

Re–Os ISOTOPIC STUDY OF KOMATIITIC VOLCANISM AND MAGMATIC SULFIDE FORMATION IN THE SOUTHERN ABITIBI GREENSTONE BELT, ONTARIO, CANADA

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ABSTRACT

We have investigated the Re–Os isotope geochemistry of 2.7-Ga metakomatiitic flows and associated Ni–Cu sulfide deposits from Alexo, Texmont and Hart in the Abitibi greenstone belt of Ontario in order to refine the thermal erosion model and evaluate the superimposed effects of metamorphism and hydrothermal alteration on ore environments and non-ore environments. Although the geochemical characteristics of these komatiites have led to the belief that these lavas were uncontaminated, radiogenic Os isotopic compositions ($\gamma_{Os} = +20.2$ and $+33.2$) obtained from well-preserved komatiites and olivine separates suggest that the Alexo flow has been contaminated by crust-derived material. These data are compatible with the trace-element enrichment observed in melt inclusions trapped within olivine. Redistribution of Os and Re did occur at least at the mineral scale and most likely during the Grenville orogeny. Hydrothermal fluids were channeled along the contact between the komatiites and their basement, and were responsible for the remobilization of Re or Os (or both) within the sulfides at Alexo and Hart. Matrix and disseminated sulfides from Texmont are located within the pile of cumulates and seem to have escaped this localized alteration. Although the Abitibi sulfides have experienced various degrees of metamorphism (from prehnite–pumpellyite to low amphibolite facies), the initial Re–Os isotopic composition of the flows appears to have been preserved at the whole-rock scale. Re–Os isotopic heterogeneity of the Abitibi sulfides is best explained by variable *R*-factor of the sulfides. Re and Os concentrations and Os isotopic heterogeneity of the Abitibi sulfides are consistent with the current model of nickel sulfide formation, which implies that the assimilation of sulfidic sedimentary rocks was the trigger for sulfide saturation.

Keywords: komatiite, Ni–Cu sulfide, rhenium–osmium, melt inclusion, laser ablation, Alexo, Hart, Texmont, Abitibi greenstone belt, Ontario.

SOMMAIRE

Nous avons étudié la géochimie isotopique Re–Os des coulées métakomatiitiques et des gisements de sulfures de Ni–Cu associés, Alexo, Texmont et Hart, dans la ceinture de roches vertes de l'Abitibi, en Ontario, mis en place il y a 2.7 milliards d'années, afin d'évaluer le modèle de l'érosion thermique et des effets surimposés du métamorphisme et l'altération hydrothermale dans les milieux près des gisements ou non. Bien que les caractéristiques géochimiques de ces komatiites ont mené à la conclusion que ces laves ne sont pas contaminées, les proportions d'Os radiogénique ($\gamma_{Os} = +20.2$ et $+33.2$) obtenues à partir de roches komatiitiques et de fractions d'olivine bien conservées font penser que la coulée d'Alexo a été contaminée par un matériau d'origine crustale. Ces données sont compatibles avec les taux d'enrichissement décelés dans les reliquats magmatiques piégés dans l'olivine. Une redistribution de l'osmium et du rhénium a au moins eu lieu à l'échelle intergranulaire, et tout probablement au cours de l'orogénèse grenvillienne. Les fluides hydrothermaux ont été canalisés le long du contact entre les komatiites et le socle, et sont responsables de la remobilisation de Re ou de Os (ou des deux) parmi les sulfures à Alexo et Hart. Les sulfures de la matrice et disséminés à Texmont sont situés à l'intérieur d'un empilement de cumulats et semblent avoir échappé à cette altération localisée. Bien que les sulfures de ces sites dans l'Abitibi ont subi les effets variables d'une recristallisation

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métamorphique (allant du faciès prehnite–pumpellyite au faciès amphibolite inférieur), la composition isotopique Re–Os initiale des coulées semble avoir été conservée à l'échelle de la roche totale. Les hétérogénéités isotopiques Re–Os des sulfures de ces suites résulteraient du facteur *R* variable des sulfures. Les concentrations en Re et Os et les rapports isotopiques hétérogènes de l'osmium dans les sulfures de ces suites de l'Abitibi concordent avec le modèle accepté de formation des sulfures de nickel, ce qui implique une assimilation de roches sédimentaires sulfurées pour déclencher la saturation des systèmes en sulfures.

(Traduit par la Rédaction)

Mots-clés: komatiite, sulfure Ni–Cu, rhénium–osmium, reliquat magmatique, ablation au laser, Alexo, Hart, Texmont, ceinture de roches vertes de l'Abitibi, Ontario.

INTRODUCTION

Nickel sulfide ore deposits found in Archean greenstone belts are associated with komatiitic lavas. The formation of this style of ore deposit is dependent on the attainment of sulfide saturation in the komatiitic lava. Because komatiites are considered to be sulfide-undersaturated on eruption (Keays 1995), contamination of komatiite by sulfidic sedimentary rocks has been proposed as a mechanism by which sulfide saturation was achieved (Leshner *et al.* 1984). The Re–Os isotopic system is a powerful tracer of sulfide ore-forming processes because both elements have high sulfide melt – silicate melt partition coefficients ($\gg 100$) and are thus concentrated in the immiscible sulfide liquid. Considered of great importance to the study of crustal contamination processes in ore genesis, Os is highly concentrated in the mantle relative to crustal rocks, because Os is more compatible during mantle melting than Re. Therefore, crustal rocks tend to have high Re:Os ratios and, with time, evolve to very radiogenic Os isotopic compositions in comparison to mantle-derived rocks. The Re–Os isotopic system is thus a highly sensitive monitor of the extent of crustal involvement in ore genesis.

Recent Re–Os isotopic studies of Archean nickel ore from the Kambalda komatiites have suggested that the ore-forming komatiites were derived from the mantle without significant contamination by radiogenic crust either before eruption or during turbulent flow at the surface (Foster *et al.* 1996). Thus, assimilation of sulfidic sedimentary units by thermal erosion may not be as important in ore genesis as currently favored hypotheses suggest. This rather controversial result from Western Australia needs to be tested with Re–Os isotopic results of better-preserved and contemporaneous komatiites and ores from other Archean cratons. In order to refine the contamination model and evaluate the superimposed effects of metamorphism and hydrothermal alteration on assemblages from ore-forming and barren environments, we have investigated the Re–Os isotopic geochemistry of 2.7-Ga komatiitic flows from three different localities: Alexo, Texmont and Hart in the Abitibi greenstone belt of Ontario. In order to constrain the level of preservation of the initial trace element and Os isotopic composition of komatiite and

associated sulfides in the Abitibi greenstone belt, these samples were carefully selected on the basis of existing detailed petrographic descriptions and geochemical and isotopic data. These localities have been affected to different degrees by metamorphic fluids at varying pressure, temperature and fluid composition [$X(\text{CO}_2) - X(\text{H}_2\text{O})$]. Olivine is present at Alexo and locally contains primary melt inclusions. This primary mineral has been separated and analyzed for its Os isotopic composition. The melt inclusions also were analyzed for their trace-element content. These primary geochemical and isotopic compositions will be compared with the whole-rock compositions, in order to establish the effects of post-crystallization alteration and metamorphism. The level of crustal contamination and the relation with the timing of sulfide saturation will also be investigated.

GEOLOGICAL SETTING

The Abitibi belt, a major subprovince of the Archean Superior Province, is a typical granite–greenstone terrane comprising basalt-dominated supracrustal sequences intruded by granitic plutons. The Abitibi belt has been subdivided into a Northern and Southern Volcanic Zone and two regions dominated by granitic and metasedimentary rocks. Ludden & Hubert (1986) have proposed that the Southern Volcanic Zone was formed in a series of rift basins that dissected an earlier-formed volcanic arc. The Abitibi rocks have been subdivided into two supergroups, each of which commences with the eruption of komatiites and is followed successively by tholeiitic basalts and then by calc-alkaline volcanic rocks. The komatiites from the three localities discussed here (Alexo, Hart, and Texmont) unconformably overlie felsic volcanic rocks and iron-formations, and locally host nickel sulfides (Fig. 1). Komatiite flows are locally intercalated with graphitic and sulfidic argillite (Barrie *et al.* 1999). The regional and local geology is described by Barrie & Davis (1990). Regional metamorphic recrystallization may be subdivided into an earlier prehnite–pumpellyite regional burial stage and a later greenschist–amphibolite-facies stage found as metamorphic aureoles around the granite plutons (Jolly 1982, Spooner & Barrie 1993). Rocks from all three localities were deformed and metamorphosed during the Kenoran orogeny (2.6 Ga) and underwent secondary alteration

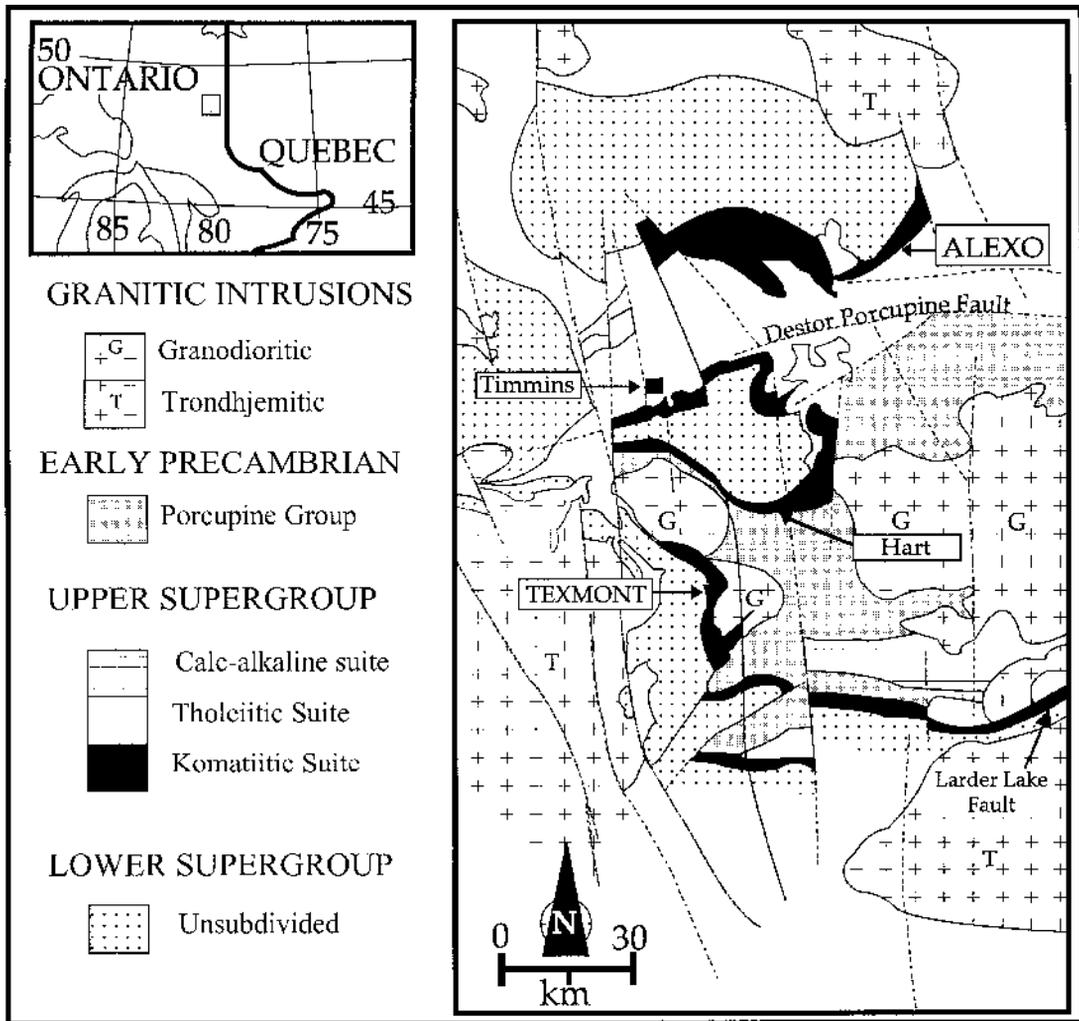


FIG. 1. Regional geology of the Abitibi greenstone belt in the Timmins area, modified after Pyke (1982).

during the Grenville orogeny (1.0–1.2 Ga). Rocks from Alexo, Hart and Texmont have experienced prehnite–pumpellyite-, upper-greenschist- and lower-amphibolite-facies metamorphism, respectively (Vaillancourt 1995).

The petrology of the Alexo komatiite flow and an underlying komatiitic basalt flow were studied by Barnes *et al.* (1983), Barnes (1985) and Arndt (1986). Oxygen, strontium, neodymium and lead isotopic compositions were the subject of studies by Dupré *et al.* (1984), Lahaye *et al.* (1995) and Lahaye & Arndt (1996). The distribution of platinum-group elements was investigated by Brüggmann *et al.* (1987), Barnes & Naldrett (1987) and Rehkämper *et al.* (1999). The min-

eralogical and chemical features of pyroxene in the komatiite and underlying basalt flows were discussed by Arndt & Fleet (1979). The age of the flow was determined by Dupré *et al.* (1984) using Pb–Pb and Sm–Nd methods to be 2690 ± 15 and 2752 ± 87 Ma, respectively. These ages agree with U–Pb zircon ages of the associated felsic rocks between 2710 Ma and 2717 Ma (Nunes & Pyke 1980, Corfu 1993, Bleeker & Parrish 1996).

The two other Abitibi komatiitic flows were sampled in drill-core from the Hart and Texmont mines, respectively located 40 km southeast and 45 km south of Timmins (Fig. 1). The komatiites were studied previously by Barnes (1985), Barnes & Naldrett (1987) and

Lahaye *et al.* (1995). The komatiites unconformably overlie the felsic metavolcanic rocks and the meta-iron-formation of the Deloro Supergroup and are themselves overlain by mafic metavolcanic rocks of the Tisdale Supergroup.

PETROLOGY AND MINERALOGY

At Alexo and Hart, massive sulfides are found at the contact between the intermediate volcanic rocks of the Hunter Mine Group and the ultramafic lavas. The massive sulfides are overlain by matrix sulfides, which are themselves overlain by disseminated sulfides. The mineralized portion at Texmont is located about 120 m above the base of the komatiite sequence and is about 30 m thick. The sulfide mineralogy consists mainly of pyrrhotite and pentlandite with minor chalcopyrite, heazlewoodite, and violarite (Alexo), pyrrhotite and pentlandite with chalcopyrite \pm pyrite (Hart), and pyrrhotite, pentlandite, minor millerite \pm heazlewoodite \pm pyrite \pm chalcopyrite (Texmont; Barnes 1985).

Three localities from the Alexo area were investigated, on what is believed to be the same stratigraphic unit: the main pit, the small pit and an unmineralized

flow (Fig. 2). The barren ultramafic flow is about 16 m thick and strongly layered, with a thick upper spinifex zone (Barnes *et al.* 1983). The two other mineralized flows are thicker, although the flows are not fully exposed, and the stratigraphic thickness is based on drill-hole data. These mineralized flows are characterized by a thinner spinifex zone, the development of a thick orthocumulate zone, and an upper and lower fine-grained chill margin. The Texmont flows are characterized by the development of an upper and basal chilled zone, and an upper random and plate spinifex layer above a thick orthocumulate pile. The mineralized flows from Hart are more differentiated, with an upper spinifex zone grading into a massive peridotitic komatiite, a pyroxenitic komatiite and an orthocumulate-textured komatiite that contains patches of skeletal olivine. Cross sections of the Hart and Texmont localities can be found in Barnes (1985), as well as a more complete description of the petrography of these flows.

Despite a generally high level of textural and mineralogical preservation, these flows have been affected by at least two types of alteration. The secondary mineralogy and mineralogical assemblages thus depend on the metamorphic grade and the local CO_2 activity of the

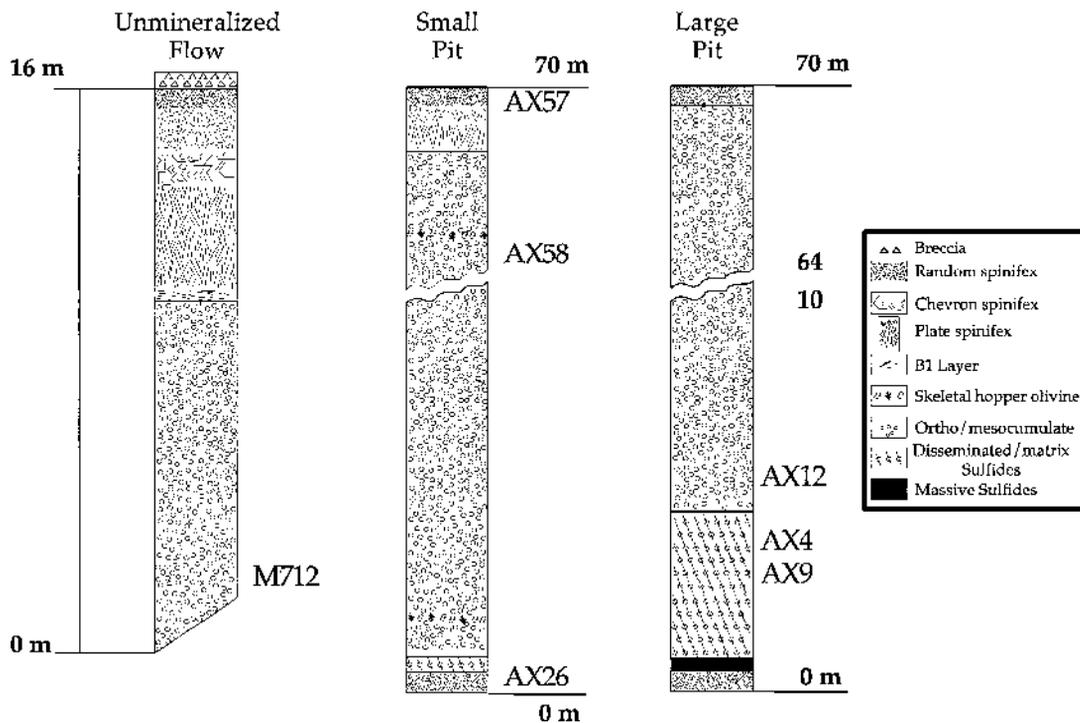


FIG. 2. Section through the Alexo flows, showing sample locations and variations in rock type and texture. The sections are not fully exposed, and the thickness is based on geophysical and drill-hole data in the area of the mineralized flows. This figure is modified from Barnes (1985) and Arndt (1986). Those sections are 200 m apart.

fluid, which generates a range of mineralogical assemblages dependent on the initial degree of olivine fractionation and accumulation from the silicate liquid. The most common mineralogical assemblage is the result of a hydration process manifested by the serpentinization of forsterite to lizardite plus magnetite, the partial alteration of pyroxene to tremolite, and the transformation of glass to an assemblage of fine-grained chlorite and titanite. In the least-altered samples, the secondary phases replacing forsterite are lizardite plus magnetite. Pyroxene is usually well preserved in these rocks and is locally replaced by less than 1% of tremolitic amphibole. The komatiites are also locally chloritized, where forsterite is completely replaced by chlorite in spinifex lavas, or by an assemblage of chrysotile plus brucite and magnetite in the cumulate layer. The chlorite is locally partially replaced by very fine-grained (<50 μm) secondary pyroxene and minor hydrogarnet (Lahaye & Arndt 1996). At higher activity of CO_2 in the fluid, the original forsterite or serpentine is locally replaced by an assemblage of talc and dolomite, with minor magnetite, whereas the matrix is intensively chloritized.

ANALYTICAL METHODS

The olivine-rich sample was crushed, and olivine grains 0.3–0.5 mm across were concentrated using heavy liquids and Frantz magnetic separation. The olivine grains were later washed in distilled water and analytical reagent-grade acetone in an ultrasonic bath. The olivine grains were carefully selected on the basis of the occurrence of large (50 μm) melt inclusions and the lack of alteration. The selected grains were mounted in epoxy and carefully polished for electron-microprobe measurements before the final analysis by laser ablation. The composition of the melt inclusions was determined on the Cameca Camebax SX–50 electron microprobe at the University of Melbourne using wavelength-dispersion spectrometry (15 kV, 25 nA), with data reduced using Cameca PAP corrections. Trace-element contents of melt inclusions were determined by laser-ablation high-resolution inductively coupled plasma – mass spectrometry (LA–HR–ICP–MS) at Monash University. The inclusion was then completely ablated using a 50 μm spot size. The signal was integrated during the time of the ablation of the whole melt inclusion in order to homogenize possible trace-element heterogeneities within the inclusion. The olivine composition was used as a blank. The Ca content of the glass inclusion as determined by electron microprobe was used as an internal standard for data reduction (Ludden *et al.* 1995). The analyses were performed using a Nd–YAG laser at a repetition rate of 4 Hz and an energy at 0.1 mJ. A detailed description of this configuration, optimal instrumental parameter, precision, accuracy and limit of detection at similar instrumental settings can be found in Lahaye *et al.* (1997).

All whole-rock powders were prepared using a ceramic jaw crusher and an agate mill. Rhenium and Os concentrations and Os isotopic compositions were obtained on 0.1–0.5 g of rock powder using a low-blank Carius tube acid-digestion method, modified from that described in Shirey & Walker (1995), the details of which are described in Lambert *et al.* (1998b), followed by double distillation for Os, and ion-exchange chromatography for Re (Lambert *et al.* 1999). Isotopic compositions were obtained using a Finnigan MAT 262 negative thermal ionization mass spectrometer using Faraday cups. During this study, total chemistry and mass spectrometry blanks were 6 pg for Re and 2 pg for Os. Analyses of an Os isotopic standard provided by the Carnegie Institution of Washington (DTM) over a period of three years yielded a mean $^{187}\text{Os}/^{188}\text{Os}$ of 0.17367 ± 0.00058 (external reproducibility at the 2σ level), within error of the DTM value of 0.17429 ± 0.00055 (Shirey 1997b). External precision on Canadian Certified Reference Materials peridotite standard WPR1 ($n = 9$), which is used as an internal standard for our laboratory, was found to be $\pm 0.23\%$ on $^{187}\text{Os}/^{188}\text{Os}$, $\pm 0.64\%$ on Os concentrations and $\pm 0.31\%$ on Re concentrations and below 1% for $^{187}\text{Re}/^{188}\text{Os}$. Our Os isotopic result ($^{187}\text{Os}/^{188}\text{Os} = 0.14559 \pm 0.00073$, external reproducibility at the 2σ level, $n = 7$ analyses) compares well with the limited number of published results of Re–Os isotopic analyses available for WRP1: $^{187}\text{Os}/^{188}\text{Os} = 0.14543 \pm 0.00018$ ($n = 3$; Cohen & Waters 1996) and $^{187}\text{Os}/^{188}\text{Os} = 0.14549 \pm 0.00018$ ($n = 6$; G. Pearson, data from DTM, quoted in Cohen & Waters 1996).

RESULTS

Melt inclusions

The remarkably fresh 2.7 Ga komatiites from Alexo contain unaltered forsterite crystals that host small glass inclusions (Fig. 3). These inclusions are spherical to ovoid and 20–50 μm across. They consist of transparent brown glass and are free of quench crystals. Melt inclusions form owing to periods of rapid growth caused by undercooling (Roedder 1979). The genesis of melt inclusions could also be related to an early degassing process since these inclusions are only found in early-crystallized forsterite at the bottom of the komatiite flows (Fig. 2, sample M712). Melt inclusions from basic and ultrabasic rocks have been analyzed in the past using the ion microprobe (Gurenko & Chaussidon 1995, Sobolev & Shimizu 1993, McDonough & Ireland 1993). Recent developments in LA–ICP–MS allow us to measure the trace-element concentrations of melt inclusions (Taylor *et al.* 1997). The average trace- and major-element compositions of the 10 melt inclusions are presented in Table 1, along with the estimated composition of the initial liquid at Alexo and the average compositions of sulfidic sediments from the Abitibi. Figure 4

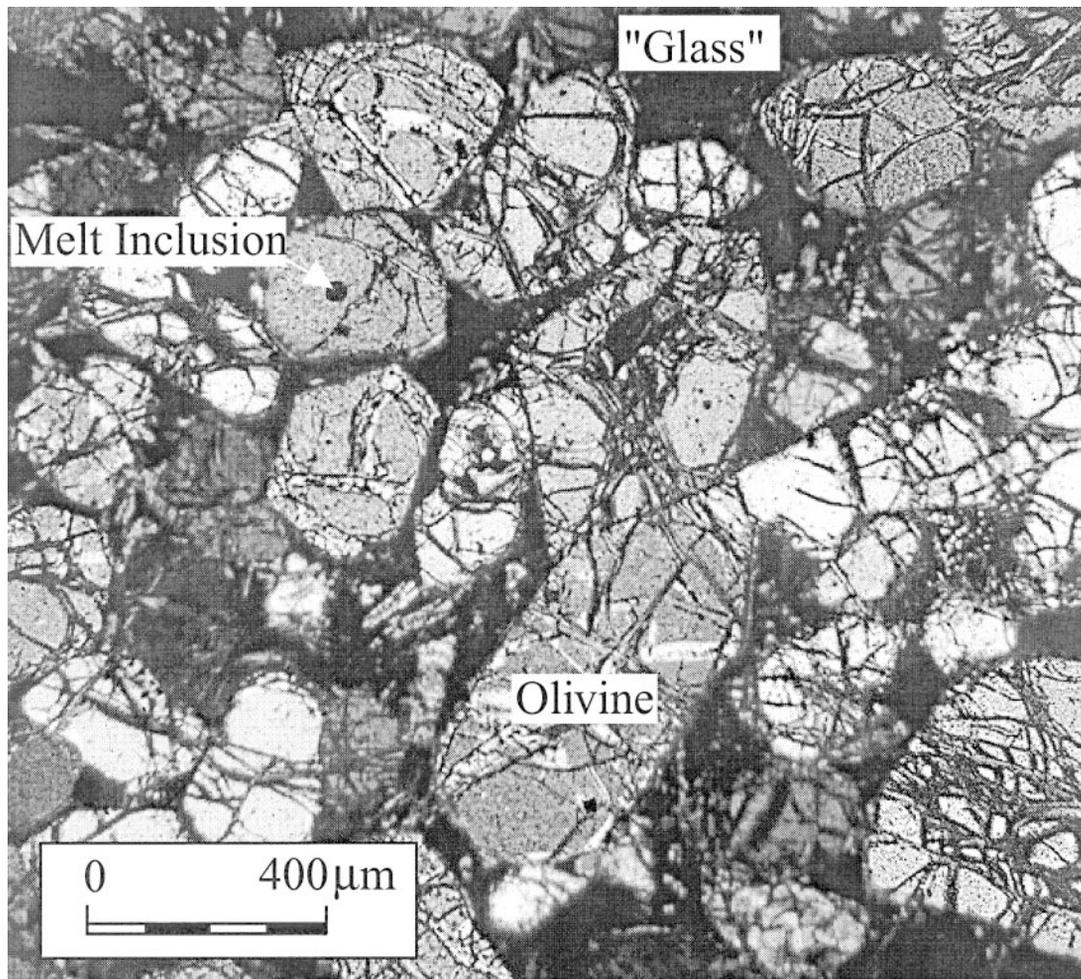


FIG. 3. Olivine orthocumulate with polyhedral and hopper crystals of olivine from the B zone (sample M712). Skeletal forsterite is partially replaced by serpentine and contains locally spherical to ovoid melt inclusions. The glass is devitrified.

shows the variations in CaO and MgO (wt%) of the melt inclusions in comparison with the estimated composition of the initial liquid (Lahaye & Arndt 1996) and the compositions of the forsterite (Arndt 1986). The melt inclusions are characterized by a geochemical heterogeneity due to post-entrapment *in situ* fractionation of olivine, as shown by the alignment of the data along an olivine-fractionation path on Figure 4. On average, the melt inclusions are characterized by a composition consistent with 40 wt% olivine fractionation. Figure 5 compares the primitive-mantle-normalized compositions of the melt inclusions at Alexo with melt inclusions from similarly unaltered 2.7 Ga komatiites from Belingwe, in Zimbabwe (McDonough & Ireland 1993). Relative to the Belingwe melt inclusions, the Alexo melt inclu-

sions are characterized by an enrichment in the most incompatible elements, such as the light rare-earth elements olivine $[(La/Yb)_N = 0.64]$, and by a depletion in Nb $[(La/Nb)_N = 1.91]$. Ba is also significantly more enriched than in the Belingwe inclusions (Table 1).

Re-Os isotopes of komatiite, sulfides and minerals

Re-Os isotopic data are given in Table 2 and plotted on a $^{187}Re/^{188}Os$ versus $^{187}Os/^{188}Os$ diagram in Figure 6. The samples of disseminated and matrix sulfide ore from Texmont are characterized by high concentrations of Os (516 and 919 ppb, respectively, recalculated to 100% sulfide) and low Re/Os values (0.086–0.129). The two samples of matrix and massive sulfide ore from Hart

TABLE 1. CHEMICAL COMPOSITION OF MELT INCLUSIONS AND CONTAMINATED KOMATIITE, ALEXO, ABITIBI GREENSTONE BELT

Sample	Sulfidic Sediment	Initial Liquid	Melt Inclusions	Contaminated	
				Liquid 1	Liquid 2
SiO ₂ wt%	56.87	46.22	50.56	49.90	50.10
Al ₂ O ₃	12.78	6.85	12.47	10.80	10.98
FeO	3.64	9.52	7.37	10.81	10.99
MnO	0.04	0.16	0.13	0.24	0.25
MgO	2.67	29.25	16.53	16.60	15.96
CaO	1.62	6.44	10.80	9.60	9.74
Na ₂ O	0.84	0.51	1.29	0.80	0.81
K ₂ O	6.37	0.03	0.05	0.37	0.40
TiO ₂	0.90	0.35	0.61	0.56	0.57
Cr ₂ O ₃	0.61	0.43	0.07	0.52	0.52
NiO	0.62	0.24	0.12	0.09	0.08
S	1.19				
LOI	13.05				
Cs ppm	3.18	0.01	0.12	0.05	0.22
Rb	132.9	0.2	2.4	1.94	9.12
Ba	649.7	2.4	23.5	12.51	47.59
Nb	14.33	0.42	0.84	0.94	1.71
La	33.90	0.49	1.54	1.31	3.14
Ce	64.55	1.49	3.98	3.50	6.98
Pr		0.27	0.73		
Sr	56.85	27.74	43.07	50.65	53.72
Nd	26.63	1.36	3.83	3.14	4.58
Sm	5.83	0.65	1.60	1.24	1.56
Zr	165.7	17.1	33.2	32.94	41.89
Hf	4.36	0.47	1.03	0.90	1.14
Ta	1.95	0.26	0.68	0.49	0.60
Tb		1.01	2.69		
Dy	0.76	0.18	0.43	0.33	0.37
Y		1.25	2.50		
Ho	34.8	8.2	14.4	15.20	17.08
Er	0.82	0.27	0.57	0.50	0.54
Tm		0.78	1.70		
Yb		0.12	0.27		
Lu	3.01	0.81	1.72	1.50	1.66
	0.54	0.13	0.24	0.24	0.27
(La/Yb) _N	8.1	0.4	0.64	0.63	1.4
(La/Nb) _N	2.5	1.2	1.91	1.5	1.9
% assimilation				0.70	3.7
% olivine crystallization				40	40

Column 1: average composition of five samples of sulfidic-graphitic shale from the Abitibi. Column 2: calculated composition of uncontaminated initial liquid for the Alexo komatiite (Lahaye & Arndt 1996). Column 3: geochemical composition of Alexo melt inclusion (sample M712). Column 4 and 5: calculated composition of the mixture of the komatiite liquid listed in column 2 with, respectively, 0.7 and 3.7% of sulfidic sedimentary rocks, using the composition listed in column 1. The La/Yb and La/Nb values are normalized to the primitive mantle values of McDonough & Sun (1995).

are characterized by lower concentrations of Os (11 to 54 ppb) and higher Re/Os values (0.196–0.096).

Two samples of matrix ore and two of disseminated sulfide ore, as well as two silicate samples (upper chilled zone and olivine cumulate) from Alexo also have been analyzed. Ore samples are characterized by lower concentrations of Os (43 to 80 ppb) and higher Re/Os values (0.308–0.868). The upper chilled margin, assumed to be representative of the initial komatiitic liquid, yields very similar concentrations to those of the komatiites from Kambalda (Foster *et al.* 1996), with a concentration of 1.79 ppb Os and a slightly higher concentration of Re, 0.9 ppb. Primary forsterite grains separated and analyzed for their Os isotopic composition (sample

M712) yield a radiogenic initial Os isotopic composition, +19.1, similar to that of the olivine cumulate ($\gamma_{Os} = +20.2$, sample AX58). Ore samples from Alexo yield more radiogenic and heterogeneous initial Os isotopic compositions ($\gamma_{Os} = +31$ to +141) in comparison to the chondritic initial value defined by the Kambalda komatiites and ores. Pyrrhotite has also been separated from an Alexo matrix sulfide sample. Replicate analyses of this sulfide gave lower concentrations of Os (38 ppb) and Re (54 ppb), but higher Re/Os values (1.4) and subchondritic initial isotopic compositions ($\gamma_{Os} = -30$).

Ore samples from Texmont yield near-chondritic initial Os isotopic compositions (γ_{Os} in the range -0.3 to +3). Pyrrhotite separated from a matrix sample confirms the chondritic Os isotopic signature of the massive sulfide, but it has lower concentrations of Os (729 ppb) and Re (88 ppb), and yet a similar Re/Os (0.121) to the whole-rock value (0.129). The initial Os isotopic composition ($\gamma_{Os} = -2.0$) is very similar to that in the whole-rock samples (γ_{Os} in the range 0 to +3). These data are displayed on Figure 6 and are grouped along the chondritic reference isochron at 2.7 Ga, defined by the ore samples from Kambalda (Foster *et al.* 1996).

Carbonate-bearing samples from the Hart locality yield radiogenic initial Os isotopic compositions ($\gamma_{Os} = +66, +135$).

On Figure 7 are plotted the Os concentrations (ppb) against Re/Os ratio for various reservoirs, compared with our data. The upper chilled margin from Alexo is inside the komatiite field, which is included in the field for mantle melts. The komatiite cumulate and the forsterite data are aligned along an olivine-fractionation trend characterized by a decrease in the Re/Os ratio [the olivine – silicate melt partition coefficient for Os, $D_{Os}^{ol/liq}$, is higher than that for Re [between 2 and 200; Brüggemann *et al.* (1987) and Hart & Ravizza (1996); $D_{Re}^{ol/liq} = 1$; Walker *et al.* (1997)]. The sulfide data are aligned along a sulfide-accumulation trend from the komatiitic liquid because of the higher partition coefficient for Os compared to Re for the sulfide phase involved in this study [$D_{Os}^{sulfide/silicate} \approx 10^4$; Fleet *et al.* (1996); see Lambert *et al.* (1999) for a review of partition-coefficient data].

DISCUSSION

Preservation of initial trace-element concentrations

Recent studies have demonstrated that even reputedly immobile elements such as the rare-earth elements (REE) and high field-strength elements (HFSE) may be mobilized during the widespread hydrothermal alteration and carbonation events that have affected the Abitibi komatiites and ores (Kerrick & Fryer 1979, Fryer *et al.* 1979, Barnes 1985, Lahaye *et al.* 1995). Alkali metals, alkaline-earth elements and the light REE tend to be preferentially mobilized in komatiites, even in the least-altered samples, because these incompatible

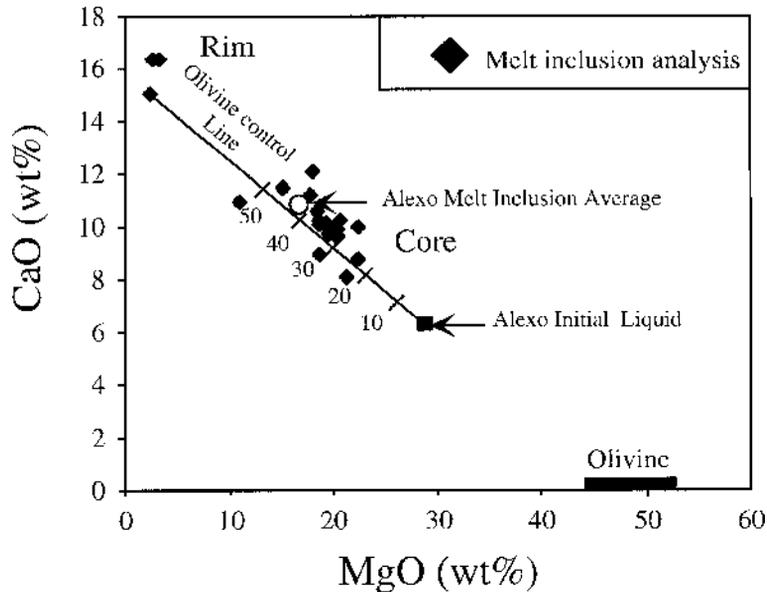


Fig. 4. Diagram illustrating the variations in the proportions of MgO and CaO (wt%) produced by olivine crystallization within the melt inclusion. The black diamonds indicate the variations in composition from the rim to the core of the melt inclusions. The white circle represents the average composition of the melt inclusions; compare with the estimated Alexo initial liquid (black square). The composition of the olivine also is shown.

TABLE 2. Re-Os ISOTOPIC DATA FOR ABITIBI MAGMATIC ORES, KOMATIITE, SULFIDE AND SILICATE MINERALS

Sample	Locality	Type	Re ppb	Os ppb	Re/Os	$\frac{^{187}\text{Os}}{^{188}\text{Os}}$	$\frac{^{187}\text{Re}}{^{188}\text{Os}}$	$\frac{^{187}\text{Os}}{^{188}\text{Os}}$ (i)	γ_{Os} (i)	$\frac{\Delta^{187}\text{Re}}{^{188}\text{Os}}$	R_{Os}
AX4	Alexo	Matrix	33.53	70.18	0.478	0.2580 (40)	2.30	0.1518	+39.8	1.72	38
AX9	Alexo	Matrix	55.66	64.09	0.868	0.3349 (12)	4.18	0.1421	+30.9	1.38	35
AX12	Alexo	Disseminated	33.30	79.75	0.418	0.2601 (22)	2.01	0.1674	+54.2	2.33	44
AX26	Alexo	Disseminated	13.36	43.34	0.308	0.3303 (10)	1.48	0.2619	+141.3	6.03	23
AX9 - Pyrrhotite	Alexo	Pyrrhotite	54.53	39.24	1.39	0.3844 (53)	6.68	0.0759	-30.1		
AX9 - Pyrrhotite	Alexo	Pyrrhotite	53.52	37.27	1.44	0.3932 (11)	6.90	0.0743	-31.6		
AX57	Alexo	Upper Chill	0.90	1.79	0.502	0.25609 (62)	2.41	0.1446	+33.2		
AX58	Alexo	Olivine Cumulate	0.45	4.88	0.091	0.1507 (10)	0.438	0.1304	+20.2		
M712 - Olivine	Alexo	Olivine	0.03	1.86	0.017	0.13314 (27)	0.083	0.1293	+19.1		
HT11	Hart	Massive	5.17	53.83	0.096	0.20187 (70)	0.462	0.1805	+66.3	2.81	29
HT23	Hart	Matrix	2.22	11.30	0.196	0.29827 (73)	0.942	0.2547	-134.7	5.74	5
TX4	Texmont	Matrix	118.8	918.8	0.129	0.13697 (51)	0.622	0.1083	-0.3	-0.02	521
TX9	Texmont	Disseminated	44.47	516.3	0.086	0.13100 (35)	0.414	0.1119	-3.1	0.12	290
TX4 - Pyrrhotite	Texmont	Pyrrhotite	87.89	729.2	0.121	0.13313 (29)	0.579	0.1064	-2.0		

Initial isotopic compositions are calculated for an age of emplacement of 2710 Ma. γ_{Os} (i) is defined as the deviation, at the age of crystallization of 2710 Ma and in parts per 100, from the isotopic composition of a 2710 Ma chondritic reference reservoir with an initial $^{187}\text{Os}/^{188}\text{Os}$ of 0.096, a $^{187}\text{Re}/^{188}\text{Os}$ value of 0.40076, and a Re decay constant of $1.666 \times 10^{-11} \text{ yr}^{-1}$ (Smoliar *et al.* 1996). The error on the $^{187}\text{Re}/^{188}\text{Os}$ ratio is below 1%, including error magnification and spike calibration. The R -factor (R , Campbell & Naldrett 1979) has been calculated for Os and with the concentration from the upper chilled margin (sample AX57) as the initial liquid (X_i^0), using the following equation: $Y_i(R+D) = X_i^0 D$. R , The partition coefficient for Os (D) used for the R -factor calculation is from Fleet *et al.* (1996).

elements are stored in a devitrified glassy phase. These elements are also concentrated in the crust. Therefore, a komatiite altered by crust-derived fluids will tend to share the same trace-element enriched pattern as a komatiite contaminated by the crust during eruption.

Several attempts have been made in the past to determine the primary composition of a komatiitic melt and to assess the implications for the geochemistry of the Archean mantle. The most successful method consists of analyzing pristine melt trapped by olivine phenocrysts during crystallization, as shown by McDonough & Ireland (1993). The trace-element signature found in the Alexo melt inclusions is significantly enriched in incompatible elements, in comparison to the estimated initial composition calculated from an average of the flow-top samples (Lahaye & Arndt 1996) and the uncontaminated melt inclusions from Belingwe (McDonough & Ireland 1993, Fig. 5).

We have assessed the ability of a crustal contamination process to produce the average composition of the Alexo melt inclusions. The data used for the modeling are presented in Table 2 and plotted on Figure 5. An average of five samples of sulfidic-graphitic sedimentary rocks from the Abitibi has been used as a possible

contaminant for the komatiite. The sedimentary rocks are characterized by an enrichment in alkali elements (Rb, Ba and Cs concentrations up to 133, 650 and 3.2 ppm, respectively) and *LREE* [$(La/Yb)_N = 8.1$] and by a depletion in Nb [$(La/Nb)_N = 2.5$], in comparison with the estimated initial liquid, which is characterized by a depletion in incompatible elements [$(La/Yb)_N = 0.4$] and a lack of a Nb anomaly [$(La/Nb)_N = 1.2$]. In order to match the incompatible trace-element enrichment and the Nb depletion characteristic of the Alexo melt inclusion, $(La/Yb)_N$ and $(La/Nb)_N$ values have been used to monitor the extent of crustal contamination. In order to match the *LREE* enrichment from its initially depleted value [$(La/Yb)_N = 0.4$] to that measured in the melt inclusion [$(La/Yb)_N = 0.63$], the required level of contamination is 0.7%. The depletion in Nb, monitored by $(La/Nb)_N$, implies a level of contamination of up to 3.7%. The amount of olivine fractionation and the trace-element abundances depend on the level of olivine differentiation after the entrapment of the melt inclusion and is set at 40%, on the basis of major-element composition (Fig. 4). Since the partition coefficients for incompatible trace elements with respect to the olivine are very low, the post-entrapment differentiation process should

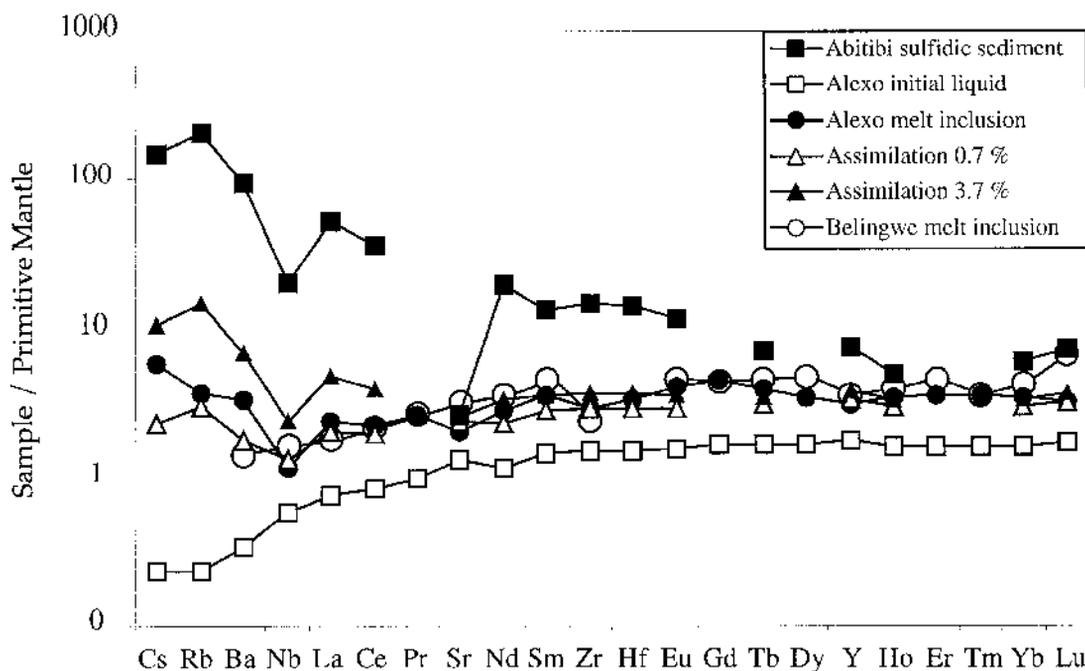


FIG. 5. Primitive-mantle-normalized diagram (McDonough & Sun 1995) showing the trace-element composition of the melt inclusions from the Belingwe komatiites (white circles, McDonough & Ireland 1993) and from the Alexo flow (black circles). The composition of the calculated contaminated komatiitic liquid (white and black triangles), based on the assimilation of 0.7 and 3.7% of an average composition of an Abitibi sulfidic sedimentary rock (black squares), and the estimated composition of an uncontaminated komatiitic liquid from Alexo (white squares, Lahaye & Arndt 1996), also are illustrated.

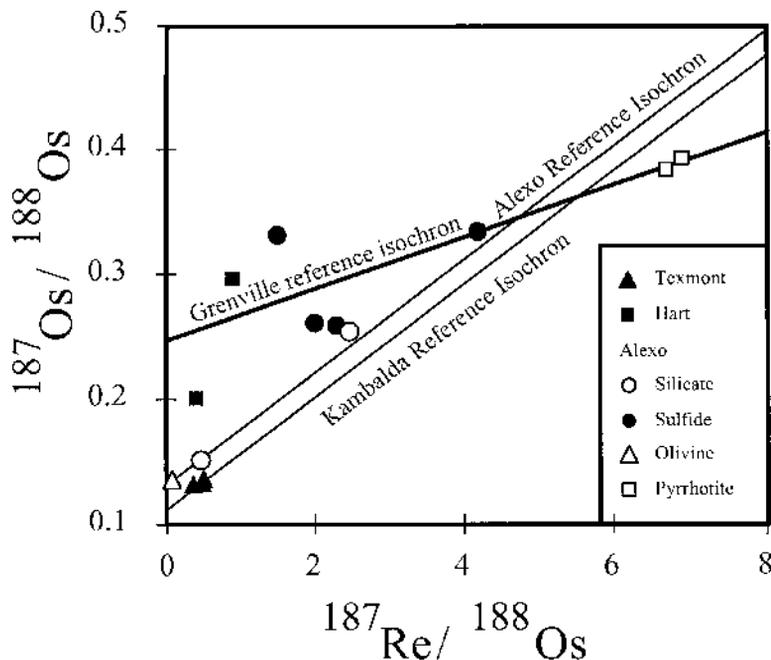


Fig. 6. Re–Os isochron diagram for samples of whole-rock sulfides from Texmont (black triangles) and Hart (black squares). The whole-rock silicates (white circles), whole-rock sulfides (black circles) and mineral separates (olivine, white triangle; pyrrhotite, white square) from Alexo also are shown. A 2.7-Ga isochron through a chondritic initial ratio defined by the Kambalda sulfides (Foster *et al.* 1996), as well as a reference isochron from the Alexo silicate and the Grenville orogeny, also are shown for comparison.

not affect the ratio of trace elements in the melt inclusions. Thus, the calculated amount of olivine fractionation may not reflect the level of differentiation of the initial komatiitic liquid before entrapment. This calculation indicates that the proportion of sulfidic sedimentary rocks assimilated was likely between 0.7 to 3.7 wt%. Therefore, the melt-inclusion data at Alexo do not record the primary geochemical composition of the mantle melt, but rather a contamination process that masks the mantle signature.

Preservation of initial osmium isotopic composition: komatiite

There have been several attempts to determine the Os isotopic composition of komatiitic lavas in order to constrain the Os isotopic evolution of the mantle through time. The komatiites from Alexo and Pyke Hill were initially targeted because of their well-preserved primary mineralogy, in comparison to other mantle-derived Archean rocks (Luck & Arndt 1986, Walker *et al.* 1988). Unfortunately, there were large analytical errors associated with these early attempts. These problems were

most likely related to the incomplete dissolution of refractory minerals (*e.g.*, magnetite, chromian spinel), lack of equilibration between the sample and the spike, and potential Re contamination during sample preparation (Shirey & Walker 1995, Shirey 1997a). More recent data have demonstrated that there was no significant ^{187}Os enrichment in the Archean mantle beneath the Abitibi greenstone belt, and that the Re–Os isotopic system was resistant to the low-grade metamorphism that altered the Pyke Hill komatiites (Shirey 1997a). Other analyses of Proterozoic and Archean ultramafic rocks also provide better constraints on the Os isotopic evolution of the mantle through time (Shirey & Barnes 1994, Foster *et al.* 1996, Walker *et al.* 1997, Shirey 1997a, Bennett *et al.* 1997). Before the early Proterozoic, only chondritic [$\gamma\text{Os}(i) = -0.1 \pm 0.32$; Foster *et al.* 1996] or slightly ^{187}Os -enriched [$\gamma\text{Os}(i) = +3.2 \pm 0.9$; Puchtel *et al.* 1998] mantle sources are observed (Shirey & Walker 1998). Figure 6 is an isochron diagram showing the upper chilled margin, the olivine cumulate and the forsterite separated from the barren Alexo flow. These compositions are compared with data for the komatiites from Kambalda, which have approxi-

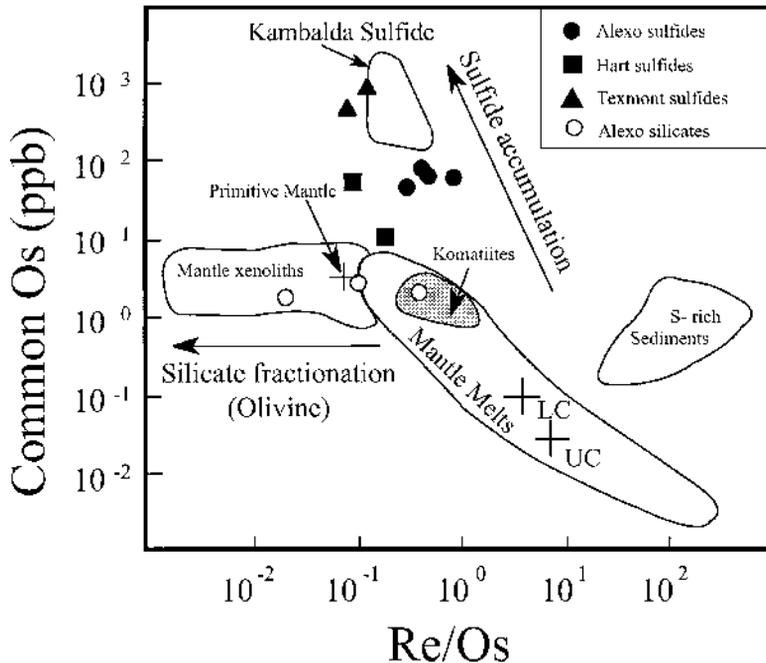


FIG. 7. Plot of Os (ppb) against Re/Os evolution as a function of degree of extraction of komatiitic melt from the mantle and subsequent formation of immiscible sulfide and fractionation of olivine. The primitive mantle values are from McDonough & Sun (1995). Fields for mantle xenoliths and mantle melts, komatiites and basalts are from Walker *et al.* (1988, 1989), Martin (1991), Hauri & Hart (1993), and Snow & Reisberg (1995). Field for S-rich sedimentary rocks is from Foster *et al.* (1996) and Ravizza & Turekian (1992). The average composition of the upper crust (UC) is from Esser & Turekian (1993), and the average composition of the lower crust (LC) is from Saal *et al.* (1998).

mately the same age (2709 ± 4 Ma; Clout 1991). The Alexo komatiite samples are aligned along a ^{187}Os -enriched isochron, parallel to the chondritic reference line defined by the Kambalda sulfides and komatiite. Therefore, the overall radiogenic Os isotopic compositions found in the Alexo komatiites could be related to the assimilation of an older crustal component. However, significant differences in initial Os isotopic compositions are found between the cumulate [$\gamma\text{Os}(i) = +20.2$] and the spinifex [$\gamma\text{Os}(i) = +33.2$] komatiites. Such differences may be related to minor local redistribution of the Re or Os (or both), or to different levels of crustal contamination in various portions of a dynamic lava-flow system.

Preservation of initial osmium isotopic composition: NiS ore

Only the Texmont sulfides lie on the reference isochron defined by the Kambalda samples. Both whole-

rock analyses and the pyrrhotite separate from Texmont have very homogeneous initial Os isotopic compositions and should therefore best represent the initial isotopic composition of the sulfide fraction. Figure 6 and Table 2 show that the sulfides from Alexo and Hart are characterized by heterogeneous calculated initial isotopic compositions and are not aligned along the two reference lines defined by the radiogenic silicates from Alexo and the chondritic komatiite and sulfides from Texmont and Kambalda. The Alexo matrix ore and the mineral separates are aligned along a calculated reference isochron at 1.2 Ga, which corresponds to the age of the Grenville orogeny disturbance. An event at around 1 Ga also was recognized by Walker *et al.* (1988) from their Rb/Sr, Re-Os and Sm-Nd studies of Pyke Hill komatiites, and by Lahaye & Arndt (1996) from their Rb/Sr and Sm-Nd study of the Alexo flow. Krogh & Davis (1974) noted a disturbance of the U-Pb system at 1250 ± 250 Ma, which they correlated with chemical alteration of zircon. In his compilation of lower inter-

cept ages of zircon in the southern Abitibi, Corfu (1993) attributed ages between 1250 and 750 Ma to faulting and enhanced flow of fluid in response to orogenic activity in the Grenville Province, and possibly to intrusion of Sudbury and Abitibi mafic dikes. In conclusion, the spread in Re/Os composition at the mineral scale for sample AX9 suggests that the isotopic system has been reset at least once at the mineral scale during the Proterozoic.

We have assessed the possibility that a secondary adjustment of the Re/Os value during hydrothermal alteration (at the whole-rock scale) could have generated the observed range of radiogenic Os isotopic values in some of the Abitibi rocks. Figure 8 shows the variations in Os isotopic composition of the sulfides as a function of time. These compositions are compared with data for sulfides from Kambalda (Foster *et al.* 1996), and the hypothetical evolution of the asthenospheric mantle defined by the composition of a IIIA iron meteorite with an initial $^{187}\text{Os}/^{188}\text{Os}$ value of 0.09531 at 4.558 Ga and an average chondrite $^{187}\text{Os}/^{188}\text{Os}$ today of 0.1270 (Shirey & Walker 1998). The $^{187}\text{Re}/^{188}\text{Os}$ values of the sulfides are low (0.4 to 4), close to those of the Kambalda komatiites and sulfides (0.01 to 1.7), and chondritic values (0.4).

In order to explain the heterogeneous initial isotopic composition of the Hart and Alexo ores, two stages of

metasomatism are required. Figure 8 represents the theoretical evolution through time of the sulfides, assuming fractionation in Re/Os at the time of emplacement as well as during the Grenville orogeny, and assuming a chondritic initial value for the sulfide samples at 2.7 Ga. This model requires an increase of the $^{187}\text{Re}/^{188}\text{Os}$ value at the time of emplacement (2.7 Ga), followed by a decrease to lower present-day $^{187}\text{Re}/^{188}\text{Os}$ values during the Grenville orogeny (1.2 Ga). The level of Re/Os fractionation required can be estimated as the difference between the measured and the calculated $^{187}\text{Re}/^{188}\text{Os}$ ($\Delta^{187}\text{Re}/^{188}\text{Os}$; Fig. 8, Table 2). A correlation between $\Delta^{187}\text{Re}/^{188}\text{Os}$ and the degree of metamorphism is expected if metamorphism is responsible for the Re/Os fractionation and the observed radiogenic initial Os isotopic composition. The range of $\Delta^{187}\text{Re}/^{188}\text{Os}$ for the different localities increases from Texmont (-0.02 to 0.12), to Hart (2.81 to 5.74) and Alexo (1.38 to 6.03). The Alexo samples have experienced a prehnite-pumpellyite-grade metamorphism, whereas the Texmont and Hart ores have experienced a lower- amphibolite- and an upper-greenschist-facies metamorphism, respectively. This model seems unrealistic because the metamorphic facies is inversely correlated with the level of Re/Os fractionation ($\Delta^{187}\text{Re}/^{188}\text{Os}$). Thus, the Re-Os isotopic heterogeneity seems to be a primary feature of the Abitibi sulfides. Although Pt and

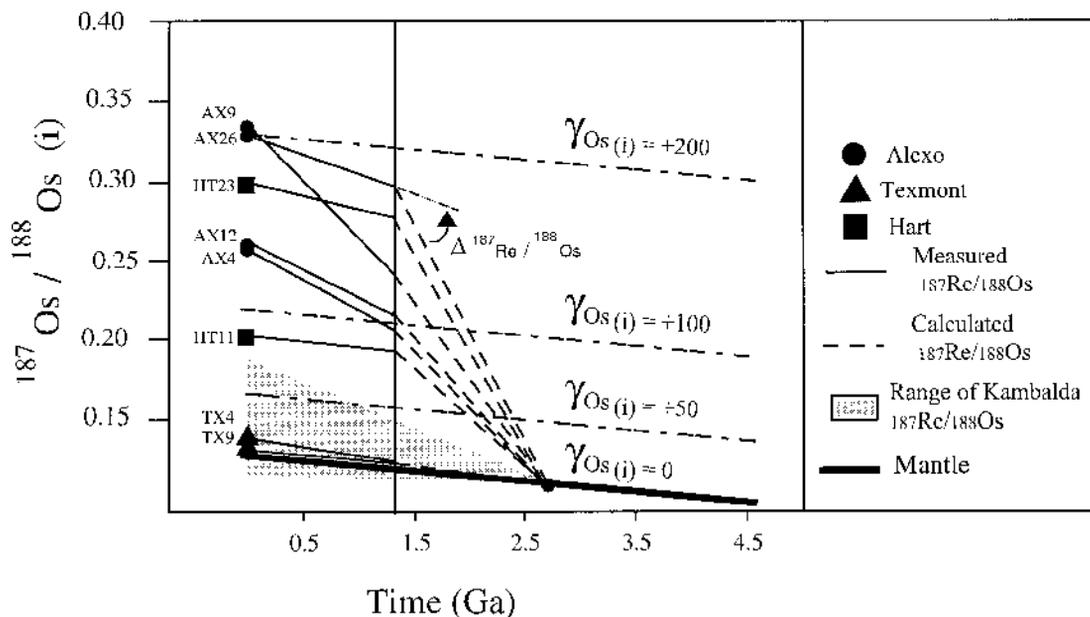


FIG. 8. Variations of the $^{187}\text{Os}/^{188}\text{Os}(i)$ versus time (Ga) for the ore samples from the Abitibi (Alexo, black circles; Texmont, black triangles; Hart, black squares). The range of $^{187}\text{Re}/^{188}\text{Os}$ values from the Kambalda ores also is shown for comparison. The solid line represents mantle evolution along an average chondritic composition.

Au mobility related to intense carbonation has been recorded at Hart (Barnes & Naldrett, 1987), the other PGE do not seem to have been remobilized at the whole-rock scale, and thus the Re–Os isotopic system does not seem to have been disturbed at the whole-rock scale by the metamorphism experienced by the komatiites and associated NiS ore.

However, the isotopic composition of the pyrrhotite from Alexo along the Grenville reference isochron seems to indicate small-scale redistribution of Os and Re at the mineral scale, which may be related to the location of the ore within the komatiite pile. At Texmont, the ore is located within the peridotitic bodies, whereas at Alexo and Hart, the ore is located at the contact between the komatiites and the felsic footwall, a major pathway for hydrothermal fluids, which could be responsible for the Re–Os redistribution at the mineral scale. Similar differences are observed in the Re–Os isotopic data from massive sulfide at Kambalda, compared to disseminated ores from Mt. Keith (which also were shielded from severe alteration and deformation: Lambert *et al.* 1998b), and Re–Os isotopic data from massive sulfide ore compared to ore minerals from the “Ovoid” at Voisey’s Bay (Lambert *et al.* 1998c, 2000).

Nature of the contaminant

Trace-element analysis of the melt inclusions has provided some new and very important insights into the level of contamination experienced by the Abitibi komatiites during emplacement. Osmium isotopic analysis of the Alexo komatiites has further demonstrated that crustal contamination occurred; the results place constraints on the nature of the contaminant. Using a simple isotopic bulk mixing equation, the Os isotopic composition of the contaminant and the Os content may be estimated, assuming the amount of contamination by sulfidic sediment (0.7 to 3.7%), the initial Os isotopic composition of the lava (0.13044, based on cumulate sample AX58), the Os content of the initial uncontaminated liquid (1.79 ppb, based on sample AX57 taken from the chilled margin), and using a chondritic initial isotopic composition for the initial komatiitic liquid. However, since the isotopic composition and atomic weights of the two end members are very different, the number of moles of ^{187}Os and ^{188}Os has to be calculated for each end member before calculating the ratio $^{187}\text{Os}/^{188}\text{Os}$ and the final initial isotopic value.

The remaining unknown parameter is the Os concentration of the contaminant (C1). The composition of the Kambalda sedimentary rocks, analyzed by Foster *et al.* (1996), with 0.3 ppb Os, has been used as a reference, since this sediment is associated with the Kambalda NiS deposits and is assumed to be responsible for the sulfide saturation of the komatiitic melt (Leshner *et al.* 1984). A contaminant with an Os concentration lower than 0.3 ppb will require an unrealistic initial Os iso-

pic composition, higher than $\gamma\text{Os}(i) = +10000$, at the time of komatiite emplacement, assuming a low level of contamination. Thus, the contaminant must have an Os content similar to that of black shales, which possess Os concentrations of up to 3 ppb and are commonly associated with komatiitic lavas within Archean greenstone belts.

The data require that the Os isotopic composition of a viable black shale contaminant with an Os content of 3 ppb at the time of eruption must have an initial Os isotopic composition $\gamma\text{Os}(i)$ of +340 (3.7% contamination) and +2200 (0.7% contamination). If the contaminant has only 0.3 ppb Os, the data require an initial Os isotopic composition $\gamma\text{Os}(i)$ of +5188 (3.7% contamination) and an unrealistically higher $\gamma\text{Os}(i)$ for a lower level of contamination (0.7% contamination; Fig. 9).

Further constraints may be placed on the nature of the contaminant, on the basis of (1) the age of the contaminant, and (2) its $^{187}\text{Re}/^{188}\text{Os}$ ratio.

(1) The Abitibi crust is made up of dominantly juvenile mantle-derived crust and is considered to have been formed in a setting remote from older crust (Machado *et al.* 1986, Corfu & Noble 1992). Although the southern Abitibi crust has a maximum age of 2750 Ma based on the age of inherited zircon (Corfu 1993), recent data document the presence of 2820^{+6}_{-3} and 2825 ± 3 Ma plutonic rocks within the Opatoca Subprovince, which may have provided an appropriate source of sedimentary rocks in the southern Abitibi (Davis *et al.* 1994). The komatiite has a minimum age of emplacement of 2710 Ma, which implies that the crust had a maximum age of 115 Ma at the time of komatiite eruption, although an age of 40 Ma seems to be more likely.

(2) Although the $^{187}\text{Re}/^{188}\text{Os}$ value could be variable within individual crustal reservoirs, recent and detailed evaluation of $^{187}\text{Re}/^{188}\text{Os}$ within the crust suggest that this ratio varies, on average, between 50 (Esser & Turekian 1993) for the upper crust and 20 (Saal *et al.* 1998) for the lower crust. Metasedimentary units from the upper crust, such as a black shale, may have even higher values (~100 to ~20000: Ravizza & Turekian 1989, Horan *et al.* 1994, Foster *et al.* 1996, Lambert *et al.* 1999, 2000) and are also characterized by high Os contents (up to 3.7 ppb: Ravizza & Turekian 1989).

Figure 9 presents the variation of Os isotopic composition of a possible contaminant as a function of its $^{187}\text{Re}/^{188}\text{Os}$ value and age. The evolution pathway will depend on the Os isotopic composition of the contaminant calculated at 2710 Ma, the initial isotopic composition of the contaminant at its “starting age”, for various levels of contamination (0.7–3.7%) and various levels of initial Os content (0.3 and 3 ppb). The nature of the contaminant may be estimated on the basis of its $^{187}\text{Re}/^{188}\text{Os}$ value. The $^{187}\text{Re}/^{188}\text{Os}$ values of the upper crust (50, Esser & Turekian 1993) and the lower crust (20, Saal *et al.* 1998) are too low to generate such a radiogenic contaminant within the 115 Ma required. Figure 9 shows that the contaminant must have a $^{187}\text{Re}/^{188}\text{Os}$

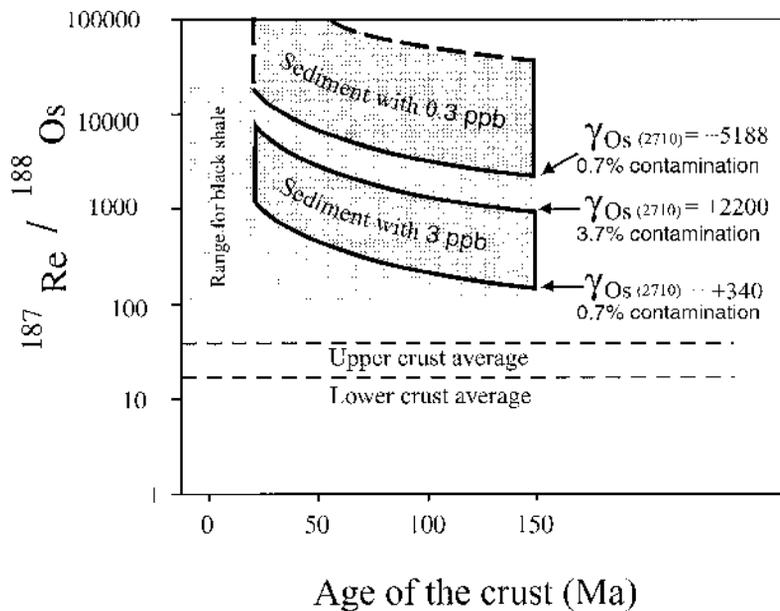


FIG. 9. Variation of the age of the crust versus $^{187}\text{Re}/^{188}\text{Os}$ ratio. The composition of the upper continental crust is from Esser & Turekian (1993), that of the lower continental crust, from Saal *et al.* (1998), and that of S-rich sedimentary rocks, from Horan *et al.* (1994). The dark fields represent the evolution of a possible contaminant prior to the komatiite emplacement; it has between 3 and 0.3 ppb Os and possibly is responsible for the radiogenic signature of the Abitibi komatiites and associated sulfides. See text for explanation.

value significantly higher and close to that of a black shale in order to generate a radiogenic initial Os isotopic crustal composition similar to our estimate, within the period of time permitted. If the contaminant was a black shale, it implies that the contamination is more likely to have occurred close to or at the surface.

Timing of sulfide saturation

One model for the formation of Ni–Cu sulfide deposits suggests that sulfide saturation is caused by thermal erosion by komatiitic magma and consequent assimilation of sedimentary material at the surface. The Os isotopic data of the Alexo and Hart komatiites imply the involvement of a crustal component during their emplacement. Moreover, evaluation of the nature of the contaminant strongly suggests that the komatiite has been contaminated by sedimentary rocks having geochemical characteristics similar to that of an Os-rich black shale. These data suggest a relationship between the assimilation of sulfidic sedimentary rocks and the process of sulfide saturation.

It has been suggested that the R -factor (defined as the effective mass of silicate magma with which a given mass of massive ore samples has equilibrated) is a mea-

sure of the dynamics of the komatiite system. A high R -factor is characteristic of highly dynamic, turbulent and proximal magmatic systems, whereas a low R -factor is characteristic of less turbulent and more distal portions of the magmatic system. Thus, a correlation between the initial Os isotopic composition and the calculated R -factor (based on initial liquid concentration of Os, sample AX57, and using $D_{\text{Os}}^{\text{sulfide/silicate melt}} = 30000$; Fleet *et al.* 1996, Table 2) is anticipated if this process is to be operative in contaminated ore systems that continue to equilibrate with uncontaminated magma during lava “flow through” (Lambert *et al.* 1998a). The calculated R -factor varies within the three different localities, from 290 to 521, from 5 to 29 and from 23 to 44 for Texmont, Hart and Alexo localities, respectively (Table 2). The correlation between the initial Os isotopic composition of the sulfides and the R -factor calculated from the Os concentration (Fig. 10) may be a reflection of the dynamic nature of komatiitic flow systems. In proximal environments (Texmont), the higher R -factor could have erased all evidence of contamination because of the dilution effect in this turbulent (or more dynamic) portion of the lava field (Leshner & Campbell 1993), whereas at lower R -factor values (less turbulent flow, Hart and Alexo), the original contaminated signature

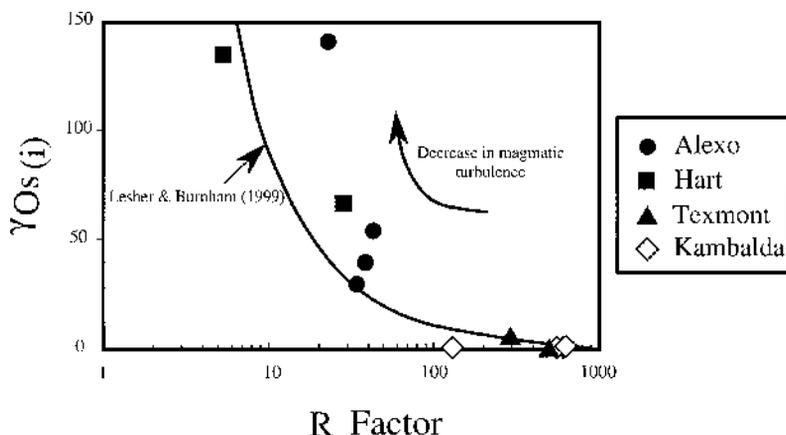


FIG. 10. R -factor versus $\gamma\text{Os}(i)$ of the sulfides. The R -factor is calculated from the Os content of the sulfide (see Table 2 for details). The calculated isotopic evolution from Leshler & Burnham (1999) also is shown for comparison.

would be preserved. Figure 10 illustrates the theoretical isotopic evolution of the sulfide as a function of the R -factor, as modeled by Leshler & Burnham (1999). There is a good agreement between their theoretical calculation and the Abitibi dataset, which implies that the isotopic composition of Os is a powerful indicator of the involvement of contamination by crust in the genesis of NiS deposits, but only in low R -factor environments. The Kambalda sulfides have a calculated R -factor similar to that of the Texmont sulfides. On the basis of this model, we suggest that the chondritic initial Os isotopic data of the Kambalda sulfides (Foster *et al.* 1996) cannot rule out the involvement of contamination during the ore-forming process.

Huppert *et al.* (1984) have suggested that thermal erosion was a possible mechanism by which the komatiitic magma eroded and assimilated their sedimentary substrate. The sulfides from Alexo are located above a low-Mg basal chilled margin (Fig. 2), which would have acted as a thermal barrier for thermal erosion. Therefore, mineralization and thermal erosion, if they occurred, must have taken place at different locations. Assimilation of sedimentary materials could have occurred upstream, closer to the vent, where turbulent flow is more likely to take place. The immiscible sulfide ore magma may then have been carried away by the komatiite flow and locally concentrated where the flow became less turbulent, in the distal regions of the flow field (Leshler 1989).

CONCLUSIONS

(1) Although these komatiites have long been assumed to be uncontaminated, on the basis of the

geochemical and isotopic characteristics, radiogenic initial Os isotopic values from well-preserved whole-rock samples (according to Archean standards) and primary olivine separates demonstrate that Re–Os isotopes are a powerful tracer of the level of crustal contamination. These radiogenic initial Os values are consistent with the incompatible trace-element enrichment in the melt inclusions trapped by the forsterite.

(2) Based on Os isotopic data from the Alexo komatiite and geochronological data for the southern Abitibi, the contaminant is most likely an Os-rich black shale. Therefore, the contamination process was more likely to have occurred close to or at the surface.

(3) Although the Abitibi sulfides have experienced various levels of metamorphism, large whole-rock samples of the sulfides have preserved their initial Os isotopic composition. Os isotopic data for pyrrhotite suggest a redistribution of Os and Re only at the mineral-grain scale. Hydrothermal fluids were channeled along the contact between the komatiites and their base-metals and were responsible for the remobilization of Re or Os (or both) during secondary hydrothermal events within the sulfides at Alexo and Hart. The matrix and disseminated sulfides from Texmont are located within the cumulate pile and have escaped this small-scale redistribution of Re and Os.

(4) Re–Os isotopic heterogeneity of the Abitibi sulfides is best explained by a variable R -factor for the sulfide in a contaminated and sulfide-saturated magmatic system. The Os isotopic compositions of the Abitibi sulfides are consistent with the current model of nickel sulfide formation, which implies that assimilation of sulfidic sedimentary rocks was a trigger for sulfide saturation.

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