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Re–Os systematics of the ca. 2.7-Ga komatiites from Alexo, Ontario, Canada

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Abstract

The Re–Os isotope systematics of a suite of komatiitic flows from Alexo Township, in the Abitibi greenstone belt, Ontario were examined in order to characterize the partitioning behaviors of Re and Os during the generation and subsequent differentiation of komatiitic magma, and also to determine the initial Os isotopic composition of the late-Archean mantle source of these rocks. This suite of komatiites was suitable for these objectives because of their high Os concentrations, $\geq \sim 1$ ppb, and low $^{187}Re/^{188}Os$ ratios (ranging between 0.4 and 2.4). The Re–Os isotope results for whole-rock komatiites and chromite separates yield a model 3 isochron age of 2762 ± 76 Ma. This age is in general agreement with previously determined U–Pb ages of zircons from associated felsic units and also with Sm–Nd and Pb–Pb isochron ages of these flows. This suite of Alexo komatiites, thus, demonstrates relatively limited mobility of Re and Os at the whole-rock scale, even after large-scale alteration and ambient lower greenschist facies metamorphism. The initial Os isotopic composition ($^{187}Os/^{188}Os_{(I)} = 0.1080 \pm 0.0012$) obtained from the regression is essentially chondritic ($\gamma_{Os} = -0.1 \pm 1.0$). Our results, therefore, suggest an absence of any large-scale deviation in initial Os isotopic composition of the mantle source of these komatiites relative to the putative chondritic composition of the contemporaneous convective upper mantle.

For these komatiites, Os was moderately compatible with the mantle residue ($D_{Os}^{mantle\text{-}melt} \sim 2.1$), whereas Re was incompatible ($D_{Re} \sim 0.20$). These D's are consistent with those previously estimated for other Archean komatiites. The apparent $D_{Os}^{olivine/liquid}$ and $D_{Re}^{olivine/liquid}$ in Alexo komatiites are 1.7 and 0.66, respectively. Our results, therefore, suggest that Os is slightly compatible, whereas Re is moderately incompatible in olivine or a coprecipitating phase during magmatic differentiation of komatiitic liquids. The concentrations of Re and Os in Alexo komatiites are also comparable to those reported for komatiites from other greenstone belts. The apparent magmatic behaviors of both Re and Os in the whole-rock komatiites indicate that the Re–Os elemental systematics are primary features of these rocks.

The Os isotopic results obtained for the Alexo komatiites, combined with those from the spatially associated Munro Township komatiites, suggest a source for komatiites in the southern volcanic zone of the Abitibi greenstone belt that was dominated by Os with a chondritic isotopic composition. Also, the Os isotopic results, combined with previous Nd and Pb isotopic results, are consistent with derivation of the komatiites from either the contemporaneous convective upper mantle or a deep mantle source with isotopically similar characteristics. These results imply that if the chondritic Os isotopic composition of the mantle sources for the komatiites were set by a chondritic "late veneer", most late accretion and subsequent homogenization within the mantle must have occurred prior to their eruption at ~ 2.7 Ga.

Keywords: Os isotopes; Abitibi; Alexo; Komatiites; Plumes

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1. Introduction

The ^{187}Re–^{187}Os isotope systematics ($^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + \beta^-$; $\lambda = 1.666 \times 10^{-11}$ year^{-1}; Smoliar et al., 1996) of materials derived from young mantle plumes show that plumes tap mantle reservoirs with significant heterogeneity in terms of Os isotopic compositions. For example, modern ocean island basalts (Reisberg et al., 1993; Hauri and Hart, 1993; Roy-Barman and Allégre, 1995), Phanerozoic flood basalts (Horan et al., 1995; Allégre et al., 1999) and ultramafic rocks (Walker et al., 1999) show a large variability in initial Os isotopic compositions with γ_{Os} ranging between 0 and ~ +25 (where γ_{Os} is the percentage deviation in ^{187}Os/^{188}Os from the projected chondritic composition at a given time). In contrast, the Os isotopic composition of the modern convecting upper mantle is within the range of chondritic meteorites (γ_{Os} ranging between about -3 and $+1$; Snow and Reisberg, 1995; Brandon et al., 2000; Walker et al., 2002). Thus, many young plume sources are considerably more radiogenic than the modern convecting upper mantle. One important question, therefore, is how and when the plume sources developed the observed Os isotopic enrichments.

Os isotopic heterogeneities in the terrestrial mantle, indeed, can be traced as far back as late Archean. For example, some Archean ultramafic systems, e.g. Munro Township komatiites in the 2.7-Ga Abitibi greenstone belt (Walker et al., 1988; Shirey, 1997) and ore-bearing sulfides from Kambalda in Western Australia (Foster et al., 1996) show broadly chondritic initial Os isotopic compositions. In contrast, there are significant deviations from projected chondritic compositions for other late Archean mantle sources. For example, the Boston Creek komatiites of the Abitibi greenstone belt were derived from a source with subchondritic ^{187}Os/^{188}Os (Walker and Stone, 2001), whereas the sources of the komatiites from Kostomuksha, Russia (Puchtel et al., 2001a) and Belingwe, Zimbabwe (Walker and Nisbet, 2002) were suprachondritic.

Understanding the origin, age and evolution of the Os isotopic heterogeneities in the terrestrial mantle requires systematic studies of both ancient and modern mantle-derived rocks. Precambrian komatiites are good candidates to study the development of Os isotopic heterogeneities in plume sources because of their high Os abundance, low Re/Os ratios and relatively robust preservation of initial Os isotopic composition during alteration and low-grade metamorphism (e.g. Walker et al., 1988). Furthermore, at least some komatiites are believed to be derived from mantle plumes (Herzberg, 1992; Nisbet et al., 1993; McDonough and Ireland, 1993) and represent high-degree partial melts of their mantle sources. Hence, the melting processes likely removed local small-scale isotopic inhomogeneities in the source during their generation. Although the high eruption temperatures of komatiitic melts make them susceptible to crustal contamination, the high Os abundances in most komatiite magmas can preserve the original Os isotopic composition of the mantle sources, even after a relatively large degree of contamination by typical low-Os crustal materials (e.g. Walker and Nisbet, 2002). Furthermore, crustal contamination for these rocks can be monitored by other isotope systems, such as Sm–Nd and Pb–Pb, which are much more sensitive to crustal assimilation (e.g. Puchtel et al., 2001b). Additionally, there are many Archean and Proterozoic komatiites that are well characterized in terms of major and trace elements and other lithophile element isotope systems and, therefore, a careful selection of least altered whole-rock samples from different flows prior to their isotopic analyses is possible.

Here we present the Re–Os isotope systematics and major and selected trace element characteristics of a suite of ca. 2.7-Ga komatiite flows from Alexo Township in the Superior Province, Ontario, Canada. Two factors guided the choice of our samples: [1] The Alexo flows are precisely dated at 2700–2727 Ma (e.g. Nunes and Pyke, 1980). Therefore, a comparison between these ages and those obtained from Re–Os isochron is possible. [2] Some of these rocks have abundant chromites that allow a precise determination of the initial Os isotopic composition of the flows.

2. Samples and analytical methods

Eight whole-rock samples and three chromite separates from the komatiite flows were analyzed. The textural characteristics of these rocks include both spinifex and cumulate (textural types are detailed in Table 1). Olivine occurs mainly in two different modes: [1] relatively large subhedral to euhedral cumulate crystals; and [2] long plates or laths (± clinopyroxene needles) defining spinifex texture. Minor secondary opaque oxides (magnetite) are also present along fracture planes of olivine crystals. Olivine is partially chloritized in some samples with spinifex texture. Samples with high modal abundances of cumulate olivine are typically mostly serpentinized. The cumulate olivines in these samples are mostly subhedral. The glassy matrix is generally devitrified.

All whole-rock samples were collected from outcrops. The samples were first crushed into mm-sized pieces and cleaned with Milli-Q™ water repeatedly under ultrasonic bath for at least 1 h. The freshest unaltered pieces were handpicked and dried in an oven at approximately 60 °C for about an hour. These pieces were then ground with an agate mill. The powders were carefully mixed and homogenized. Different aliquots of the same whole-rock powder were used in major and trace element, and isotopic analyses of each sample. The chromite separates were obtained from Eero Hanski (Geol. Surv. of Finland) and Igor Puchtel (Univ. of Chicago; also the whole-rock sample, Alx-26). X-ray fluorescence (XRF) analyses of major and trace elements of the komatiites reported here were performed with a Siemens MRS-400 multi-channel simultaneous X-ray spectrometer at the University of Massachusetts.

The chemical separation techniques for Re–Os analyses employed in this study have followed previously published work (Shirey and Walker, 1995; Cohen and Waters, 1996). In brief, approximately 2–3 g of whole-rock powders was added to ~ 3 g of concentrated HCl and 6 g of concentrated HNO_3 and frozen into Pyrex™ Carius tubes. Unlike the whole-rock powders, relatively smaller amounts of chromites (Table 2) were used due to their limited available quantities. Appropriate amounts of separate ^{190}Os and ^{185}Re spikes were added and the tube was subsequently sealed and heated at 240 °C for at least 12 h. Sample digestion for chromites lasted at least 24 h to ensure complete dissolution. Unlike the whole-rock powders, mixed ^{190}Os–^{185}Re spikes were used for the chromite separates. Osmium was sepa-

Table 1
Bulk major oxides (recalculated on anhydrous basis) and selected trace element data for the Alexo komatiites

Sample texture	Alx-1 cumulate	Alx-2 random spinifex	Alx-3 plate spinifex	Alx-4 basal cumulate	Alx-5H Cpx-spinifex	Alx-5W komatitic basalt	Alx-6 cumulate	Alx-26 chevron spinifex
SiO_2 (wt.%)	45.43	45.66	45.64	44.63	44.63	47.73	43.77	45.47
TiO_2	0.19	0.30	0.31	0.20	0.16	0.59	0.25	0.32
Al_2O_3	3.70	6.31	6.41	3.84	3.69	11.26	5.17	6.44
Fe_2O_3[a]	8.30	11.09	10.93	8.72	9.17	11.75	13.24	11.13
MnO	0.14	0.18	0.18	0.14	0.17	0.19	0.22	0.16
MgO	40.20	30.21	29.86	39.54	39.83	11.62	31.37	30.16
CaO	1.66	5.57	5.70	2.65	1.39	17.04	5.40	5.99
Na_2O	0.00	0.47	0.27	0.00	0.00	0.09	0.11	0.24
K_2O	0.01	0.11	0.08	0.00	0.00	0.01	0.02	0.06
P_2O_5	0.01	0.02	0.02	0.01	0.01	0.04	0.02	0.02
Total	99.64	99.92	99.40	99.73	99.05	100.32	99.57	99.99
Mg#[b]	0.91	0.84	0.84	0.90	0.90	0.66	0.82	0.84
CaO/Al_2O_3	0.45	0.88	0.89	0.69	0.38	1.51	1.04	0.93
$CaO/(CaO+Al_2O_3)$	0.31	0.47	0.47	0.41	0.27	0.60	0.51	0.48
Al_2O_3/TiO_2	19.5	21.0	20.7	19.2	23.1	19.1	20.7	20.1
TiO_2/P_2O_5	19	15	15.5	20	16	14.75	12.5	16
Trace elements (ppm)								
Cr	1703	2456	2383	1757	3671	840	2679	2280
Ni	2218	1650	1680	2268	1957	199	1068	1557

[a] Fe_2O_3 as total Fe.

[b] Calculated as mol% MgO/(MgO + FeO) with 90% of total iron as FeO.

rated by solvent extraction into carbon tetrachloride and subsequently transferred into high-purity concentrated HBr (Cohen and Waters, 1996). The final purification and pre-concentration for Os was accomplished via microdistillation in a conical Teflon™ vial. Rhenium was recovered from aqua regia via anion exchange techniques (Morgan and Walker, 1989). The analytical blanks for Re and Os were 7.6 ± 1.7 and 2.5 ± 1.0 pg ($n=4$), respectively, and are negligible compared to their concentrations in most samples. The blank contribution, however, was substantial (>6%) for some of the Re analyses of chromites. The isotopic compositions of the blanks were natural for Re and had ^{187}Os/^{188}Os of 0.313 ± 0.367 ($n=4$). All data were corrected for blanks and the isotopic and concentration data in Table 2 reflect the corrected values. The uncertainties in blanks are reflected in respective uncertainties for isotopic and concentration data in Table 2. The external reproducibilities for Os analyses, as determined from multiple analyses of comparable amounts of standard, were better than ± 0.2% on the electron multiplier and ± 0.1% on the Faraday cup. The Re analyses of all samples were performed with an electron multiplier and the reproducibilities of standard analyses were typically better than ± 0.2%.

The isotopic compositions of Re and Os were obtained using negative thermal ionization mass spectrometry (Creaser et al., 1991; Völkening et al., 1991). The mass spectrometric procedures followed in this study have been discussed in Walker et al. (1994) and Morgan et al. (1995). Samples with high Os abundances were analyzed with Faraday cups under static mode (using a Sector 54 mass spectrometer), whereas those with relatively low abundances of Os and/or Re were analyzed with electron multiplier using a 12″ NBS mass spectrometer.

Table 2
Rhenium and osmium isotopic and compositional data[a] for the whole-rock Alexo komatiites and primary chromite separates

Samples	Sample[b] types	Sample weight (g)	Re (ppb)	Os (ppb)	^{192}Os (ppb)	^{187}Os/^{188}Os	^{187}Re/^{188}Os	$\gamma_{Os}(T)$[c]
Alx-1	WR	2.00	0.2519	2.572	1.05	0.13138	0.4722	+1.0 ± 0.2
Repl.[d]	WR	3.00	0.2391	2.597	1.06	0.13041	0.4438	+1.3 ± 0.2
Alx-2	WR	2.00	0.4136	1.911	0.78	0.1561(3)	1.047	−1.2 ± 0.4
Alx-3	WR	3.01	0.4834	1.609	0.65	0.17521	1.456	−1.3 ± 0.4
Alx-4	WR	2.00	0.2892	3.315	1.36	0.1261(2)	0.4203	−1.6 ± 0.2
Repl.	WR	3.00	0.2479	3.390	1.39	0.1252(5)	0.3522	+0.5 ± 0.5
Alx-5H	WR	3.01	0.2256	1.055	0.43	0.15601	1.034	−0.7 ± 0.3
Cm-A5c	CMT.	0.074	0.9355	13.39	5.48	0.12135	0.336(20)	−2.4 ± 1.0
Repl.	CMT.	0.107	0.8502	11.58	4.74	0.12640	0.354(15)	+1.5 ± 0.8
Cm-A5b	CMT.	0.408	0.6312	9.048	3.70	0.1254(2)	0.336(12)	+1.4 ± 0.8
Alx-5W[e]	WR	2.00	0.7275	0.451	0.18	0.4992(2)*	8.148(32)	+7.1 ± 2.8
Repl.	WR	3.01	0.7510	0.405	0.16	0.5550(6)	9.442	+2.4 ± 1.8
Alx-6	WR	2.00	0.3508	0.704	0.28	0.2232(4)	2.433	+0.6 ± 0.7
Repl.	WR	3.01	0.3478	0.727	0.29	0.21865	2.332	+0.8 ± 0.5
Alx-26	WR	3.01	0.4143	1.877	0.77	0.1615(5)*	1.068	+2.9 ± 0.6
Alx-26c	CMT.	0.122	0.5204	27.42	11.2	0.1131(3)*	0.0913(56)	+0.6 ± 0.6

Total analytical uncertainties, except where noted in parentheses, are ± 0.3% for ^{187}Re/^{188}Os and ± 0.1% for ^{187}Os/^{188}Os (2σ%) for both whole rocks (WR) and chromites (CMT.).

[a] All Os analyses (except where marked with asterisks) were accomplished using a Faraday cup, whereas Re analyses were performed with an electron multiplier.

[b] WR = whole rock; CMT. = chromite.

[c] Calculated values at the Re–Os regression age of 2.76 Ga. The chondritic ^{187}Os/^{188}Os at 2.76 Ga is calculated to be 0.10810, based on average ^{187}Re/^{188}Os ratio of chondrites and initial ^{187}Os/^{188}Os ($T=4.558$ Ga) for early Solar System materials (IIIA irons) of 0.40186 and 0.09531, respectively (Shirey and Walker, 1998). $\lambda = 1.666 \times 10^{-11}$ year^{-1} (Smoliar et al., 1996).

[d] Repl. = replicate analyses of different aliquots from separate powder splits.

[e] Komatiitic basalt; the rest of the whole-rock samples are high-MgO komatiites.

3. Results

Detailed discussions of the geochemical characteristics of the Alexo flows may be found in Arndt (1986), Lahaye et al. (1995) and Lahaye and Arndt (1996). In brief, the komatiites are highly magnesian (MgO up to 40.2 wt.%, Table 1) and typically have $CaO/Al_2O_3 \leq 1$ (with the exception of a komatiitic basalt, Alx-5W). The rocks show uniform Al_2O_3/TiO_2, TiO_2/P_2O_5 (and also Sr/Y and Zr/Y ratios, not reported here) ratios, suggesting apparently unaltered whole-rock compositions. All of the whole rocks have chondritic Al_2O_3/TiO_2 ratios of 19 to 23, similar to Al-undepleted komatiites from Tisdale Township (Fan

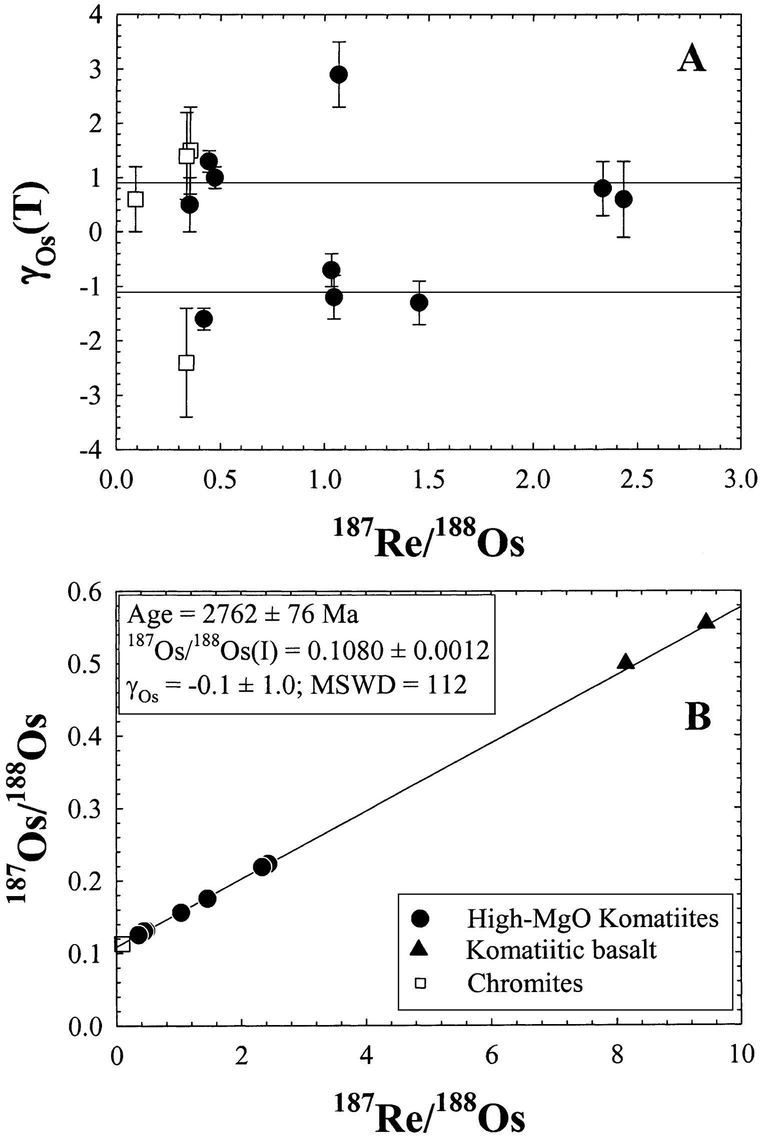

Fig. 1. Re–Os isotope diagram for whole-rock komatiites and chromite separates from Alexo flows. (A) The uncertainties in calculated γ_{Os} values of the samples and their replicates, plotted against $^{187}Re/^{188}Os$. The two solid horizontal lines mark the upper and lower limits of calculated γ_{Os} values at 2.76 Ga, based on uncertainty in the initial $^{187}Os/^{188}Os$ obtained from the Re–Os regression, as shown in the lower diagram (B).

and Kerrich, 1997) and Munro Township (Arndt, 1977; 1986), also of the Abitibi belt.

The Re and Os concentrations and isotopic data are given in Table 2. Whole-rock Re and Os concentrations vary between 0.239–0.751 and 0.405–3.390 ppb, respectively. The highest concentration of Re and the lowest concentration of Os are found in the komatiitic basalt (Alx-5W). The concentrations of Os in the chromite separates, on the other hand, are much higher (9–27 ppb) with typically low $^{187}Re/^{188}Os$ ratios (0.09–0.35).

Based on a comparative study of different komatiite terrains, Nisbet et al. (1993) concluded that random spinifex komatiites most closely represent parental liquid compositions. If true for the Alexo flows, then parental magmas (represented by Alx-2 random spinifex) had ca. 30 wt.% MgO (Mg# 0.84) and Os and Re concentrations of approximately 1.9 and 0.4 ppb, respectively. The major and trace element characteristics of our sample Alx-2 are in good agreement with the assumed Alexo parental liquid composition, represented by sample M666 obtained from a larger dataset of Arndt (1986). Major element characteristics (Table 1), consistent with 30 wt.% MgO, including 6 wt.% Al_2O_3, 45 wt.% SiO_2 and a $CaO/(CaO+Al_2O_3)$ ratio of 0.41–0.47 for Alexo komatiites, all correspond to about 50% partial melting at a pressure of ~ 5 GPa or ~ 160 km (Herzberg, 1992).

The Re–Os data for whole-rock komatiite samples, excluding the two data points for komatiitic basalt Alx-5W, and chromite separates were regressed via a least squares fitting routine (Ludwig, 1998; Fig. 1). The model 3 age of 2762 ± 76 Ma is in general agreement with the more precise U–Pb zircon ages of 2725 ± 2 and 2702 ± 2 Ma for the underlying and overlying felsic units, respectively (Nunes and Pyke, 1980; Corfu, 1993). Also, our Re–Os regression age is within uncertainties of Sm–Nd isochron age of 2752 ± 87 Ma and the Pb–Pb isochron age of 2690 ± 15 Ma for these flows (Dupre et al., 1984). However, the MSWD value for our regression is high (112). The possible causes of the high MSWD value are discussed below. The initial $^{187}Os/^{188}Os$ obtained from the regression (0.1080 ± 0.0012) is essentially chondritic ($\gamma_{Os} = -0.1 \pm 1.0$). The two data points for komatiitic basalt, Alx-5W, when included in the regression calculation, result in a relatively more precise, yet significantly older age of 2790 ± 23 Ma with similarly high MSWD value (103). The initial $^{187}Os/^{188}Os$ ratios of the regressions in both cases, however, are identical and chondritic ($\gamma_{Os} = +0.1 \pm 1.0$). Note that the duplicate analyses for this sample do not overlap within the analytical uncertainties ($\gamma_{Os} = +3.4 \pm 2.8$ versus -2.0 ± 1.8) suggestive of modest, post-magmatic open-system behavior.

4. Discussion

4.1. Distribution and magmatic behavior of Re and Os

The importance of isolating secondary processes and demonstrating magmatic behavior of both Re and Os in the study of Os isotopic compositions of ancient komatiite source mantles cannot be over-emphasized. Precambrian komatiites, in general, have undergone different combinations of secondary processes: [i] surficial weathering; [ii] post-crystallization hydrothermal alteration; [iii] low- to medium-grade metamorphism; [iv] seawater interaction; [v] assimilation of crustal component (± fractional crystallization); and [vi] contamination by lithospheric mantle. The degrees of these secondary processes vary from one suite to another. In this section, we consider distributions of Re and Os in Alexo komatiites, and compare them with those in komatiites from other greenstone belts in order to evaluate whether or not the distribution patterns were generated via a magmatic origin.

The whole rocks show a primary control of olivine over the abundance of Ni, defined by a straight line, when regressed on a plot of MgO versus Ni (Fig. 2). This apparent olivine control line is, however, parallel but shifted towards lower values of Ni relative to that obtained by Arndt (1986). This shift is likely a result of two points on our plot with significantly lower values of Ni concentrations relative to other whole rocks at similar levels of MgO. Although there is a significant scatter about the apparent olivine control line, it projects back to the approximate field of olivine compositions obtained for Alexo flows (Arndt, 1986). Similarly, the field for MgO contents and Cr concentrations of these olivines are also plotted (Fig. 2). It is not clear, however, whether Cr concentrations are primarily controlled by late-fractionating Cr-spinels, as there is one sample (Alx-5H) with signifi-

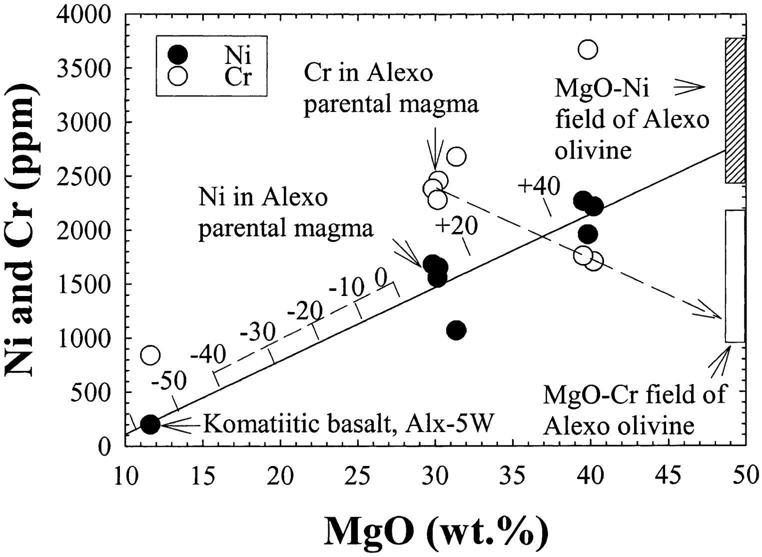

Fig. 2. A positive correlation between MgO and abundances of Ni in Alexo whole rocks, shown by the solid line, suggests that Ni concentration is primarily controlled by olivine fractionation–accumulation. The shaded rectangular box is the approximate field of olivine in Alexo lavas (Arndt, 1986). Note that the apparent olivine control line projects back to this olivine field. The line with short dashes is the apparent olivine control line in Arndt (1986) and the negative numbers (e.g. − 10, − 20, etc.) indicate the percentages of olivine fractionation in the Alexo komatiites, and are extrapolated beyond 40%. Similarly, the positive numbers (e.g. + 20) are percentages of olivine accumulations (Arndt, 1986). The dashed arrow shows the effect of olivine accumulation, based on the approximate range of MgO and Cr (empty box) in olivine in Alexo flows (Arndt, 1986). Also note that Alx-5H is the only cpx-spinifex komatiite and has the highest concentrations of Cr, consistent with high $D_{Cr}^{cpx/melt}$.

cantly higher Cr at similar MgO (~ 40 wt.%, Fig. 2). The dashed arrow, on the other hand, shows the effect of olivine accumulation. The apparent straight line (dashed arrow) joining the Alexo parental magma composition and Cr concentrations of olivine in Alexo flows similarly extends back to the approximate MgO–Cr field of olivine in Alexo komatiites (Arndt, 1986). It is likely, therefore, that olivine accumulation in the samples with ~ 40 wt.% MgO was accompanied by an increase in Ni concentrations and a corresponding decrease in Cr concentrations. This interpretation is consistent with olivine being the only major fractionating phase in Alexo flows (Arndt, 1986). Such an apparent olivine control, therefore, suggests a relatively well-preserved nature at the whole-rock scale of our suite of samples. Also plotted in Fig. 2 are the calculated proportions of olivine fractionation (Arndt, 1986). The basaltic komatiite (Alx-5W) is likely to have undergone more than 50% of olivine fractionation, whereas the rocks with ~ 40 wt.% MgO have accumulated approximately 40% olivine. Our suite of Alexo samples, therefore, is representative of a large differentiation sequence.

There is a positive correlation between concentrations of Os and Ni for the whole rocks (Fig. 3). Nickel is partitioned into olivine during magmatic differentiation and, hence, its covariance with Os suggests that a significant fraction of Os resides either in olivine or in a coprecipitating minor or trace phase. Based on microprobe data of core and rim compositions of olivine in the assumed Alexo parental liquid (sample M666), Arndt (1986) estimated $D_{Ni}^{olivine/liquid}$ at 2.0 ± 0.1. Using this value for $D_{Ni}^{olivine/liquid}$ gives a calculated $D_{Os}^{olivine/liquid}$ of 1.7 ± 0.1. This $D_{Os}^{olivine/liquid}$ value is consistent with the one obtained in a previous study of the same komatiites ($D_{Os}^{olivine/melt}$ ~ 1.8; Brügmann et al., 1987). This suggests that Os was moderately compatible in olivine during magmatic differentiation of Alexo komaiites. Alternatively, the Os may be highly compatible in sulfide inclusions trapped in olivine, as suggested by Lahaye et al. (2001). The calculated $D_{Re}^{olivine/liquid}$

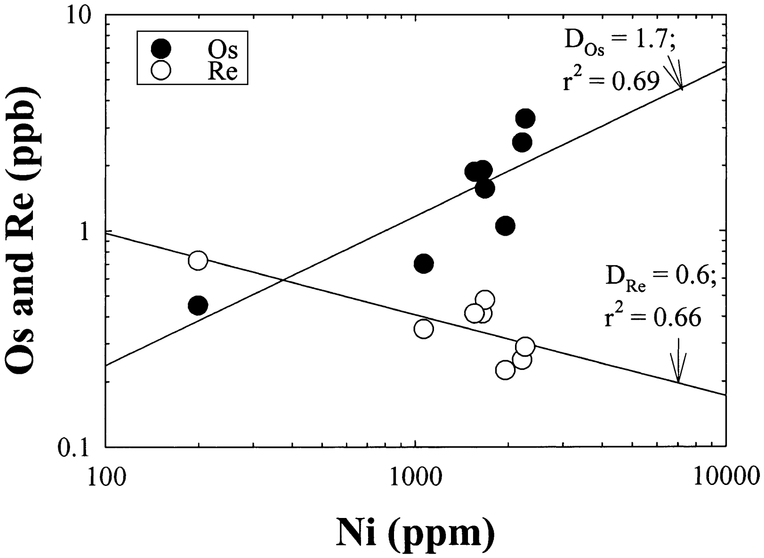

Fig. 3. The concentrations of Os and Re in Alexo whole rocks are plotted against Ni. The two solid lines are the best-fit linear regressions through the Os and Re concentration data against Ni. The *D* values for Os and Re, as shown on the plot, are calculated from the slopes of these lines.

(0.6), in contrast, indicates that Re was moderately incompatible during crystal–liquid fractionation.

The concentrations of both Re and Os are considerably higher in the chromite separates relative to their host komatiites (Table 2). The concentrations, however, vary significantly even within different aliquots of the chromite splits from the same host rock. In addition, the Re and Os abundances in the present set of samples are not primarily controlled by Cr concentrations (Fig. 4). This interpretation is consistent with a lack of correlation between Os and Cr concentrations in Munro Township komatiites (Walker et al., 1988). Therefore, an uneven distribution of Os in chromites, combined with an inverse relation between the concentrations of Os and Cr in the whole rocks, suggests that Os is more likely hosted in sulfide inclusions within Cr-spinels, rather than spinel lattices, as a positive correlation would be likely in the latter case.

For some komatiite suites (e.g. Walker and Nisbet, 2002), Re shows variable degrees of mobilization during weathering, hydrothermal alteration or low-grade metamorphism. For the Alexo rocks, however, a positive linear correlation between Re concentration and alumina content in the whole-rocks is consistent with a constant distribution coefficient during magmatic differentiation (Fig. 5). Alumina is normally immobile during alteration and its concentration increases as a function of higher degrees of magmatic differentiation. The positive linear correlation obtained for our Alexo samples, therefore, suggests that Re experienced very limited mobility at the whole-rock scale during post-crystallization alteration. The magmatic behavior of both Re and Os in these rocks is, therefore, consistent with several elemental covariation diagrams (Figs. 2–5). It is important to note that the komatiitic basalt (Alx-5W) is highly differentiated yet shows magmatic characteristics cogenetic with other samples in the present suite (e.g. Fig. 5). It is likely, therefore, that the komatiites and the highly differentiated komatiitic basalt were derived from the same batch of magma.

The concentrations of MgO and Os in Alexo komatiites, along with those for other komatiite whole-rock data, have been plotted in Fig. 6. The relatively higher concentrations of MgO in three Alexo komatiites are due to high modal abundances of cumulate olivine in those samples. Concentrations of Os in Alexo komatiites are, however, similar to those in other komatiites. In general, there is a positive correlation between the concentrations of Os and MgO (between approximately 25 and 10 wt.%).

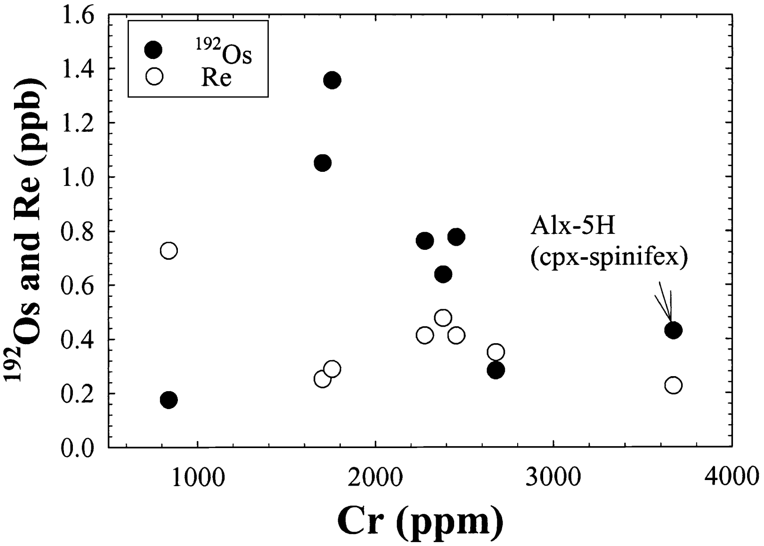

Fig. 4. Concentrations of Cr and ^{192}Os show an inverse relation, suggesting that the chromites are not the primary hosts of Os in these rocks. Note that Alx-5H has the highest Cr concentrations and yet its Os concentrations fall towards the low end of the array. Rhenium concentrations slightly decrease with increasing Cr contents.

Similarly, Os concentrations and Re/Os ratios in Alexo komatiites fall within the ranges observed in other komatiites (Fig. 7). The mantle source of the Alexo komatiites was, therefore, typical in terms of the above geochemical parameters and comparable with other komatiites.

The bulk distribution coefficients for Re and Os between the komatiite melt and the mantle residue

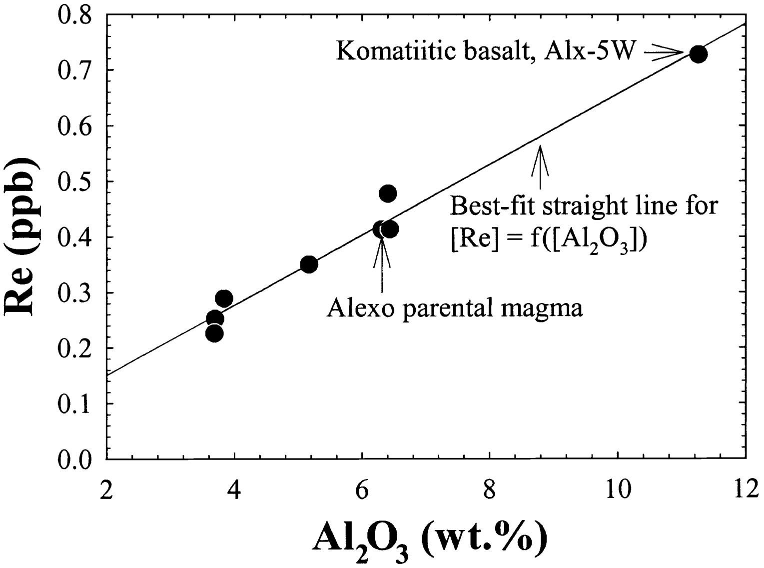

Fig. 5. A positive correlation between Re concentrations (ppb) and Al_2O_3 contents (wt.%) in these whole-rock komatiites is consistent with their similar compatibilities in magmatic liquids. Rhenium is susceptible to weathering and alteration, whereas alumina is relatively immobile. This plot, therefore, suggests an absence of significant mobilization of Re among the present set of samples.

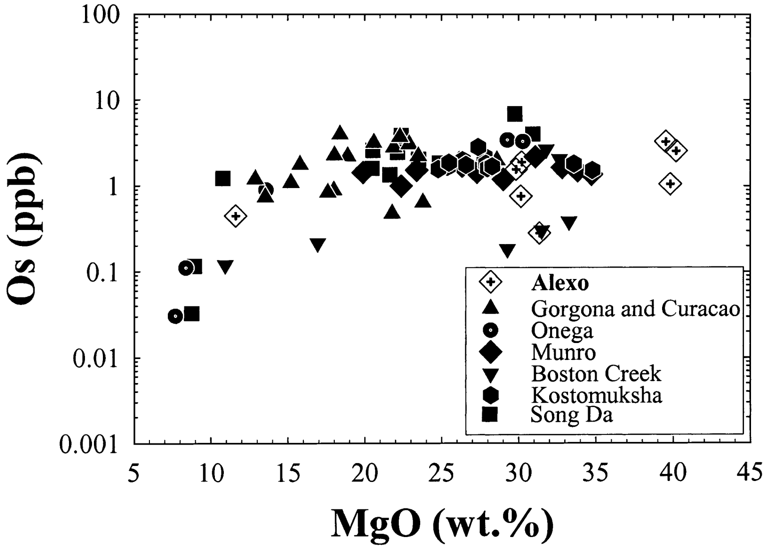

Fig. 6. The MgO contents (wt.%) and Os concentrations in whole-rock Alexo komatiites are compared with those from other selected plume-related ultramafic lavas. The three samples of Alexo rocks in our study with ∼ 40 wt.% MgO have high modal abundance of cumulate olivine. Data sources: komatiites from Song Da, Vietnam (Hanski et al., 2002); komatiitic and picritic flows from Gorgona island and Curacao, Colombia (Walker et al., 1999); mafic–ultramafic sill from Onega, Russia (Puchtel et al., 1999); Munro komatiites from Abitibi, Canada (Walker et al., 1988); Boston Creek komatiites, Canada (Walker and Stone, 2001); Kostomuksha komatiites, Russia (Puchtel et al., 2001a,b).

have been calculated based on the assumptions that: [1] Alx-2 random spinifex komatiite (with Os and Re concentrations of 1.9 and 0.4 ppb, respectively) is representative of the Alexo parental magma, and [2] the komatiites were generated by 50% equilibrium batch melting from a fertile mantle source with Re and Os concentrations of 0.3 and 3 ppb, respectively (Morgan, 1986). Our estimate of 1.9 ppb for the Os

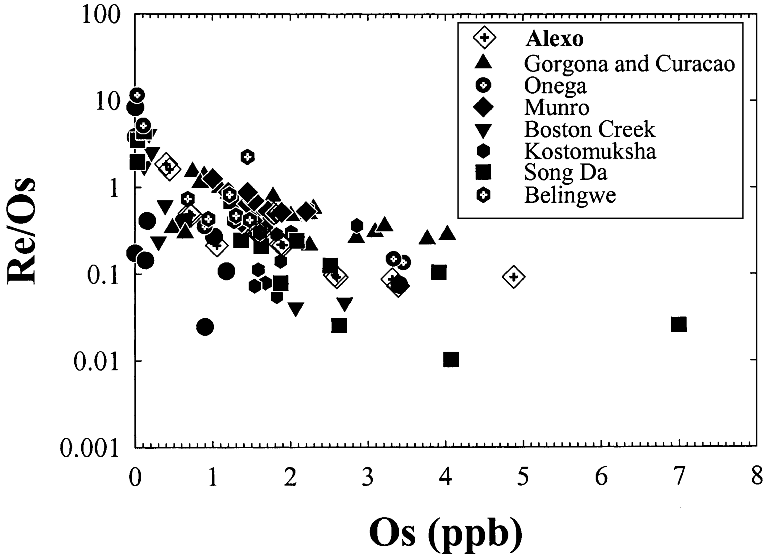

Fig. 7. Plot of Re/Os versus Os. The range of Re/Os relative to Os in the Alexo komatiite suite is within the ranges observed in other komatiites. Data sources as in Fig. 6 with additional data from Belingwe komatiites, Zimbabwe (Walker and Nisbet, 2002).

concentrations of Alexo parental magma is in good agreement with that independently estimated from the KAL-1 standard (1.8 ± 0.1 ppb; Puchtel and Humayun, 2000). The assumed extent of melting is in agreement with separate estimates based on experimental results (Herzberg, 1992) and geochemical considerations (~ 45% of Arndt, 1986). The calculated D values for Re and Os are 0.2 and 2.1, respectively. The D value of 2.1 for Os is consistent with that obtained by Walker et al. (1988) for Munro Township komatiites (D_{Os} of 1.9 assuming 26% melting). Similarly, the Gorgona komatiites were interpreted to yield a D value of 1.5 with somewhat lower degrees of melting (20%; Walker et al., 1999). Our D values, therefore, suggest that Os was moderately compatible, whereas Re was incompatible in the mantle residue during the generation of Alexo komatiite magma.

4.2. Preservation of Re–Os isotope system of Alexo komatiites

The present study has important implications for the degree of preservation of Re–Os isotope system at the scale of whole rocks and minerals in komatiite lavas. The high MSWD value (112) obtained for our regression indicates significant scatter outside of estimated analytical uncertainties. Possible causes that might have contributed to the excess scatter about the regression are: (a) differences in the ages of the samples; (b) variation in initial $^{187}Os/^{188}Os$ ratios; (c) the assigned analytical uncertainties have underestimated the actual uncertainties in the corrected isotopic ratios; and (d) limited open-system behavior of Re and/or Os in these rocks.

Although the samples include multiple flows within a small area, the data are consistent with magmatic behavior of both Re and Os in the samples, which, in turn, is indicative of a cogenetic suite. In addition, no large differences in the ages of ultramafic rocks from the Abitibi Greenstone Belt, in general, and Alexo, in particular, have, so far, been recorded. As mentioned earlier, the age of Alexo flows is precisely known from U–Pb zircon dating of overlying and underlying units, and includes a restricted range between 2700 and 2727 Ma (Nunes and Pyke, 1980). Moreover, new high-resolution U–Pb zircon ages along with compilation of previous geochronological data strongly suggests that the southern Abitibi greenstone belt represents an autochthonous stratigraphy with the dominantly volcanic assemblages ranging in age from 2697 to 2750 Ma (Ayer et al., 2002). It is, unlikely, therefore, that differences in ages of the rocks have contributed to the high MSWD value.

The actual variations in initial $^{187}Os/^{188}Os$ ratios of the samples are likewise unlikely, but cannot categorically be ruled out. Komatiites, in general, are believed to be generated through high degrees of partial melting from their mantle sources. As a result, it is likely that the high degrees of melting (~ 50%) that generated the Alexo parental magma would have removed small-scale differences, if any, in initial $^{187}Os/^{188}Os$ ratios of the source. Significant variations in the initial $^{187}Os/^{188}Os$ within a single suite of the Mesozoic Gorgona komatiites, however, were reported by Walker et al. (1999).

The whole rocks as well as the chromites have very high concentrations of Os (Table 2) and had minor blank contributions in the total Os analyzed for these samples. Also, most of the Os analyses were performed with Faraday cups with high precision (typically 0.05% 2σ) under static analytical mode. The total analytical blanks for both Re and Os, and also the external reproducibility on Re and Os standards, are well within the ranges we have obtained in our laboratory over the years. It is unlikely, therefore, that any significant analytical uncertainties have remained unaccounted for in our regression calculation.

The high MSWD value may most likely be a result of minor open-system behavior in the Re–Os isotope systematics in our samples. This is because the Abitibi rocks, in general, are significantly altered and metamorphosed dominantly to greenschist facies that locally reach up to amphibolite facies (Jolly, 1982). The Alexo flows, however, had undergone prehnite–pumpellyite grade of metamorphism (Lahaye et al., 2001 and references therein). The signature of alteration is documented in Lahaye and Arndt (1996) and also in our petrographic study of these rocks. For example, most of our samples have undergone secondary replacement of olivine by serpentine, oxidation of olivine to magnetite and devitrification of glass. There is, however, no apparent correlation between isotopic characteristics of our whole rocks and their degrees of alteration, as suggested by studied petrographic characteristics. Nevertheless, as noted earlier, duplicate analyses of the basaltic komatiite sample (Alx-5W) yield γ_{Os} values that are outside of the analytical uncertainties of each other ($+7.1 \pm 2.8$ versus $+2.4 \pm 1.8$; Table 2). The scatter may, therefore, be due to limited open-system behavior as a result of low-grade metamorphism and/or hydrothermal alteration. Note, however, that the elimination of the two points slightly increases the MSWD value of the regressions (103 to 112). Nonetheless, there is evidence for minor open-system behavior in Pb–Pb system of these rocks. For example, using the ISOPLOT program (Ludwig, 1998), we have recalculated the ^{207}Pb–^{206}Pb isochron regression of Alexo komatiites, based on the data in Table 1 of Dupré et al. (1984). The age we have obtained from the model 2 regression is similar but has slightly larger uncertainty (2692 ± 34 Ma) relative to that of Dupré et al. (1984) (2690 ± 15 Ma). The MSWD value of the isochron, although unspecified in Dupré et al. (1984), is also high (77). As noted by Dupré et al. (1984), the spread in U–Pb, however, was most likely caused by post-magmatic hydrothermal alteration. Therefore, it is possible that the same hydrothermal alteration event has contributed to the minor open-system behavior of the Re–Os isotope system of our samples. Also, similar excess scatters about Re–Os regressions have been documented in the previous studies of ancient komatiites. For example, Puchtel et al. (1999) have reported an MSWD value of 108 for their Re–Os regression for Onega plume-related lavas even with relatively larger degrees of analytical uncertainties (± 0.5% for both ^{187}Os/^{188}Os and ^{187}Re/^{188}Os ratios).

The apparent magmatic behaviors of both Re and Os, and preservation of a reliable isochron for the Alexo rocks suggest that the Re–Os isotope system offers a relatively robust tracer of mantle processes related to this ultramafic magmatic system. This is in contrast to the Rb–Sr system which is usually compromised due to post-crsytallization secondary processes (e.g. Walker et al., 1988). The apparent resistance of the Re–Os system to the secondary processes, combined with high concentrations of Os in chromites and also moderate compatibility of Os in olivine suggest that these elements were mostly concentrated in trapped inclusions within olivines, chromites and possibly other trace phases, and were relatively immobile during mineral replacements at the whole-rock scale.

4.3. Implications of a chondritic initial Os isotopic composition for the Alexo mantle source

It is now widely believed that the ultimate source of Re and Os in modern and ancient mantle-derived rocks was a ‘late veneer’ of chondritic material added to the mantle following their presumed nearly quantitative removal during core formation (e.g. Kimura et al., 1974; Chou, 1978; Morgan, 1985; Morgan et al., 2001). If true for the Alexo mantle source, the chondritic initial ^{187}Os/^{188}Os for these rocks implies that sufficient late accretion and subsequent homogenization of the mantle source of these rocks must have occurred prior to the time of their crystallization at 2.7 Ga and since had not undergone any long-term fractionation of Re/Os or ^{187}Os enrichment. Such a chondritic Os isotopic evolution of the mantle source for Alexo komatiites is consistent with chondritic Os isotopic compositions of even older mantle-derived systems, such as 3.8-Ga spinel peidotite from West Greenland and ∼ 3.5-Ga komatiites from the Pilbara region of Western Australia (Bennett et al., 2002). The essentially chondritic initial ^{187}Os/^{188}Os for Alexo is also consistent with that previously reported from spatially associated Munro Township komatiites (Walker et al., 1988; Shirey, 1997). Combined, these results may suggest an absence of any large-scale Os isotopic heterogeneity in the southern volcanic zone of the Abitibi greenstone belt. Similar chondritic initial ^{187}Os/^{188}Os ratios have also been reported for komatiites from ∼ 2.7-Ga Norseman–Wiluna Belt (Foster et al., 1996) and ∼ 2.8-Ga Ruth Well komatiites in Australia (Meisel et al., 2001a), and komatiitic basalts from ∼ 2.5-Ga Vetreny belt in the Baltic shield (Puchtel et al., 2001b). Collectively, these results indicate the presence of a chondritic mantle source of plumes in several areas worldwide at the end of the Archean. Also, the chondritic initial ^{187}Os/^{188}Os for Alexo komatiites is consistent with the generally chondritic evolution of Proterozoic and Phanerozoic upper mantle (e.g. Snow and Reisberg, 1995; Brandon et al., 2000; Walker et al., 1996, 2002).

The chondritic initial Os isotopic composition for Alexo komatiites ($\gamma_{Os} = -0.1 \pm 1.0$), within uncertainties, overlaps with the Os isotopic evolution trajectories for both hypothetical primitive upper mantle (PUM; Meisel et al., 2001b) and convective upper mantle (Snow and Reisberg, 1995; Brandon et al., 2000; Walker et al., 2002), projected back at the eruption age of these lavas at ~ 2.7 Ga. In other words, the source of Alexo komatites, based on our Os isotopic results, is indistinguishable from the contemporaneous convective upper mantle. The Nd-isotopic compositions of Alexo flows, on the other hand, unequivocally record a long-term depletion in LREE ($\varepsilon_{Nd} = +2.4 \pm 0.5$; Dupré et al., 1984). Also note that this initial Nd isotopic composition, within uncertainties, overlaps with the depleted mantle trajectories of DePaolo (1981) and Goldstein et al. (1984) at 2.7 Ga. The initial Nd isotopic composition of these komatiites is, therefore, consistent with their derivation from a mantle reservoir with a long-term depletion in LREE. An LREE-depleted, relatively shallow mantle source for Al-undepleted komatiites, such as those from Alexo and Munro Townships, is also consistent with a flat HREE pattern, common absence of HFSE anomaly (e.g. Xie et al., 1993; Kerrich and Xie, 2002) and estimated depth of melting at ~ 160 km (Herzberg, 1992), all suggesting the absence of either majorite or pyrope garnet signature.

As suggested by our estimated D values, Os is slightly compatible, whereas Re is moderately incompatible during high degrees of mantle melting. Hence, LREE-depletion as a result of prior extraction of melt could potentially generate a Re/Os ratio in the residue that would be lower than that in the unmelted source mantle. It is, therefore, interesting to note that the depleted Nd isotopic composition is not accompanied by evidence for long-term depletion in Re/Os. Similar decoupling of Os and Nd isotopes may be found in other Archean komatiites. For example, the komatiites from Munro Township record a depleted Nd isotopic composition ($\varepsilon_{Nd} = +2$ to $+3$) and yet also have chondritic initial Os isotopic composition (Walker et al., 1988). Such isotopic decoupling is also found for much large scale of crust-mantle differentiation. The convective upper mantle records progressively higher degrees of depletion in terms of Nd isotopic composition through geologic time (DePaolo, 1981; McCulloch and Bennett, 1994) and yet may have evolved through a broadly chondritic Os isotopic trajectory (Snow and Reisberg, 1995; Brandon et al., 2000; Walker et al., 1996, 2002).

The apparent lack of correlation between the Re–Os and Sm–Nd isotope systematics in these Archean komatiites may indicate any combination of the following possibilities: [a] the degree of prior melting was too low to generate resolvable Re depletion and yet sufficient to reflect on Nd isotopic record; [b] a fortuitous change in the partitioning behavior of Re and Os possibly as a result of different melting conditions and abundance of other phases (such as sulfide) in the Early Archean mantle that did not allow resolvable fractionation of Re from Os; and [c] sufficient late accretion occurred subsequent to the extraction of melts that caused the depletion in Nd/Sm ratio so that the observed chondritic Os isotopic composition of these mantle sources essentially represents that of the late veneer.

5. Summary

[1] Alexo komatiites demonstrate apparent magmatic behavior of Re and Os in the whole rocks. The concentrations of Re and Os in these rocks are comparable with those in both Precambrian and Phanerozoic komatiites from elsewhere. Our calculated bulk distribution coefficients for Os and Re between the Alexo parental magma and the mantle residue are 2.1 and 0.2, respectively. These D values, therefore, suggest that Os was slightly compatible in the mantle residue, whereas Re was moderately incompatible during the melting of the Alexo mantle source. Similarly, our calculated partition coefficients for Os and Re between olivine and the fractionating liquid are 1.7 and 0.66, respectively. These K_d values, therefore, suggest that Os was slightly compatible, whereas Re was moderately incompatible during the fractionation of the Alexo parental magma. The moderate compatibility of Os in olivine may suggest preferential entrapment of Os in sulfide inclusions within olivine and/or incorporation of Os in olivine crystal structures.

[2] Re–Os regression of these rocks yields an age of 2762 ± 76 Ma. This age is in general agreement with the U–Pb zircon ages of associated felsic units (2710–2717 Ma; Nunes and Pyke, 1980; Corfu, 1993). Our Re–Os regression age is also in agreement with Pb–Pb (2690 ± 15 Ma) and Sm–Nd isochron ages (2752 ± 87 Ma) obtained in a previous study of these lavas (Dupré et al., 1984). The high MSWD value (112) obtained for

the Re–Os regression suggests modest degrees of mobility of Re and/or Os during post-crystallization alteration and low-grade metamorphism.

[3] The initial $^{187}Os/^{188}Os$ obtained from our regression (0.1080 ± 0.0012) is essentially chondritic ($\gamma_{Os} = -0.1 \pm 1.0$). The chondritic initial Os isotopic composition for Alexo rocks is consistent with that obtained for spatially associated komatiites from Munro Township (e.g. $\gamma_{Os} = +0.1 \pm 1.5$ for Pyke Hill komatiites; Shirey, 1997). The initial Nd isotopic composition of Alexo ($\varepsilon_{Nd} \sim +3.8$; Lahaye et al., 1995) and Munro Township ($\varepsilon_{Nd} = +2$ to $+3$; Dupré et al., 1984) komatiites, on the other hand, unequivocally reflect LREE-depleted mantle sources for these rocks. Combined, the chondritic initial Os isotopic composition for the source of Alexo komatiites is indistinguishable from the contemporaneous convective upper mantle.

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