

**Re-Os ISOTOPE SYSTEMATICS OF THE RANKIN INLET Ni ORES:
AN EXAMPLE OF THE APPLICATION OF ICP-MS TO INVESTIGATE
Ni-Cu-PGE MINERALIZATION, AND THE POTENTIAL USE
OF Os ISOTOPES IN MINERAL EXPLORATION***

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ABSTRACT

Samples of massive sulfide and mineralized peridotite from the main orebody of the North Rankin Nickel Mine, Northwest Territories, were analyzed for their Re and Os concentrations and Os isotopic compositions by a new ICP-MS, isotope-dilution technique developed at the Geological Survey of Canada. The Re-Os isotope data give ages of 2748 ± 92 Ma and 2776 ± 88 Ma based on isochrons for mineralized peridotite and massive sulfide groupings, respectively. Initial $^{187}\text{Os}/^{186}\text{Os}$ ratios for these two mineralized groups are 1.031 to 1.053 and have average γ_{Os} values of +13.62 and +16.70, respectively. These findings end the enigma concerning the age of the only Ni-producing deposit from the Northwest Territories, and suggest the role of crustal contamination by proximal As-rich sulfidic metasediments. Chondrite-normalized PGE + Au profiles in 100% sulfide and platinum-group-element ratios indicate that the ores are of komatiitic origin, and the sulfide melt had experienced a significant degree of fractional crystallization during the evolution of this deposit. Serpentinization and metamorphism do not appear to have modified the magmatic Re-Os isotope characteristics. This study illustrates the practical utility of ICP-MS-based Re-Os isotope analysis, and how it could be adapted as an exploration and research tool inasmuch as the required instrumentation is present in many laboratories and is being implemented in increasing numbers by commercial laboratories.

Keywords: Re-Os isotopes, ICP-MS, isotope dilution, Ni-Cu-PGE ore, komatiite, Archean, isochron, crustal contamination, exploration tool, Rankin Inlet, Northwest Territories.

SOMMAIRE

Nous avons analysé des échantillons de sulfure massif et de péridotite minéralisée du gîte principal à la mine de nickel de North Rankin, dans les Territoires du Nord-Ouest, afin d'en déterminer la teneur en Re et Os et le rapport des isotopes d'osmium sur plasma par spectrométrie de masse avec couplage inductif; nous nous sommes servis d'une technique nouvelle de dilution des isotopes développée à la Commission géologique du Canada. Les données isotopiques Re-Os mènent à un âge de 2748 ± 92 Ma et 2776 ± 88 Ma, fondé sur isochrones pour la péridotite minéralisée et les sulfures massifs, respectivement. Le rapport initial $^{187}\text{Os}/^{186}\text{Os}$ pour ces deux groupes d'échantillons minéralisés varie de 1.031 à 1.053; les échantillons ont des valeurs de γ_{Os} de +13.62 et +16.70, respectivement. Ces valeurs mettent fin aux questions à propos de l'âge du seul gîte nickelifère sous production dans les Territoires du Nord-Ouest, et attribueraient un rôle à la contamination des roches ignées par des roches métasédimentaires arsenifères et sulfurées. Les teneurs des éléments du groupe du platine (EGP) et de l'or dans la fraction sulfurée, normalisées par rapport aux concentrations chondritiques, ainsi que les rapports des EGP, indiquent que le minerai a une origine komatiitique, et que le liquide sulfuré a subi un degré important de cristallisation fractionnée au cours de l'évolution de ce gisement. La serpentinisation et le métamorphisme ne semblent pas avoir modifié le caractère magmatique des rapports Re-Os. Cette étude illustre bien l'utilité pratique des rapports isotopiques Re-Os par cette technique nouvelle, et l'application des résultats dans un programme d'exploration et de recherche; les instruments requis sont déjà disponibles dans plusieurs laboratoires, et sont en cours d'installation dans plusieurs laboratoires commerciaux.

(Traduit par la Rédaction)

Mots-clés: isotopes Re-Os, ICP-MS, dilution des isotopes, minerai de Ni-Cu-PGE, komatiite, archéen, isochrone, contamination crustale, outil d'exploration, Rankin Inlet, Territoires du Nord-Ouest.

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INTRODUCTION

The investigation of mineralized ultramafic rocks (particularly in Precambrian terranes) is difficult because of problems associated with accurate dating of such bodies, and in the assessment of the role of crustal contamination and its influence in inducing sulfide immiscibility. Most ultramafic rocks and their ores have extremely low concentrations and limited ranges of Sr, Nd and Pb; as a result, they are generally unsuited for age-dating and also more difficult to evaluate with respect to the role of crustal contamination. In addition, phases such as zircon and baddeleyite, which are precisely datable by U–Pb methods, are virtually absent. The practical use of S-isotopes to evaluate the source of sulfur in the associated sulfides is severely limited in Archean and most Proterozoic terranes, as $\delta^{34}\text{S}$ signatures for igneous and sedimentary rocks are indistinguishable during this period of earth's history owing to lack of biogenic fractionation of sedimentary sulfides.

This study presents the results of a Re–Os isotopic investigation conducted on Ni–Cu–PGE ores from Rankin Inlet, Northwest Territories. Unlike most other Re–Os isotopic investigations to date, our study is based on ICP–MS instrumentation similar to that presently available in an increasing number of commercial laboratories, and on techniques developed at the Geological Survey of Canada. This study demonstrates that Re–Os isotope systematics can overcome some of the problems mentioned above, in the investigation of mineralized ultramafic bodies. Also, this technique has potential for widespread application in both research and exploration.

Although most ultramafic rocks have low abundances of Nd, Sr and Pb, their associated sulfides and oxides can contain relatively high concentrations of Re and Os (Crocket 1969, Morse & Short 1969). ^{187}Re is a long-lived radioactive nuclide with a decay constant (λ) on the order of 10^{-11} yr^{-1} ; it produces ^{187}Os by (β^-) decay. Therefore, like ^{87}Rb – ^{87}Sr , the ^{187}Re – ^{187}Os system is a potential geochronometer. The Re–Os geochronometer – cosmochronometer was first used to date meteorites, which could not be dated directly by other methods (Herr *et al.* 1961), but difficulty in measuring the Os isotopes prevented widespread use of the method. In the past, Re–Os isotope geochemistry has been fraught with technical problems, because most rocks at the earth's surface contain Os in concentrations of less than 1 ppb (Morgan & Lovering 1967), making the measurement of its isotopic composition very difficult. Until recently, all high-precision Re–Os isotopic analyses were determined by secondary-ion mass spectrometry (SIMS; *e.g.* Luck & Allègre 1983); however, at present four techniques other than SIMS can produce high-quality Re–Os isotopic analyses. These new techniques are: 1) resonance ionization mass spectrometry (RIMS;

e.g., Walker & Fassett 1986), 2) inductively coupled plasma – mass spectrometry (ICP–MS; *e.g.* Masuda *et al.* 1986, Russ *et al.* 1987, Grégoire 1987, 1988, 1990), 3) accelerator mass spectrometry (AMS; *e.g.*, Fehn *et al.* 1986), and 4) negative thermal ionization mass spectrometry (NTIMS; *e.g.*, Creaser *et al.* 1991, Shirey & Carlson 1991).

The Re–Os system has great potential use not only in geochronology, but also as a tracer of geological processes in ultramafic and mafic rocks. This stems from the fact that $^{187}\text{Os}/^{186}\text{Os}$ can vary by several tens of percent, and $^{187}\text{Re}/^{186}\text{Os}$ can range over several orders of magnitude. In the past, radiogenic isotopes have proven to be extremely useful in tracking the chemical evolution of the earth on both a large and a small scale. Unlike other radiogenic isotopes commonly used to investigate mantle processes (Nd, Sr and Pb), Os behaves compatibly during partial melting; as a result, ultramafic rocks have much higher concentrations of Os than most other rock types (Shirey 1991). In addition, because Re and Os are chalcophile and siderophile elements, they can potentially provide evidence for processes that do not affect Nd and Sr, which are controlled by silicate phases. It is possible that Os isotopes, with their unique characteristics, will provide new constraints, and therefore new understanding of the evolution of the earth and the metallogeny of mafic–ultramafic rocks.

The utilization of this isotope system is increasing rapidly as a result of improved techniques for the chemical extraction of Os from rocks and more efficient ionization during mass spectrometry. However, in order to be of practical application for exploration geologists, the technique must be readily accessible, expeditious, precise and commercially affordable. We believe that at present the ICP–MS technique best meets these requirements.

GEOLOGY

The Rankin Inlet nickel mine is located at Rankin Inlet on the west shore of Hudson Bay, Northwest Territories (Fig. 1). The serpentinized ultramafic body hosting the Ni mineralization is part of the Rankin Inlet Group (Bannatyne 1958), and lies in the Rankin–Ennadai belt, the second largest Archean greenstone belt in Canada. The Rankin Inlet Group is composed of a lower and upper volcanic sequence, each consisting of various proportions of basaltic, andesitic, and dacitic flows and interflow sediments (greywacke, quartz–magnetite iron formation). The two sequences are separated by conformable sedimentary strata consisting of dolomite, ripple-marked quartzite, argillite, and derived schists. Intrusions of serpentinite and gabbro occur as sills within the mafic volcanic sequence of this group. The metavolcanic and metasedimentary strata form an east-dipping F_1 homocline that is folded into a southeast-plunging F_2 upright syncline. The

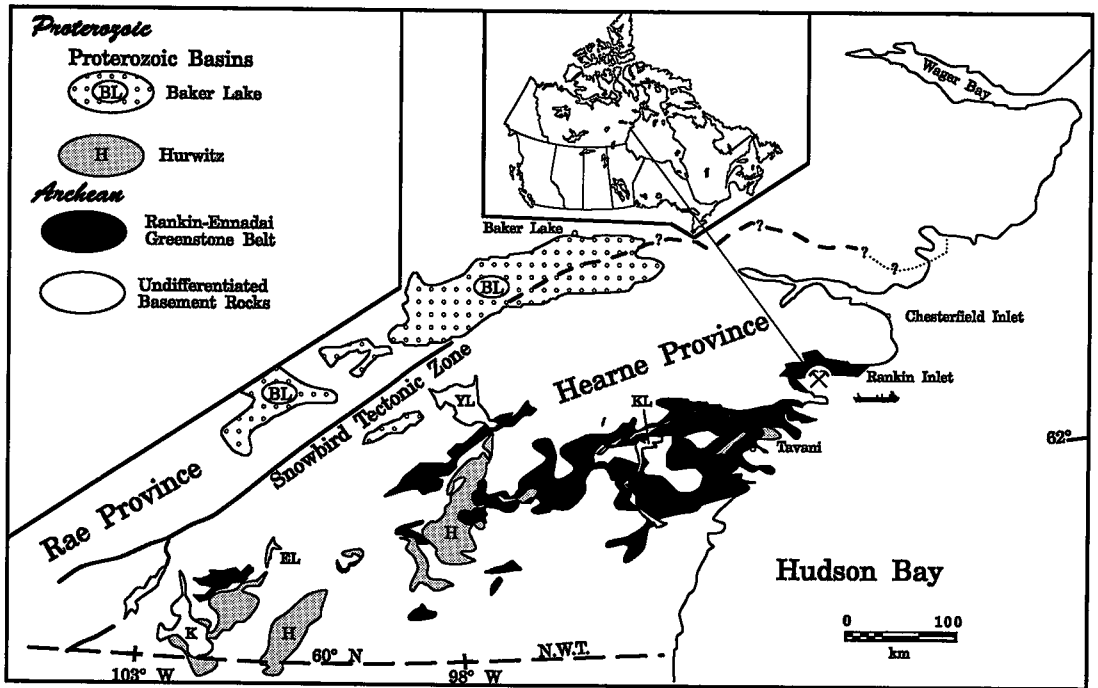


FIG. 1. Map showing the location and geological setting of the Rankin Inlet Ni deposit (modified from Tella *et al.* 1992). Symbols: EL Ennadai Lake, YL Yathkyed Lake, KL Kaminak Lake, K Kasba Lake.

metamorphic grade is subgreenschist to lower amphibolite facies (Tella *et al.* 1986).

The age of the Rankin Inlet Group has been the subject of considerable controversy over the years. Wright (1967) and Bell (1968) believed that rocks of both Archean and Aphebian age are present in the Rankin Inlet region. Bannatyne (1958) and Heywood (1973) considered the Rankin Inlet Group to be Archean, whereas P.P. Hudec (unpubl. data) and Laporte (1975, 1983) assigned an Aphebian age. Recently, Tella *et al.* (1992) dated the felsic volcanic rocks from the upper sequence at 2629 ± 14 Ma and a layered felsic orthogneiss with metasedimentary inclusions at 2704 ± 4 Ma based on U-Pb (zircon) data. The new dates presented in this study confirm the Archean age for the Rankin Inlet Group.

The serpentinized ultramafic sill that hosts the North Rankin nickel deposit is approximately 100 meters thick and at least 1800 meters long, and seems to be emplaced along the contact between sediments and the upper volcanic sequence. The sill strikes 080° and dips $55\text{--}60^\circ$ south, and is located on the northern limb of a broad regional, southeast-plunging synform. The ultramafic body consists of a fine- to medium-grained, dark green pyroxenite and a grey-green, medium- to coarse-grained, totally serpen-

tinized talc-rich peridotite. The contact between the two units can be either sharp or gradational. The sill is characterized by poorly developed macroscopic layering, relict cumulate textures, and a coarsening of grain size with depth, *i.e.*, finer pyroxenite in the upper portion of the sill, and coarser peridotite at the base. The footwall formations consist of an intercalated sequence of greywackes, grey-black tuffs and grey quartzites.

Ni-Cu-PGE mineralization was discovered at Rankin Inlet in 1928, and drilling in 1929 outlined 108,862 tonnes of ore grading 4.62% Ni, 1.22% Cu and 3.77 ppm PGE. Subsequently, calculations of reserves indicated 453,592 tonnes of ore containing 3.3% Ni, 0.8% Cu, 1.02 ppm Pt and 2.05 ppm Pd. Between 1957 and 1962, North Rankin Nickel Mines Ltd. mined and concentrated nickel-copper ore from the main pod of massive sulfide within the deposit.

The Ni-Cu-PGE-bearing sulfide mineralization at Rankin Inlet occurs within depressions at the base of the serpentinized pyroxenite-peridotite sill. This preferential association suggests that immiscible Ni-Cu sulfides segregated from the parental silicate magma and accumulated in basal depressions on the floor of the intrusion. The distribution of mineralization conforms to the classic idealized sequence,

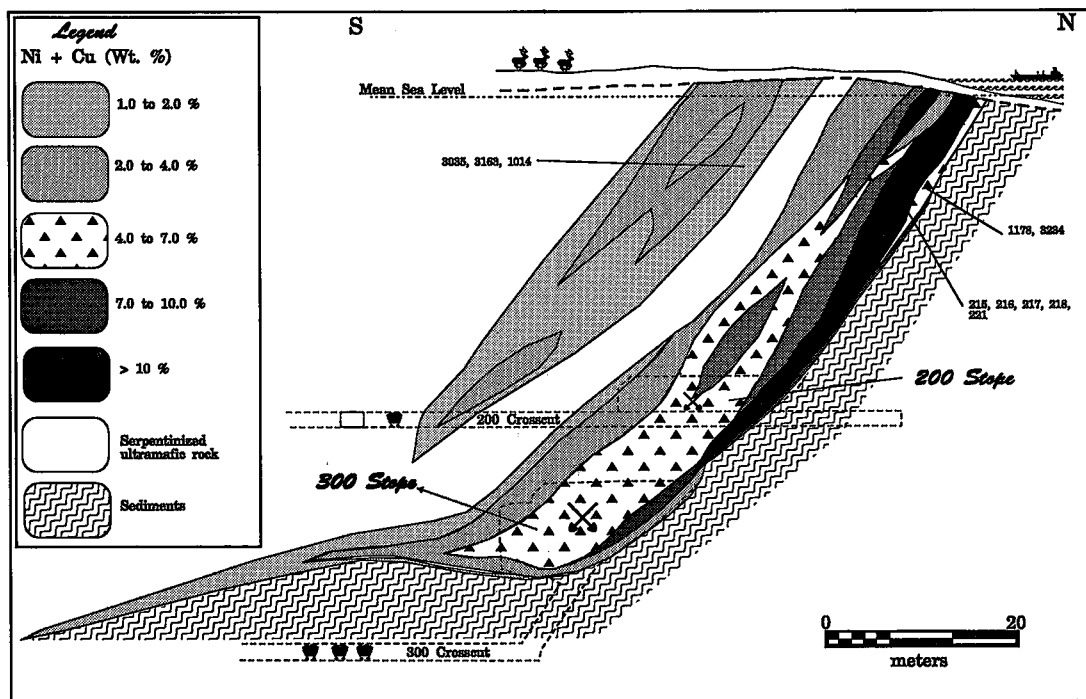


FIG. 2. Cross section of the main orebody at North Rankin Nickel Mines, showing the geology and the distribution of sulfides, based on the combined percentage of Ni and Cu (modified from Bannatyne 1958). Crossed-shovels and enclosed outline represent 200 & 300 Stopes. 3035, 3163, 1014, 1178, 3234, 215, 216, 217, 218, 221: sample numbers and location.

beginning with massive sulfides at the base, overlain successively by net-textured and disseminated sulfides. The metallic phases, in order of decreasing abundance, are pyrrhotite, pentlandite, chalcopyrite, magnetite, pyrite, gersdorffite, violarite and marcasite. The PGE are spatially associated with the sulfides, but the identity and distribution of the platinum-group minerals (PGM) have not been studied. Sulfide mineralization within the intrusion is illustrated by the distribution of Ni + Cu grades in Figure 2. The cross-section demonstrates that the location and shape of the greatest thickness and highest grades of sulfide ore are consistent with the interpretation that the sill was in a near-horizontal position when the immiscible sulfides originally accumulated within basal depressions. Despite serpentinization and rotation accompanying metamorphism and folding, the Rankin Inlet ultramafic body and ores retain most of their primary magmatic features and represent a relatively well-preserved ultramafic-rock-hosted magmatic Ni-sulfide deposit.

Mineralized samples from the main orebody of the Rankin Inlet nickel mine examined in this study include massive sulfides (215, 216, 217, 218, 221,

3234), semi-massive sulfides (1178), net-textured sulfides (3035, 3163) and disseminated sulfides (1014). Sample locations are shown in Figure 2.

ANALYTICAL METHODS

Instrumentation, apparatus and reagents

A Perkin-Elmer SCIEX Elan model 250 inductively coupled plasma - mass spectrometer (ICP-MS) was used for the determination of Re and Os isotopes. Instrumental conditions used for the determination of concentrations of Re, Os and the Os isotopes were as described by Grégoire (1990). Correction factors for instrumental mass-discrimination for Os were obtained using the method of Masuda *et al.* (1986). The instrumental mass-discrimination correction-factor for determinations of the Re isotope ratio was obtained by adding an Ir spike to the Re-containing sample solution and measuring the deviation of the $^{193}\text{Ir}/^{191}\text{Ir}$ ratio from the known natural abundance as given by De Bièvre *et al.* (1984). Parameters of data acquisition for the ICP-MS were set so as to obtain sufficient counts to provide for the determination of

isotope ratios with a precision of better than 0.3%. Data pertaining to all seven isotopes of Os were collected.

The ^{185}Re -enriched and ^{190}Os -enriched isotope spikes were obtained as metal (U.S. Services Inc.). Enriched isotope spike metals were dissolved using a sodium peroxide fusion followed by dissolution of the melt using 6 M HCl. The concentration of isotopes in the resulting spike solution for each element was determined using both external calibration and reverse isotope-dilution analysis by ICP-MS. The acidified Os spike solution was stored in the dark to prevent photo-reduction of the Os in solution.

The distillation apparatus used was similar to that used by Allan & Beamish (1952) and consisted of four vessels connected in series. The first vessel (500 mL) was the primary distillation flask, which contained the spike, sample and the oxidizing reagent. The second vessel in the series (250 mL) contained distilled water and served as a trap to prevent oxidant from reaching the last two vessels (100 mL), which contained the receiving or Os-trapping solution. Condensers were installed between the distillation vessel and water trap and the first receiving vessel. A water aspirator was used to continuously draw a flow of air through the distillation apparatus. The stream of air served to carry the distilled Os from the distillation flask to the receiving vessels. The flow rate of air drawn through the system was controlled and kept to a minimum using a stopcock located on the air line.

Concentrated perchloric acid was used as the oxidizing reagent for Os. The receiving or trapping solution for the oxidized Os consisted of a mixture of thiourea (1% by weight) dissolved in 10% vol./vol. HCl. To 100 mL of this receiving solution was added 0.15 mL of 20% SnCl_2 solution (in 11 M HCl), which served as a reducing agent for Os and any perchloric acid reaching the receiving vessels.

Sample preparation and distillation of osmium

Three grams of powdered sample material were first treated with 10 mL of concentrated HCl at 50°C for a period of 3 hours in order to drive off H_2S prior to the distillation procedure. Following this treatment, ^{185}Re and ^{190}Os spike solution was added to the sample. The mass of spike added was approximately the mass of the Re and Os contained in the sample, as determined by prior analysis by neutron-activation techniques. The sample was then quantitatively transferred to a distillation apparatus. To the sample flask was added 20 mL of concentrated perchloric acid. Heat was applied to the flask by means of a Bunsen burner. The mixture was heated to boiling and boiled continuously for a period of approximately 2 hours or until the sample was completely dissolved. After adding 3 mL of concentrated perchloric acid to the water trap, the water trap was heated to boiling for a

period of 30 minutes to remove any traces of Os remaining there following the initial dissolution of the sample and distillation step. The solution remaining in the distillation vessel (pot liquor) was saved for Re extraction. The receiving solutions were collected, combined and slowly evaporated on a hot plate at low heat to a volume of 10 mL. The concentrated Os solution containing both spike and sample osmium were transferred to the (empty) water trap flask on the distillation apparatus. Following the addition of 25 mL of a 1:1 mixture of concentrated H_2SO_4 and H_2O_2 , the Os contained in the evaporated receiving solution was redistilled for a period of 15 minutes into ice-cold distilled water contained in the receiving vessels. Distilled water containing dissolved OsO_4 is not stable for more than a few hours at room temperature and therefore was immediately analyzed for Os isotopes by ICP-MS. The determination of Os as the tetroxide in solution by ICP-MS was about 20-fold more sensitive than the determination of an equivalent concentration of Os in reduced form (Grégoire 1990). The quantitative determination of Os was accomplished by isotope dilution analysis using the measured ratio of reference ^{192}Os to spike ^{190}Os . Between each distillation (sample), the distillation apparatus was rinsed with concentrated nitric acid. A distillation of perchloric acid alone also was done to further clean the system. Blanks for the method were found to be below the detection limit for both Os and Re.

Determination of rhenium

The pot liquor from the initial Os distillation was removed from the reaction vessel and evaporated to near-dryness in order to expel most of the perchloric acid. The Re was extracted from the pot liquor by a solvent-extraction procedure similar to that reported by Walker (1988). Fifty mL of concentrated sulfuric acid was added to the sample, and any remaining solid material was removed by centrifugation. The Re was extracted from the solution with an equal volume of 1% tribenzylamine in chloroform, then back-extracted with ammonium hydroxide. The resulting extract was evaporated to dryness and dissolved in 1 M nitric acid prior to analysis by ICP-MS.

Throughput

Analytical sample throughput is very dependent on the sample type; materials containing refractory minerals take longer to dissolve during the initial distillation step. The dissolution procedure described above dissolves sulfides, silicates, and even chromite. For sulfide materials, the analytical sample throughput is about one sample per working day, taking into account all steps of the process including distillations, extractions, determination by ICP-MS and data reduction. Instrumentation advancements will certainly improve

the sensitivity of the method; *i.e.* recent acquisition of a Perkin-Elmer SCIEX Elan model 5000 ICP-MS demonstrates that sensitivity has improved by an order of magnitude (limit of detection for Os is ≈ 0.9 ppb) over that obtained in this study (≈ 9.0 ppb).

RESULTS

Re, Os concentrations and isotopic ratios are given in Table 1. Errors for Os and Re determinations are approximately 1%. The concentration of Os in some samples was found to be so high that dilution was necessary to obtain counts for the more abundant isotopes. The concentrations of five other PGE and Au, along with Ni, Cu and S, are provided in Table 2. Re and Os concentrations vary from 38 to 392.8 ppb and from 130.3 to 4362 ppb, respectively. As a result of the compositional variation, the $^{187}\text{Re}/^{186}\text{Os}$ value ranges from 3.56 to 26.67. The highest $^{187}\text{Re}/^{186}\text{Os}$

ratios (26.67 and 16.63) are associated with the massive sulfide samples (#218, 215, Table 1). These sulfide-rich samples seem to be relatively poor in Os and Re, as well as Ir, Ru and Rh (Table 2) if compared with similar samples of equivalent sulfide (\approx wt.% S) and Ni concentrations. Conversely, the lowest ratios encountered in this study also are associated with the massive sulfides. Thus it is evident that the entire range in $^{187}\text{Re}/^{186}\text{Os}$ (3.56 to 26.67) can be found within the massive sulfides alone. A relatively high ratio of 11.52 also was found associated with a sample of net-textured peridotite (3035). With the exception of samples 218, 215 and 3035, the $^{187}\text{Re}/^{186}\text{Os}$ ratios of the investigated samples generally fall within the range 3.56 to 8.70.

Values of γ_{Os} for the Rankin samples are given in Table 1. The $\gamma_{\text{Os}}(T)$ expression describes the isotopic composition of Os at the time of crystallization. This parameter is analogous to the ϵ parameter used in

TABLE 1. Re AND Os ISOTOPIC TRACE ELEMENT DATA FOR RANKIN INLET Ni-Cu ORES AND HOST PERIDOTITES

Sample #	Rock Type	Os	Re	$^{187}\text{Re}/^{186}\text{Os}$	$^{187}\text{Os}/^{186}\text{Os}$	γ_{Os}
215	MSS	454.1	190.8	16.63 \pm 0.05	1.829 \pm 0.005	17.04
216	MSS	1305	287.1	8.7 \pm 0.03	1.473 \pm 0.004	18.09
217	MSS	2572	332.9	5.12 \pm 0.02	1.301 \pm 0.004	17.03
218	MSS	270	182	26.67 \pm 0.08	2.292 \pm 0.007	17.04
221	MSS	4362	392.8	3.56 \pm 0.01	1.200 \pm 0.004	14.18
3234	MSS	1496	140.5	3.70 \pm 0.01	1.177 \pm 0.004	10.82
1178	SMS	1372	166.9	4.81 \pm 0.01	1.241 \pm 0.004	12.27
3035	Prd(net)	130.3	38	11.52 \pm 0.03	1.562 \pm 0.005	13.56
3163	Prd(d-net)	253.5	40	6.23 \pm 0.02	1.322 \pm 0.004	13.95
1014	Prd(diss)	397.9	50.5	5.01 \pm 0.02	1.260 \pm 0.004	13.35

Re and Os abundances are given in ppb. MSS: Massive Sulfides, SMS: Semi-Massive Sulfides, Prd: peridotite, net: net-textured sulfides, d-net: disseminated to net-textured sulfides, diss: disseminated sulfides. γ_{Os} calculated at 2748 Ma.

TABLE 2. CONCENTRATIONS OF PLATINUM-GROUP ELEMENTS, Ni, Cu AND S IN RANKIN INLET ORES AND HOSTS PERIDOTITES

Sample #	Rock Type	Ir	Ru	Rh	Pt	Pd	Au	S	Cu	Ni
215	MSS	59	150	290	1200	1900	64	36.00	2.60	11.60
216	MSS	170	630	540	1200	2400	120	37.40	1.10	9.70
217	MSS	320	1200	830	910	800	82	36.60	1.20	10.40
218	MSS	25	83	130	2300	2600	90	36.50	0.34	10.20
221	MSS	540	2400	1000	860	600	31	37.50	1.10	9.90
3234	MSS	350	1600	500	890	1500	120	23.10	0.51	4.40
1178	SMS	260	450	380	1300	390	270	16.60	1.20	3.70
3035	Prd(net)	29	110	52	820	1200	78	7.85	0.32	1.20
3163	Prd(d-net)	60	220	74	600	1480	74	6.98	0.31	1.20
1014	Prd(diss)	43	130	69	520	930	29	7.77	0.22	1.40

Concentrations of the platinum-group elements are given in ppb. Concentrations of Ni, Cu, and S are reported in wt.%.

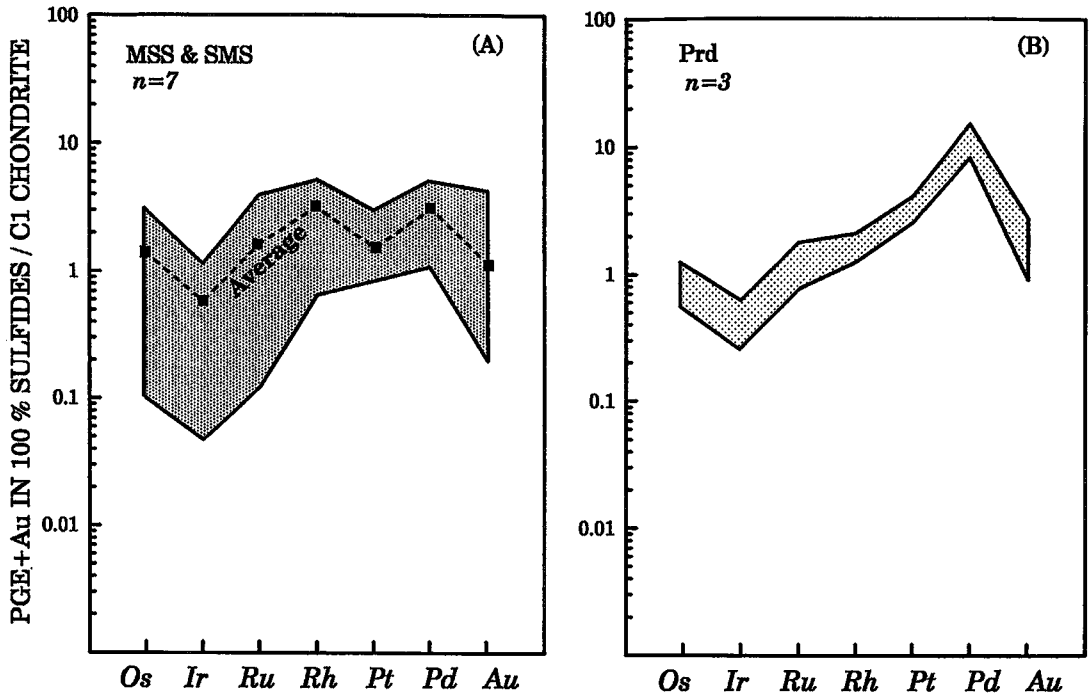


FIG. 3A. Chondrite-normalized concentrations of the noble metals for massive and semimassive sulfides from the main orebody at North Rankin Nickel Mines. B. Chondrite-normalized concentrations of noble metals for mineralized peridotite samples from the main orebody at North Rankin Nickel Mines.

Rb–Sr and Sm–Nd isotopic systems. The parameter $\gamma_{Os}(T)$ expresses the percentage difference between the isotopic composition of Os in the sample at any time (T) and the reference mantle (carbonaceous chondritic reservoir) value at that time. Crustal rocks have relatively high Re/Os values and evolve to large positive γ_{Os} values with time, whereas Re-depleted reservoirs evolve to negative γ_{Os} signatures (Walker *et al.* 1989). The Rankin $\gamma_{Os}(2748 \text{ Ma})$ values range from 10.82 to 18.09. In general, higher γ_{Os} signatures are associated with massive sulfides, whereas mineralized peridotite samples have lower values.

Chondrite-normalized PGE + Au concentrations in 100% sulfide vary considerably with respect to the different types of ore. Basal massive sulfide concentrations (Fig. 3A) have significantly lower (Pt + Pd)/(Ru + Ir + Os) ratios than the overlying net-textured and disseminated sulfide in peridotite (Fig. 3B). Similar trends for the massive and disseminated ores, based on approximately 100 full PGE + Au assays, disclosed comparable trends.

The Re–Os isotopic data are plotted on $^{187}\text{Os}/^{186}\text{Os}$ versus $^{187}\text{Re}/^{186}\text{Os}$ diagrams in Figures 4A and 4B.

These data regress to give ages of $2803 \pm 97 \text{ Ma}$ and $2841 \pm 105 \text{ Ma}$ based on 8-point (Fig. 4A) and 10-point (Fig. 4B) isochrons, respectively, using a standard regression treatment (York 1969) and the ^{187}Re decay constant $\lambda = 1.64 \times 10^{-11} \text{ yr}^{-1}$ of Lindner *et al.* (1989). Isochrons for the mineralized peridotite ($n = 3$) and massive sulfide ($n = 5$) samples give ages of $2748 \pm 92 \text{ Ma}$ and $2776 \pm 88 \text{ Ma}$, respectively, and regress to give initial $^{187}\text{Os}/^{186}\text{Os}$ ratios of 1.031 and 1.053, respectively. Combined data for the eight samples regress to give an initial $^{187}\text{Os}/^{186}\text{Os}$ of 1.038 (Fig. 4A). The basis for these lithological groupings was discerned from log–log plots of Os versus $^{187}\text{Re}/^{186}\text{Os}$ and Re versus $^{187}\text{Re}/^{186}\text{Os}$ (not shown), which define distinct parallel groupings for the mineralized peridotite (3035, 3163, 1014) and the massive sulfide (215, 216, 218, 221) samples. However, semimassive and massive sulfide samples 3234 and 1178 display an abnormal trend as well as significantly lower values of γ_{Os} (10.82 to 12.27) than the other massive sulfide samples and thus were excluded from these groupings.

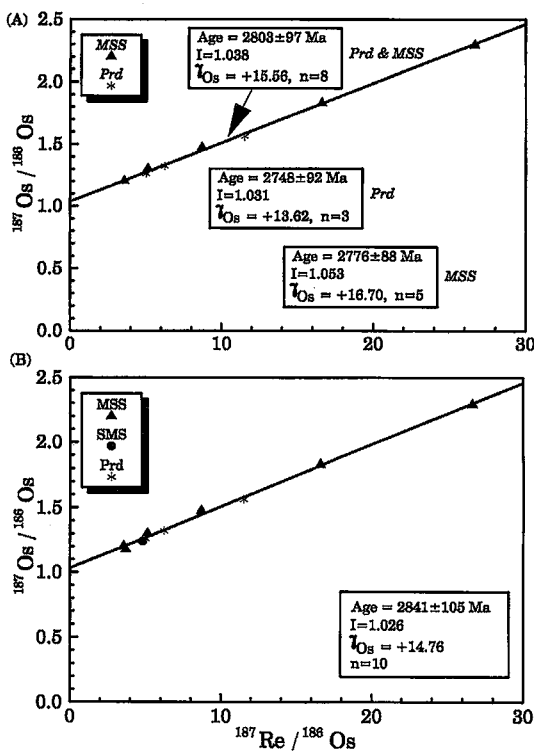


FIG. 4A. $^{187}\text{Os}/^{186}\text{Os}$ versus $^{187}\text{Re}/^{186}\text{Os}$ plot for North Rankin Nickel Mines ores. Age and initial $^{187}\text{Os}/^{186}\text{Os}$ ratio (I) based on isochrons for mineralized peridotite (Prd) and massive sulfide groups. Average γ_{Os} value for each group also is given. Regression line based on the combined data (eight samples) for the peridotite and massive sulfide groups. Symbols: MSS massive sulfides, SMS semimassive sulfides, Prd mineralized peridotite, n number of samples. B. $^{187}\text{Os}/^{186}\text{Os}$ versus $^{187}\text{Re}/^{186}\text{Os}$ plot for North Rankin Nickel Mines ores. Data based on 10 samples and defines an isochron age of 2841 ± 105 Ma. Symbols: MSS massive sulfides, SMS semimassive sulfides, Prd mineralized peridotite.

DISCUSSION

This study has revealed some important findings concerning the petrogenetic nature of the Rankin Inlet intrusion, its age, the relationship between crustal contamination and ore genesis, and the behavior of Re–Os during the formation of the Ni–Cu sulfide mineralization and subsequent metamorphism.

This investigation has revealed that the Rankin ores have primitive (flat) chondrite-normalized PGE + Au profiles (Fig. 3A), similar to those of “typical komatiites”

(Naldrett 1981). The concentrations of Os used in this plot are based on INAA and Ni-sulfide fire-assay data [following the procedure of Hoffman *et al.* (1978)], and not those given in Table 1. Os concentrations obtained by INAA – fire assay were used in order to facilitate comparison with mineralized samples from other Ni camps and tectonic regimes, since most of the analytical data in the literature are based on this technique. The flat to shallow PGE + Au profiles of the massive and disseminated ores, respectively, are similar to those of komatiite-hosted Ni deposits (Naldrett 1981) and characterize the geochemical nature of the parental magma. In addition, the high Ni/Cu values and Ir, Rh, Os, Ru, Pt and Pd concentrations (Tables 1, 2) of the massive and semimassive sulfide ores confirm the komatiitic origin of this mineralization. Higher (Pt + Pd)/(Ru + Ir + Os) values associated with the disseminated mineralization illustrate the fractionation of PGE in an evolving sulfide melt.

Besides being a useful tool in the chronology of meteorites, the Re–Os system has been successfully utilized to date Archean and Phanerozoic volcanic komatiites from Munro Township (Walker *et al.* 1988) and Gorgona Island, Columbia (Walker *et al.* 1991b), respectively, and Ni–Cu sulfide deposits, *i.e.*, at Sudbury (Walker *et al.* 1991a) and Noril’sk–Talnakh (Walker *et al.* 1992). These recent studies employed highly sophisticated and intricate mass spectrometric instrumentation (RIMS). However, the Rankin Inlet Re–Os isotopic investigation of sulfide ores utilized ICP–MS instrumentation and, to the best of our knowledge, has produced the first Re–Os isochrons using this method. Preliminary geochronological results from this study have been presented by Grégoire (1987, 1988). Since our chondrite-normalized PGE + Au profiles in 100% sulfide demonstrate that the Rankin ultramafic body is of komatiitic origin, our results will be compared with Re–Os isotope data from other komatiitic bodies, as well as from other mafic–ultramafic bodies and associated mineralization.

The range in whole-rock Re/Os from the Rankin Inlet Ni-deposit allows one to date the Ni sulfide mineralization, and thus indirectly to date the host intrusion. Based on the ^{187}Re decay constant of Lindner *et al.* (1989), our regression plots of the $^{187}\text{Os}/^{186}\text{Os}$ and $^{187}\text{Re}/^{186}\text{Os}$ data suggest a crystallization age of 2748 ± 92 Ma for the peridotite sill and 2776 ± 88 Ma for the comagmatic sulfide ores (Figs. 4A, B). These two ages are indistinguishable if the error (\pm) is taken into consideration and also are compatible with the findings of Tella *et al.* (1992), who dated the younger suite of felsic volcanic rocks from the upper sequence at 2629 ± 14 Ma and a layered felsic orthogneiss with metasedimentary inclusions at 2704 ± 4 Ma based on U–Pb (zircon) systematics. Quartz–feldspar porphyry intrusions within the mafic volcanic sequence gave

model Nd ages of 2820 Ma (pers. comm., Tella 1990). It is interesting to note that komatiites from the Munro Township of the Abitibi belt, Ontario, are similar in age: 2726 ± 93 Ma (Walker *et al.* 1988).

Bannatyne (1958) pointed out that another ultramafic body "very similar in appearance to the North Rankin" body occurs in the lower volcanic sequence. This observation invites speculation that the host ultramafic body to the North Rankin orebody is older than its present position would suggest; it may be coeval with the older lower volcanic sequence. A parental komatiitic magma, such as that which gave rise to the North Rankin ultramafic body, would certainly have a greater petrological affinity with the voluminous mafic extrusive rocks in the lower volcanic sequence than with the more felsic upper sequence. Thus the possibility of the North Rankin ultramafic body being thrust into its present position must be considered. Nevertheless, one cannot rule out the possibility that the marginally older age determined during this study may be a consequence of the less precise nature of the ^{187}Re decay constant or scatter due to the influence of inherited crustal Os. Re-Os dating of the Bird River Sill, Manitoba (by the GSC) using the same procedure and techniques used in this study, gave an age of 2703 Ma, which is in good agreement with a U-Pb (zircon) age of 2745 ± 5 Ma obtained by Timmins *et al.* (1985), thus suggesting that this technique of dating gives reliable ages.

From the Re/Os data, one can determine the isotopic composition of the parental magma and make inferences concerning the role of crustal contamination. The regression plot in Figure 4A suggests that the Rankin parental komatiitic magma had an initial $^{187}\text{Os}/^{186}\text{Os}$ composition of ~ 1.03 . This is significantly higher than that found in the age-equivalent Munro Township komatiites, *i.e.*, $(^{187}\text{Os}/^{186}\text{Os})_i = 0.873 \pm 0.035$ (Walker *et al.* 1988). The relatively young Gorgona komatiites (155 ± 43 Ma) have $(^{187}\text{Os}/^{186}\text{Os})_i = 1.13 \pm 0.01$ (Walker *et al.* 1991b).

Because the $^{187}\text{Os}/^{186}\text{Os}$ evolves with time, the expression $\gamma_{\text{Os}}(T)$ is used to describe the difference (in percent) between the isotopic composition of a sample and that of the mantle at a specified time (T). Given that mantle with chondritic Re/Os would have $= \gamma_{\text{Os}} = 0$, mineralized komatiitic rocks of the Rankin Inlet ultramafic body are enriched relative to the mantle, with a mean (\bar{X}) $\gamma_{\text{Os}} = +14.76$, $n = 10$. In addition, most massive sulfide samples have higher γ_{Os} values than the sulfide-poor samples. Computed values of γ_{Os} for the Munro Township komatiites, based on the data of Walker *et al.* (1988), range from +2.7 to -21.60 ($\bar{X} = -8.0$, $n = 12$). Because of their high Re/Os ratios, crustal rocks evolve to larger positive values of γ_{Os} with time, whereas Re-depleted sources evolve to negative γ_{Os} values. The negative values of γ_{Os} associated with the Munro komatiites demonstrate that the source that gave rise to these

melts was somewhat depleted in the relatively incompatible Re. Negative values of γ_{Os} , as low as -15, have also been recorded in peridotite xenoliths associated with kimberlites in South Africa (Walker *et al.* 1989). The Gorgona Island komatiites demonstrate positive values of γ_{Os} (0 to +22). Walker *et al.* (1991b) proposed that this large range in γ_{Os} reflects heterogeneities in Os isotopic compositions of the mantle source for the komatiites. They also proposed that the enriched isotopic composition could not be the product of interaction between komatiitic melt and continental or oceanic crust since the komatiites from Gorgona have 10 to 100 times the amount of common Os as continental crust and 10,000 times that contained in seawater (Walker *et al.* 1991b). However, Ravizza *et al.* (1988) and Ravizza & Turekian (1989) have demonstrated that black shales and organic-matter-rich sediments can contain very high background levels of both Os and Re. In fact, black shales from the Devonian Bakken Formation (Williston Basin, North Dakota and Saskatchewan) have Os and Re concentrations that range from 0.91 to 3.69 ($\bar{X} = 2.08$) ppb and 56 to 285 ($\bar{X} = 162$) ppb, respectively (Ravizza & Turekian 1989). These Os values are more than an order of magnitude greater than those of average crustal rocks and are appreciably greater than those of Munro Township komatiites (1.004 to 2.204 ppb, $\bar{X} = 1.56$ ppb, $n = 12$). Black Sea sediments contain from 0.28 to 0.65 ppb Os and from 41 to 83 ppb Re (Ravizza *et al.* 1988). Hulbert *et al.* (1992) demonstrated that ore-grade concentrations of Ni and PGE occur in Devonian black shales that have Re concentrations up to 61,000 ppb and associated Os values of 70 ppb, respectively. Similar but more extensive mineralization occurs in a 1600-km-long east-north-east-trending arc over ten provinces in southern China. This mineralization is associated with Lower Cambrian metal-rich black shales (Coveney *et al.* 1992). Therefore, it is apparent that some sediments have the potential, through some mechanism of contamination, to directly influence the Re-Os isotope systematics of magmatic systems.

The positive γ_{Os} values of the Rankin ores, and the tendency for massive sulfides to have more strongly positive values than the disseminated mineralization, are consistent with the suggestion that crustal contamination and magma mixing have induced sulfide immiscibility. The relationship between the proportion of silicate and sulfide melt that mixed, and the associated metal content of the sulfides, are controlled by the "R-factor" (Campbell *et al.* 1983). The concentration of metals in a sulfide melt can be expressed in the following:

$$Y_i = \frac{D_i \times C_{oi} \times (R + 1)}{(R + D_i)} \quad (1)$$

where Y_i is the concentration of any metal i in the sulfide melt (Y), D_i the partition coefficient (sulfide/silicate), R is the ratio of the mass of silicate

magma in equilibrium with the mass of sulfide melt, and C_{oi} is the initial concentration of the metal i that equilibrates with it. This expression demonstrates that where R is low, in the range 100 to 2,000, the Ni and Co contents of sulfides will be typical of most Ni sulfide ores, and the Pt values will be relatively low and would be less than or equal to those values observed in normal Sudbury ores. R values in the range 10,000 to 100,000 will lead to Ni and Co contents not much higher than at lower R values, but the concentration of the PGE (*i.e.*, Os) will be much higher and in the range characteristic of those of the Merensky and J-M Reefes.

R -factor calculations for Os are based on an assumed initial concentration of 1.56 ppb Os in a parental komatiitic liquid, similar to that from komatiites in the Munro Township, and a sulfide/silicate partition coefficient of 2×10^4 . Since there are few data for the sulfide/silicate melt partition coefficient for Os, and there is a near-perfect statistical correlation between Os and Ir ($r = 0.99$) in the Rankin ores, we will assume for the sake of discussion that the value for Ir (Mathez & Peach 1989) will not be too unlike that of Os. Calculation of the R value for the most Os-poor (#218; Os = 280 ppb) and most Os-rich (#221; Os = 4400 ppb) massive sulfides indicates that the Os-rich samples have a much higher value ($R = 3314$) than the Os-poor sample ($R = 181$). However, by virtue of the R -factor, Os-rich massive sulfides should also contain high concentrations of Pt and Pd. This is not the case in the Rankin ores; Os-poor massive sulfide sample #218 contains the highest Pt and Pd concentrations (2300 and 2600 ppb, respectively) encountered in this study, whereas Os-rich sample #221 from the same massive sulfide zone contains the lowest levels of Pt and Pd (860 and 600 ppb, respectively). The existence of such extreme values of R in the same orebody is difficult to accept. Therefore, these considerations suggest that the distribution of the PGE + Au is not only controlled by magma-mixing parameters but also by *fractional crystallization of the sulfide melt*. Pd/Ir values for the massive sulfides increase from 1.1 to 104 during the evolution from Os-rich to Os-poor compositions. Similar changes in Pd/Ir ratio have been observed in Ni sulfide deposits in komatiites of the Abitibi greenstone belt (Barnes & Naldrett 1987) and have been attributed to fractionation of a monosulfide solid-solution from the sulfide liquid.

The Rankin Inlet Ni mineralization is unique relative to comparable Ni ores elsewhere in that it has an anomalously high As content. Gersdorffite (NiAsS) is a common constituent in most of the massive, net-textured and disseminated sulfide ores. In the net-textured ores, gersdorffite can be seen included in the sulfides and is clearly a primary phase that has exsolved from the sulfide melt upon cooling. Bannatyne (1958) noted that small concentrations of

gersdorffite occur within the ultramafic rock separating the massive sulfide ore from the underlying tuffaceous sediments. Four small pockets, ranging in size from a few centimeters to a meter in length, were observed during the course of his underground mapping at widely spaced locations in the mine. Microscopic investigation of the footwall sediments, in the present study, revealed the presence of fine lath-shaped crystals of arsenopyrite. The arsenic content of these footwall sediments (having sulfur contents of 0.17 to 0.42 wt.%) range from 20 to 450 ppm. Visible grains of arsenopyrite have been noted elsewhere in the country rock. From this, one would conclude that the anomalous As contents in the Rankin ores and the unmineralized ultramafic rocks are a direct consequence of magma contamination resulting from the assimilation of As-enriched sulfidic sediments.

Further evidence for crustal contamination from the underlying sulfidic sediments is present in the S/Se ratios of the ores. Mineralized peridotites have a S/Se ratio that averages 5,411, whereas the underlying massive sulfides have an average value of 10,270. S/Se ratios for sediment-hosted sulfides in the Rankin area fall in the range 11,351 to 17,000, ($\bar{X} = 14,810$). Although the S/Se ratio for mantle-derived sulfides has yet to be precisely established, available information suggests that it is less than or equal to 3,000 (Eckstrand & Hulbert 1987). On the basis of S/Se ratios alone, it seems clear that the Rankin sulfide mineralization is a direct consequence of contamination of a komatiitic magma by Se-poor sulfidic sediments rather than of an accumulation of mantle-derived sulfides. The positive γ_{Os} signatures of the Rankin ores, along with the tendency for higher positive γ_{Os} values in massive sulfides relative to lower ones in disseminated mineralization in peridotites, correlate well with the high and low S/Se ratios found in massive sulfides and mineralized peridotites, respectively. These relations could also imply that the parental magma to the mineralized peridotite experienced less extensive crustal contamination than the melt that gave rise to the basal accumulations of massive sulfides. It is also possible that the basal sulfides received a larger crustal component, resulting from sulfides forming at an interface between melt and country rock and thus represent a more contaminated boundary-layer to a homogeneous melt injected into the magma chamber. Nevertheless, the high As content and S/Se value of the Rankin ores, and that of the underlying footwall sediments, and the positive γ_{Os} values of the Rankin ores, all support the hypothesis of crustal contamination.

In order to constrain the proportions of crustal material contained in the Rankin ores, binary mixing calculations are presented for two different models (Fig. 5) with the objective of explaining the observed Os content and isotope ratios. The calculations were performed using an estimated Archean average

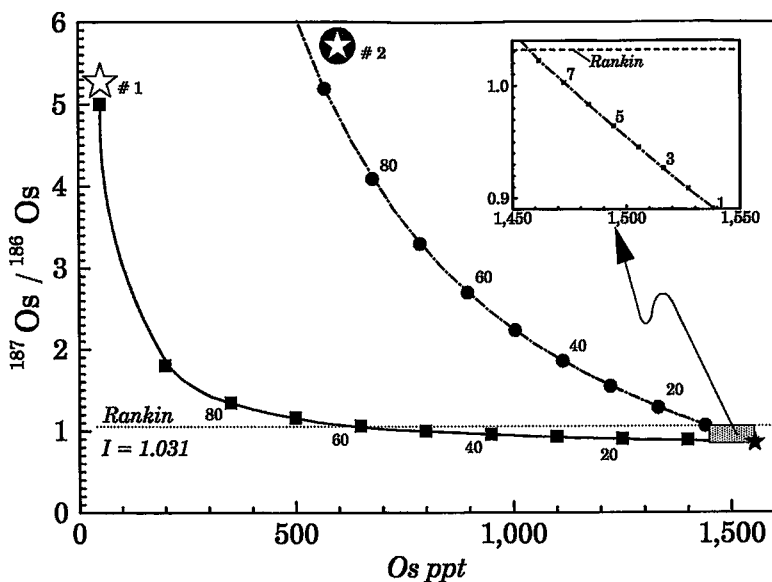


Fig. 5. Mixing curves showing $^{187}\text{Os}/^{186}\text{Os}$ versus Os concentration (ppt) for a komatiitic parental magma and two different types of crustal contaminant end-members. Model 1 depicts contamination by Archean crust from the Wyoming-Hearne Province, and model 2 represents a contaminant similar to Black Sea sediments (see text for further details).

komatiite $^{187}\text{Os}/^{186}\text{Os}$ ratios and Os concentration of 0.873 and 1560 ppt, respectively, based on the data of Walker *et al.* (1988) for Munro Township of the Abitibi greenstone belt. The contaminant for model 1 is that of Archean continental crust from the Wyoming craton, having $^{187}\text{Os}/^{186}\text{Os}$ ratio and Os concentration of 5.0 and 50 ppt, respectively (Lambert *et al.* 1989). The data from the Wyoming craton are considered to be most suitable for this model since the Hearne Province (Fig. 1) and Wyoming Province are considered to be consanguineous Archean greenstone-granite gneiss provinces (Hoffman 1988). The results for model 1 demonstrate that such a contaminant would require approximately 55% crustal component in the Rankin ores. Magmatic assimilation of such a large mass of crustal material is unrealistic in view of the known geology, petrology and geochemistry of the complex. If the crustal material were assumed to contain even less Os, say 7 ppt, the required crustal component increases to an impossible 90%. Osmium analyses of one sample of As-enriched country-rock sediment, conducted at Lamont-Doherty Geological Observatory employing the N-TIMS method for $^{187}\text{Os}/^{186}\text{Os}$ and Os concentration, gave values of 52.0 ± 0.2 and 4.0 ppt, respectively. The corresponding $^{187}\text{Re}/^{186}\text{Os}$ and Re concentrations are 1219 and 68 ppt.

Model 2 assumes an initial $^{187}\text{Os}/^{186}\text{Os}$ ratio of 6.8 and an average Os concentration of 460 ppt for the undisclosed contaminant, similar to that of Black Sea sediments (Ravizza *et al.* 1988). Assimilation of material of this nature would require approximately 9% crustal component to produce a shift of $^{187}\text{Os}/^{186}\text{Os}$ initial ratio from 0.873 to 1.031 (Fig. 5). Although not shown, if one assumed an Archean contaminant with a composition similar to the Devonian black shales of the Bakken Formation, having a $(^{187}\text{Os}/^{186}\text{Os})_i$ of 6.2 and an average Os concentration of 2,080 ppt (Ravizza & Turekian 1989), as little as 2.3% crustal component could account for the observed isotopic shift. The existence of sediments with an initial $^{187}\text{Os}/^{186}\text{Os}$ ratio of 6.2 at 2748 Ma is a debatable point. Os isotope analysis of one of the metasedimentary horizons from the Rankin area clearly indicates that this horizon could not produce the isotopic and concentration shifts observed within the Rankin Inlet komatiitic magma. However, it is now apparent that sedimentary rocks differ significantly in their Os contents (Ravizza *et al.* 1988, Ravizza & Turekian 1989, Hulbert *et al.* 1992, Walker *et al.* 1991a), and the correct sedimentary horizon in the Rankin Inlet area has yet to be identified. That the contaminants are of sedimentary origin seems clear from the As and S/Se data and the geological relationships.

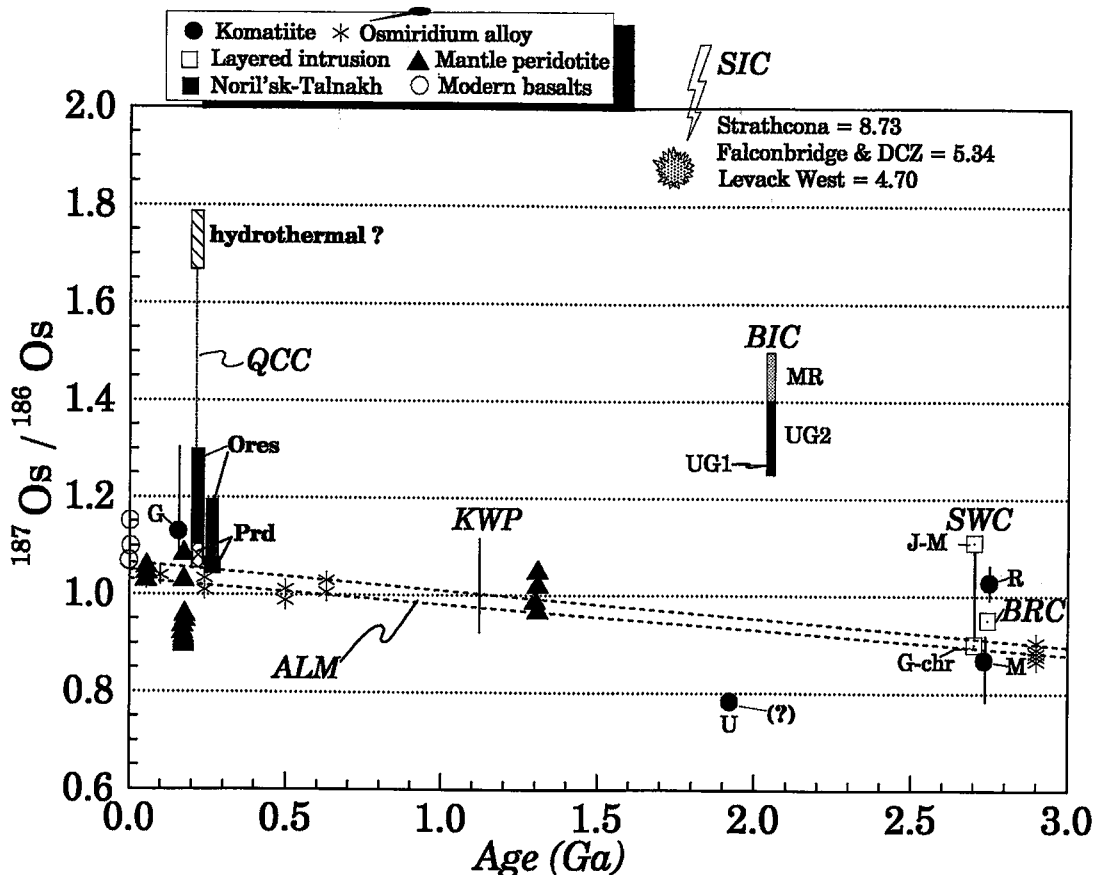


FIG. 6. Initial $^{187}\text{Os}/^{186}\text{Os}$ versus time of formation; data from GSC studies and from the available literature. Symbols: R Rankin Inlet, BRC Bird River Sill, M Munro Township komatiites (Walker *et al.* 1988), SWC Stillwater Complex (J-M, J-M Reef; G-chr, G-chromitite) (Martin 1989, Lambert *et al.* 1989), BIC Bushveld Igneous Complex (MR, Merensky Reef; UG2, UG2 chromitite; UG1, UG1 chromitite) (McCandless & Ruiz 1990, Ruiz & McCandless 1990, Hart & Kinloch 1989), U Ungava Ni-sulfide ore (Luck & Allègre 1984), KWP Keweenaw picrites (Shirey & Carlson 1991), G Gorgona komatiites (Walker *et al.* 1991b), QCC Quill Creek Complex (Wellgreen deposit) (Marcantonio *et al.* 1991), SIC Sudbury Igneous Complex (Walker *et al.* 1991a), osmiridium alloys (from youngest to oldest: Borneo, Columbia, Tulameen, B.C., Australia, Japan, Tasmania and Witwatersrand, RSA) (Allègre & Luck 1980, Hattori *et al.* 1991, Hattori & Hart 1991, Hart & Kinloch 1989), Noril'sk-Talnakh, Russia (Horan *et al.* 1991, Walker *et al.* 1992), mantle peridotites: S.W. Indian Ridge, Zabargad Island (Red Sea), Zambales ophiolite, Philippines, Kaapvaal craton, RSA and Ronda Complex, Spain (Martin 1991, Reisberg *et al.* 1991, Walker *et al.* 1989), modern basalts, Hawaii, Iceland, East Pacific Rise (Martin 1991). The two broken curves in the lower half of the diagram represent the osmium isotopic evolution of the mantle. 1) The lower curve (ALM) is the evolution curve for the mantle source of osmiridium alloys based on the findings of Allègre & Luck (1980), recently published data of Hattori *et al.* (1991), Hattori & Hart (1991) and Hart & Kinloch (1989); 2) the upper curve passes through the meteorite initial composition at 4.55 Ga (Luck & Allègre 1983, Walker & Morgan 1989) and undifferentiated mantle follows an Os isotopic evolution with $^{187}\text{Re}/^{186}\text{Os}$ of 3.3, giving a present-day $^{187}\text{Os}/^{186}\text{Os}$ of 1.06, which is typical of present-day values measured for carbonaceous chondrites (Walker & Morgan 1989).

Rankin Inlet samples (R) have been plotted in Figure 6 to facilitate comparison with other mineralized and unmineralized ultramafic and mafic bodies. Figure 6 shows the osmium isotopic evolution of the mantle and the isotopic composition of various mag-

matic rocks and ores at a given time, based on a compilation of available Re-Os isotope data to date. The lower curve (ALM) is the evolution curve for the mantle source of osmiridium alloys based on the findings of Allègre & Luck (1980) and recently published

data of Hattori *et al.* (1991), Hattori & Hart (1991) and Hart & Kinloch (1989). The upper curve passes through the meteorite initial composition at 4.55 Ga (Luck & Allègre 1983, Walker & Morgan 1989). The undifferentiated mantle follows an Os isotopic evolution with $^{187}\text{Re}/^{186}\text{Os}$ of 3.3, giving rise to a present-day $^{187}\text{Os}/^{186}\text{Os}$ of 1.06, which is typical of present-day values measured for carbonaceous chondrites (Walker & Morgan 1989).

The Munro Township komatiites (Walker *et al.* 1988) have ϵ_{Nd} values of +2 to +3, indicating a *LREE*-depleted mantle source-region for these magmas. The Re-depleted nature of the Munro samples is demonstrated in Figure 6, as well as by their negative γ_{Os} values. It is possible that the *LREE* depletion was accompanied by depletion in Re as a result of melt extraction. The existence of a Re- and *LREE*-depleted mantle in the source region for the Stillwater Complex (SWC) ultramafic series (which hosts the G-chromite layer) has been suggested by Lambert *et al.* (1989). It is probable that magmas from these early times could be derived from either depleted or chondritic sources. Mantle peridotites derived from both suboceanic and subcontinental mantle (Martin 1991, Reisberg *et al.* 1991, Walker *et al.* 1989) would appear to have been derived from a reservoir that was relatively Re-depleted since Precambrian time (Fig. 6).

The chondritic to slightly Re-depleted nature of most pristine mantle-derived magmas establishes a baseline from which one can interpret the Re-Os isotope systematics in other ultramafic and mafic bodies, and to evaluate the potential of Os isotopes as an exploration tool to characterize contaminated magmas, which have a greater potential to produce Ni - Cu \pm PGE deposits than uncontaminated magmas. The Re-enriched nature of the Rankin Inlet komatiite clearly distinguishes it from the sulfide-barren, age-equivalent, Re-depleted Munro Township komatiites examined by Walker *et al.* (1988). Figure 6 suggests that mafic-ultramafic intrusions that host ore-grade Ni-Cu-PGE mineralization have anomalous to extreme $^{187}\text{Os}/^{186}\text{Os}$ ratios (Re-enriched) regardless of age. Examples include the Quill Creek Complex (QCC), which hosts the Wellgreen Ni-Cu deposit (Marcantonio *et al.* 1991), the Noril'sk-Talnakh deposit (Horan *et al.* 1991, Walker *et al.* 1992), Ungava (U) (Ungava or Cape Smith ore, Luck & Allègre 1984), the Bushveld Igneous Complex (BIC) (McCandless & Ruiz 1990, Ruiz & McCandless 1990, Hart & Kinloch 1989), the Stillwater Complex (SWC) (Martin 1989, Lambert *et al.* 1989) and the Sudbury Igneous Complex (SIC) (Walker *et al.* 1991a). Unmineralized ultramafic rocks and chromitites from the 2745 ± 5 Ma stratiform Bird River Complex (BRC), Manitoba (analyzed at the GSC by isotope dilution and ICP-MS) have higher $^{187}\text{Os}/^{186}\text{Os}$ ratios than contemporaneous mantle. Two small Ni-Cu deposits occur at the base of this large stratiform intru-

sion, approximately 8 km along strike from the site of the samples reported in this study.

Many of the economic ores in these mafic-ultramafic bodies (Fig. 6) are hosted in the gabbroic or more feldspathic portions of the intrusions, and contain the highest $^{187}\text{Os}/^{186}\text{Os}$ values. One of the most unusual features of these intrusions is the more chondritic character (lower $^{187}\text{Os}/^{186}\text{Os}$ ratios) of the barren to weakly mineralized ultramafic portions. Such a relationship may imply that the gabbros and contained sulfides have elevated $^{187}\text{Os}/^{186}\text{Os}$ ratios owing to assimilation of crustal material, as the sulfur-isotope and S/Se data from many of these intrusions suggest, whereas the magmas that gave rise to the ultramafic rocks have not interacted significantly with the crust and thus retain a nearly chondritic character. If this is the case, it seems clear that significant degrees of crustal contamination are required to generate ore-grade sulfide and PGE deposits. This may also have petrogenetic implications concerning the origin of feldspathic (gabbroic) sequences in stratiform intrusions. Could it be that the later gabbroic differentiates represent nothing more than ingressions of more contaminated coeval magma with an initial composition not unlike that which gave rise to the underlying ultramafic sequence, rather than new magma derived from partial melting of a different source? Whatever the genetic explanation, intrusions hosting economic concentrations of Ni-Cu and PGE mineralization have a significantly higher $^{187}\text{Os}/^{186}\text{Os}$ value than the chondritic mantle of the same age.

SUMMARY AND CONCLUSIONS

- (1) Chondrite-normalized PGE + Au profiles for 100% sulfide suggest that the Rankin Inlet parental magma had komatiitic characteristics.
- (2) A study of Re-Os isotope geochronology of the Rankin Inlet Ni-Cu-PGE ores demonstrates that the mineralization and host intrusion are Archean in age. The data represent the first Re-Os isochron determined by ICP-MS instrumentation.
- (3) The positive γ_{Os} values, along with high As contents and S/Se ratios of associated ores, support the hypothesis that the Ni-Cu-PGE sulfide ores formed in response to sulfide saturation resulting from assimilation of sulfidic sediments.
- (4) Massive sulfides from the Rankin Inlet Ni-Cu-PGE deposit demonstrate a high degree of PGE fractionation as the sulfide melt evolved during the early magmatic history of the deposit.
- (5) Metamorphism and postconsolidation processes have not had a large influence on the Re-Os isotope systematics of this deposit.
- (6) A compilation of Re-Os isotope data from the literature suggests that mafic and ultramafic bodies that host economic concentrations of Ni, Cu and PGE have elevated $^{187}\text{Os}/^{186}\text{Os}$ values relative to chondritic

mantle of the same age.

(7) Re–Os isotopic ICP–MS investigations offer a practical and cost-effective tool for research and exploration in the investigation of mineralized mafic and ultramafic bodies. Although the method is not as sensitive nor as precise as other high-precision methods of research currently in use (SIMS, NTIMS), it could also be used as a reconnaissance research tool in a number of different mineralized geological environments (magmatic, sedimentary and hydrothermal) that are known to contain relatively high concentrations of Re and Os. Unique or aberrant systematics observed during this type of survey could be followed up by methods with higher precision in order to expand our understanding of this isotopic system.

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