

Os isotopic systematics in mantle xenoliths; age constraints on the Canadian Cordillera lithosphere

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Abstract

The $^{187}\text{Os}/^{188}\text{Os}$ ratios of lherzolites from eight xenolith suites from the Canadian Cordillera show a correlation with Al_2O_3 and heavy rare earth elements (HREE). The best interpretation of these correlations appears to be ancient melt depletion followed by a long period of radiogenic ingrowth. The $^{187}\text{Os}/^{188}\text{Os}$ –Lu correlation is used to calculate an Os model age of 1.12 ± 0.26 Ga for the lithospheric mantle throughout the Canadian Cordillera. This single melting age suggests that the mantle lithosphere now underlying the entire Canadian Cordillera may have formed by melting events closely spaced in time. This is consistent with seismic evidence of the extension of crustal basement under much of the Canadian Cordillera that is independent of the upper-crustal terranes overlying it. Indeed, this Proterozoic Os model age for the mantle contrasts with the younger formation ages (Nd model ages and U–Pb ages of zircons) of most crustal terranes of the region which are around 0.5 Ga. Early Proterozoic basement is exposed only in southeastern British Columbia and has the same age (1.9 to 2.3 Ga) as the ancestral North American crust, but is older than the Os model age of the mantle lithosphere underlying the Canadian Cordillera. The Canadian Cordilleran mantle is thus probably not a simple extension of the North American cratonic lithosphere beneath the adjacent mobile orogenic belt of the Canadian Cordillera. The difference in age between the formation of the Canadian Cordillera upper-crust and the formation of the underlying mantle suggests that this mantle lithosphere does not represent the mantle roots of the crustal terranes overlying it. Instead, these crustal terranes were thrust onto the mantle lithosphere during Canadian Cordillera orogeny. This contrasts strongly with Archean cratonic zones and Early Proterozoic belts where oldest crustal rocks and mantle may have the same formation age. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Osmium behaves as a compatible element during partial melting of peridotite. Consequently, the Re–Os isotopic system is considered to be relatively

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immune to the effects of metasomatism that often disturb the Sr, Nd and Pb systematics of mantle rocks (Walker et al., 1989). Rhenium, however, is moderately incompatible and thus may be mobile during the percolation of fluids or melts in the mantle (Morgan, 1986). The Re–Os system is to date, the most useful isotopic system for obtaining melting age estimations of mantle rocks. Three types of ages are commonly calculated for peridotites with the Re–Os system: a conventional model age, a minimum age of Re-depletion (Walker et al., 1989) and model ages based on Os isotopic ratio vs. aluminum content correlation (Reisberg and Lorand, 1995).

The possibility of obtaining melt depletion ages on mantle rocks allows better constraints to be placed on the relationships between mantle and its overlying crust. The timing of crustal extraction that results from melting of the mantle can be estimated using Nd model ages of sediments, granitoids, or lavas and Pb dating of zircons from sediments. Indeed, while crustal rocks provide information on the tectonic development of modern orogenic belts or Archean cratons, mantle xenoliths are critical for understanding the inaccessible part of the lithosphere and its role in crustal formation. In Archean cratonic environments and Early Proterozoic belts, mantle and overlying crust seem to have similar formation ages (Walker et al., 1989; Carlson and Irving, 1994; Pearson et al., 1994; Pearson et al., 1995a; Pearson et al., 1995b), implying contemporaneous formation, if not necessarily a genetic link between crust and lithospheric mantle in these regions. Proterozoic model ages have been found under Cambrian terranes close to craton margins (Handler et al., 1997), suggesting a lateral extension of the cratonic lithosphere beneath the adjacent crustal units. There are few geochemical constraints, however, on the genetic link between crust and the underlying lithospheric mantle.

The Canadian Cordillera is one of the most extensively studied Phanerozoic accretionary tectonic zones, and is thus an ideal region to study how continental lithosphere was formed. Therefore, in this investigation, the melt depletion age of the lithospheric mantle underlying this region is constrained from Os isotopic data from peridotite xenoliths from widely spaced locales. These ages are

compared with crustal formation ages in order to assess the link between mantle and crust in off-cratonic regions of continents.

2. Regional geology

The Canadian Cordillera spans more than 1000 km north–south along the edge of the North Ameri-

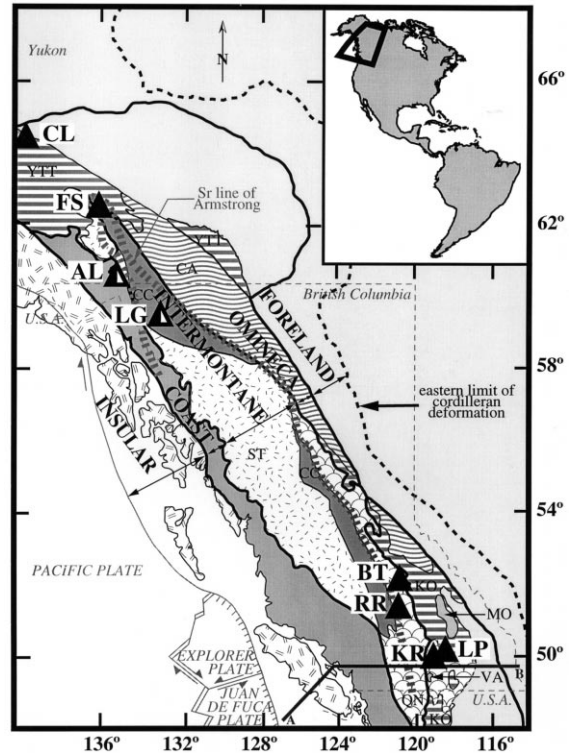


Fig. 1. Map of the Canadian Cordillera, showing the xenolith sites and the tectonic terranes accreted to the stable margin of North America. Black triangles are for unimodal suites, and black and white triangles for bimodal suites. Xenolith site name abbreviations: CL = Clinton, FS = Fort Selkirk, AL = Alligator Lake, LG = Llangorse, BT = Big Timothy, RR = Rayfield River, KR = West Kettle River, LP = Lightning Peak. Tectonic terrane name abbreviations: YTT = Yukon–Tanana (= similar characteristics to the Kootenay terrane (KO) of British Columbia; Mortensen, 1992), CA = Cassiar, QN = Quesnellia, CC = Cache Creek, ST = Stikine. Proterozoic basement exposures: MO = Monashee, VA = Vaseaux formation. The Sr line of Armstrong corresponds to a boundary between granitoids having $^{87}\text{Sr}/^{86}\text{Sr}$ ratios below 0.704 (broadly the Intermontane Belt) and those having $^{87}\text{Sr}/^{86}\text{Sr}$ greater than 0.704 (Armstrong, 1988). Oceanic plate boundaries are from Riddiough and Hyndman (1991).

can craton, and includes more than a dozen Late–Tertiary to Recent volcanic centers containing innumerable fresh mantle xenoliths (Fig. 1). It is composed of numerous tectonostratigraphic terranes that were accreted to the stable margin of North America from the Jurassic to the early Tertiary, many of which have oceanic-island arc affinities (Monger et al., 1982; Umhoefer, 1987; Gabrielse and Yorath, 1991; and references therein). These terranes can be distinguished from each other by their specific stratigraphic, paleontological and paleomagnetic signatures that indicate that they formed at various distances from the American protocontinent (Gabrielse et al., 1991). The main terranes are Quesnellia (QN), Cache Creek (CC), Stikinia (ST) and the terranes composing the Coast Belt (Fig. 1). Between the American continent and these accreted terranes, are located the pericratonic terranes (Yukon–Tanana YTT, Kootenay KO and Cassiar CA belonging to the Omenica belt) which formed close to and never moved far away from the American continent, and as such include elements derived from that continent in their stratigraphy (Gabrielse et al., 1991). The Canadian Cordillera, one of the best studied Phanerozoic orogenic belts, has been considered to be a modern analog of Proterozoic crustal growth (Samson et al., 1989; Samson and Patchett, 1991). A large regional sampling of mantle xenoliths was analyzed for Re–Os in order to constrain the age of the lithospheric mantle beneath the accreted terranes of the Canadian Cordillera.

3. Sample description

The 13 fresh spinel-lherzolite samples of this study were derived from 6 suites composed almost solely of lherzolites, with only minor harzburgites (about 5%). This type of suite is referred to as “unimodal” in contrast to some “bimodal” suites in the northern Canadian Cordillera, which contain a large proportion of harzburgite as well as lherzolite xenoliths (Francis, 1987; Shi et al., 1998). Nine lherzolites from two of these bimodal suites (Peslier et al., 1999b) are also included in the age calculations of Section 6. All xenoliths analyzed here have major and trace element compositions reflecting var-

ious degrees of fusion (Peslier et al., 1999a) and belong to the Type I Cr-diopside peridotite group defined by Frey and Prinz (1978). Only one suite, that from Lightning Peak, contains significant hydrous minerals, around 5% modal amphibole.

4. Analytical procedures

Re–Os chemical procedures are based on those described by Shirey and Walker (1995) and Roy-Barman (1993), and only a brief summary is given here. The Carius tube digestion technique was used on about 1.5 g of whole-rock powder splits. Os and Re were separated by a double distillation technique. Os was then further purified by microdistillation, while Re was concentrated via AG1X8 anion columns. Os was analyzed on a Finnigan MAT 262 mass spectrometer as negative ions (Creaser et al., 1991; Volkening et al., 1991; CRPG-CNRS, Nancy, France), with Os total blanks typically about 5 pg. Re was analyzed on an Elan 6000 ICP-MS (CRPG-CNRS, Nancy, France). Owing to high Re blanks obtained using this chemical procedure, several samples were redone for Re. Powder splits (about 1.5 g) were dissolved in a 3HF:1HNO₃ mixture at 140°C for 3 days, and Re was then purified through one AG1X8 anion column (Reisberg et al., 1991). Re blanks by this procedure are 7–25 pg, meaning that the blank correction magnitude varied from 2.5% to 50% (in the low-Re content samples, i.e., < 0.02 ppb).

¹⁸⁷Os/¹⁸⁸Os ratio precision is better than 0.3% (2σ-m; Table 1). Reproducibility of ¹⁸⁷Os/¹⁸⁸Os ratios measured on duplicate powder splits for two samples is within 1%. Os contents were less reproducible, perhaps reflecting a nugget effect. In addition, separate pieces of samples KRX-11 and BTX-26 (quoted P in Table 1) crushed in an agate crusher have ¹⁸⁷Os/¹⁸⁸Os ratios and Al₂O₃ compositions (ICP emission) that differ from the values found in the powders prepared in an alumina crusher. These variations, however, probably reflect cm-scale heterogeneity in the sample, rather than pollution related to the crushing method, as the shifts in composition are not systematic in the two samples (KRX-11 P has a lower ¹⁸⁷Os/¹⁸⁸Os ratio and Al₂O₃ content

Table 1

Os isotope data from mantle xenoliths of the Canadian Cordillera. Precision on $^{187}\text{Os}/^{188}\text{Os}$ ratio listed are 2σ -run statistics
 P = samples crushed in agate instead of an alumina crusher (see text for explanations). Model age calculations (T_{MA}) and minimum Re depletion age (T_{RD}) were made using a $\lambda = 1.666 \times 10^{-11} \text{ year}^{-1}$ (Smoliar et al., 1996) and a present primitive mantle $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.1290 and $^{187}\text{Re}/^{188}\text{Os}$ ratio of 0.428 (Meisel et al., 1996b). Al_2O_3 compositions were determined by a Philips PW1400 X-ray fluorescence spectrometer at McGill University, Canada. Lu and Yb concentrations (detection limit = 0.0001 ppm) were analyzed by ICP-MS at the CRPG-CNRS, Nancy, France. S contents were analyzed by combustion followed by impulsion coulometry at the CRPG, and reproducibility ranges from 10% to 40%. Uncertainties on the Lu and Al_2O_3 contents are ± 0.1 ppb (analytical precision calculated from three replicate analyses of two solutions at 6.5 and 1.2 ppb, method developed at CRPG) and 0.03 wt.% (analytical precision calculated from 20 replicate analysis), respectively.

Location name	Tectonic terrane	Sample	Rock type	[Re] (ppb)	[Os] (ppb)	$^{187}\text{Os}/^{188}\text{Os}$	$^{187}\text{Re}/^{188}\text{Os}$	T_{MA} (Ga)	T_{RD} (Ga)	S (ppm)	Al_2O_3 (wt.%)	Mg#	Yb (ppm)	Lu (ppm)	
West Kettle River, KR	Quesnel (thrust onto Kootenay), KO	KRX-11	Iherz	0.011	1.1728	0.12363 ± 21	0.0451	0.8363	0.7488	27	1.81	90.44	0.1077	0.0166	
			P			0.7684	0.12494 ± 43					1.73			
Lightning peak	KO	KRX-14 LPX-18	Iherz		1.8037	0.12860 ± 33			0.0561	29	3.45	88.75	0.3441	0.0586	
			Iherz	0.198	0.9236	0.12797 ± 25	1.0298	< 0	0.1443		3.06	89.10	0.4652	0.0780	
Big Timothy, BT	Quesnel, QN	BTX-26	Iherz	0.054	1.0532	0.13090 ± 58	0.2463	< 0	< 0	29	4.56	89.51	0.4326	0.0684	
			P			1.2346	0.13111 ± 22					5.37			
			Iherz	0.018	0.3021	0.12670 ± 28	0.2862	0.9660	0.3217	32	2.14	90.12	0.1376	0.0227	
			Iherz	0.081	2.1703	0.12640 ± 31	0.1793	0.6242	0.3635	57	3.05	89.85	0.2629	0.0448	
Rayfield River, RR		RRX-10 RRX-14	Iherz		0.7731	0.12745 ± 56			0.2170	42	2.81	90.13	0.2098	0.0344	
			Iherz		1.8258	0.12416 ± 61			0.6750	35	1.75	89.76	0.1120	0.0209	
Fort Selkirk, FS	Stikine, ST	VM-10 FS-41	Iherz	0.161	1.5186	0.13010 ± 44	0.5092	0.8074	< 0	66	3.86	88.97	0.3694	0.0625	
			Iherz		1.7983	0.12651 ± 13			0.3482	83	2.81	90.15	0.2764	0.0397	
Clinton, CL	Kootenay, KO	CL-3 CL-17	Iherz		3.1171	0.12512 ± 25			0.5417	71	1.99	90.13	0.1687	0.0262	
			Iherz		0.2502	0.12774 ± 11			0.1764	34	2.62	89.33	0.2427	0.0418	

than KRX-11, while BTX-26 P has higher values of these parameters than BTX-26). The high Al_2O_3 content of BTX-26 P (5.37 wt.%) in particular may indicate that the piece of the xenolith used to make the second powder may have contained a small unobserved mafic vein, thus explaining its high $^{187}Os/^{188}Os$ ratio compared to the piece of the same xenolith crushed in alumina.

5. Results

Most samples have whole-rock Os concentrations between 0.25 ppb and 2.5 ppb, except sample CL-3 which contains 3.12 ppb Os (Table 1). These Os concentration values, typical of spinel continental xenoliths (Meisel et al., 1996b; Handler et al., 1997),

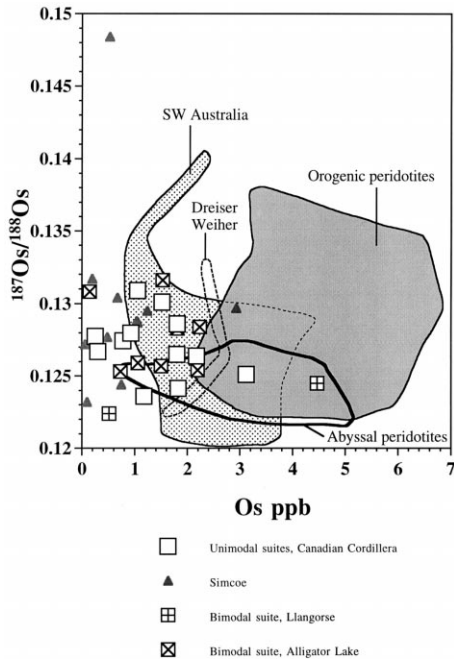


Fig. 2. $^{187}Os/^{188}Os$ vs. Os. Canadian Cordillera data sources: white squares, Table 1; squares with an x inside, Peslier et al., 1999b. Orogenic peridotites are from Reisberg et al. (1991), Reisberg and Lorand (1995), Meisel et al. (1996a), Roy-Barman et al. (1996), and Burnham et al. (1998). Dreiser Weiher xenolith data are from Meisel et al. (1996b). Simcoe xenolith data are from Brandon et al. (1996; 1999a). SW Australia xenoliths are from McBride et al. (1996), and Handler et al. (1997). Abyssal peridotite values are the ones selected for being free of sea water alteration by Snow and Reisberg (1995).

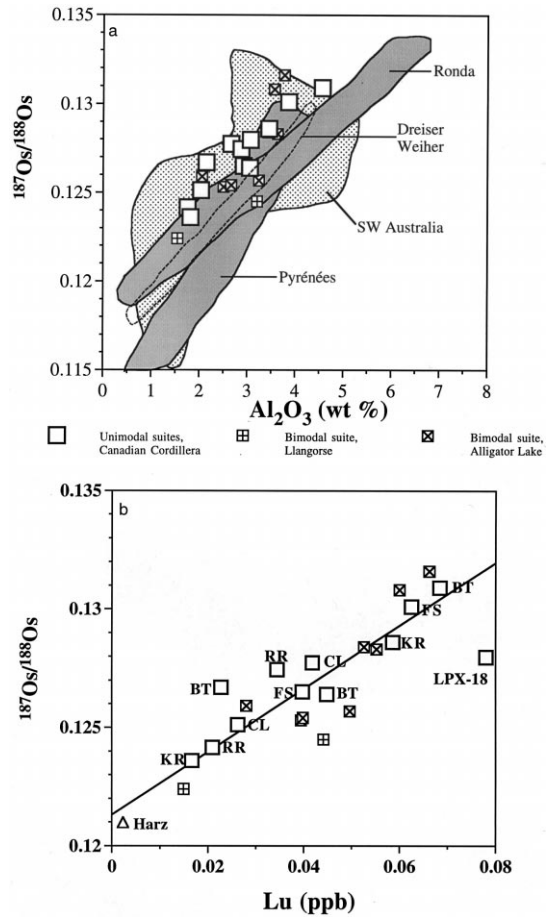


Fig. 3. (a) $^{187}Os/^{188}Os$ vs. Al_2O_3 . Ronda, Pyrenees, SW Australia and Dreiser Weiher data are from Reisberg and Lorand (1995), Meisel et al. (1996b), and Handler et al. (1997). (b) $^{187}Os/^{188}Os$ vs. Lu. The triangle corresponds to the depleted harzburgite AL-49 from Alligator Lake. This harzburgite was not included in the calculation of the regression line. White squares = lherzolites from southern Canadian Cordillera; squares with an x inside = lherzolites from the bimodal suite of Alligator Lake; squares with a cross inside = lherzolites from the bimodal suite of Llangorse.

are similar to those measured in bimodal suites from the Canadian Cordillera (Peslier et al., 1999b; Fig. 2). They are, however, lower on average than Os contents in peridotite orogenic massifs (e.g., Reisberg et al., 1991; Fig. 2). The $^{187}Os/^{188}Os$ ratios of the xenoliths (Table 1 and data of the bimodal suite lherzolites; Peslier et al., 1999b) are subchondritic to chondritic and similar to present-day values of orogenic peridotite massifs and noncratonic mantle

xenoliths (e.g., Reisberg and Lorand, 1995; Handler et al., 1997; Fig. 2), but extend to more radiogenic values than the Os isotopic ratios of abyssal peridotites (Snow and Reisberg, 1995; Fig. 2). $^{187}\text{Os}/^{188}\text{Os}$ ratios do not correlate with the $^{187}\text{Re}/^{188}\text{Os}$ ratios. This lack of correlation has been noted in other peridotite suites and may reflect Re and/or Os mobility during metasomatism or alteration. In contrast, $^{187}\text{Os}/^{188}\text{Os}$ ratios of the lherzolites correlate well with indices of melt extraction, such as whole-rock Al_2O_3 and heavy rare earth elements (HREE) concentrations (Fig. 3). This is surprising, since the samples come from widely spaced locations situated in several different tectonic terranes (Fig. 1, and including lherzolite data from Peslier et al., 1999b). The sole amphibole-rich lherzolite (LPX-18) plots on the correlation of $^{187}\text{Os}/^{188}\text{Os}$ with Al_2O_3 but falls below the correlation with Lu, reflecting an unusually high Lu content for this sample relative to its Al_2O_3 content. It is one of the most rare earth elements, especially light rare earth elements (LREE), enriched xenoliths analyzed in the Canadian Cordillera. Some samples of this suite, however, have bulk-rock LREE depleted patterns despite the presence of amphibole. Because of its unusual characteristics, sample LPX-18 is excluded from the following discussion. Finally, the Os isotopic ratio of “fertile” lherzolite, deduced from the lherzolite $^{187}\text{Os}/^{188}\text{Os}$ –Lu trend (at a Lu value of 0.068 ppm) is 0.130, which agrees with the present-day primitive upper mantle (PUM) value of 0.129 ± 1 proposed by Meisel et al. (1996b).

6. Discussion

6.1. Model ages

Mantle model age dates the time of separation of a liquid from its mantle source. The isotopic composition of this source is assumed to be evolving along either a chondritic or a long-term history mantle-reservoir. A Rhenium–Osmium model age thus dates the melting event that left the peridotite as residue. Model age calculations (Walker et al., 1989), based on the $^{187}\text{Re}/^{188}\text{Os}$ ratio, often lead to aberrant values (both future ages and ages older than the

Earth, Table 1 and Peslier et al., 1999b), probably resulting from post-melting perturbation of Re during metasomatism or alteration. Among the Canadian Cordillera samples, the nonaberrant values range from 0.62 to 0.97 Ga. However, no compositional difference exists between xenoliths with aberrant values and those with nonaberrant values. The latter are thus likely to be meaningless as well.

“Re depletion” ages are commonly used to estimate the melting age of the mantle in studies of xenoliths from cratonic regions (Walker et al., 1989; Pearson et al., 1995a; Pearson et al., 1995b). The concept of Re depletion age is based on the hypothesis that melting removes all of the Re from the peridotite (Walker et al., 1989). Thus Re depletion ages are minimum values. These values approach the true ages of melting for very depleted peridotites such as those of Archean cratons, as Re almost completely leaves the residue at very high degrees of melting (Walker et al., 1989). The oldest Re depletion age of an entire xenolith suite is generally assumed to be the best estimate of the melting age because later Re addition may have occurred in many xenoliths (Walker et al., 1989). Peridotites from alkali basalts, such as the Canadian Cordillera xenoliths studied here, are much less depleted than cratonic peridotites from kimberlite pipes (Boyd, 1989). The Re-depletion ages of the Canadian Cordillera lherzolites range from 0.06 to 0.74 Ga (Table 1). These ages probably greatly underestimate the true melting age due to the fact that significant Re was still present in the residue after melting. The only Canadian Cordillera harzburgite whose Os composition was apparently undisturbed by later metasomatism lies very close to $^{187}\text{Os}/^{188}\text{Os}$ –Lu correlation in Fig. 3b. This highly depleted sample, which is from one of the bimodal suite of the northern Cordillera (Peslier et al., 1999b), yields a Re depletion age of 1.1 Ga.

Because very few of the Canadian Cordillera samples are highly depleted, a different method was used to obtain model ages of mantle melt extraction. The initial value of the $^{187}\text{Os}/^{188}\text{Os}$ –Lu correlation is projected onto a mantle evolution curve, defined by the present-day primitive upper mantle (PUM) values of 0.1290 for $^{187}\text{Os}/^{188}\text{Os}$ and 0.428 for $^{187}\text{Re}/^{188}\text{Os}$ (Meisel et al., 1996b). Unlike Re-depletion ages, the model age obtained is not a minimum

value. As expected, this technique yields older ages than the Re-depletion age method.

6.2. The correlation between $^{187}\text{Os}/^{188}\text{Os}$ and indices of melt extraction

Correlations between Os isotopic ratios and indices of peridotite fusion have already been reported in orogenic peridotite massifs (Reisberg et al., 1991; Reisberg and Lorand, 1995) and individual mantle xenolith suites (Walker et al., 1989; Meisel et al., 1996b; Fig. 2a). These correlations have been interpreted to be the result of radiogenic ingrowth following partial melting, possibly associated with lithospheric stabilization. Reisberg and Lorand (1995) consider the y-intercept of the $^{187}\text{Os}/^{188}\text{Os}$ - Al_2O_3 correlation to represent the Os isotopic ratio of the convective mantle when it was incorporated into the subcontinental lithospheric mantle (SCLM). This y-intercept value, projected onto the mantle evolution curve, can be used to determine a model age (i.e., melt depletion age) of the lithosphere (Fig. 5).

Given that the lherzolites were collected over a very large geographic area spanning several accreted terranes, it is somewhat surprising to find a single, fairly well-defined trend in Fig. 3. Thus, possible origins for this correlation other than melt depletion linked to lithosphere formation must be considered. One possibility is that it results from mixing between depleted harzburgites and basaltic melts, but this is untenable, as such mixtures would produce strongly curved and poorly defined arrays lying below the Canadian Cordillera trend (Reisberg and Lorand, 1995). Furthermore, the apparent uniformity of the trend would imply that the basaltic and harzburgitic endmembers would each have single isotopic and major element characteristics, for the entire Canadian Cordillera, which is highly unlikely. Alternatively, it may be argued that the range of $^{187}\text{Os}/^{188}\text{Os}$ ratios and Os contents may reflect metasomatism in the arc mantle (Brandon et al., 1996), a consequence of the tectonic setting and arc affinities of many crustal terranes of the Canadian Cordillera. However, arc mantle xenoliths are much more depleted than the lherzolites presented here (they are generally harzburgitic in composition), are more oxidized, have overall lower Os concentrations (see Simcoe on Fig.

2), and finally, do not display correlations between $^{187}\text{Os}/^{188}\text{Os}$ ratios and indices of fusion (Brandon et al., 1996; Parkinson et al., 1998; Peslier et al., 1999a; Peslier et al., 1999b). A more plausible alternative is that the correlation reflects a global trend resulting from continuous processes in the convecting upper mantle. However, the fact that similar correlations noted elsewhere in the world (Fig. 2a) display different slopes and y-intercepts argues against this interpretation. Thus the simplest explanation for the trend is that it records an ancient melting event or series of melting events closely spaced in time.

The calculation of the $^{187}\text{Os}/^{188}\text{Os}$ -Lu correlation age is subject to uncertainties. These arise from (1) the choice of the mantle evolution curve (Reisberg and Lorand, 1995), (2) the quality of the least-square fit of the line to the data, (3) the adequacy of the element chosen as the Re/Os-ratio proxy and (4) the appropriateness of the use of the y-intercept as the ‘‘initial’’ $^{187}\text{Os}/^{188}\text{Os}$ ratio.

(1) The choice of the mantle curve depends on which mantle reservoir is considered to have partially melted to leave the peridotites as residues. It may be argued that the Canadian Cordillera xenoliths were derived from a source similar to abyssal peridotites, if those represent the depleted convecting mantle. Indeed, the Os isotopic range of the Canadian Cordillera xenolith spans most of that of abyssal peridotites (Fig. 2). However, recent studies (Brandon et al., 1999b; Esperana et al., 1999) suggest that individual suites of abyssal peridotites from different locales appear to be old pieces of mantle (> 1 Ga), each with a specific melting history. Furthermore many of the Canadian Cordillera samples that are more fertile than abyssal peridotites have Os isotopic ratios considerably higher than that of the average (or even the most radiogenic) abyssal peridotite (Fig. 2). These cannot be derived by radiogenic ingrowth following melt extraction from a mantle evolving towards present abyssal peridotite Os ratios. It consequently appears inappropriate to use abyssal peridotite values to calculate a mantle evolution curve. A more appropriate choice for the evolution curve may be made by assuming that the Canadian Cordillera lherzolites were derived from a source similar to the fertile mantle, as the most fertile samples have Os ratios similar to that pro-

posed for PUM (Meisel et al., 1996b). Another possibility would be to assume that the xenoliths are the result of melting of chondritic mantle in terms of Os isotopes, as the Re/Os ratio of the upper mantle is essentially chondritic (Shirey and Walker, 1998; and references therein). The lowest value for the chondritic (enstatite and ordinary) mantle evolution curve (Meisel et al., 1996b) produces ages systematically 0.1 Ga younger than those obtained using the PUM curve. This age shift is small compared to the uncertainties calculated on the ages (Table 2).

(2) The error in the fit of the correlation line to the data can be calculated using expanded uncertainties on the y -intercept and which mainly reflect the amount of scatter of the data about this line (McIntyre et al., 1966; York, 1969; Titterton and Halliday, 1979; Table 2).

(3) The Os isotopic ratios of the lherzolites are correlated with both Al_2O_3 and HREE (Lu is shown in Fig. 3b). Hence, a choice has to be made of which of these elements would be the best proxy for the Re/Os ratio in the model age calculations. The element with the behavior which is the closest to that of Re in mantle melting processes should be used.

HREE are probably a better choice than Al_2O_3 for a Re/Os proxy, because both Re and HREE are not network-forming elements in peridotite minerals, and because both are mildly incompatible. In particular, Re and Lu seem to be similarly incompatible during peridotite melting (Hauri and Hart, 1997). The reasons for the similar behavior of Re and Lu are not well understood. HREE are mainly hosted by clinopyroxene in the spinel stability field (Stosch,

1982; Bodinier et al., 1996). On the other hand, since Re and Os are chalcophile elements, their behavior during melting may depend on their distribution in minor sulfide phases, until the latter are consumed at higher degrees of melting (Hamlyn and Keays, 1986; Crocket et al., 1997; Pearson et al., 1998). Experimental studies of Re partitioning between silicate and sulfide melts under mantle conditions are scarce. Righter and Hauri (1998) have suggested that Re may be compatible in garnet. Experimental data for other silicate phases are nonexistent. Sulfur contents of the Canadian Cordillera lherzolites (Table 1) show no relationship with Re, Os concentrations, $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ ratios, or with indices of melt extraction. This could reflect post-eruption alteration of the xenoliths (S loss during secondary oxihydration of mantle sulfides; Lorand, 1990), or the difficulty of measuring low S contents in mantle xenoliths. Lorand (1989) has observed a correlation between S and clinopyroxene contents in orogenic peridotites, suggesting that sulfide and clinopyroxene are removed at similar rates during melting. Consequently, the HREE content and the Re/Os ratio of mantle rocks may be proportional during melting processes, and Lu will be used here as a Re/Os proxy.

The y -intercept of the $^{187}\text{Os}/^{188}\text{Os}$ –Lu correlation differs somewhat from that of the correlation with Al_2O_3 (0.11943 for Al_2O_3 and 0.12093 for Lu), giving an age difference of 0.21 Ga for the entire Canadian Cordillera (older ages with Al_2O_3). The fit to the data is generally better for Lu than for Al_2O_3 (see uncertainties in Table 2).

Table 2

Mantle ages in the possible domains of the Canadian Cordillera. Ages are calculated using the method of Reisberg and Lorand (1995) but with Lu as a Re/Os ratio proxy. The error on the fit of the correlation line of the data can be calculated using expanded uncertainties on the y -intercept (McIntyre et al., 1966; York, 1969; Titterton and Halliday, 1979)

Tectonic Unit	Xenolith sites	Number of data used	Age Lu (Ga)	Uncertainty	Age Al_2O_3 (Ga)	Uncertainty
Canadian Cordillera	AII	21	1.1212	0.2621	1.3273	0.4254
South	KR, RR, BT	7	0.9144	0.2686	1.2821	0.3718
North	LG, AL, FS, CL	14	1.3369	0.4253	1.3356	1.1046
Intermontane Belt	FS, LG, BT, RR	9	0.9710	0.4543	1.1666	0.6222
Omenica Belt, KO-YTT	CL, KR	4	1.0372	0.2500	1.5710	0.5586
Coast Belt	AL	8	1.5519	0.7163	1.6352	0.5209
Coast Belt incl. 1 Harz	AL	9	1.2093	0.4775	1.3424	0.5608
Quesnellia (QN)	BT, RR	5	0.6694	0.4566	0.9172	0.5216

(4) The interpretation of an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio at 0 ppm Lu (or Al_2O_3) assumes that both Re and Lu are completely removed from the residue at similar degrees of melting. The Re contents of the Canadian Cordillera unimodal suite lherzolites are comparable to those of other xenolith suites worldwide (e.g., Handler et al., 1997). In particular, a broad correlation of Re with HREE exists (Yb shown in Fig. 4). The correlation line intersects the Yb (or any HREE) axis at a positive value, thus indicating that Yb (and any other HREE) was still present in the residue after Re was totally exhausted. The initial $^{187}\text{Os}/^{188}\text{Os}$ ratio (at 0 ppm Lu) used for model age determinations in the Canadian Cordillera might thus be slightly underestimated, leading to model ages somewhat older than the true ages. On the other hand, lherzolites from the bimodal Canadian Cordillera suites have higher Re concentrations for similar Yb contents (Peslier et al., 1999b), comparable to those measured in orogenic massifs such as those of the Pyrenees (Burnham et al., 1998; Fig. 4). Pyrenean samples thought to be free of metasomatic sulfur (selected on the basis of their Cu/S ratios; Burnham et al., 1998) define a correlation that intersects the Yb axis at a positive value of Re. This suggests an opposite conclusion compared to that based on the Canadian Cordillera unimodal suite

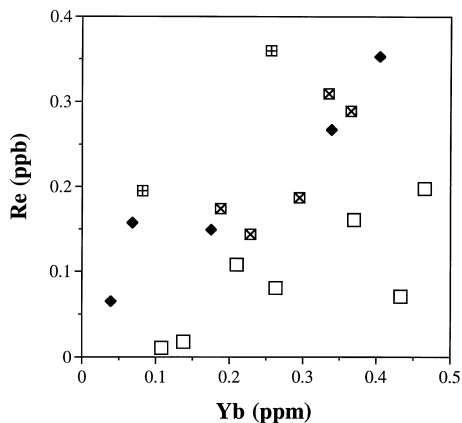


Fig. 4. Re vs. Yb in the Canadian Cordillera. Diamonds are the E. Pyrenean data of Burnham et al. (1998), including only those points thought by Burnham et al. to be free of interaction with an exotic sulfur component. Yb was chosen instead of Lu here because no Lu data are available on the E. Pyrenean peridotites. Other symbols as in Fig. 2.

data, i.e., HREE are exhausted before Re. Further investigation is needed to determine the exact similarities and differences of behavior between Re and HREE. For the purpose of age estimation using the Os isotopic ratio vs. HREE correlation, uncertainties in the HREE concentration equivalent to 0 ppm Re will induce ambiguity in the proper choice of an “initial” $^{187}\text{Os}/^{188}\text{Os}$ ratio, which will translate into uncertainties in the estimated model age. However, these errors are smaller than those related to scatter in the data and uncertainty in the appropriate mantle evolution curve.

A final remark concerning the choice of Lu instead of Al_2O_3 for the Re/Os ratio proxy is that the reproducibility of Lu measurements by the ICP-MS is good (± 0.1 ppb). This leads to a relative precision similar to that of Al_2O_3 analyses (± 0.03 wt.%, analytical precision). Analytical precision thus is not a determining factor in this choice.

6.3. Mantle domains

The model ages of the mantle lithosphere from individual mantle domains, defined on the basis of the overlying tectonic terrane or belt boundaries (Fig. 1, Table 2), were calculated using the $^{187}\text{Os}/^{188}\text{Os}$ vs. Lu correlation as described in Section 6.2. The significance of these model ages is limited by the small number of Os isotopic data for each domain. Nevertheless, these calculations allow a determination of whether tectonically logical subgroups of the total data set have markedly different model age from one another. In these calculations (Table 2) samples from the bimodal suites discussed elsewhere (Peslier et al., 1999b) have also been included (Fig. 6).

6.3.1. The southern sites (KR, LP, RR, BT) vs. the northern sites (LG, AL, FS, CL)

The southern sites are situated closer to the craton border than the northern sites and are separated by a xenolith-free region about 300 km in length. Model-age estimates of the mantle yield 0.91 ± 0.27 Ga for the southern region, and 1.33 ± 0.43 Ga for the northern region (Fig. 6). The fit of the correlation line to the data is better in the South than in the North (Table 2, Fig. 6).

6.3.2. Orogenic belts

The belts of the Canadian Cordillera are defined by various lithological, structural, tectonic and physiographic criteria (Gabrielse et al., 1991). More interestingly for this study, isotopic data on granitoids (Armstrong, 1988) and basalts (Abraham et al., 1998) in the northern part of the Canadian Cordillera define a region of lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (region surrounded by the “Sr line of Armstrong” in Fig. 1), lower Pb isotopic ratios and higher $^{143}\text{Nd}/^{144}\text{Nd}$ compared to other parts of the Canadian Cordillera. This region broadly corresponds to the Intermontane Belt (Fig. 1). These igneous rocks may reflect heterogeneity of mantle source regions corresponding to the Canadian Cordillera Belts (Abraham et al., 1998). The four Os data available for the Omenica Belt (sites CL, KR) yield an age of 1.04 ± 0.25 Ga, despite the fact that the two samples from the south and the two from the north are separated by about 800 km. The model age found for the Intermontane Belt (sites FS, LG, BT, RR) is 0.97 ± 0.45 Ga. The only xenolith site from the Coast Belt (AL) yields a model age estimation of 1.55 ± 0.72 Ga, but gives 1.21 ± 0.48 Ga when the harzburgite lying on the correlation is included (Peslier et al., 1999b).

6.3.3. Tectonic terranes

Five samples from the Quesnellia terrane (sites BT, RR) yield a mantle model age of 0.67 ± 0.46 Ga, which is younger than all the ages found previously. The two other terrane groupings were already discussed in (2): the Yukon–Tanana–Kootenay terrane (i.e., the Omenica Belt) and the Coast Belt. Note that the West Kettle River samples were included in the Kootenay terrane as this site lies on an overthrusting of the Kootenay terrane by the Quesnellia terrane (Gabrielse and Yorath, 1991; Fig. 1).

Finally, applying the $^{187}\text{Os}/^{188}\text{Os}$ –Lu correlation method to all the samples from the Canadian Cordillera, regardless of their geographic provenance, gives an overall model age of 1.12 ± 0.26 Ga for the Canadian Cordillera (Figs. 5 and 6). This calculation takes into account the Os isotopic ratios of lherzolites from bimodal suites as well (Peslier et al., 1999b). If the oceanic mantle is poorly mixed with respect to Os (Parkinson et al., 1998; Brandon et al., 1999b), it may be possible that Os isotopic evidence for ancient melting in a portion of astheno-

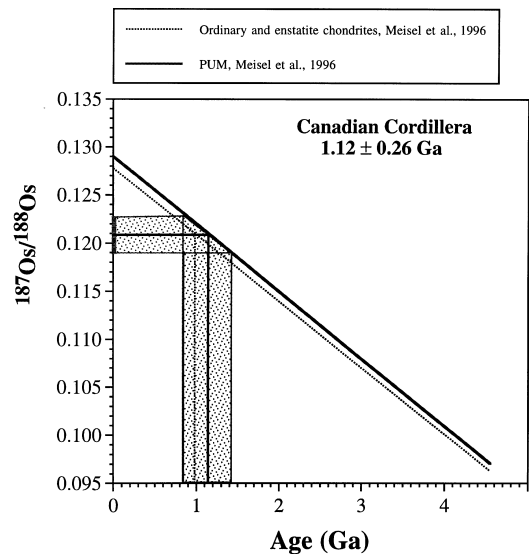


Fig. 5. Os mantle evolution curve and model age determination. Parameters used are $\lambda = 1.666 \times 10^{-11} \text{ year}^{-1}$ (Smoliar et al., 1996) and a present primitive mantle $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.1290 and $^{187}\text{Re}/^{188}\text{Os}$ ratio of 0.428 (Meisel et al., 1996b). Lower curve from Meisel et al. (1996b) representing the lowest value for enstatite and ordinary chondrites. The model age obtained for the Canadian Cordillera is 1.12 ± 0.26 Ga.

spheric mantle is preserved for long time periods prior to incorporation of that portion in the continental lithosphere (see Section 6.5). If not, melt extraction directly associated with lithospheric stabilization remains the most likely explanation of the data (see Section 6.6). In either case, the well-defined correlation observed here suggests that the mantle lithosphere currently underlying the Canadian Cordillera, or all the domains of which it is composed, underwent melting about 1.1 Ga ago.

In summary, owing to the uncertainties on these calculated ages, no fundamental age difference can be seen in the different possible mantle domains of the Canadian Cordillera (Table 2, Fig. 5). The ages are all about 1.1 Ga and are in agreement with the Re-depletion age calculated for the one depleted harzburgite (Peslier et al., 1999b). The younger age found for the Quesnellia terrane xenoliths is likely due to the reduced number of samples used for the correlation (5 samples). We therefore suggest that the overall model age of 1.12 ± 0.26 Ga is a reasonable estimate of the age of the lithospheric mantle

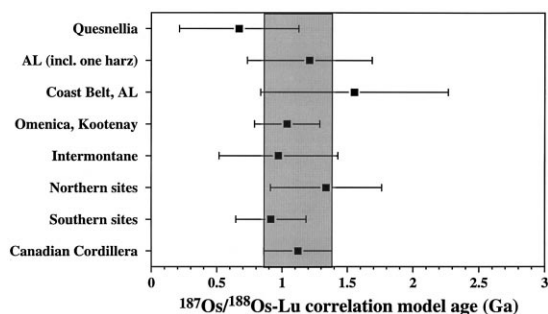


Fig. 6. Os model ages of the mantle obtained by the Reisberg and Lorand method (Reisberg and Lorand, 1995) beneath various crustal units of the Canadian Cordillera.

underlying the Canadian Cordillera, taking into account the uncertainties discussed above on the method used to calculate this age. This could mean that the mantle beneath each of the accreted terranes experienced melting at roughly the same time, about 1.1 Ga ago, or alternatively that a single mantle block of Middle to Late Proterozoic age is attached to the Canadian craton. The question whether this lithospheric mantle was all formed by one event, or several events occurring within a short period of time is difficult to answer. In order to better constrain this problem, the link between the accreted terranes and the mantle must also be addressed in terms of formation age, as is done in Section 6.4. Finally, the Re–Os Proterozoic ages found in the Canadian Cordillera confirm the long-term stability of the lithospheric mantle underlying continental regions, as previously noted both in cratonic and off-cratonic environments (e.g., Walker et al., 1989; Pearson et al., 1995a; Reisberg and Lorand, 1995).

6.4. Relations between crust and mantle

Armstrong and Ghosh (1990) and Ghosh (1995) used Sr and Nd isotopic values of granitoids to locate the western boundary of the North American basement in the southern Canadian Cordillera almost at the limit between the Intermontane and the Coast Belts and following the 0.704 Sr line of Armstrong, 1988 (Fig. 1). However, recent seismic results (Clowes et al., 1995; Clowes et al., 1998) indicate that North-American crustal basement extends in the lower crust as far as the limit between the Intermon-

tane and the Coast belt. Furthermore, Proterozoic metamorphic rocks, such as the Monashee complex (MO on Fig. 1) or similar outcrops in southeastern British Columbia (VA in Fig. 1; Armstrong et al., 1991; Parrish, 1991), provide evidence that the North American crustal basement extends to the limit between the Intermontane and Omenica Belts at the latitude of the Canada–US border (Armstrong et al., 1991). Crustal residence ages (Nd model ages, U–Pb on zircons and Rb–Sr isochrons) of these Precambrian exposures range from 1.9 to 2.3 Ga (Armstrong et al., 1991). This age corresponds to the age of the cratonic North American crust east of the Canadian Cordillera (Parrish, 1991) but is older than the 1.12 ± 0.26 Ga age proposed here for the mantle lithosphere. This age discrepancy suggests that there is no direct genetic link (i.e., a melt–residue relation) between the mantle and the crustal basement in the southeastern region of the Canadian Cordillera. This differs from what has been observed in Archean and early Proterozoic regions of South Africa and Siberia (Walker et al., 1989; Pearson et al., 1994; Pearson et al., 1995a; Pearson et al., 1995b), where mantle and the oldest crustal rocks share the same formation age. It also suggests that the Proterozoic mantle under the Cordillera may not represent the extension of the ancestral continental lithosphere as was proposed for SE Australia (Handler et al., 1997).

With the exception of those in southeastern British Columbia, no other Precambrian basement exposure has been reported in the Canadian Cordillera (Parrish, 1991). Thus interpretation of crust–mantle relationships must be based on Nd model ages or zircon U–Pb ages for crustal extraction, and on tectonic relationships between the crustal units. Sediments from the easternmost terranes (Kootenay KO and Cassiar CA), the closest to the stable margin of North America, have negative ϵ_{Nd} and Nd model ages older than 1.7 Ga. These values likely reflect derivation of the sediments in these accreted terranes from the North American craton (Patchett and Gehrels, 1998). The Yukon–Tanana terrane (YTT on Fig. 1) has been close to the North American margin throughout its history, and the nature of its basement is unknown (Mortensen, 1992). Most of the Nd depleted mantle model ages and the U–Pb zircon ages in the YTT range from 1.24 to 2.3 Ga (Stevens et al., 1995; Creaser et al., 1997; and references in

Samson et al., 1991b); these ages might simply reflect a North-American cratonic source. Negative ε_{Nd} in Omenica Belt plutons in southeastern British Columbia suggest that they result from crustal anatexis of Early Proterozoic basement rocks exposed in this region (Brandon and Lambert, 1993; Brandon and Lambert, 1994; Brandon and Smith, 1994).

Most of the Nd model ages on sediments and volcanics from the Quesnel, Cache Creek and Stikinia oceanic terranes, which developed far from the craton, are around 0.55, 0.35 and 0.55 Ga, respectively (Fig. 7; Samson et al., 1989; Patchett and Gehrels, 1998). The few Proterozoic Nd model ages (Fig. 7) are thought to reflect addition of sediments from the American continent in Triassic time, i.e., after terrane assembly (Patchett and Gehrels, 1998). The young crustal formation age of the Cache Creek terrane (CC on Fig. 1) compared to the age of the mantle lithosphere (Fig. 7) is no surprise as this

terrane is believed to be a slice of crust lying on top of the Stikinia terrane (Monger et al., 1982; Mihalyuk et al., 1994), and probably completely decoupled from its original mantle root. The Stikinia terrane (ST on Fig. 1) may also be a crustal unit lying on top of the Yukon–Tanana terrane (Samson et al., 1991b). As such, these terranes were likely decoupled from their mantle roots during accretion and now rest unconformably on other crustal units.

The majority of plutonic and metamorphic rocks of the Coast Belt have positive ε_{Nd} and Nd model ages around 0.35 Ga (Fig. 7; Cui and Russel, 1995; Friedman et al., 1995). The northern Coast Belt plutonic and metamorphic rocks define a peak in Nd model age distribution around 0.75 Ga (Fig. 5; Armstrong, 1988; Samson et al., 1991b; Patchett et al., 1998). Indeed, some of these northern Coast Belt rocks have Proterozoic Nd model ages and were tectonically interleaved in the Coast Mountains (Patchett et al., 1998; Fig. 7). These Proterozoic Nd model ages thus likely result from crustal contamination by an archean crust of unclear origin (Patchett et al., 1998). The Nd model ages around the 0.35 Ga distribution peak (Fig. 7) are probably the best representatives of the Coast Belt formation in terms of its time of extraction from its mantle source. These crust formation ages are considerably younger than the 1.12 ± 0.26 Ga of the mantle.

To summarize (Fig. 8), in the southeastern region of the Canadian Cordillera basement exposures indicate that cratonic rocks with crustal residence ages of about 2 Ga overlay a mantle lithosphere with an age of about 1.1 Ga. The formation age of the crust is difficult to evaluate for the pericratonic Yukon–Tanana (Clinton xenolith site)–Kootenay (West Kettle River xenolith site) terrane because of derivation of crustal sediments from the adjacent craton. In the more western terranes lithospheric mantle of this age is overlain by crust with mostly Phanerozoic crustal formation ages. If the mantle is indeed of different age than the overlying crust, several inferences can be drawn: (1) the mantle underlying the terranes may not represent the mantle from which the terranes were derived; (2) alternatively, if the mantle is related to the overlying terranes, it may have preserved mantle with older melt-extraction ages (3) while accreting to the margin of the North American craton, the tectonic terranes may have been separated

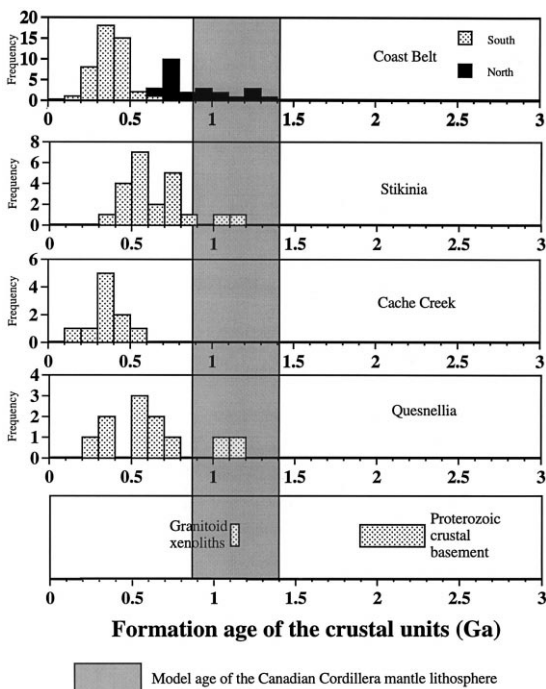


Fig. 7. Depleted-mantle Nd model ages of crustal tectonic units (Quesnel and Cache Creek data from Patchett and Gehrels, 1998 and Coast Belt data from Samson et al., 1991a,b; and Patchett et al., 1998). Proterozoic crustal basement ages are from Armstrong et al. (1991). Granitoid xenolith data are from Mortensen and Colpron (1998).

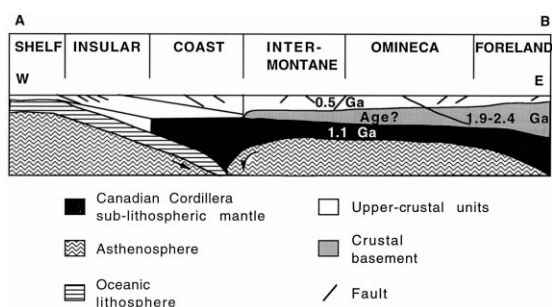


Fig. 8. Schematic cross-section of the Canadian Cordillera, drawn after Clowes et al. (1998). See text for discussion of the ages. Total depth is about 150 km. A–B corresponds to the A–B line on the map of Fig. 1.

from their mantle roots; (4) the Proterozoic mantle to the west of the limits of the cratonic crustal rocks may not represent the prolongation of the ancestral North American cratonic mantle.

If the terranes are separated from their mantle roots, it raises the question of what has become of the crust associated with this 1.1 Ga mantle. One intriguing clue to this puzzle comes from the presence of xenocrystic zircons of 1.0–1.1 Ga in diatremes from southeastern British Columbia and detrital zircons of this age throughout the Cordillera (Ross, 1991; and references therein). According to Ross, these zircons testify to the existence of a 1.0 to 1.1-Ga-old crust whose location and present state are unknown, but which may have been widespread before exotic terrane accretion and tectonic shortening started. Other authors (Rainbird et al., 1997) have argued, however, that the source of some of these zircons is the Grenville Province of the Canadian craton, and thus they do not represent a 1-Ga-old crust of the Canadian Cordillera. Additional crust formation evidence of that age comes from granitoid xenoliths found in a diatreme in the McKenzie Mountains, i.e., slightly northeast of the Canadian Cordillera (at the northeast limit of the Omineca belt on Fig. 1). These rocks have been dated at 1.1 Ga by U–Pb geochronology (Mortensen and Colpron, 1998). Another question raised by the age difference between crust and mantle is the mechanism by which the mantle and the overlying crust were separated. Before trying to answer this question, several possi-

ble interpretations of the apparent 1.1 Ga mantle age are discussed in Sections 6.5 and 6.6.

6.5. Possibility of long-term isolation in the convective mantle

The Re–Os isotopic systematics for spinel peridotite xenoliths from Phanerozoic crustal terranes (this study; Handler et al., 1997), and for peridotite orogenic massifs (Reisberg and Lorand, 1995), appear to record Proterozoic melting ages. However, spinel lherzolites such as those analyzed here, have major element compositions very similar to mantle xenoliths found in Hawaiian lavas (Peslier et al., 1999a; and references therein). Thus the possibility must be considered where the mantle currently underlying the Canadian Cordillera was not incorporated into the subcontinental lithosphere at the time of melting about 1.1 Ga ago, but rather was preserved within the convective oceanic mantle for an ensuing time period. Such a process may be typical of convergent settings at craton margins as the Canadian Cordillera lherzolites share similar compositional and isotopic characteristics with other spinel continental xenoliths (e.g., Ionov et al., 1995; Brandon et al., 1996; Brandon and Draper, 1996; Handler et al., 1997). There is growing evidence for preservation of old melting ages in the oceanic mantle. As noted above, single blocks of abyssal peridotites appear to be more than 1 Ga old, and likely represent different events of melting for each block (Brandon et al., 1999b; Esperança et al., 1999). Re depletion ages of xenoliths from the Kerguelen plume lava are as old as 1.36 Ga (Hassler and Shimizu, 1998). Geophysical and geochemical arguments, however, suggest that the lithosphere beneath Kerguelen may actually be derived from delaminated subcontinental Gondwana lithosphere incorporated in the oceanic mantle during the initiation of the Indian Ocean (Hassler and Shimizu, 1998; and references therein). Peridotites from the Izu–Bonin–Mariana forearc basin (Parkinson et al., 1998) have Re-depletion ages ranging from 0.82 to 1.23 Ga. Peridotites with such ancient ages may be preferentially preserved in the asthenosphere because they are strongly melt depleted and thus buoyant (Parkinson et al., 1998). If ancient Re–Os mantle ages can be preserved for a

long time in the convecting oceanic mantle, the age of SCLM like that of the Canadian Cordillera may represent a melt extraction event in the oceanic mantle, and not necessarily the age of stabilization of the subcontinental lithosphere.

If the mantle beneath the Canadian Cordillera really is of oceanic character, two possible scenarios may explain the age difference between mantle and upper crust. One would imply that older mantle within the Os-heterogeneous oceanic mantle was accreted and incorporated to the subcontinental lithosphere at the time of tectonic accretion of the terranes. However, the widespread age of 1.1 Ga for the mantle below the Canadian Cordillera, and the geophysical evidence for the extension of the North American basement beneath most southern Cordillera, argues for an homogeneous mantle in this region, and not a heterogeneous mixture of old and young mantle material as appears to be the case for the oceanic examples cited above (abyssal peridotites, Kerguelen and Izu–Bonin). A second scenario would imply an oceanic mantle generated 1 Ga ago at the North American continental margin. Two episodes of rifting in the Proterozoic affected crustal rocks of the western edge of North America; one around 1.4 Ga (Höy, 1989) and another starting at 0.8 Ga (Gabrielse and Yorath, 1991). The melting age of the lithospheric mantle beneath the Canadian Cordillera (1.1 ± 0.26 Ga) is situated in the 600 Ma interval between these two events for which no geological testimony exists. It could be speculated that young, warm and thin oceanic lithosphere created in a young ocean or in back-arc basins is not easily subducted (Meissner and Wever, 1988), and may remain stable at a continental edge if the oceanic basin remains small.

6.6. Continental lithosphere formation

Despite the note of caution introduced above, the most plausible interpretation of the data is that the Canadian Cordillera peridotites have been isolated within the subcontinental lithosphere for about 1.1 Ga. This is consistent with the widespread 1.1 Ga age for the lithospheric mantle, with the presence of 1.1 Ga granitoid xenoliths, and with the seismic

evidence for ancestral North America lower crust extending as far as the Coast Belt (Fig. 8). Decoupling thus appears to have occurred between the upper crust, represented by the accreted terranes, and the lower crust. In Archean cratonic areas, the harzburgitic character of the lithospheric mantle is invoked to explain its stability over several Ga, because of its density contrast with the more fertile, and thus more Fe-rich, convective mantle (Walker et al., 1989; and references therein). The lithospheric mantle underlying noncratonic regions such as the Canadian Cordillera is less depleted than cratonic lithosphere and as such the density contrast relative to the convective mantle is smaller. Nonetheless, a significant compositional difference exists between noncratonic lithosphere as represented by continental spinel peridotite xenoliths and the average convective mantle composition (determined by mass balance after continental crust extraction). For example, the average Al_2O_3 content of worldwide spinel xenolith samples is about 2.3 wt.% (McDonough, 1990); that of average lherzolites from the Canadian Cordillera is 3 wt.% (Peslier et al., 1999a). This is much lower than the convective mantle Al_2O_3 content of about 3.9 wt.% obtained by mass balance (assuming primitive mantle with 4.06% Al_2O_3 and continental crust with 15 wt.% Al_2O_3 ; (Hofmann, 1988). It is not clear whether such differences in major element composition are sufficient to explain the stability of the subcontinental off-cratonic lithosphere, or if another mechanism is required.

This study suggests that mantle underlying mobile orogenic belts surrounding ancestral continents may not have the same age as the upper-crust terranes of these belts. Proterozoic Os model ages in mantle xenoliths have also been found as far as 500 km south-eastward off the Australian craton, underlying Cambrian greenstone belts (Handler et al., 1997). In contrast, Re–Os studies of mantle xenoliths from Archean (e.g., Walker et al., 1989; Pearson et al., 1995b) and early Proterozoic areas (Pearson et al., 1994) suggest that the age of the mantle corresponds to the oldest ages found in the overlying crustal rocks, and thus implies long term mantle–crust coupling in these Precambrian regions. These differences may simply be related to different mechanisms of preservation in the ancient geological record relative to the present.

7. Conclusion

Lherzolite xenoliths from the Canadian Cordillera were sampled by alkali basalts from a mantle with long term melt depletion at about 1.1 Ga. This contrasts with the younger model ages of the upper-crust. Together with seismic profiles showing the lower crust extending below the entire region from the craton margin (Clowes et al., 1998), this supports a tectonic model of decoupling of lower crust + lithospheric mantle from upper-crust during formation of the Canadian Cordillera. The mantle underlying this region may have formed either as oceanic lithosphere later incorporated into the subcontinental lithosphere, or may have been added directly to the subcontinental lithosphere at the time of melt extraction.

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