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## Re-Os systematics of komatiites and komatiitic basalts at Dundonald Beach, Ontario, Canada: Evidence for a complex alteration history and implications of a late-Archean chondritic mantle source

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**Abstract**—Osmium isotopic compositions, and Re and Os concentrations have been examined in one komatiite unit and two komatiitic basalt units at Dundonald Beach, part of the 2.7 Ga Kidd-Munro volcanic assemblage in the Abitibi greenstone belt, Ontario, Canada. The komatiitic rocks in this locality record at least three episodes of alteration of Re-Os elemental and isotope systematics. First, an average of 40% and as much as 75% Re may have been lost due to shallow degassing during eruption and/or hydrothermal leaching during or immediately after emplacement. Second, the Re-Os isotope systematics of whole rock samples with  $^{187}\text{Re}/^{188}\text{Os}$  ratios  $>1$  were reset at  $\sim 2.5$  Ga, possibly due to a regional metamorphic event. Third, there is evidence for relatively recent gain and loss of Re in some rocks.

Despite the open-system behavior, some aspects of the Re-Os systematics of these rocks can be deciphered. The bulk distribution coefficient for Os ( $D_{\text{Os}}^{\text{solid/liquid}}$ ) for the Dundonald rocks is  $\sim 3 \pm 1$  and is well within the estimated D values obtained for komatiites from the nearby Alexo area and stratigraphically-equivalent komatiites from Munro Township. This suggests that Os was moderately compatible during crystal-liquid fractionation of the magmas parental to the Kidd-Munro komatiitic rocks. Whole-rock samples and chromite separates with low  $^{187}\text{Re}/^{188}\text{Os}$  ratios ( $<1$ ) yield a precise chondritic average initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio of  $0.1083 \pm 0.0006$  ( $\gamma_{\text{Os}} = 0.0 \pm 0.6$ ) for their well-constrained  $\sim 2715$  Ma crystallization age. The chondritic initial Os isotopic composition of the mantle source for the Dundonald rocks is consistent with that determined for komatiites in the Alexo area and in Munro Township, suggesting that the mantle source region for the Kidd-Munro volcanic assemblage had evolved with a long-term chondritic Re/Os before eruption. The chondritic initial Os isotopic composition of the Kidd-Munro komatiites is indistinguishable from that of the projected contemporaneous convective upper mantle. The uniform chondritic Os isotopic composition of the Kidd-Munro komatiites contrasts with the typical large-scale Os isotopic heterogeneity in the mantle sources for ca. 89 Ma komatiites from the Gorgona Island, arc-related rocks and present-day ocean island basalts. This suggests that the Kidd-Munro komatiites sampled a late-Archean mantle source region that was significantly more homogeneous with respect to Re/Os relative to most modern mantle-derived rocks. Copyright © 2005 Elsevier Ltd

### 1. INTRODUCTION

Petrographic and geochemical studies have shown that Precambrian komatiites have undergone variable degrees of weathering, hydrothermal alteration and metamorphism (Beswick, 1982; Jolly, 1982; Arndt et al., 1989; Arndt and Lesher, 1992; Lesher and Arndt, 1995; Lahaye et al., 1995; Lahaye and Arndt, 1996; Rollinson, 1999; Hanski et al., 2001). The effects of these secondary processes in some suites are manifested by open-system behavior of Re-Os elemental and isotope systematics of whole rocks, which, in some cases, yield inaccurate ages and large uncertainties in calculated initial  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the emplaced lavas (e.g., Walker and Nisbet, 2002). Thus, some previous Os isotopic studies of Precambrian komatiites, for which the crystallization ages were known from other radiogenic isotope systematics (e.g., Sm-Nd, Pb-Pb), have relied on Os-rich, relatively well-preserved primary igneous minerals (e.g., olivine and chromite) to determine

initial Os isotopic compositions of host lavas (Walker and Nisbet, 2002). The nature and causes of open-system behavior in the Re-Os system of whole rock komatiite samples, however, have not been well documented. In this paper, we report Re-Os concentrations and isotopic compositions of whole rocks and chromite separates from a suite of ca. 2.7-Ga komatiites and komatiitic basalts in the Dundonald Beach area of the Abitibi greenstone belt, Ontario, Canada. We estimate early losses of Re in our suite of samples through comparison between measured Re concentrations and those calculated from correlations with the similarly incompatible, yet relatively immobile major element Al, as observed in stratigraphically-equivalent, least-altered komatiites in the Alexo and Pyke Hill areas. Based on our estimates of Re loss, the known crystallization age for the Dundonald rocks, and Os isotopic results, we consider the processes that may have contributed to the disturbances in the Re-Os elemental and isotopic systematics of these rocks.

Another objective of this study was to determine the initial Os isotopic composition of the  $\sim 2.7$ -Ga mantle sources for these rocks and to compare it with those previously obtained for other rocks from the region. Compilation of the growing global database for high-precision initial Os isotopic composi-

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tions of ultramafic rocks suggests that by the late Archean, Os present in the mantle sources for most ultramafic rocks had generally chondritic  $^{187}\text{Os}/^{188}\text{Os}$  (Bennett et al., 2002; Wilson et al., 2003; Shirey, 1997; Gangopadhyay and Walker, 2003; Puchtel et al., 2004a), yet there were some exceptions, such as those with positive or negative deviations from the chondritic Os isotopic evolution trajectory (Puchtel et al., 2001; Walker and Nisbet, 2002; Walker and Stone, 2001). However, the spatial scales of these heterogeneities are yet largely unknown. The Re-Os systematics of komatiitic rocks from the Abitibi greenstone belt are the most comprehensively studied among the greenstone belts worldwide. Given the importance of defining spatial scales of Os isotopic heterogeneity or its lack thereof in the mantle source of a large volcanic province, Os isotopic analyses of Dundonald Beach rocks provide an important additional point of comparison to other Abitibi komatiites.

## 2. SAMPLES

The samples examined here were collected from the Dundonald Beach outcrop, a mechanically- and hydraulically-stripped area covering  $\sim 150\text{m} \times 60\text{m}$ , that is located in the SW part of Dundonald Township in northern Ontario (Houlé et al., 2002; Arndt et al., 2004). The geochemical characteristics of the komatiites and associated magmatic Ni-Cu-PGE deposits and volcanogenic massive Cu-Zn sulfide deposits in the Dundonald Township have been reported by previous studies (e.g., Naldrett and Mason, 1968; Muir and Comba, 1979; Barnes et al., 1983; Barnes, 1985; Barnes and Naldrett, 1987; Davis, 1997, 1999; Barrie et al., 1999). The U-Pb zircon age of a dacite unit that is presumably near coeval with the komatiites in the Dundonald Township is  $2717.3 \pm 1.2\text{ Ma}$  (Barrie et al., 1999). This age is in excellent agreement with U-Pb zircon ages ( $2717.7 \pm 1.1\text{ Ma}$ ) for the bimodal komatiite and rhyolite volcanic rocks in the Kidd Creek area 40 km west of Dundonald Township (Bleeker et al., 1999). The Dundonald Beach komatiites are stratigraphically equivalent to those exposed in the Alexo area and in Munro Township, and are part of the spatially extensive ( $\sim 180\text{ km} \times 12\text{ km}$ ) Kidd-Munro volcanic assemblage, which ranges in age from 2719 to 2710 Ma (Nunes and Pyke, 1980; Corfu and Noble, 1992; Bleeker et al., 1999; Ayer et al., 2002). The volcanic assemblage of Dundonald Township includes volumetrically dominant basalts ( $\sim 75\%$ ) with relatively minor komatiitic rocks ( $\sim 10\%$ ), calc-alkaline basalts to rhyolites ( $\sim 10\%$ ) and tholeiitic rhyolites ( $\sim 5\%$ ; Barrie, 1999). Though relatively minor, the proportion of komatiitic rocks in this assemblage is greater than for other assemblages in the Abitibi greenstone belt.

All whole rock samples examined here were collected in relatively large volumes (typically more than 5 kg) from three surface units. These surface units were originally interpreted to be extrusive (e.g., Muir and Comba, 1979), but which Arndt et al. (2004) have suggested to be intrusive. Samples DUNBCH-1 through DUNBCH-6 were collected from one single ( $\sim 10\text{ m}$ -thick) komatiite unit, which is one of several differentiated komatiite units with thick lower olivine mesocumulate zones and thin upper olivine spinifex-textured zones (Davis, 1997; 1999). Samples DUNBCH-7 through DUNBCH-10 were collected from a single komatiitic basalt unit. This  $\sim 9\text{ m}$ -thick unit consists of a lower olivine-clinopyroxene-(orthopyroxene) cu-

mulate zone, a thick parallel acicular ("string-beef") pyroxene spinifex-textured zone, a thin random platy olivine spinifex-textured zone, and a very thin, very fine-grained, upper "chilled" margin (Davis 1997, 1999). Samples DUNBCH-11 through DUNBCH-15 were collected from another single komatiitic basalt unit. This  $\sim 25\text{ m}$ -thick unit is composed of a basal peridotite, an overlying unit of peridotite with postcumulus pyroxene oikocrysts, an overlying unit of skeletal-textured pyroxenite, and an uppermost random pyroxene spinifex unit. The komatiites and komatiitic basalts in the Dundonald Beach area have been metamorphosed to lowermost greenschist facies and are locally faulted and/or sheared, but primary structures and textures are well preserved. All of the interstitial glass has been converted to chlorite, most sulfides have been recrystallized, most of the olivine has been pseudomorphed by serpentine and magnetite, and some of the pyroxene has been pseudomorphed by chlorite. However, some of the olivine, much of the pyroxene, and most of the chromite are preserved (Davis, 1997, 1999; Arndt et al., 2004).

## 3. SAMPLE PREPARATION AND ANALYTICAL METHODS

Whole rock samples were crushed into mm-sized pieces using a ceramic jaw crusher. The freshest pieces were cleaned with Milli-Q water in an ultrasonic bath for  $\frac{1}{2}\text{ h}$  and were subsequently dried in an oven at  $60^\circ\text{C}$  for  $\sim 1\text{ h}$ . These pieces were then finely ground using an agate mill to obtain typically  $\sim 50\text{--}60\text{ g}$  of sample powder. The powders were carefully mixed and homogenized, and separate aliquots of the same whole rock powder were used for analyses of major and minor elements and Re-Os isotopes.

Chromite separates were obtained by crushing whole rock samples using a ceramic jaw crusher, followed by separation of the ferromagnetic (magnetite) fraction using a hand magnet. The residual, least-ferromagnetic fraction was ground to submillimeter grain size using a conventional ceramic mill and a least-magnetic fraction was separated using a Frantz magnetic separator with appropriate current settings. Finally, the chromite fraction was purified using heavy liquids.

The major element data (Table 1) were obtained by wavelength-dispersive X-ray fluorescence spectrometry (WD-XRFS) at the University of Western Ontario (Dr. C. Wu, analyst) using fused glass disks of whole-rock sample powders. Nickel and Cr concentrations were determined by WD-XRFS of pressed powder pellets. Comparison of routine sample replicates indicate that major elements ( $>1\text{ wt.}\%$ ) are precise to within  $\pm 2\%$  and that minor elements (Ni, Cr) are precise within  $\pm 5\%$  of the amount present.

Chemical separations of Re and Os, and analysis of Re-Os isotopes were performed at the University of Maryland by the senior author. The chemical separation procedures for Re and Os employed in this study have followed previously published work (Shirey and Walker, 1995; Cohen and Waters, 1996) and described in detail elsewhere (e.g., Gangopadhyay and Walker, 2003). In this study, however, relatively large volumes of whole-rock sample aliquots (typically  $\sim 4\text{ g}$  as opposed to  $2\text{--}3\text{ g}$  that are commonly used) were digested using  $4\text{ g}$  concentrated HCl and  $8\text{ g}$  concentrated  $\text{HNO}_3$  in large Carius tubes to extract sufficient quantity of Os from most samples for analyses on the Faraday cups. The analytical blanks for Re and Os were  $5.4 \pm 4.2\text{ pg}$  and  $4.3 \pm 2.6\text{ pg}$  ( $n = 4$ ), respectively, and are negligible ( $<0.5\%$ ) compared to their concentrations in whole rock samples. The Re blank contribution, however, was substantial ( $>5\%$ ) for some chromites. The isotopic compositions of the blanks were natural for Re and had  $^{187}\text{Os}/^{188}\text{Os}$  of  $0.249 \pm 0.070$  ( $n = 4$ ). All data were blank corrected. The uncertainties in the compositions of the blanks are reflected in the respective uncertainties for the isotopic data and concentrations reported in Table 2.

Osmium isotopic compositions were analyzed by negative thermal ionization mass spectrometry (Creaser et al., 1991; Völkening et al., 1991) using the procedures discussed in Walker et al. (1994) and Morgan et al. (1995). Samples with high Os abundances were analyzed with Faraday cups in static analytical mode using a VG Sector 54 mass

Table 1. Whole rock major and selected trace element data for Dundonald Beach komatiites and komatiitic rocks. All major element oxides are recalculated on 100% volatile-free basis.

Samples	Komatiite unit						Komatiitic basalt unit I	
	DUNBCH-1	DUNBCH-2	DUNBCH-3	DUNBCH-4	DUNBCH-5	DUNBCH-6	DUNBCH-7	DUNBCH-8
Major oxides (wt. %)								
SiO <sub>2</sub>	44.1	44.3	44.1	43.9	44.1	45.1	50.3	50.5
TiO <sub>2</sub>	0.14	0.14	0.15	0.46	0.43	0.38	0.55	0.64
Al <sub>2</sub> O <sub>3</sub>	3.3	3.5	3.4	11.1	9.5	8.4	11.7	14.6
Fe <sub>2</sub> O <sub>3</sub>	9.6	8.5	9.4	10.7	12.9	11.7	11.6	12.3
MnO	0.10	0.12	0.13	0.24	0.20	0.17	0.22	0.18
MgO	42.3	42.9	42.2	21.2	22.7	25.2	12.6	8.4
CaO	0.16	0.14	0.29	12.1	9.78	8.63	11.2	10.2
Na <sub>2</sub> O	—*	—	—	—	—	—	0.97	2.06
K <sub>2</sub> O	—	—	0.01	—	—	—	0.75	1.06
P <sub>2</sub> O <sub>5</sub>	—	0.01	0.01	0.03	0.02	0.03	0.04	0.05
Cr <sub>2</sub> O <sub>3</sub>	0.31	0.29	0.31	0.29	0.40	0.42	0.16	0.05
LOI	12.5	12.8	12.4	4.84	5.57	6.29	2.26	1.92
Mg# <sup>1</sup>	0.90	0.91	0.90	0.80	0.78	0.81	0.68	0.58
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	24	26	23	24	22	22	21	23
CaO/Al <sub>2</sub> O <sub>3</sub>	0.05	0.04	0.08	1.1	1.0	1.0	0.96	0.70
Ni (ppm)	2844	2659	2688	829	765	1082	118	70
Cr (ppm)	1528	1546	1621	1823	2782	2585	1022	303
Komatiitic basalt unit I			Komatiitic basalt unit II					
Samples	DUNBCH-9	DUNBCH-10	DUNBCH-11	DUNBCH-12	DUNBCH-13	DUNBCH-14	DUNBCH-15	
Major oxides (wt. %)								
SiO <sub>2</sub>	47.8	47.9	44.0	44.2	49.2	48.7	49.2	
TiO <sub>2</sub>	0.56	0.56	0.26	0.28	0.44	0.56	0.56	
Al <sub>2</sub> O <sub>3</sub>	12.7	12.0	6.4	6.4	10.2	13.7	13.3	
Fe <sub>2</sub> O <sub>3</sub>	12.9	12.6	12.5	12.9	12.0	11.9	11.1	
MnO	0.22	0.21	0.18	0.18	0.22	0.21	0.20	
MgO	12.5	12.2	30.9	30.5	14.7	9.2	12.0	
CaO	11.6	13.7	5.12	5.13	11.6	13.5	11.3	
Na <sub>2</sub> O	0.36	0.01	0.02	0.02	0.73	0.15	0.38	
K <sub>2</sub> O	1.10	0.74	0.00	0.00	0.74	1.93	1.89	
P <sub>2</sub> O <sub>5</sub>	0.04	0.04	0.02	0.02	0.03	0.04	0.03	
Cr <sub>2</sub> O <sub>3</sub>	0.12	0.10	0.61	0.40	0.20	0.06	0.07	
LOI	2.98	2.72	7.39	6.77	2.38	2.66	3.09	
Mg# <sup>1</sup>	0.66	0.66	0.83	0.82	0.71	0.60	0.68	
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	23	22	25	23	23	24	24	
CaO/Al <sub>2</sub> O <sub>3</sub>	0.91	1.1	0.80	0.81	1.1	0.98	0.85	
Ni (ppm)	199	178	1412	1344	223	115	119	
Cr (ppm)	888	708	2936	1662	1139	327	400	

\* — = not determined.

spectrometer, whereas those with relatively low abundances of Os were analyzed with an electron multiplier in dynamic mode using a 12' radius NBS mass spectrometer. The external reproducibilities for Os isotopic ratios were determined through analyses of comparable quantities of Os in standard solutions (UMCP Johnson-Matthey standards). The <sup>187</sup>Os/<sup>188</sup>Os ratios obtained for standard analyses on electron multiplier ( $0.1139 \pm 0.0004$ ;  $n = 7$ ) and Faraday cups ( $0.11380 \pm 0.00002$ ;  $n = 4$ ) during the course of our analyses varied within a limited range relative to the ratios previously reported for the same standard (<sup>187</sup>Os/<sup>188</sup>Os =  $0.11379 \pm 0.00002$ ; Shirey and Walker, 1998). The internal precisions for <sup>187</sup>Os/<sup>188</sup>Os ratios obtained from analyses on electron multiplier and Faraday cups were typically better than  $\pm 0.5\%$  and  $\pm 0.3$  ( $2\sigma$ ), respectively.

The concentrations of Re were determined using a Nu Plasma multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) via static mode collection and either Faraday cup or electron multiplier detectors (Belshaw et al., 1998). The sample solution (in 2% HNO<sub>3</sub>) was introduced to an Ar plasma using an Aridus desolvating nebulizer. The instrumental fractionation of <sup>185</sup>Re/<sup>187</sup>Re for the samples was monitored and corrected via interspersed analyses of standards (<sup>185</sup>Re/<sup>187</sup>Re = 0.597; Gramlich et al., 1973) of comparable Re con-

centrations. The total analytical uncertainty in Re concentrations of the same standard solution (UMCP standard) previously determined was  $\pm 0.2\%$ .

#### 4. RESULTS

The Dundonald komatiites and komatiitic basalts show strong olivine control on MgO vs. Al<sub>2</sub>O<sub>3</sub> (Fig. 1) and TiO<sub>2</sub> fractionation-accumulation trends. These rocks have near-chondritic Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratios (21–26 vs. chondritic ratio of  $\sim 22$ ; McDonough and Sun, 1995), unfractionated chondrite-normalized (CN) heavy rare earth element (HREE) patterns (Gd/Yb<sub>CN</sub>  $\sim 0.9$ – $1.1$ ) similar to Al-undepleted komatiites at Alexo and Pyke Hill (Lahaye and Arndt, 1996; Fan and Kerrich, 1997) and to Al-undepleted komatiites worldwide (Nesbitt et al., 1979; Lahaye et al., 1995; Sproule et al., 2002).

The distribution of Os in whole rock samples from the komatiite unit is bimodal. The cumulate komatiites (MgO  $\sim 42$

Table 2. Rhenium and Os concentration and isotope data for the whole rock Dundonald komatiites and komatiitic basalts, and chromite separates

Samples	Re <sup>1</sup> (ppb)	Os (ppb)	<sup>187</sup> Re/ <sup>188</sup> Os <sup>1</sup>	<sup>187</sup> Os/ <sup>188</sup> Os <sup>1</sup>	γOs (2.7Ga) <sup>2</sup>	Model age (Ga)
Komatiite unit:						
DUNBCH-1	0.324 (2)	3.384	0.4610 (23)	0.1306 (4)	+0.8 ± 0.5	
<b>DUNBCH-1A*</b>	0.439 (2)	6.392	0.3308 (17)	0.1231 (4)	-0.6 ± 0.4	
<b>DUNBCH-1B</b>	0.537 (3)	7.038	0.3673 (18)	0.1250 (4)	-0.4 ± 0.4	
DUNBCH-2	0.177 (1)	4.093	0.2082 (10)	0.1171 (4)	-0.9 ± 0.4	
Dupl.**	0.144 (1)	3.715	0.1863 (9)	0.1169 (4)	-0.1 ± 0.4	
<b>DUNBCH-2A</b>	0.283 (1)	9.610	0.1417 (7)	0.1158 (3)	+0.7 ± 0.4	
<b>DUNBCH-2B</b>	0.339 (2)	9.825	0.1662 (8)	0.1156 (3)	-0.5 ± 0.4	
DUNBCH-3	0.168 (1)	4.252	0.1906 (10)	0.1198 (4)	+2.3 ± 0.4	
Dupl.	0.107 (1)	3.797	0.1356 (7)	0.1155 (3)	+0.6 ± 0.3	
DUNBCH-4	0.613 (3)	0.3794	8.102 (41)	0.4473 (22)	-30.1	2.4
Dupl.	0.191 (1)	0.3260	2.940 (15)	0.4378 (22)	+179	6.9
DUNBCH-5	0.543 (3)	0.8623	3.082 (15)	0.2466 (12)	-3.0	2.6
Dupl.	0.326 (2)	0.7522	2.123 (11)	0.2516 (13)	+42.1	4.2
DUNBCH-6	0.362 (2)	0.5870	3.014 (15)	0.2394 (12)	-6.8	2.5
Dupl.	0.435 (2)	0.6479	3.280 (16)	0.2383 (12)	-19.0	2.3
Komatiitic basalt unit I:						
DUNBCH-7	0.727 (4)	1.025	3.475 (17)	0.2624 (13)	-5.0	2.6
DUNBCH-8	0.741 (4)	0.3204	11.86 (6)	0.6282 (31)	-22.1	2.6
DUNBCH-9	0.489 (2)	0.4239	5.701 (28)	0.3310 (17)	-35.8	2.3
Dupl.	0.602 (3)	0.6132	4.848 (24)	0.3126 (16)	-16.8	2.5
DUNBCH-10	0.446 (2)	0.4354	5.057 (25)	0.3224 (16)	-16.6	2.5
Komatiitic basalt unit II:						
DUNBCH-11	0.254 (1)	0.3980	3.108 (16)	0.2244 (11)	-24.5	2.1
DUNBCH-12	0.280 (1)	0.4415	3.096 (16)	0.2295 (11)	-19.4	2.2
DUNBCH-13	0.402 (2)	2.438	0.7963 (40)	0.1441 (4)	-0.9 ± 0.6	2.7
DUNBCH-14	0.551 (3)	0.3881	7.054 (35)	0.3724 (19)	-54.8	2.2
DUNBCH-15	0.384 (2)	0.7376	2.540 (13)	0.2209 (11)	-3.8	2.6

\* Bold-faced sample numbers represent chromite separates from the corresponding whole rock sample.

\*\* Dupl. = Duplicate analyses of separate aliquots of powder splits, obtained through thoroughly mixing of whole-rock powders of the same batch of crushed rock chips.

<sup>1</sup> The total analytical uncertainties for Re concentrations and all analyzed ratios (<sup>187</sup>Re/<sup>188</sup>Os and <sup>187</sup>Os/<sup>188</sup>Os) are reported in parentheses as the uncertainties in the last decimal places.

<sup>2</sup> γOs is calculated at the assumed age of 2.715 Ga for the crystallization of these rocks. This age is based on U-Pb zircon ages of the volcanics associated with the stratigraphically-equivalent rocks from Alexo and Pyke Hill (Ayer et al., 2002). The chondritic <sup>187</sup>Os/<sup>188</sup>Os at 2.7 Ga is calculated to be 0.1084, based on average <sup>187</sup>Re/<sup>188</sup>Os ratio of chondrites and initial <sup>187</sup>Os/<sup>188</sup>Os (T = 4.558 Ga) for early solar system materials (IIIA irons) of 0.40186 and 0.09531, respectively (Shirey and Walker, 1998). The decay constant (λ) used here is 1.666 × 10<sup>-11</sup> year<sup>-1</sup> (Smoliar et al., 1996).

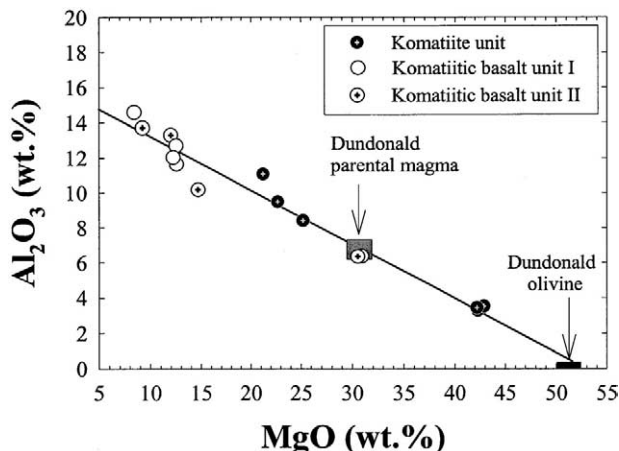


Fig. 1. Plot of MgO vs. Al<sub>2</sub>O<sub>3</sub> (wt.%, volatile-free) of the Dundonald komatiites and komatiitic basalts. The Dundonald parental magma composition is plotted after Barnes (1985). The field of olivine for Dundonald Beach cumulate rocks is plotted using the chemical compositions reported in Teasdale (1990).

wt.%) have the highest Os concentrations (up to ~4.3 ppb), whereas the less-magnesian non-cumulate rocks (MgO ~21–25 wt.%) have substantially lower Os concentrations (< 1 ppb; Fig. 2A). A positive correlation between MgO and Os concentrations may also be observed for the two komatiitic basalt units, but is more poorly defined. The MgO-Os variation trends for the komatiites and most komatiitic basalts are roughly parallel, but the komatiitic basalts are shifted towards higher Os concentrations relative to the projected Os concentrations at a given MgO content (Fig. 2A). Similar systematics have been observed for MgO vs. Ir concentrations for komatiites from Pyke Hill, compared to komatiitic basalts from Fred's flow, and tholeiitic basalts from Theo's flow, all in Munro Township (Crocket and MacRae, 1986). Two samples with relatively high MgO (~30 wt.%) from komatiitic basalt unit II, however, have similar Os concentrations to most samples with considerably lower MgO (down to ~8 wt.%; Fig. 2A).

There is an overall increase in Re concentration with decreasing MgO content in the whole rocks over the entire komatiite and komatiitic basalt fractionation sequences, consistent with the incompatible behavior of Re during fractionation of mafic-ultramafic melts (Fig. 2B; also see Brenan et al.,



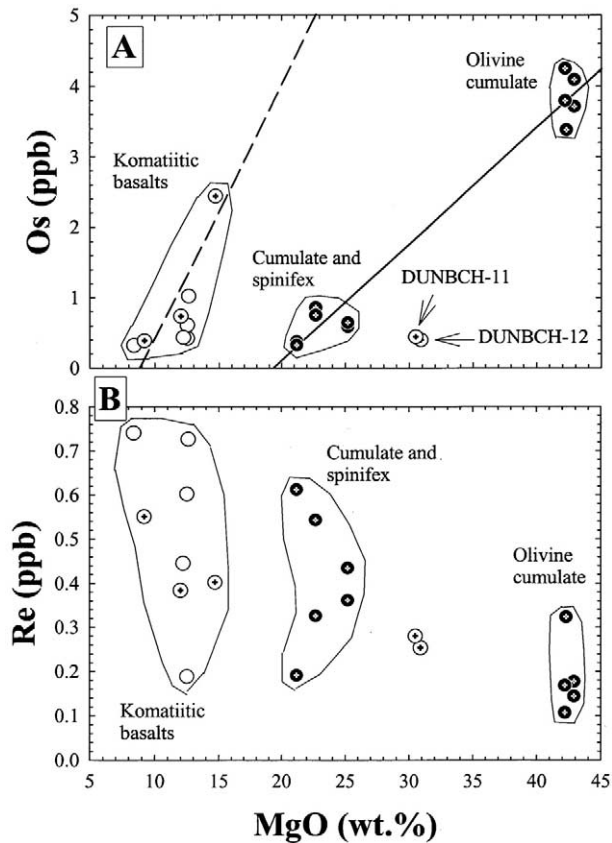


Fig. 2. Plot of whole rock MgO (wt.%, volatile-free) vs. (A) Os and (B) Re concentrations (ppb) in the Dundonald komatiites and komatiitic basalts (symbols as in Fig. 1). The solid and dotted lines represent two separate best-fit regression lines for Os concentrations in komatiite and komatiitic basalts, respectively. Note that two samples with high MgO (~30 wt.%) from the komatiitic basalt unit II have Os concentrations similar to those in most samples of komatiites and komatiitic basalts with much less MgO (down to ~ 8 wt.%).

2003). The olivine cumulate, spinifex and komatiitic basalt samples, however, when considered separately, show large variations in Re concentrations even within duplicate analyses of separate aliquots of a single whole rock sample powder. The total variation in Re concentrations between two separate powder splits of a single sample ranges between 17 and 40%, excluding one sample (DUNBCH-4) for which the difference is ~70% (Table 2). Reasons for this apparent heterogeneity will be discussed below.

Whole rock samples and chromite separates with  $^{187}\text{Re}/^{188}\text{Os} < 1$  display a very limited range in the calculated initial  $^{187}\text{Os}/^{188}\text{Os}$  isotopic ratios (Fig. 3A), whereas whole rocks with  $^{187}\text{Re}/^{188}\text{Os} > 1$  (DUNBCH-4 through DUNBCH-15, except DUNBCH-13) show highly variable calculated initial  $^{187}\text{Os}/^{188}\text{Os}$  isotopic ratios ( $\gamma_{\text{Os}}$  at 2.715 Ga varying between approximately -55 and +179; Table 2). Some of the variability is due to error magnifications in the calculated initial  $^{187}\text{Os}/^{188}\text{Os}$  ratios resulting from the relatively high Re/Os (Walker et al., 1994). Nonetheless, most of the whole rock samples plot below a 2.715 Ga chondritic reference isochron (Fig. 3B). The variable initial Os isotopic compositions cannot be due to heterogeneity in the mantle source because most

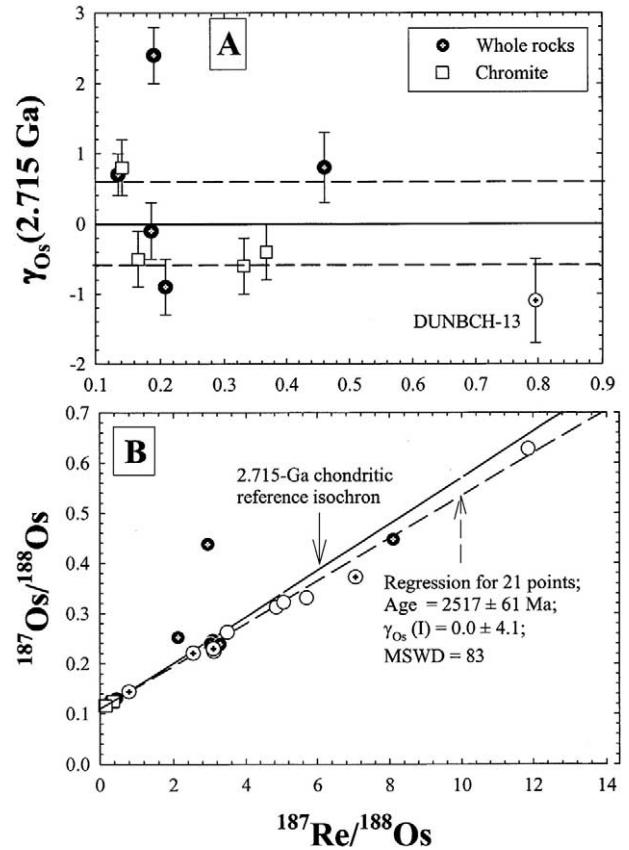


Fig. 3. (A) Plot of calculated initial  $\gamma_{\text{Os}}$  at 2.715 Ga vs.  $^{187}\text{Re}/^{188}\text{Os}$  ratios ( $< 1$ ) for the whole rock Dundonald komatiites and chromite separates (symbols as in Fig. 1). Note that, excluding one outlier of whole rock, all of these samples define a narrow range of initial  $\gamma_{\text{Os}}$  of  $0.0 \pm 0.6$ . (B) Plot of  $^{187}\text{Os}/^{188}\text{Os}$  vs.  $^{187}\text{Re}/^{188}\text{Os}$  ratios of all the whole rocks and chromite separates examined in this study. Note that 21 points define a regression that yields an age, which is ~200 Ma younger than the presumed crystallization age for these rocks. Also shown for comparison is a 2.7 Ga chondritic reference isochron.

non-isochronous samples yield unrealistically low initial  $\gamma_{\text{Os}}$  ( $< -16$ ). Furthermore, it is unlikely that such a large initial Os isotopic variation would be present in a single cooling unit.

## 5. DISCUSSION

### 5.1. Partitioning Behavior of Os during Differentiation of Komatiitic Magmas

On a plot of Os vs. Ni concentrations, whole rock samples of Dundonald komatiites and komatiitic basalts define two distinct linear trends with similar slopes (Fig. 4). The Dundonald komatiite samples with high MgO and correspondingly high Ni concentrations plot along a broad linear array together with those from Alexo (Gangopadhyay and Walker, 2003; Puchtel et al., 2004b) and Pyke Hill (Puchtel et al., 2004b). The entire range of Os and Ni concentrations for komatiites from Alexo, Pyke Hill, and Dundonald Beach is best approximated with linear regressions that yield  $D_{\text{Os}}$  between 2 and 4 (Fig. 5). These  $D_{\text{Os}}$  values are consistent with those independently estimated for komatiites from Alexo and Pyke Hill (1.7–2.8 and

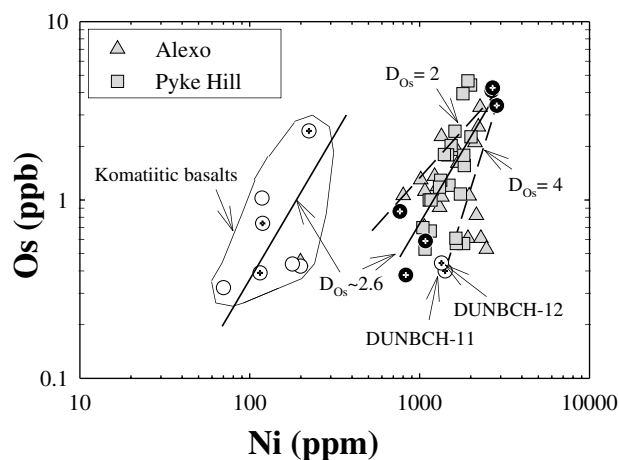


Fig. 4. Plot of Os and Ni concentrations in the Dundonald rocks (symbols as in Fig. 1) are compared with those from Alexo and Pyke Hill in the Abitibi greenstone belt. Using  $D_{Ni}^{olivine/liquid} = 2.0 \pm 0.1$ , as determined for Alexo komatiites (Arndt, 1986), the entire range of variations in Ni and Os concentrations in these rocks can be best approximated (shown by two dashed lines) by  $D_{Os}^{crystal/liquid} \sim 2$  to 4.

3.8–7.1, respectively: Gangopadhyay and Walker, 2003; Puchtel et al., 2004b) and are in general agreement with the compatibility of IPGEs (Ir, Os, Ru) during mantle melting and magmatic differentiation in mafic-ultramafic system (e.g., Barnes et al., 1985; Brüggmann et al., 1987; Lesher and Stone, 1996; Lesher et al., 2001). The shift of the komatiitic basalts towards higher Os concentrations relative to the olivine (+chromite) fractionation trend for komatiites (also noted in Fig. 2A) is likely due to accumulation of fractionating chromite or other Os-rich trace phases in the komatiitic basalts. Combined, these results are consistent with the interpretation that Os is moderately to strongly compatible during the differentiation of komatiitic magmas.

A compilation of Cr and MgO data for a variety of ferropicritic, Al-undepleted, Al-depleted ( $Al_2O_3/TiO_2$  of  $\sim 5$ –11; Walker and Stone, 2001), and Ti-enriched (Sproule et al., 2002; Gangopadhyay et al., in press) ultramafic rocks suggests that olivine crystallizes in komatiitic (*sensu stricto*) magmas, but that chromite and olivine co-precipitate in komatiitic basaltic magmas (Fig. 5A). The latter interpretation is consistent with the experimental results of Murck and Campbell (1986) and Thy (1995), and with the empirical observations of Lesher and Stone (1996) and Barnes (1998). Importantly, the same suites of samples that show chromite fractionation/accumulation also show a broad positive correlation between MgO and Os concentrations (Fig. 5B). The absence of any significant correlation between MgO (at  $>25$  wt.%) and Os concentrations for olivine-only fractionation, combined with a positive correlation between MgO and Os concentrations for olivine+chromite fractionation (see Fig. 5B) suggests that chromite and/or co-precipitating trace phase(s) play a significant role in controlling the partitioning behavior of Os during crystallization in komatiitic basalts, but not in most komatiites. Some studies have proposed an early fractionating Os-rich trace phase(s) in high-MgO komatiites, but the identity of the phase remains unknown (see Puchtel et al., 2004b). Nevertheless, the consistent decrease in Os concentrations with chromite fractionation in the

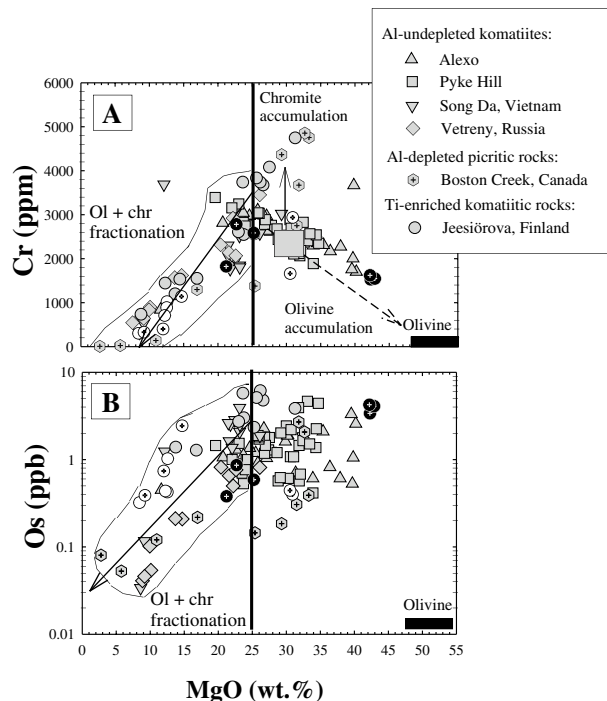


Fig. 5. Plot of whole rock MgO (wt.%, anhydrous) and (A) Cr (ppm) and (B) Os (ppb) in the Al-undepleted komatiites from Dundonald Beach (this study; symbols as in Fig. 1), Alexo (Gangopadhyay and Walker, 2003), Pyke Hill (Puchtel et al., 2004b) in the Abitibi greenstone belt, Song Da, Vietnam (Hanski et al., 2004), Vetreny, Russia (Puchtel et al., 2001b) and Ti-enriched komatiitic rocks (Gangopadhyay et al., in press) and Al-depleted picritic rocks (Walker and Stone, 2001). The shaded rectangle is the estimated parental magma composition for the Dundonald komatiites (Barnes, 1985). The field of olivine composition is drawn after Teasdale (1990) and Arndt (1986). Note that the low-magnesian komatiitic rocks ( $MgO < \sim 25$  wt.%) show a strong positive correlation between chromite fractionation (in Fig. 5A) and Os concentrations (in Fig. 5B).

different komatiite types is consistent with (a) the experimentally-determined compatibility of IPGE in chromites (Capobianco and Drake, 1990; Richter et al., 2004), (b) preferential partitioning of PGE into sulfide or accessory platinum group minerals (e.g., laurite or alloys) included within chromite crystals (Sattari et al., 2002; also see Mathez, 1999), (c) direct crystallization of laurite onto the surface of chromite crystals (Bockrath et al., 2004), and (d) up to 2 orders of magnitude higher Os concentrations in chromite separates than in the komatiitic host rocks (Gangopadhyay and Walker, 2003; Gangopadhyay et al., in press).

## 5.2. Estimates of Primary Re Concentrations in the Emplaced Magmas

The variations in Re concentrations between analyses of separate aliquots of the same whole rock powders (typically between 17 and 40%, as noted above; Table 2) are considerable. These variations are significantly greater than the percentage contributions from analytical blanks ( $<1\%$ ) and uncertainties resulting from mass spectrometry ( $\leq 0.5\%$ ). The analytical techniques used are identical to those used by previous studies that achieved much better reproducibility in Re concentrations

of whole rock samples (Gangopadhyay and Walker, 2003; Puchtel et al., 2004a). Thus, the lack of reproducibility for Dundonald rocks likely suggests that the whole rock sample powders are heterogeneous with respect to their Re concentrations. Heterogeneous distributions of Re, albeit on a relatively smaller scale, were also reported for komatiites from the Alexo area, where some whole rocks and their duplicate analyses varied as much as ~14% (Gangopadhyay and Walker, 2003). Rhenium is incompatible in both of the primary crystallizing phases in komatiites, namely, olivine and chromite (e.g., Burton et al., 2002; Richter et al., 2004), whereas it is commonly enriched in sulfides (e.g., Gangopadhyay et al., in press). Thus, it is possible that the variations in Re concentrations result from inhomogeneous distribution of minor or trace sulfides in the powders. It is also possible that a significant proportion of Re in these rocks is hosted by a phase that is resistant to dissolution using the acid digestion technique. Variable, incomplete digestion of such a phase could lead to the apparent inhomogeneity. Acid-resistant, Re-rich and Os-poor phases, however, have not been previously reported for komatiites.

Despite significant within-sample variations in whole rock Re concentrations reported in previous studies of Alexo komatiites, the preservation of Re-Os isotope systematics of those rocks was demonstrated via the generation of an isochron that yielded a precise age, consistent with those obtained from Sm-Nd and Pb-Pb isotope systematics (Gangopadhyay and Walker, 2003). The closed-system behavior of the elemental Re abundances in these rocks is also manifested by a strong linear correlation between whole rock  $\text{Al}_2\text{O}_3$  and Re concentrations (Fig. 6). The  $\text{Al}_2\text{O}_3$ -Re regression for the whole rock Alexo komatiites projects back to the field of olivine (Lahaye et al., 2001; Puchtel et al., 2004a), suggestive of a primary magmatic correlation for the Alexo rocks. Moreover, the  $\text{Al}_2\text{O}_3$  and Re concentrations in the Pyke Hill rocks (Puchtel et al., 2004a) also plot on the correlation line obtained for Alexo rocks (Fig. 6). This suggests that Re in the komatiites from Alexo and Pyke Hill was similarly incompatible during the differentiation of their respective parental magmas. In contrast to the Alexo and Pyke Hill rocks, and despite the use of identical analytical techniques, whole rock samples of the Dundonald Beach komatiites and komatiitic basalts largely do not plot on an isochron of correct age (Fig. 3B) and also show a large degree of scatter on a plot of  $\text{Al}_2\text{O}_3$  vs. Re concentrations (Fig. 6). Given that the Al concentrations in the same set of samples of Dundonald rocks show a strong olivine control (Fig. 1), the significant degree of scatter is most likely due to mobility of Re rather than Al. For this reason, and the fact that the Alexo and Pyke Hill komatiites are stratigraphically-equivalent and chemically very similar to the Dundonald komatiites, what may have been primary eruptive concentrations of Re in the Dundonald rocks are calculated based on the regression for  $\text{Al}_2\text{O}_3$ -Re concentrations in the Alexo komatiites. Because Re and Al have similar incompatibilities, yet the latter is less mobile, a similar method has been commonly used in altered peridotites to calculate initial  $^{187}\text{Os}/^{188}\text{Os}$  ratios (Reisberg and Lorand, 1995; Rudnick and Lee, 2002 and references therein). Also, Lahaye and Arndt (1996) followed a similar method for Alexo komatiites, where whole rock concentrations of  $\text{Al}_2\text{O}_3$  were used to evaluate the mobility of other incompatible trace elements (including REE).

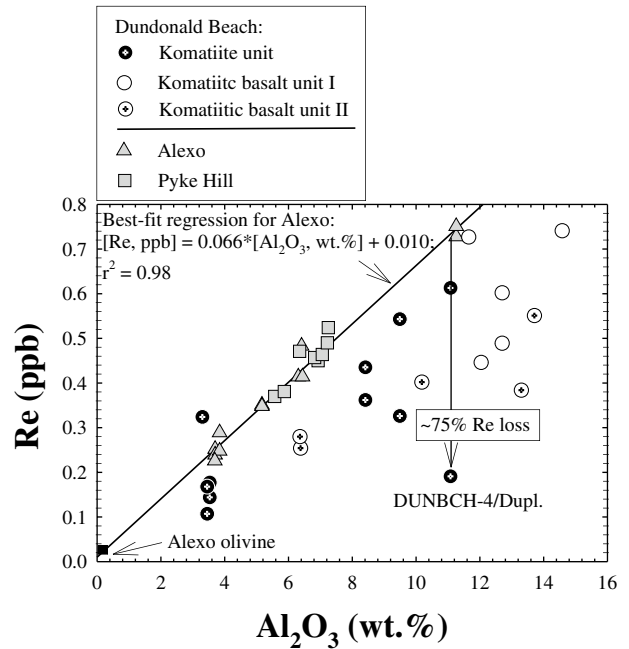


Fig. 6. Plot of whole rock Re and  $\text{Al}_2\text{O}_3$  concentrations in the Dundonald rocks (present study) and those for the Alexo and Pyke Hill komatiites that were shown to define a magmatic Re-Os isochron, consistent with minimal Re mobility (Gangopadhyay and Walker, 2003; Puchtel et al., 2004a). The best-fit  $\text{Al}_2\text{O}_3$ -Re regression for Alexo rocks projects back to the field for Alexo olivine (Lahaye et al., 2001; Puchtel et al., 2004a). The Pyke Hill rocks (excluding two outliers that were interpreted to have suffered Re loss during or soon after emplacement; Puchtel et al., 2004a) also plot on the  $\text{Al}_2\text{O}_3$ -Re correlation line for Alexo komatiites. Note that all but one of the Dundonald rocks plot below the regression, suggesting large percentages of Re loss.

The linear correlation between  $\text{Al}_2\text{O}_3$  vs. Re concentrations in the Alexo komatiites (Gangopadhyay and Walker, 2003) yield an equation of  $[\text{Re}, \text{ppb}] = 0.066 * [\text{Al}_2\text{O}_3, \text{wt.}\% \text{ (anhydrous)}] + 0.010$  ( $r^2 = 0.98$ ). This equation and the  $\text{Al}_2\text{O}_3$  contents of each Dundonald rock were used to estimate the primary Re concentration for each Al-Re sample pair. Although it cannot be conclusively demonstrated that the emplaced Dundonald magmas would have plotted along the same  $\text{Al}_2\text{O}_3$ -Re trend correlation as Alexo rocks, given that the Dundonald rocks were derived from chemically very similar parental magmas, we believe that this is a justifiable assumption. Using this assumption and that Al was immobile, all of our samples except DUNBCH-1, which plots above the trend, appear to have lost variable amounts of Re. Average estimated Re loss is ~40%, but one rock may have lost as much as ~75% Re. The amount of Re loss was evidently as great in the Al-Re-rich, olivine-poor (non-cumulate) samples as in the Al-Re-poor, olivine-rich (cumulate) samples.

### 5.3. Constraints on the Timing and Causes of Re Loss and Open-System Behavior of Re-Os Systematics

Are the apparent Re loss and the open-system behavior of the Re-Os system in the Dundonald rocks related? Variable Re loss at the time of eruption would have no effect on the development of isochronous relations among samples. Conversely,

extensive variable Re loss significantly after eruption, would result in completely non-isochronous relations. Neither of these two scenarios is consistent with the data. As noted above, whole rock samples do not define an isochron consistent with the eruptive age. Surprisingly, however, when four samples with extreme values of calculated initial  $\gamma_{Os}$  (DUNBCH-4/Dupl., DUNBCH-5/Dupl., DUNBCH-9 and DUNBCH-14) are eliminated from the regression, Re-Os data for the remaining 21 samples yield a model 3 isochron age (Ludwig, 1998) of  $2517 \pm 61$  Ma and an initial  $^{187}Os/^{188}Os$  ratio of  $0.1079 \pm 0.0041$  (Fig. 3A). Although this regression has a high MSWD of 83 and large uncertainty for the initial Os isotopic composition, the age is relatively well-constrained and is  $\sim 200$  Ma younger than the eruptive age of the rocks.

Whole rock komatiites and komatiitic basalts with  $^{187}Re/^{188}Os > 1$  generally plot below the 2.7 Ga chondritic reference isochron, suggesting either post-crystallization Re gain and/or Os loss. The positive correlation between MgO and Os concentrations in the Dundonald komatiites and komatiitic basalts, as noted in Figure 2A, is common among komatiites (Walker et al., 1999; Hanski et al., 2004; Puchtel et al., 2004b). This suggests that Os was relatively immobile during the alteration of Dundonald rocks, so the isotopic systematics are most consistent with Re gain subsequent to crystallization. However, the Re concentrations in the whole rock samples generally plot below the presumed magmatic Al-Re correlation, suggesting Re loss from most samples (Fig. 6). The conflicting requirements for Re mobility may suggest that the high percentages of Re losses indicated by the Al-Re plot (Fig. 6) and the much more modest (maximum of  $\sim 6\%$ ) addition of Re indicated by the Re-Os isotopic data (Fig. 3) were caused by two separate events. The Re loss likely occurred at an early stage that did not significantly affect the evolution of the Re-Os isotope system. The more minor addition of Re may have occurred at a later stage. Because modest Os losses of no greater than  $\sim 6\%$  would not be discernible on the plot of MgO vs. Os concentrations (Fig. 2A), it is also possible that minor Os loss occurred at this time. Consequently, this event of Re gain and/or Os loss modestly affected the Os isotopic systematics of most rocks.

As noted, the variably large Re losses appear to have occurred at or soon after the time of emplacement of Dundonald magmas. One mechanism that could potentially be responsible is volatility-related Re loss (Bennett et al., 2000; Lassiter, 2003). The putative Re losses from the Dundonald rocks are similar in magnitude to losses estimated for Hawaiian lavas that were inferred to have occurred from flows that erupted subaerially or in shallow-water (Lassiter, 2003).

Another potential cause of large degrees of Re loss is hydrothermal leaching of Re soon after emplacement. For example, Re and Os-rich sulfides are commonly oxidized during hydrothermal alteration of abyssal peridotites and this may cause their mobility (Roy-Barman and Allègre, 1994). Also, interactions between komatiites and hydrothermal fluids may produce high contents of halogen salts that can be removed by circulating seawater or hydrothermal solution (Appel, 1997). Rhenium, and also likely Os, is highly soluble in Cl-rich hydrothermal solutions (Xiong and Wood, 1999), and can therefore be potentially leached from the komatiites during their hydrothermal alteration.

The two mechanisms proposed for early Re losses are diffi-

cult to discriminate. There is some evidence to support each interpretation for the Dundonald rocks. Puchtel et al. (2004a) noted significant early Re losses from only 2 (out of 10) whole rock samples of Pyke Hill komatiites that were otherwise isochronous with other samples. There is no evidence for Re loss in the Alexo komatiites (Gangopadhyay and Walker, 2003). Thus, there is little or no evidence for volatile degassing and accompanying Re loss in the Alexo and Pyke Hill flows, where vesicular pillowed komatiitic basalts, hyaloclastite breccias, polyhedral jointing, and O isotope data all suggest a shallow subaqueous environment of eruption (Arndt et al., 1977; Beatty and Taylor, 1982). In contrast, the Dundonald magmas intruded into relatively deep-water unconsolidated graphitic sulfidic sediments (Davis, 1999; Houlé et al., 2002; Arndt et al., 2004), where the likelihood of extensive volatile degassing of Re during eruption, as suggested for Hawaiian lavas (Lassiter, 2003), would seemingly have been less.

On the other hand, the presence of large amounts of vesicles and associated peperites in the intrusive units of Dundonald rocks (Davis, 1999; Houlé et al., 2002; Arndt et al., 2004) provide strong evidence for at least some volatile degassing during emplacement. The consistently high percentages of presumed Re loss (typically 40%–50%) from virtually all Dundonald samples, which were collected from three separate  $\sim 10$ – $25$  m-thick units, suggest that Re loss was also pervasive in each unit. Additionally, the limited evidence for similarly large degrees of Re gain in our samples suggests a relatively large scale of transportation of Re out of the units, which was most likely beyond the 10–25 m thicknesses of sampled intrusive units. Furthermore, the degrees of Re loss in highly serpentinized (LOI up to  $\sim 13$  wt.%), cumulate komatiites (MgO  $\sim 42$ – $43$  wt.%) are comparable to those in the least-serpentinized, highly-differentiated, non-cumulate samples, suggesting that the Re loss from the Dundonald parental magma was (a) relatively uniform during its magmatic differentiation and (b) not a function of the degree of hydration and associated serpentinization of the rocks. Combined, these characteristics may be more consistent with volatility-related degassing of Re compared with hydrothermal leaching.

The dominant alteration event that disturbed the Re-Os isotope systematics for the Dundonald rocks likely occurred at  $\sim 2.4$ – $2.5$  Ga, consistent with both the Os model ages for most samples with high Re/Os ratios (Table 2) and the errorchron results (Fig. 3B). Unlike the clear case for significant early Re loss, the cause of isotopic resetting is more difficult to assess. As noted, the effects are more consistent with minor Re gain and/or Os loss. The  $\sim 2.5$  Ga age may reflect the time of a regional metamorphic event for the Kidd-Munro komatiitic rocks, although the precise age of metamorphism of the Kidd-Munro rocks is poorly constrained. For the Pyke Hill komatiites, U-Pb zircon ages are in general agreement with their Pb-Pb isochron ages (e.g., Carignan et al., 1995), which often record the last event of hydrothermal alteration or metamorphic re-equilibration of Pb isotopes in mafic-ultramafic rocks (Dupré et al., 1984; Brévar et al., 1986; Dupré and Arndt, 1990; Frei et al., 2004). In contrast, the Re-Os errorchron age of  $2517 \pm 61$  Ma obtained for the Dundonald rocks is, within uncertainty, in agreement with the previously reported Pb-Pb isotope results for the komatiitic basalts from Fred's flow and tholeiitic basalts from Theo's flow ( $2580 \pm 20$  Ma and  $2470 \pm 130$  Ma,



respectively) that crop out near Pyke Hill (Brévarat et al., 1986). The Pb-Pb isochron ages for the Fred's and Theo's flows that are ~200 Ma younger than the adjoining Pyke Hill komatiites were also interpreted to reflect a regional metamorphic resetting event (Brévarat et al., 1986). Although it seems unlikely that the Re and Os could be completely redistributed within these rocks, minor Re gain and/or Os loss could give the appearance of resetting of the Re-Os system. It is difficult to envision another cause for the concordance of most samples on or near a 2.5-Ga isochron, so we conclude this was the second event that affected the distribution of Re and Os in these rocks.

Finally, there is also evidence for relatively late-stage, possibly recent mobility of Re in several of the Dundonald rocks. For example, the two pairs of whole rock samples (DUNBCH-5 and DUNBCH-6) and their corresponding duplicate analyses yield negative slopes for their respective two-point Re-Os isochrons that can best be explained by very recent Re loss or gain. Additionally, another two pairs of whole rocks (DUNBCH-4 and DUNBCH-9) and their duplicate analyses yield significantly younger two-point isochron ages of ~110 Ma and ~1.3 Ga, respectively. The significance of these ages is not obvious, yet the ~1 Ga age for DUNBCH-4 is in agreement with the previously obtained Rb-Sr errorchron age for the Munro komatiites, which was interpreted to reflect a late-stage metamorphic event (Walker et al., 1988).

#### 5.4. A Chondritic Initial Os Isotopic Composition for the Dundonald Rocks and its Implications for the Kidd-Munro Assemblage

The initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio of the mantle source for the Dundonald komatiites can be determined by regressing the calculated initial  $^{187}\text{Os}/^{188}\text{Os}$  ratios (at 2.715 Ga) of several cumulate rocks (DUNBCH-1, DUNBCH-2, DUNBCH-3), a komatiitic basalt (DUNBCH-13), and the chromite separates (Fig. 3B). These samples are appropriate for determining initial  $^{187}\text{Os}/^{188}\text{Os}$  because they all have high Os concentrations and low  $^{187}\text{Re}/^{188}\text{Os}$  ratios ( $<1$ ), and are therefore less susceptible to isotopic resetting than samples with lower Os concentrations and higher Re/Os ratios. The low Re/Os ratios also result in modest corrections for age and limited sensitivity to Re gain or loss and Os loss. With one outlier out of the 10 samples with  $^{187}\text{Re}/^{188}\text{Os} < 1$  eliminated from the regression, the average initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio of  $0.1083 \pm 0.0006$  ( $2\sigma$ ) corresponds to an initial  $\gamma_{\text{Os}} = 0.0 \pm 0.6$  (Fig. 3A). This indicates that the Os isotopic composition of the mantle source for the Dundonald komatiites was essentially chondritic at the time of eruption.

The chondritic initial Os isotopic composition of the mantle source for the Dundonald rocks is consistent with ratios previously reported for the Alexo and Pyke Hill komatiites (Gangopadhyay and Walker, 2003; Puchtel et al., 2004a). It is also in agreement with the long-term chondritic Os isotopic evolution of the modern terrestrial convecting upper mantle (Walker et al., 1996; 2002; Brandon et al., 2000). The chondritic initial Os isotopic composition of the Dundonald rocks, within uncertainties, is also indistinguishable from the composition of the modern convective upper mantle projected back to ~2.7 Ga, as determined through analyses of abyssal peridotites (Snow and Reisberg, 1995). Furthermore, the initial Os isotopic composi-

tion of the ~2.7-Ga mantle source for the Kidd-Munro komatiites, within uncertainties, is indistinguishable from the projected Os isotopic trajectory of the primitive upper mantle (PUM; Meisel et al., 2001). Thus, if the initial  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the Dundonald Beach, Alexo and Pyke Hill komatiites collectively reflect those of a mantle source for the entire Kidd-Munro volcanic assemblage, their uniformly chondritic initial Os isotopic compositions suggest that this voluminous eruption sampled a mantle source that had no prior history of resolvable  $^{187}\text{Os}$ -enrichments or depletions with respect to the projected Os isotopic evolution trajectory for PUM.

The uniform chondritic Os isotopic composition of the ~2.7 Ga mantle source for the Al-undepleted komatiites from Kidd-Munro volcanic assemblage contrasts with the subchondritic Os isotopic composition of the contemporaneous mantle source for the Al-depleted Boston Creek ferropicrites in the 2723–2720 Ma Stoughton-Roquemaure assemblage, also of the Abitibi greenstone belt (initial  $\gamma_{\text{Os}} = -3.8 \pm 0.8$ ; Walker and Stone, 2001). The subchondritic initial Os isotopic composition of the Boston Creek flows was interpreted to indicate their derivation dominantly from a source [1] that underwent long-term prior depletion in Re, similar to SCLM (subcontinental lithospheric mantle), or [2] from which a Re-rich phase, such as garnet separated a significant time before the eruption of the lavas (Richter and Hauri, 1998). Our Os isotopic results for the Dundonald rocks, combined with those for the Alexo (initial  $\gamma_{\text{Os}} = -0.1 \pm 1.0$ ; Gangopadhyay and Walker, 2003) and Pyke Hill (initial  $\gamma_{\text{Os}} = 0.6 \pm 0.2$ ; Puchtel et al., 2004a) komatiites, on the other hand, suggest very limited interaction between the typical mantle sources for these komatiites and the SCLM. The chondritic Os isotopic composition of Al-undepleted komatiites from the Kidd-Munro assemblage is indistinguishable from the normal shallow convective upper mantle.

As for Phanerozoic analogs, the uniform chondritic Os isotopic composition of the Kidd-Munro komatiites is consistent with that recently reported for the Permo-Triassic komatiites from NW Vietnam (Hanski et al., 2004). This suggests that the Vietnamese komatiites, although areally limited, were derived from mantle sources with uniform chondritic Os isotopic composition similar to those for late-Archean Kidd-Munro komatiites. The uniform chondritic Os isotopic composition of the ~2.7 Ga mantle source for the Kidd-Munro komatiites, however, contrasts with the highly heterogeneous and variably  $^{187}\text{Os}$ -enriched mantle sources for the Mesozoic Gorgona Island komatiites (Walker et al., 1999), present-day ocean island basalts (OIB;  $\gamma_{\text{Os}}$  up to ~+25; e.g., Hauri and Hart, 1993). This suggests a different nature of mantle sources and/or petrogenetic processes for the generation of the Kidd-Munro komatiites vs. those from Gorgona Island and modern ocean island basalts.

The uniformly chondritic Os isotopic composition of the mantle source for the Kidd-Munro komatiites is in contrast to the variably radiogenic Os isotopic composition of modern arc-related mafic-ultramafic lavas (Lassiter and Luhr, 2001; Woodland et al., 2002; Alves et al., 2002 and references therein) and subarc mantle xenoliths (e.g., Brandon et al., 1999; Widom et al., 2003). The contrasting Os isotopic composition of Kidd-Munro komatiites vs. modern arc-related mafic-ultramafic rocks suggests that (1) the Kidd-Munro komatiites formed in a non-arc (e.g., intraplate; McDonough and Ireland,

1993) setting or (2) the processes responsible for enrichments in radiogenic  $^{187}\text{Os}$  for modern arc-related lavas (e.g., transport of radiogenic Os via Cl-rich hydrous fluid flux into the overlying mantle wedge: Brandon et al., 1996, 1999; Peslier et al., 2000; Widom et al., 2003) were either not operative at all in the mantle source for these komatiites or the processes had only limited efficacy.

## 6. SUMMARY AND CONCLUSIONS

The Re-Os systematics of the ca. 2.7 Ga komatiites and komatiitic basalts at Dundonald Beach record a complex history of at least three episodes of alteration. First, an average of 40% and as much as 75% of Re was lost from virtually all samples due most likely to volatility-related shallow degassing and/or hydrothermal leaching during or soon after the emplacement of magmas as shallow intrusions into unconsolidated sediments. In the second phase of alteration, the Re-Os isotope systematics of these rocks were reset presumably during a regional metamorphic event at ca. 2.5 Ga. Finally, some samples with high Re/Os ratios were affected by relatively late-stage, possibly recent mobility of Re.

Despite these multiple stages of alteration, the olivine cumulate whole rock komatiites and their chromite separates, owing to their high Os concentrations and low Re/Os ratios, have preserved the original initial Os isotopic composition of the emplaced magmas. This suggests that olivine cumulate whole rocks and their chromite separates are preferred samples for the determination of initial Os isotopic composition of mantle sources for altered Precambrian komatiites. The olivine cumulate whole rocks and corresponding chromite separates in our suite of Dundonald rocks yield a precisely chondritic average initial Os isotopic composition ( $\gamma_{\text{Os}} = 0.0 \pm 0.6$ ) for their mantle source. The chondritic initial Os isotopic composition of the Dundonald rocks is consistent with that previously obtained for the stratigraphically-equivalent komatiites from the Alexo and Pyke Hill areas that together belong to the spatially-extensive Kidd-Munro volcanic assemblage in the Abitibi greenstone belt. Combined, these results suggest that the voluminous eruptions of the Kidd-Munro komatiitic rocks sampled mantle source(s), dominated by Os with chondritic isotopic composition.

The precisely chondritic initial Os isotopic composition of the late-Archean mantle source for the Kidd-Munro komatiites is in contrast with the heterogeneous and variably  $^{187}\text{Os}$ -enriched mantle sources for the Mesozoic komatiites from the Gorgona Island, present-day ocean island basalts and modern arc-related rocks. This may suggest that a significant portion of the late-Archean mantle source for the Abitibi komatiites was more homogeneous with respect to Re/Os compared to the present-day mantle. This may also suggest that the petrogenetic processes responsible for variable  $^{187}\text{Os}$ -enrichments in the Gorgona Island komatiites, modern ocean island basalts and arc-related rocks were either not operative or they had very limited role in the generation of the Kidd-Munro komatiites.

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