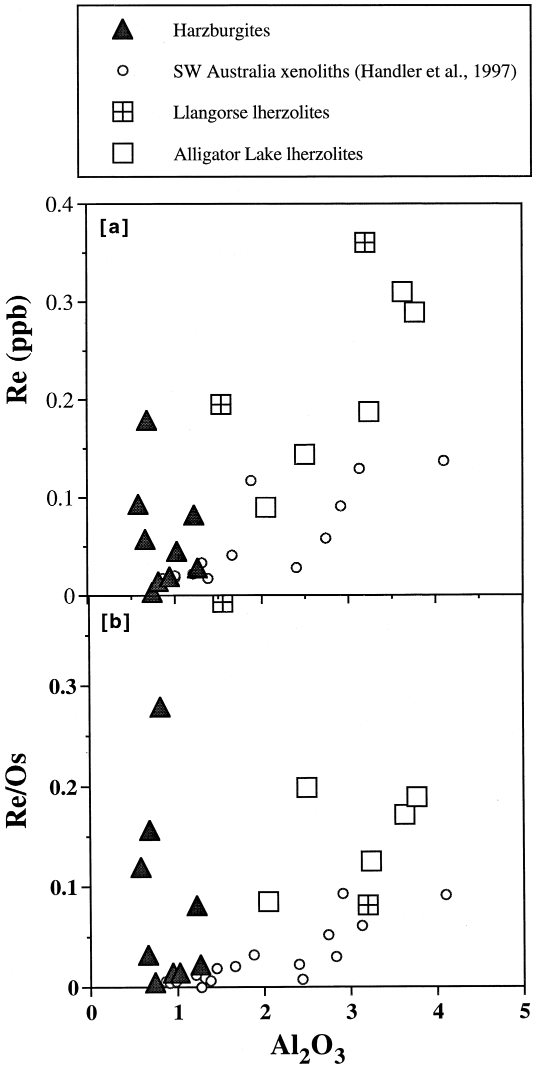

Fig. 3. Re content (ppb) (a) and Re/Os ratio (b) versus Al_2O_3 content (wt.%).

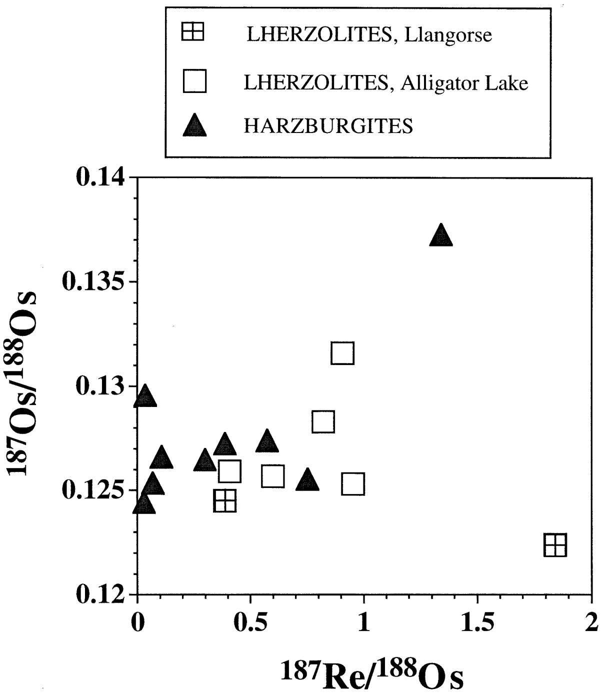

Fig. 4. ^{187}Os/^{188}Os vs ^{187}Re/^{188}Os.

fined by the lherzolites, despite exhibiting the LREE enriched patterns typical of most other harzburgites (AL-49 Ce/Yb = 50.67; Table 1; unpublished data from Shi and Francis). Finally, no correlation was observed between Os isotopes and Pb isotopes (Carignan et al., 1996) in lherzolites or harzburgites.

6. DISCUSSION

6.1. Do Harzburgites and Lherzolites Share a Common History?

Harzburgites and lherzolites can be formed by different extents of melt removal from fertile peridotite during a common melting event. Partial melting of 20–25 % from the most fertile lherzolite is required to reproduce the bulk-rock major-element and clinopyroxene HREE contents of the most depleted harzburgite (Francis, 1987; Shi et al., 1998). In the case of the northern Canadian Cordillera samples, however, there are several reasons to believe that the history of the harzburgites was more complex than that of the lherzolites. First, the distribution of harzburgite and lherzolite rock types in the northern locales studied here is strikingly bimodal (see Fig. 2 in Shi et al, 1998). While more extensive melting could lead to a higher proportion of harzburgite, there is no reason that it should produce a distribution with two distinct compositional peaks. Instead, as suggested by Shi et al., this distribution may have been produced by remelting of a dominantly lherzolitic lithosphere, reheated by the underlying zone of anomalous mantle. Second, within each bimodal suite, intermineral equilibration temperatures of the harzburgites are about 60 to 80°C higher than those of the lherzolites (Shi et al., 1998). This corresponds to a depth difference of about 8 km. Thus the harzburgites may not be derived from the same depth interval as the lherzolites. Third, bimodal suite harzburgites, and particularly clinopyroxenes derived from these harzburgites (Shi et al., 1998, their Fig. 12), have much higher LREE contents than the lherzolites and their corresponding clinopyroxenes. This implies that the harzburgites have interacted much more strongly with enriched magmas or fluids than the lherzolites. Finally, the Os data themselves suggest that the harzburgites and lherzolites have different histories, as the harzburgites lie above the trends relating ^{187}Os/^{188}Os to Al_2O_3 or Lu contents among the lherzolites (Fig. 5). For all of these reasons, we believe that the harzburgites and the lherzolites have different histories, and will therefore discuss the two rock types separately.

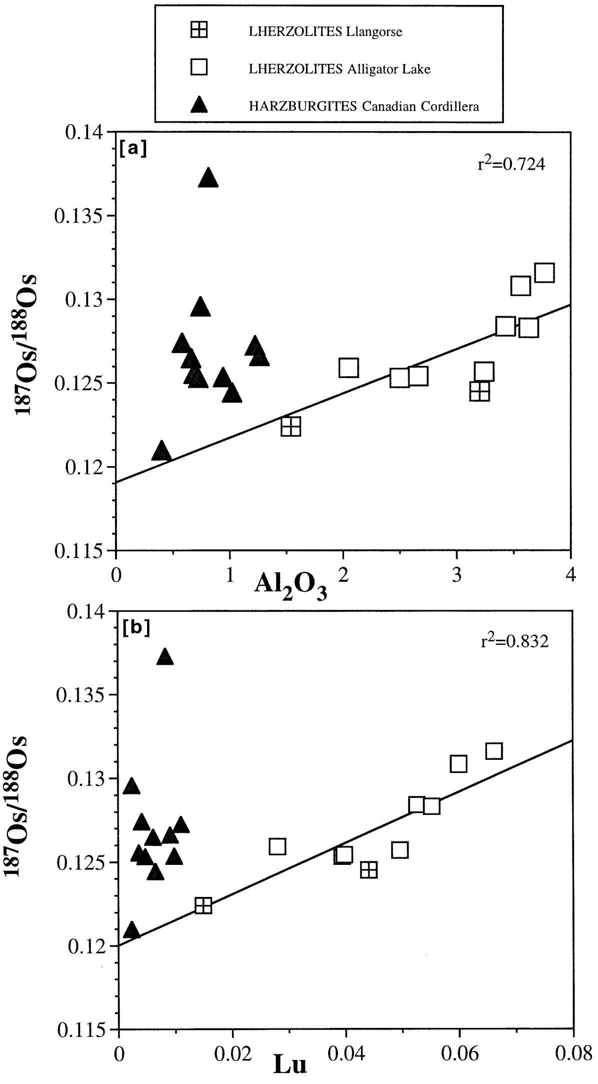

Fig. 5. ^{187}Os/^{188}Os vs Al_2O_3 (a) and [Lu] (b). Lu concentrations in ppm. The coefficients of correlation (r^2) for the lherzolite trends were calculated including harzburgite AL-49 which lies on these correlations.

6.2. Re–Os Systematics of the Lherzolites

Lherzolites with similar major element and Os isotopic characteristics to those of the bimodal suites studied here are the

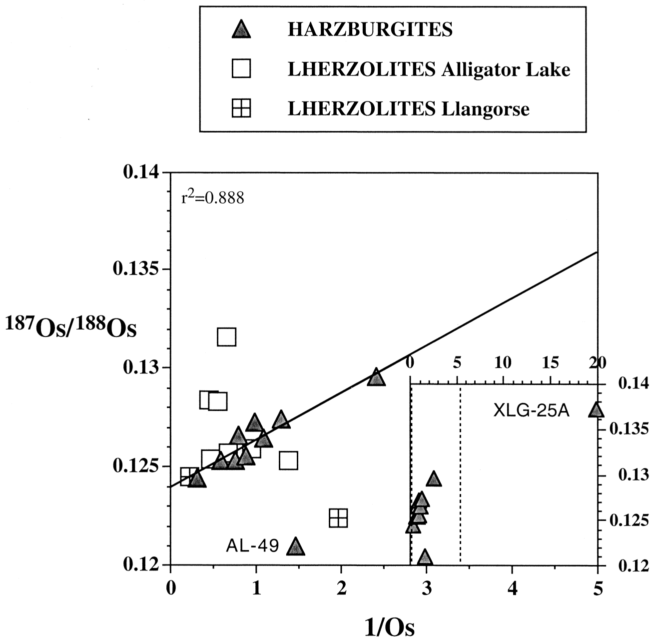

Fig. 6. ^{187}Os/^{188}Os vs 1/[Os] for the harzburgitic xenoliths, derived from both bimodal and unimodal suites. The larger graph is an expanded view of the dashed portion of the small graph. The coefficient of correlation of the harzburgite alignment ($r^2 = 0.888$) was calculated excluding samples AL-49 and XLG-25A.

most abundant type of mantle xenoliths found throughout the entire Canadian Cordillera, suggesting that this rock type is volumetrically dominant in the mantle lithosphere underlying this orogenic belt. No correlation is observed between ^{187}Os/^{188}Os and ^{187}Re/^{188}Os among these samples (Fig. 4) despite the existence of a good correlation between ^{187}Os/^{188}Os and Al_2O_3 or HREE contents (Fig. 5). A similar lack of correlation between ^{187}Re/^{188}Os and ^{187}Os/^{188}Os in other peridotite suites has often been attributed to disturbance of the moderately incompatible element Re by metasomatic processes (e.g., Walker et al., 1989; Reisberg and Lorand, 1995). The concentration of Re in the lherzolites and harzburgites of the suites studied here correlates roughly with Al_2O_3 (Fig. 3a) and HREE contents, but the Os content does not. Re concentrations of harzburgites are lower than those of lherzolites. The Re concentrations of the lherzolites are higher than those observed in similar xenolith suites (Handler et al., 1997; Fig. 3a) and approach those of fertile orogenic lherzolites (~0.3 ppb). The rough correlation of Re and Al_2O_3 of the xenoliths (Fig. 3a), coupled with the lack of correlation between Re/Os and Al_2O_3 (Fig. 3b) suggests that the lherzolites may have experienced substantial recent Os loss. Alternatively, their higher Re contents compared to those of the other xenoliths shown in Fig. 3a may indicate that Re was added to them. The ^{187}Re/^{188}Os ratios of nearly all the lherzolites are considerably higher (Table 1) than that of modern fertile upper mantle (~0.4), despite the fact that their Os isotopic ratios indicate time-integrated Re/Os ratios lower than that of the fertile mantle. Thus regardless of which process (Os loss or Re addition) was more important, the increase of the ^{187}Re/^{188}Os ratios must have been recent.

The decoupling of ^{187}Re/^{188}Os and ^{187}Os/^{188}Os observed in the Canadian Cordillera xenolith data also affects the calculation of Os model ages, and leads to “future” ages or ages older than the Earth (Table 1). Calculated minimum ages, assuming a Re/Os of zero (Walker et al., 1989), range from 0.08 to 1.11 Ga, with no significant difference between lherzolites and harzburgites, but four xenoliths still yield “future” ages (Table 1). Since the lherzolites almost certainly had Re/Os ratios significantly higher than zero after melt extraction these “Re depletion ages” seriously underestimate the true ages of the melting events. Because of the apparent perturbation of the Re/Os ratios, age information cannot be obtained from an isochron diagram. Nevertheless, the good correlation between ^{187}Os/^{188}Os vs. Al_2O_3 in the lherzolite xenoliths permits the use of the method of Reisberg and Lorand (1995) to estimate the age of the last depletion event. In this method, Al_2O_3 is taken as a proxy for the Re/Os ratio, and gives an age of 1.64 ± 0.52 Ga for the Alligator Lake lherzolites ($r^2 = 0.622$ for the ^{187}Os/^{188}Os vs. Al_2O_3 correlation). Meisel et al. (1996) and Hauri and Hart (1997) consider Lu and Re as similarly incompatible. Because of possible post-fusion Re addition, we have used the Lu content of the whole rocks as a Re/Os ratio proxy (Peslier et al., 2000a; 2000b). The ^{187}Os/^{188}Os vs. Lu correlation for the Alligator Lake lherzolites ($r^2 = 0.708$; Fig. 5b) yields a model age of 1.55 ± 0.72 Ga. If the harzburgite AL-49 is included in the correlation ($r^2 = 0.832$), the model age is 1.21 ± 0.48 Ga (1.34 ± 0.56 using Al_2O_3; $r^2 = 0.724$). These ages were calculated using a mantle evolution curve similar to that of primitive mantle (Meisel et al., 1996). If the average “chondritic” mantle evolution curve (ordinary and enstatite chondrites; Meisel et al., 1996) is used instead, the estimated ages decrease by 0.1 Ga. The uncertainties on the ages are based on the expanded uncertainties on the *y* intercept, and mainly reflect how well the data fit an “isochron” line (McIntyre et al., 1966; York, 1969; Titterington and Halliday, 1979). A conservative interpretation of these uncertainties suggests that the Alligator

Lake lherzolites are the residues of melting events which took place between 0.73 and 2.27 Ga ago, i.e., during the Proterozoic. It is quite possible, however, that most melt extraction associated with lithosphere formation was limited to a much shorter time interval within this period. The implications of mantle age calculations for the lithosphere bordering cratons such as that of the Canadian Cordillera are discussed in detail in another paper with additional Re–Os analysis of lherzolites from seven unimodal suites (Peslier et al., 2000a,b).

6.3. Re-Os Systematics of the Harzburgites

6.3.1. The ^{187}Os/^{188}Os–1/Os correlation

In contrast to the lherzolites, the Os isotopic ratios of the harzburgites show no relation with HREE or Al_2O_3. The positive correlation between ^{187}Os/^{188}Os and 1/Os, observed in harzburgites from both bimodal and unimodal suites (Fig. 6), however, suggests a mixing process between peridotite and components with radiogenic Os and low Os concentrations. Given the scatter in the trend, a wide range of radiogenic components is permitted. For example ^{187}Os/^{188}Os ratios between about 0.132 and 0.146 would be consistent with the observed scatter if the radiogenic component contained 0.2 ppb Os. Thus the general trend observed in Fig. 6 does not imply that all of the harzburgites interacted with a single, well-defined enriched component, which would be improbable given their geographic separation. Sample Al-49 which lies off the ^{187}Os/^{188}Os vs. 1/Os correlation, although enriched in incompatible elements like most other harzburgites (Table 1; Shi et al., 1998), may represent a depleted end member of the lherzolite trend. The exceptionally low Os content of XLG-25A (0.05 ppb), on the other end, suggests that it may have been affected by post-eruptive Os loss (Lorand, 1990), or a different metasomatic agent. The two harzburgites having the highest Os isotopic ratios (XLG-25A and XLG-12A) are the only harzburgites analyzed from the Llangorse site. In contrast to the Alligator Lake site, where the xenoliths were removed from scoria, mantle xenoliths at Llangorse were extracted from a lava lake and may have exchanged Os with their host lava. However, lherzolite xenoliths from the Llangorse suite do not show similar Os isotopic enrichments or particularly low Os contents (Table 1), suggesting the Os characteristics of the Llangorse harzburgites are primary.

Finally, the harzburgite ^{187}Os/^{188}Os–1/Os correlation (Fig. 6) indicates that the Os concentration variation in the harzburgites is not the result of sulfur loss through post-eruptive alteration processes such as described by Lorand (1990), and that such processes are not the primary cause of the low Os contents of spinel xenoliths compared to those of orogenic peridotitic massifs. Such processes could lower the Os contents of the harzburgites, but not change their Os isotopic ratios. Ionov et al. (1992) argued that the difference in sulfur content between alkali basalt mantle xenoliths and peridotite massifs is due to the former representing subcontinental lithospheric mantle and the latter being convecting "MORB-type" mantle. Crustal fluids would be responsible for metasomatic S-enrichment during tectonic emplacement of the peridotite orogenic massif into the crust (Ionov et al., 1992). However, the fact that peridotite massifs have also higher Os contents than alkali basalt mantle xenoliths excludes crustal fluids as possible Os-enrichment agents, as crustal fluids are likely to be extremely poor in Os. The phenomenon responsible for the Os concentration difference between xenoliths and orogenic peridotitic massifs (Fig. 2) thus remains unclear, but it was probably pre-eruptive.

6.3.2. Harzburgite formation

Recent simple re-melting of the lithospheric mantle cannot explain the harzburgite Os data. In theory, this process could have produced the harzburgites from the lherzolites without changing the ^{187}Os/^{188}Os ratios, thus causing them to plot above the lherzolite trend in Fig. 5. However, it could not have produced harzburgite XLG-25A with a ^{187}Os/^{188}Os ratio (0.137) exceeding that of fertile mantle (0.1290; Meisel et al., 1996). Furthermore, melting alone would not generate the ^{187}Os/^{188}Os–1/Os correlation.

These observations suggest that metasomatic enrichment is the process most likely to explain the Os isotopic characteristics of the harzburgites. The ^{187}Os/^{188}Os–1/Os correlation (Fig. 6) could be a mixing line representing the interaction of low-Os content, high-Os isotopic ratio metasomatic fluids or melts with the depleted mantle lithosphere. If the harzburgite correlation is modeled as simple mixing between a low-Os isotopic ratio, high Os content harzburgite (e.g., sample RRX-19) and a high Os isotopic ratio, low Os content mixing component, at least 80% of the radiogenic component would be required to reproduce the Os content range of the harzburgites. This is clearly unrealistic from the perspective of major element bulk addition of any type of melt or fluid, as this process would have completely transformed the bulk and mineral compositions of the harzburgites. Instead, this simple calculation indicates that Os may have been preferentially scavenged from the peridotite to the fluid. It is for instance well known that PGE (Platinum Group Elements) such as Os can be mobile under certain conditions of temperature, and oxygen, sulfur and chlorine fugacities (Wood, 1987; Fleet et al., 1999).

Two hypothetical scenarios may explain the fact that only the harzburgite type xenoliths display ^{187}Os/^{188}Os ratios that fall above the regional lherzolite trend. One possibility is that metasomatic melts/fluids with high Os isotopic ratios preferentially migrated through pre-existing harzburgites and reset their Os isotopic characteristics. This is in agreement with the fact that these distinct Os features are displayed by harzburgites found throughout the Canadian Cordillera (Table 1). Two of the southern Canadian Cordillera samples have LREE depleted whole-rock patterns (RRX-19 and RRX-21; Table 1), unlike the distinctly LREE enriched patterns of the other harzburgites, suggesting that Os and LREE metasomatism may have been decoupled. Decoupling between Os isotopes and incompatible trace elements has been noted before (Pearson et al., 1995a; Pearson et al., 1995b; Olive et al., 1997) but in these studies Os isotopes were affected solely by melting, and only Nd and Sm showed the effects of metasomatism. In the case of the Canadian Cordillera harzburgites, Os isotopes are disturbed by metasomatism as well, but this metasomatism may be different from that which affected the incompatible trace elements in terms of agent composition, timing or source. It is also possible that Os and REE fractionation occurred during the metasomatic process itself, given the very different chemical affinities of these elements. In particular, the fact that Os resides in sulfides whereas LREE are stored in silicate phases may have a strong influence on their relative behavior during metasomatism. Metasomatism of pre-existing harzburgites nicely explains the ^{187}Os/^{188}Os–1/Os trend, but offers no explanation for the preferential association of harzburgites with the underlying mantle seismic anomaly (Fig. 1).

A second hypothesis is that harzburgite formation was triggered by the percolation of melts or fluids (e.g., Kelemen et al., 1992; Shi et al., 1998) with radiogenic Os compositions in the lherzolitic lithospheric mantle. Harzburgite formation could then result from either lherzolite melting (increasing magma volume; Shi et al., 1998) or by lherzolite-magma interaction (constant or decreasing magma volume) in reaction zones surrounding melt conduits (e.g., Kelemen et al., 1992). In either case, interaction with such fluids could have both enhanced the incompatible trace element contents of the residual peridotite (Ionov et al., 1994; Shi et al., 1998) and increased their ^{187}Os/^{188}Os ratios. The existence of such melts at depth is consistent with the presence of the low-velocity seismic anomaly in the region which may represent the source of the metasomatic agents (Frederiksen et al., 1998; Shi et al., 1998). This melting-metasomatism process was particularly intense above the thermal mantle anomaly above which harzburgite xenoliths are more abundant than in other parts of the Canadian Cordillera. An Os poor, ^{187}Os/^{188}Os radiogenic fluid may have triggered melting and scavenged Os, increasing the Os isotopic ratios of the residual peridotite. Such fluids may also have enriched the trace elements, although as noted above, incompatible-trace element and Os exchange may be largely decoupled, as there is no relationship between Os ratio and LREE content in the harzburgites.

6.3.3. *Origin of the metasomatic agent*

In summary, the Re–Os characteristics and REE patterns of the harzburgites require the presence of metasomatic agents. Two possible origins for these agents can be examined.

(1) Subduction related fluids or melts. A Sr–Pb study of lherzolites and harzburgites from the Alligator Lake site (Carignan et al., 1996) concluded that there may have been a slab-related metasomatic enrichment of the Canadian Cordillera lithosphere. The material of a downgoing slab is likely to be enriched in radiogenic Os (Walker et al., 1991), thus providing a potential source of high-^{187}Os/^{188}Os fluids or melts. A harzburgite suite from a similar tectonic setting in the US Cordillera (Simcoe; Brandon et al., 1996; Brandon et al., 1999) has a similar ^{187}Os/^{188}Os range (excluding sample AL-49) to that of the Canadian Cordillera. Simple mass balance calculations led Brandon et al. (1996) to suggest that Os might have fluid/melt affinities when the Os-undersaturated fluid/melt from a slab reacts with a relatively Os rich peridotite in the presumably more oxidizing conditions of a mantle wedge (Brandon and Draper, 1996; Parkinson and Pearce, 1998a; 1998b; Parkinson and Arculus, 1999). There is also growing evidence for Os metasomatism in oceanic arc environments (Parkinson et al., 1998a; 1998b; McInnes et al., 1999). While metasomatism by slab-derived fluids could explain the Canadian Cordillera Os harzburgite data, it does not explain the larger number of harzburgites in locales overlying the thermal anomaly.

(2) Asthenosphere derived metasomatic agent. The correspondence between geophysical and petrological observations in the northern Canadian Cordillera suggests a model in which the genesis of the bimodal suites may be linked to the presence of the seismic, and presumably thermal, anomaly in the underlying mantle (Frederiksen et al., 1998). A model for inducing melting in the lithosphere via the influx of fluids from this anomalous region was developed for the bimodal suites by Shi et al. (1998), based on trace element data for clinopyroxenes. These authors discussed in detail why harzburgites could not represent the asthenospheric mantle, i.e., the anomaly itself. This model could explain the Os data if the fluids were derived from either an OIB-type (e.g., Widom and Shirey, 1996) or a MORB-type source, if MORBs indeed have radiogenic Os ratios as suggested by the data of Schiano et al. (1997). Nevertheless, Sr–Pb data (Carignan et al., 1996) favor an OIB over a MORB-type metasomatic agent. An OIB mantle source for Os radiogenic metasomatic melts has already been invoked for explaining the Os characteristics of mantle xenoliths from a cratonic setting (Chesley et al., 1999). However, OIB-type metasomatic agents would be less radiogenic than subduction ones (^{187}Os/^{188}Os ratios up to 0.15 are found in OIB; e.g., Martin, 1991, Roy-Barman and Allègre, 1995, Widom et al., 1996; ^{187}Os/^{188}Os ratios of 0.3020 are calculated for subduction fluids from a young slab of 15–20 Ma; Borg et al., 2000, Brandon et al., 1999), and thus less akin to modify the Os budget of the harzburgites without changing their bulk composition. On the other hand, the rare harzburgites from unimodal suites located far from the mantle anomaly, though not LREE enriched, record similar Re–Os systematics to those associated with the anomaly. This might suggest that the type of metasomatism responsible for the Os isotopic characteristics of the harzburgites has thus occurred throughout the length of the Canadian Cordillera, and may not be linked to the thermal anomaly and the metasomatism responsible for LREE enrichment of some of the harzburgites.

7. CONCLUSION

Re–Os measurements in mantle xenoliths found in alkali basalts from the Canadian Cordillera indicate the occurrence of two mantle processes:

(1) The lherzolite xenoliths record various degrees of melt depletion that occurred during the middle Proterozoic. The REE patterns of some of the lherzolites were later modified by interaction with an incompatible trace-element enriched melt or fluid (Shi et al., 1998; and unpublished whole-rock data from Shi and Francis). The Os isotopic ratios of the lherzolites were not significantly affected by this latter process.

(2) The harzburgite xenoliths were affected by recent metasomatism or melting triggered by the influx of fluids or melts bearing radiogenic Os. This event may have been partially or wholly decoupled from that responsible for the incompatible trace element enrichment of most harzburgites (which happened less than 30 Ma; Carignan et al., 1996). The radiogenic Os-bearing fluids may have been derived either from the seismically anomalous mantle region located beneath the northern Canadian Cordillera or from slabs subducted along the western

edge of North America. The harzburgite data confirm the previous suggestion by Brandon et al. (1996) that Os can indeed be mobile during certain metasomatic processes, and that this effect can significantly alter the Os isotopic ratios of mantle peridotites.

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