The Canadian Mineralogist
Vol. 42, pp. 291-302 (2004)

THE KO ZONE: A NEW MODEL FOR PGE–Cu–Ni MINERALIZATION IN THE MARGINAL ZONE OF THE FOX RIVER SILL, NORTHERN MANITOBA, CANADA

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ABSTRACT

The Fox River Sill is a Paleoproterozoic intrusion that extends for most of the length of the >250 km long Fox River Belt in northeastern Manitoba, Canada. Previous exploration for platinum-group elements (PGE) mineralization in the sill delineated an interval several hundred meters thick of weakly and sporadically mineralized ultramafic and mafic rocks occurring in the upper part of the sill (Upper Central Layered Zone). We describe a second mineralized interval, the KO Zone, near the base of the sill (Marginal Zone). Maximum metal contents obtained to date from the KO Zone are 2.1% Cu, 0.9% Ni and 5.5 g/t combined Pd + Pt + Au. The Marginal Zone comprises the Basal Contact Unit, which is variably contaminated and contains gabbro, melagabbro and lherzolite, overlain by two cyclic units (Cyclic Unit 1, and Cyclic Unit 2) that grade from lherzolite at their base through melagabbro, gabbro, leucogabbro and, locally, anorthosite. The KO Zone occurs at the contact between Cyclic Units 1 and 2 and locally contains disseminated, Cu-, Ni- and PGE-rich sulfide mineralization. The KO Zone features a discontinuous, coarse-grained actinolite-bearing olivine websterite unit, and an overlying medium-grained lherzolite that locally hosts irregularly shaped varitextured gabbro pods. The basal contact of the KO Zone is undulatory and scalloped, with sulfides being concentrated in trough structures. The mineralization is interpreted to have formed in a two-stage process. (1) Early deposition of immiscible magmatic sulfides at the base of Cyclic Unit 2. (2) Upgrading of PGE tenors of the sulfides by interaction with upward migrating, PGE- and volatile-rich intercumulus melt derived from the underlying Cyclic Unit 1.

Keywords: Fox River Sill, KO Zone, platinum-group elements, nickel, copper, model, soft deformation, fluids, Manitoba.

SOMMAIRE

Le filon-couche de Fox River, d'âge paléoprotérozoïque, s'étend sur presque toute la longueur de la ceinture de Fox River dans le nord-ouest du Manitoba, au Canada, c'est-à-dire sur plus de 250 km. Les programmes d'exploration antérieurs, ciblés sur les éléments du groupe du platine, ont délimité un intervalle de plusieurs centaines de mètres en épaisseur dans la partie supérieure du filon-couche, sur lequel les roches mafiques et ultramafiques sont faiblement et sporadiquement minéralisées. Nous décrivons un deuxième intervalle minéralisé, la zone KO, située près du contact inférieur du filon couche (zone limitrophe). Les teneurs maximales en métaux obtenues de la zone KO à date sont: 2.1% Cu, 0.9% Ni et 5.5 g/t de Pd + Pt + Au combinés. La zone limitrophe du filon-couche comprend le contact inférieur, les roches (gabbro, mélagabbro et lherzolite) variablement contaminées, et deux unités cycliques (1 et 2) qui vont de lherzolite à leur base à mélagabbro, gabbro, leucogabbro et, localement, anorthosite. La zone KO se situe entre les unités cycliques 1 et 2, et contient ici et là des produits disséminés de minéralisation en Cu, Ni et éléments du groupe du platine. Elle contient une couche discontinue à grains grossiers de websterite à olivine et à actinolite, et une

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couche supérieure de lherzolite à granulométrie moyenne qui renferme des lentilles de forme irrégulière de gabbro à texture variable. Le contact inférieur de la zone KO est ondulant et festonné, et les sulfures sont concentrés dans les structures en auge. La minéralisation se serait formée par un processus à deux étapes. (1) Déposition précoce d'un liquide sulfuré immiscible à la base de l'unité cyclique 2. (2) Enrichissement des sulfures en éléments du groupe du platine par interaction avec un liquide intercumulus enrichi dans ces éléments et en phase volatile, migrant vers le sommet de la séquence et issu de l'unité cyclique 1 sous-jacente.

(Traduit par la Rédaction)

Mots-clés: filon-couche de Fox River, zone KO, éléments du groupe du platine, nickel, cuivre, modèle, déformation plastique, phase fluide, Manitoba.

Introduction

The Fox River Sill, in northern Manitoba, is a predominantly ultramafic layered intrusion with a true thickness of up to 2 km at the present erosional level, and an age of $1882.9^{-1.4}{}_{+1.5}$ Ma (Heaman *et al.* 1986). The sill has undergone a single lower-greenschist to subgreenschist-grade metamorphic event related to burial by the Upper Volcanic Formation (Scoates 1981). The sill, which intrudes argillaceous metasediments (Scoates 1990), is subdivided into four main stratigraphic units: from stratigraphic base to top, these are (1) the Marginal Zone, (2) the Lower Central Layered Zone, (3) the Upper Central Layered Zone, and (4) the Hybrid Roof Zone. The Marginal Zone, described in detail below, is 275 meters thick and is absent in some parts of the sill (Scoates 1990). The 850-m-thick Lower Central Layered Zone contains nine or more cyclic units composed of thick layers of olivine cumulate overlain by thinner layers of clinopyroxene cumulate. The Upper Central Layered Zone, approximately 900 meters thick, is distinguished from the underlying rock by the presence of plagioclase cumulates and cyclic units having a wider range in rock types. The base of this zone comprises three intervals containing anomalous concentrations of the platinum-group elements (PGE) (>100 ppb) over a total thickness of 135 meters (Scoates & Eckstrand 1986, Schwann 1989, Naldrett *et al.* 1994, Peck *et al.* 2002). The Hybrid Roof Zone attains a thickness of 100 meters, and contains granophyre and discrete grains of quartz (Scoates 1990). The Fox River Sill is interpreted to have behaved as an open system for most of its history. For example, the composition of cumulate rocks within the sill, taken as a whole, is much too primitive to be accounted for by the evolution of the magma in a closed system.

The Great Falls area on the Fox River provides a rare, well-exposed section through the lower part of the sill and the upper part of the Lower Volcanic Formation in the western part of the Fox River Belt (Fig. 1). In 1999, a new PGE–Cu–Ni occurrence, the KO Zone, was recognized in the Great Falls area by Falconbridge Limited geologist Kevin Olshefsky. Results obtained from detailed mapping and chemostratigraphic studies are summarized below and provide constraints on the genesis and economic potential of this mineralization. A more complete review of the geology and geochemistry of the Fox River Belt and Fox River Sill is provided by Peck *et al.* (2002).

In this paper, we consider all of the observed field characteristics as well as geological and geochemical relationships as a means of constraining a model for the mineralization of the KO Zone. The mineralization appears to be the result of cumulus and post-cumulus processes operating together to form PGE–Cu–Ni-rich sulfides. We provide criteria that could be used to recognize similar mineralization in other layered intrusions.

Geology of the Marginal Zone

As observed in the Great Falls study area, the intrusive complex was emplaced into pyrite-bearing argillites and siltstones of the Middle Sedimentary Formation; these rocks are metamorphosed to hornfels within several meters from the base of the sill (Scoates 1990). The Marginal Zone comprises three main subunits in the Great Falls area, but is known to be absent in some sections of the sill. The lowermost lithology is the Basal Contact Unit, which contains xenoliths and partial melts derived from the underlying Middle Sedimentary Formation (Peck *et al.* 1999). The Basal Contact Unit is overlain by the ~100-m-thick Cyclic Unit 1, which grades from lherzolite (UM1) at its base through websterite, melagabbro, gabbro, leucogabbro and, locally, anorthosite at its top (LG1) (Huminicki 2000). Cyclic Unit 2, also about 100 m thick, is interpreted to have been generated from a separate pulse of magma that was intruded before Cyclic Unit 1 was fully solidified (Desharnais *et al.* 2000). Cyclic Unit 2 was formed from a pulse of magma that was sulfide-saturated, as shown by the presence of magmatic sulfides throughout much of the unit. The KO Zone occurs at the contact between leucogabbro and anorthosite from the top of Cyclic Unit 1 (LG1) and ultramafic rocks at the base the Cyclic Unit 2 (UM2). Above the KO Zone, Cyclic Unit 2 grades into several meters of lherzolite (UM2). The lherzolite is a fine- to medium-grained olivine cumulate containing both clinopyroxene and orthopyroxene oikocrysts and, locally, disseminated sulfides (<1%). The lherzolite unit grades upward into a dm-

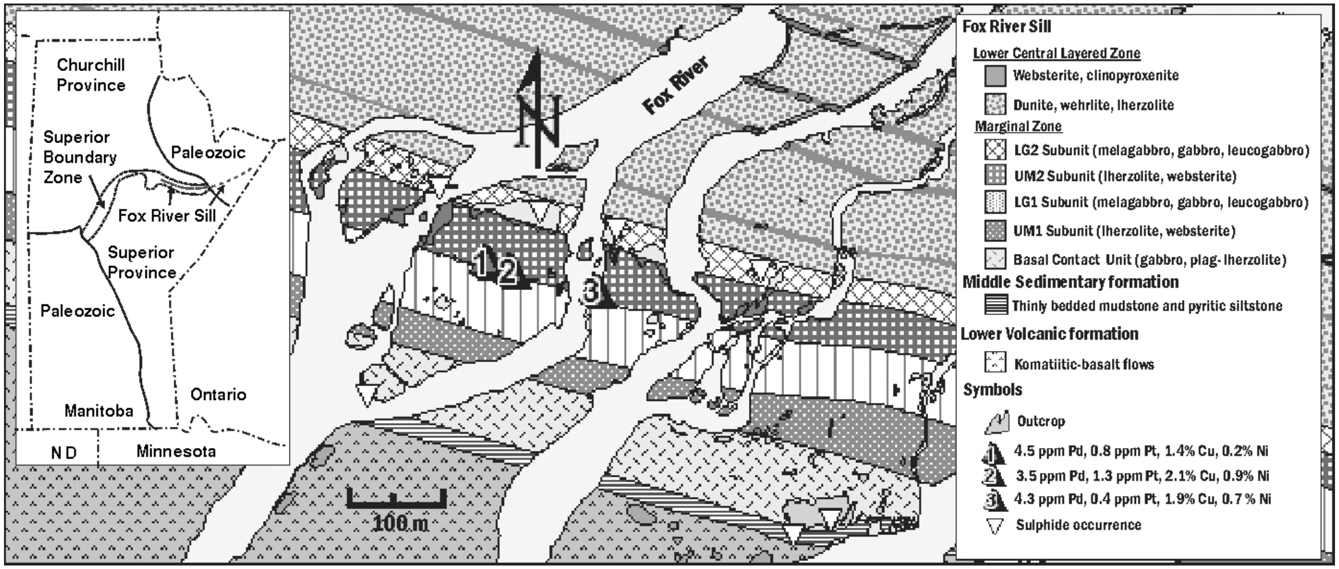

FIG. 1. Geological map of the Great Falls area on the Fox River. Numbered triangles show locations of mineralized samples of the KO Zone. Locations 1 and 2 are examples of the mineralization found in the basal websterite, whereas location 3 is an example of a mineralized pod of varitextured gabbro near the top of the KO Zone.

scale layered sequence, comprising lherzolite, melagabbro and gabbro, which is in turn overlain by massive gabbro and leucogabbro that correspond to the LG2 subunit. Up to 15% disseminated pyrrhotite and chalcopyrite having low tenors of the PGE are present in the LG2 subunit (Peck *et al.* 1999).

GEOCHEMISTRY OF THE MARGINAL ZONE

Olivine compositions within the Marginal Zone suggest that the parental magma had an Mg content from 12 to 16% MgO (Osiowy 2000). Table 1 contains information on a selection of samples intended to represent the typical composition of each unit within the Marginal Zone. Geochemical relationships and the paucity of magmatic sulfides observed in outcrop suggest that the contact between Cyclic Units 1 and 2 reflects a major shift from a sulfide-undersaturated magma below to a sulfide-saturated magma above (Huminicki 2000). Upward buildup of Pd and Cu values in Cyclic Unit 1 reflects the incompatibility of the chalcophile metals in a sulfide-undersaturated system (Peck *et al.* 2002). The differing behavior of Cu and the PGE in Cyclic Unit 1 *versus* Cyclic Unit 2 is well illustrated in Figure 2. The positive trend in Figure 2a and 2b reflects the sulfide-undersaturation of Cyclic Unit 1, causing these elements to behave incompatibly and to become concentrated in the residual magma.

The geochemical data illustrate several trends that reflect the heterogeneous nature of the Basal Contact Unit, as well as the similar yet distinct geochemistry of Cyclic Unit 1 and Cyclic Unit 2 (Fig. 3). Values of magnesium number (Mg# = 100Mg/Mg + Fe^{2+}) for the Marginal Zone generally range from 50 to 76. These values are lower than maximum Mg# values calculated for other parts of the sill, particularly the Lower Central Layered Zone, which has an average Mg# of approximately 87. The Mg content of the various lithologies within the Marginal Zone ranges from 6% to 33% MgO, with values covering almost the entire spectrum (Fig. 3b). The transition from lherzolite to gabbro between Cyclic Units 1 and 2 is relatively sharp. The wider range in Mg concentrations within UM2 is related to the decimeter-scale layered sequence described above.

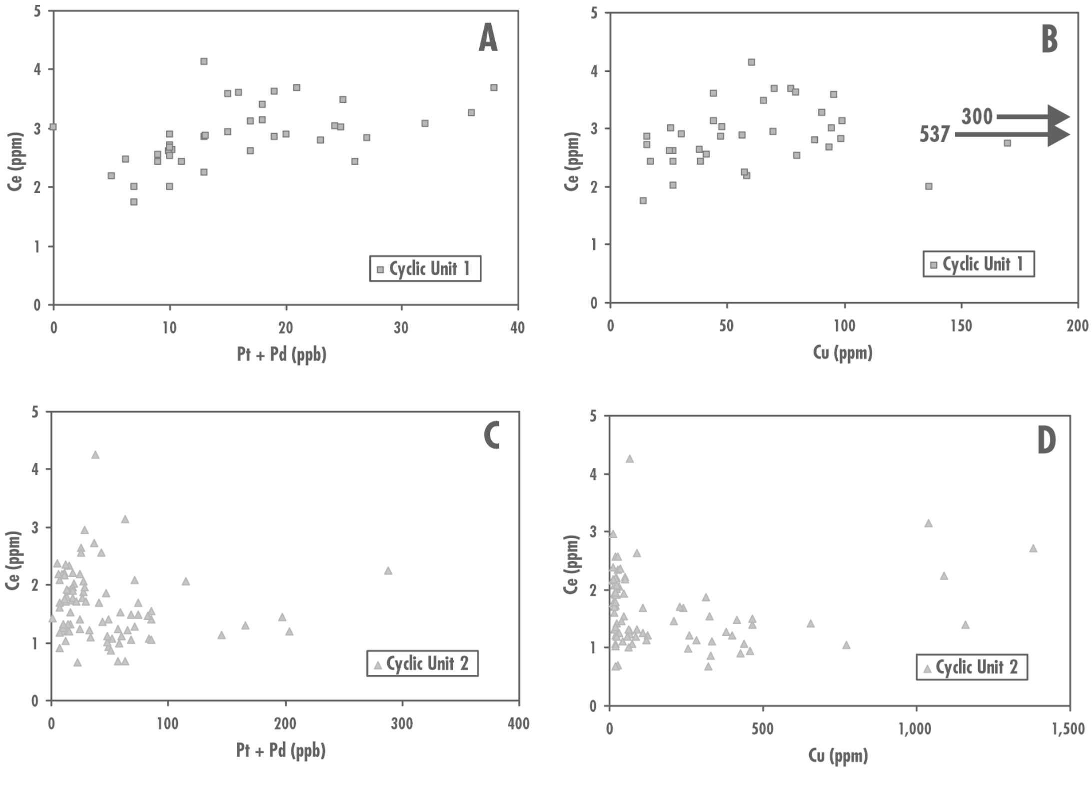

FIG. 2. Harker-type diagrams illustrating the behavior of chalcophile elements in the Marginal Zone of the Fox River Sill. A and B show data from Cyclic Unit 1; C and D are from Cyclic Unit 2 (excluding samples from the KO Zone).

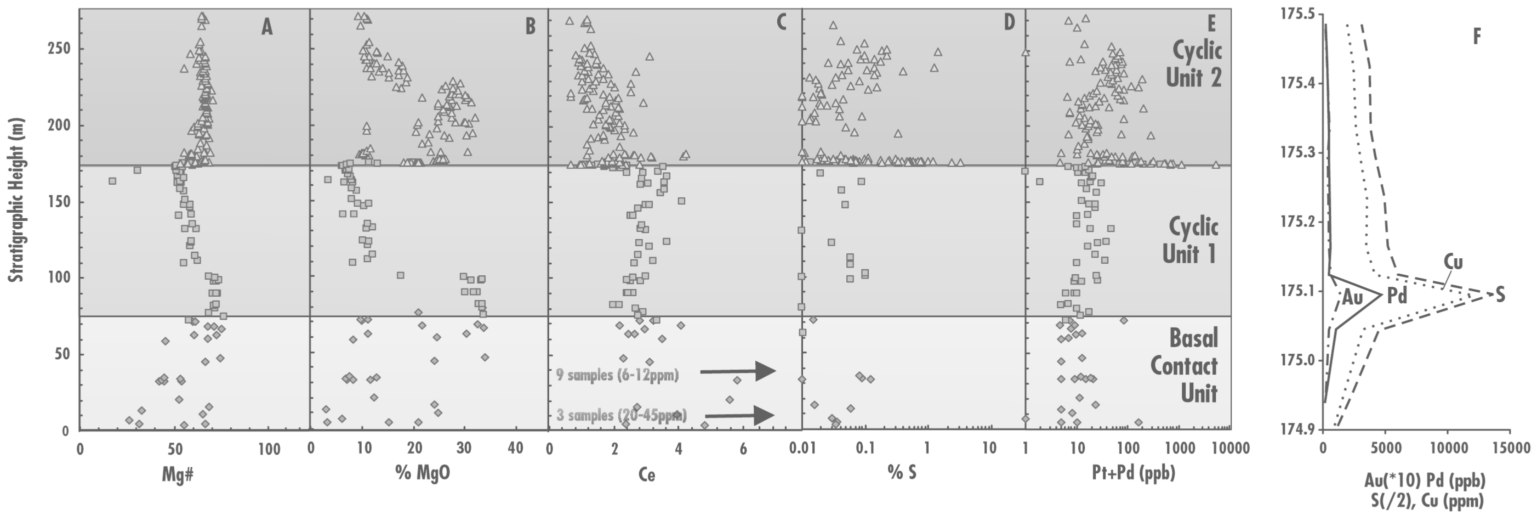

FIG. 3. Chemostratigraphic plots of the Marginal Zone, where stratigraphic height is measured from the base of the Fox River Sill. These data represent a compilation of samples collected in the Great Falls area, projected onto a single section line. A. Mg# = 100*[MgO/(MgO+FeO)]. B. MgO (%). C. Several samples within the Basal Contact Unit have Ce concentrations that plot outside the limits of this plot. D. Samples with S values below the 0.01% detection limit were assigned an arbitrary value of 0.01%. E. Pt +Pd. F. Stratigraphic section of the basal portion of the KO Zone; Au values were multiplied by ten, and S concentrations were divided by two.

The highest Cr concentrations occur at the base of the first cyclic unit, with values up to 3390 ppm Cr. The loss on ignition of samples from the Marginal Zone ranges from 1.0% to 9.6%; this range is due to the presence of a serpentine-group mineral replacing olivine.

The Mg# value and the concentration of Ce, chosen to highlight trace-element concentrations, are highly variable within the Basal Contact Unit (Figs. 3a, c). Some of the samples of the Basal Contact Unit have very high concentrations of Ce, suggesting contamination by a light-rare-earth-element-enriched lithology. Trace-element patterns and Nd and Hf isotopic compositions support this (Desharnais *et al.* 2002). A likely contaminant is the Middle Sedimentary Formation, in which the Ce concentrations range from 12 to 66 ppm. Cyclic Unit 1 has a trend of decreasing Mg# with increasing stratigraphic height, which is what would be expected from the process of normal differentiation in a closed system (Figs. 3a, b). This trend is supported by Ce concentrations, which increase with increasing stratigraphic height (Fig. 3c). Cyclic Unit 2, on the other hand, seems to have been continuously replenished by a depleted magma, as shown by the Mg#, which decreases only slightly with increasing height, and the Ce concentrations, which decrease upward. The system thus became open at some point during the formation of Cyclic Unit 2.

TABLE 1. THE COMPOSITION OF REPRESENTATIVE SAMPLES FROM EACH OF THE UNITS WITHIN THE MARGINAL ZONE OF THE BIRD RIVER SILL, MANITOBA

	1	2	3	4	5	6	7	8
SiO_2 wt.%	78.10	50.35	48.42	47.78	47.24	49.97	43.11	47.33
Al_2O_3	9.75	16.49	10.25	16.57	3.56	15.82	8.45	13.16
Fe_2O_3	3.91	9.67	11.60	5.72	15.56	6.62	11.65	6.81
MnO	0.02	0.11	0.20	0.10	0.18	0.12	0.15	0.12
MgO	1.49	8.02	14.50	10.56	18.05	9.25	23.12	12.74
CaO	0.33	6.73	8.00	14.88	10.59	10.99	7.30	14.61
Na_2O	3.09	3.18	2.01	1.73	0.16	2.67	0.22	1.34
K_2O	1.79	1.82	0.68	0.44	0.05	0.87	0.08	0.60
TiO_2	0.29	0.79	0.57	0.19	0.38	0.75	0.27	0.21
P_2O_5	0.05	0.10	0.05	0.02	0.04	0.15	0.02	n.r.
S	0.37	0.01	n.r.	0.01	2.37	0.01	0.05	0.19
LOI	1.37	2.52	7.39	2.06	3.92	2.94	5.71	2.83
Total	100.22	99.78	99.58	100.04	99.72	100.23	100.08	100.13
Cu ppm	61.7	58.8	53.0	436.0	13566.0	56.2	32.5	328
Ni	20.3	114	1089.0	250.1	2037.0	123.5	654.2	268
Zn	14.8	164	59.0	47.2	166.3	27.0	43.1	32
Co	14.1	52	87.0	40.5	161.2	26.9	99.2	39
Cr	111.0	283	2520.0	1060.0	376.5	100.7	1700.0	561
V	137.0	273	119.1	119.3	178.1	183.2	126.4	133
Au ppb	n.a.	2	2.0	2.0	132.7	8.0	2.0	7
Pt	n.a.	3	3.0	8.0	835.8	71.0	17.0	13
Pd	n.a.	6	10.0	13.0	4530.0	68.0	10.0	38

Samples: 1. GMD-01-003: sulfidic siltstone from the Middle Sedimentary Formation; 2. 98-99-311-5: hornblende gabbro from the Basal Contact Unit; 3. 98-99-243-3: lherzolite from UM1; 4. 98-99-250-19: leucogabbro from LG1; 5. 98-00-011-M1A-C: olivine websterite from the KO Zone; 6. 98-00-011-M3BC: varitextured gabbro from the KO Zone; 7. 98-99-312-11: plagioclase lherzolite from UM2; 8. 98-00-006-1Z: gabbronorite from LG2. Total iron is expressed as Fe_2O_3. Analyses were made by by Activation Laboratories, Ancaster, Ontario. Abbreviations: n.r.: no response, n.a.: not analyzed.

The KO Zone

Detailed mapping of bush and river outcrop areas has delineated a heterogeneous sequence of mineralized (PGE–Cu–Ni) ultramafic and mafic rocks referred to as the KO Zone (Fig. 4) (Desharnais *et al.* 2000). The KO Zone is several meters thick, and is the stratigraphically lowermost interval in the sill to contain significant amounts of sulfides and elevated PGE concentrations (Figs. 3d, e). The base of the KO Zone is represented by an irregular, commonly scalloped and undulating contact between gabbroic to anorthositic rocks of the LG1 subunit and coarse-grained actinolite-bearing olivine websterite of the KO Zone (base of UM2 subunit) (Fig. 5). The cause of the irregular contact appears to be soft deformation that occurred early in the evolution of the cumulate pile. Similar relationships have been recognized in other intrusions at the contact between cyclic units, specifically the Klokken Intrusion in Greenland and the Bushveld Complex in South Africa (Parsons & Butterfield 1981, Lee 1981, Parsons & Becker 1987). Alternatively, it could represent small-scale erosional features related to magmatic currents (Desharnais *et al.* 2000). It would seem extremely difficult to produce erosional channels on such a small scale (as little as 10 centimeters), as well as some of the more fluidal structures that protrude laterally into the leucogabbro of LG1 (see left-hand side of Fig. 4).

The olivine websterite layer ranges from <1 to 3 m in thickness. It typically contains net-textured, blebby, and disseminated sulfides concentrated within dm- to m-scale trough structures along the irregular LG1–UM2 contact. The mineralized websterite is typically one meter thick and generally decreases upward in grain size (2 to <0.5 cm) and sulfide content (15 to <1%) (Desharnais *et al.* 2000). Chalcopyrite is the dominant sulfide, attaining a maximum concentration of 15% near the bottom of some of the troughs. The layer of websterite contains up to 10% fine-grained gabbroic material occurring as pockets (up to 5 cm wide) or interstitially between the large grains of pyroxene. Actinolite makes up approximately 15% of the rock, as a secondary mineral replacing olivine and augite (Fig. 6). The grain shadow that is preserved within amphibole in Figure 6a indicates that the grain of olivine had a shape and size comparable to that of olivine within the overlying lherzolite. Figure 6b gives an idea of the timing of replacement; the amphibole seems to have replaced the grain of augite while chalcopyrite was still a melt (*i.e.*, before the magma had completely crystallized). These textures are taken to represent disequilibrium between an olivine augite cumulate and a more evolved intercumulus melt. The presence of orthopyroxene and accessory ilmenite in the websterite represents a significant change in the normal order of crystallization (olivine → clinopyroxene → plagioclase → orthopyroxene) that is commonly observed in the mafic and ultramafic rocks in the Fox River Belt (Scoates 1990, Desharnais *et al.* 2000).

Within the mineralized portion of the KO Zone, there is an apparent decrease upward in Cu, Ni, S, and PGE concentrations (Fig. 3f). The PGE are closely associated with the sulfides, and display a relatively good correlation with Cu and Ni concentrations (Desharnais *et al.* 2000, Peck *et al.* 2002). Given the primitive composition of Cyclic Unit 2, a Cu:Ni ratio of <1 is expected if the KO Zone mineralization represents an accumulation of an immiscible, magmatic sulfide melt (Naldrett 1989); however, the values of the Cu:Ni ratio in the KO zone are typically between 2:1 and 3:1 (Desharnais *et al.* 2000). Metal concentrations recalculated to 100% sulfide are as high as 27% Cu, 4% Ni and 110 g/t combined Pd + Pt + Au.

Crescent-shaped pods and discontinuous, meter-size layers of varitextured gabbro, diorite, leucogabbro and leucodiorite occur locally within weakly mineralized lherzolite in the upper part of the KO Zone. These pods are also commonly mineralized and locally display a normal size and compositional grading of sulfide and silicate components (Peck *et al.* 1999, Huminicki 2000). The pods are considered to reflect late-stage intercumulus magma derived from the underlying, gabbroic upper part of Cyclic Unit 1 (LG1) that ascended into the lower part of Cyclic Unit 2 (Desharnais *et al.* 2000). These pods could also represent recrystallization of parts of Cyclic Unit 2 induced by upward moving fluids.

In several areas along the contact between Cyclic Units 1 and 2, the coarse-grained olivine websterite unit is absent, as well as the varitextured gabbro pods. In these places, sulfides are present, but they are barren of Cu, Ni, or PGE.

EVALUATION OF CLASSIC MODELS

In the Bushveld Complex and in Alaskan-type intrusions, the PGE commonly are associated with chromian spinel. It is therefore postulated that chromian spinel is related to the concentrating mechanism of the PGE in these intrusions (Capobianco *et al.* 1994, Merkle 1992, Scoon & Teigler 1994, Johan 2002). Chromian

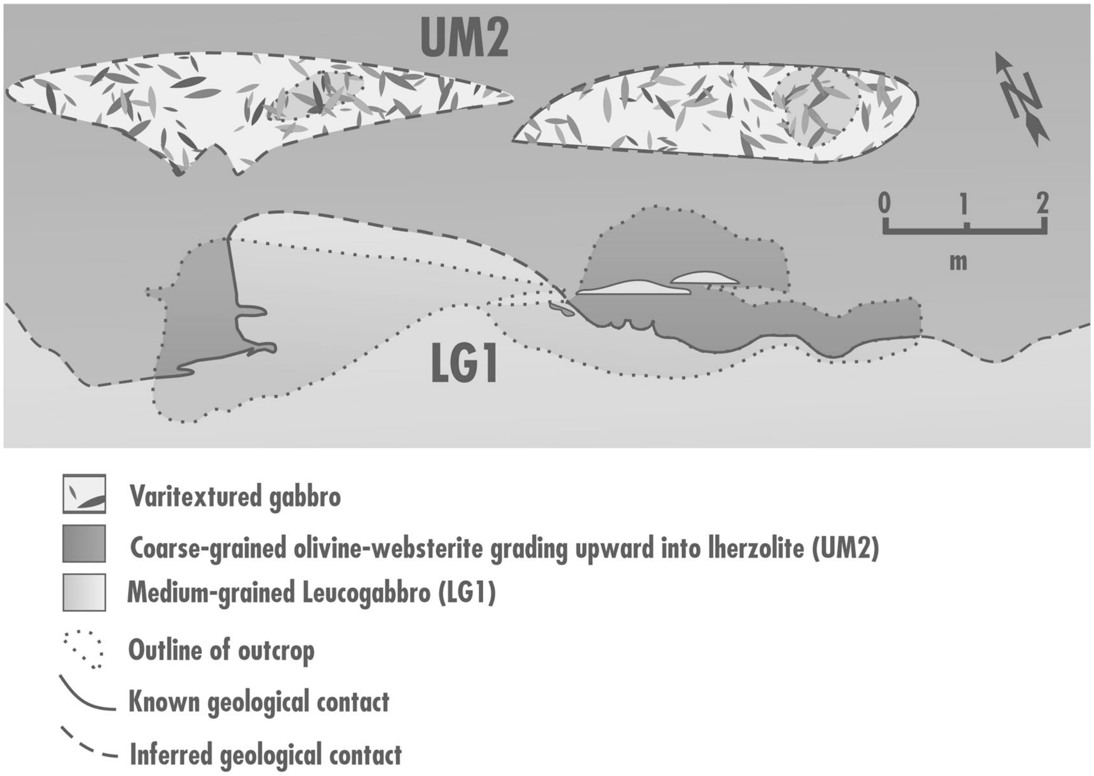

FIG. 4. Outcrop map of the KO Zone. The KO Zone is defined as the area between LG1 and the top of the pods of varitextured gabbro. Note the undulatory and scalloped contact between the leucogabbro from LG1 and the base of the KO Zone.

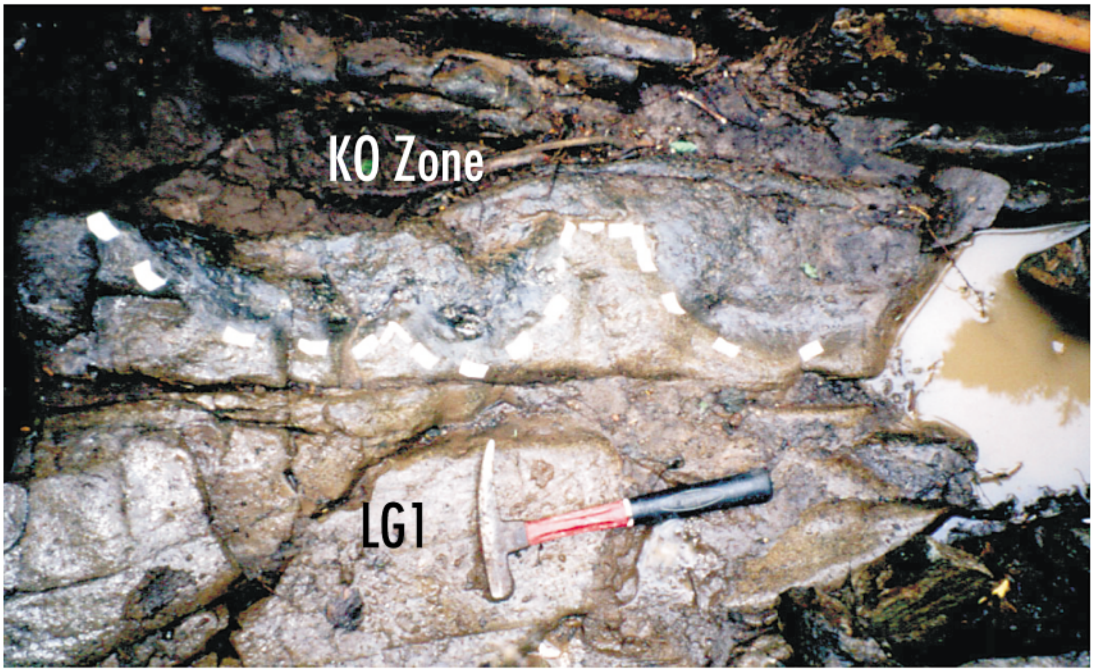

FIG. 5. Photograph of the scalloped contact between the top of LG1 and the KO Zone. The mineralization tends to be concentrated at base of the troughs. Pieces of white tape were used to help demarcate the contact.

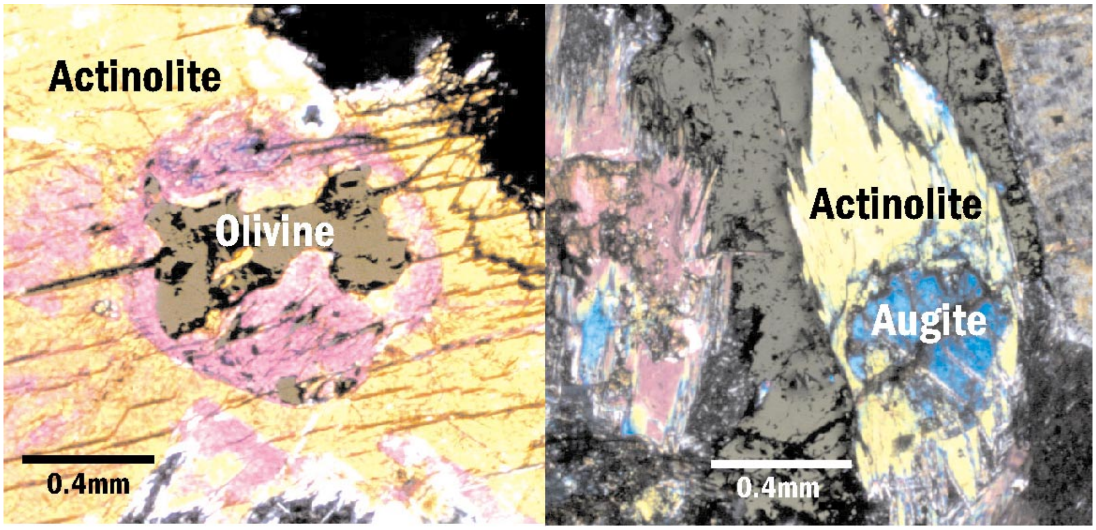

FIG. 6. Photomicrographs showing replacement textures. A. Olivine relic found in a grain of actinolite with a "grain-shadow" representing the original size and shape of the grain. B. Relict grain of augite found within an actinolite crystal that is growing into chalcopyrite.

spinel is not recognized within the KO Zone, and there is no correlation of PGE with Cr content (Fig. 7). Therefore, accumulation of chromian spinel is an unlikely candidate as a concentrating mechanism for the PGE.

The most conventionally accepted model used to explain the PGE mineralization in the Bushveld and Stillwater complexes is the one proposed by Campbell *et al.* (1983). The model, as proposed for the Bushveld complex, is that a mixing event between two magmas caused saturation in sulfides and formation of a turbulent environment. Owing to the very high partition-coefficient of PGE into sulfides, mixing of immiscible sulfide droplets with a large volume of magma would have caused them to become enriched in these elements. A 3000-m-thick column of magma above the pile of cumulates is necessary to account for the PGE tenor of the Merensky Reef (for an R factor of 10^6 and an equivalent of 3 cm of sulfide in the Merensky Reef) (Cawthorn 1999). Concentrations of the PGE within the Merensky Reef in the Bushveld Complex are also very consistent across the entire intrusion (Naldrett 1989, Cawthorn *et al.* 2002). The Marginal Zone of the Fox River Sill is considered to have formed from relatively small pulses of magma with a restricted aerial extent (Scoates 1990). With such a limited amount of magma (100–200 m), it would be difficult to scavenge sufficient amounts of the PGE to produce the observed tenors. In addition, a depletion in PGE within Cyclic Unit 2 would be expected, but this is not the case (Fig. 3e). The presence of low PGE-tenor sulfides within a few hundred meters along strike indicates that the process of enrichment is somehow of local extent. The fact that the sulfides have a high Cu:Ni ratio argues for a more evolved magma than the one that produced the lherzolite at the base of Cyclic Unit 2. On the basis of these three points, the mineralization did not occur through a process of PGE-rich sulfide droplets sinking to the top of the cumulate pile.

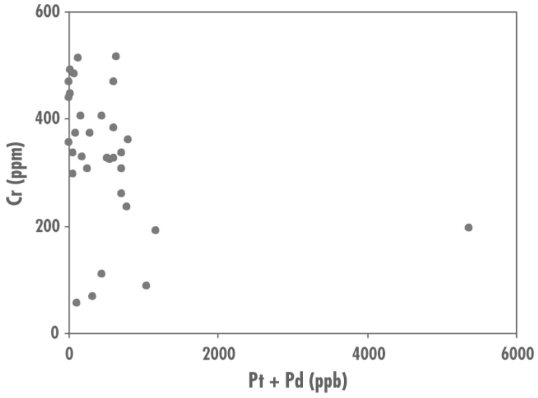

FIG. 7. Plot of Cr *versus* Pt + Pd for mineralized samples within the KO Zone.

A third model often used to explain PGE mineralization in layered intrusions imposes fluids (including a vapor phase) that move upward, scavenging PGE from underlying cumulates and depositing them along a reef horizon (Boudreau & Meurer 1999, Mathez *et al.* 1997, Willmore *et al.* 2000). Degassing of the cumulate pile below the KO Zone seems like an unlikely cause for the mineralization for two main reasons: i) the sulfide are present at the contact regardless of the presence of a pegmatitic phase, and, ii) there is no apparent vertical offset in S, Au and Cu compared with Pt and Pd (Fig. 3d), as would be expected if the metals had traveled *via* a vapor phase (as modeled by Boudreau & Meurer 1999).

The proposed model for the formation of the KO Zone is as follows:

1) A single pulse of magma is emplaced into the Middle Sedimentary Unit, which gives rise to the Basal Contact Unit and Cyclic Unit 1.

2) A second pulse of magma (represented by Cyclic Unit 2) is emplaced into the chamber above Cyclic Unit 1 before it has had time to crystallize completely. Unlike the first pulse of magma, this one was sulfide-saturated at the time of emplacement, or became sulfide-saturated soon thereafter.

3) Sulfides and an olivine–clinopyroxene cumulate from the second pulse of magma were deposited onto the crystal mush – magma interface corresponding to the top of LG1 (Fig. 8a).

4) Accumulation of the crystals caused compaction of Cyclic Unit 1 and expulsion of a volatile-rich intercumulus liquid that percolated upward through the base of the UM2 subunit (Fig. 8b). This liquid was also rich in the PGE because the system had not reached sulfide-saturation during the evolution of Cyclic Unit 1.

5) The Cu and PGE tenor of pre-existing sulfides present at the base of the UM2 subunit increased by reaction with the ascending liquid. This more evolved liquid could account for the high Cu:Ni ratio observed in the mineralized sequence.

6) The upward movement of the liquid caused the LG1–KO Zone contact to sag and become convoluted, akin to the behavior of unlithified sediments during dewatering. It also caused the base of the pile of crystals to be partially recrystallized (replacement of olivine and clinopyroxene by orthopyroxene and amphibole), and eventually led to crystallization of interstitial gabbroic material. The high volatile content of the intercumulus melt could account for the large grain-size at the base of the KO Zone (Fig. 8c).

7) The upward percolating volatile-rich intercumulus liquid appears to have ponded a few meters above the base of the UM2 subunit, to form the pods of varitextured gabbro. The pods could have resulted from trapping of the volatile-rich gabbroic liquid beneath several meters of olivine-rich cumulates (lherzolite) that acted as an impermeable or reactive barrier. In places, the liquid may have been sufficiently sulfide-undersatu-

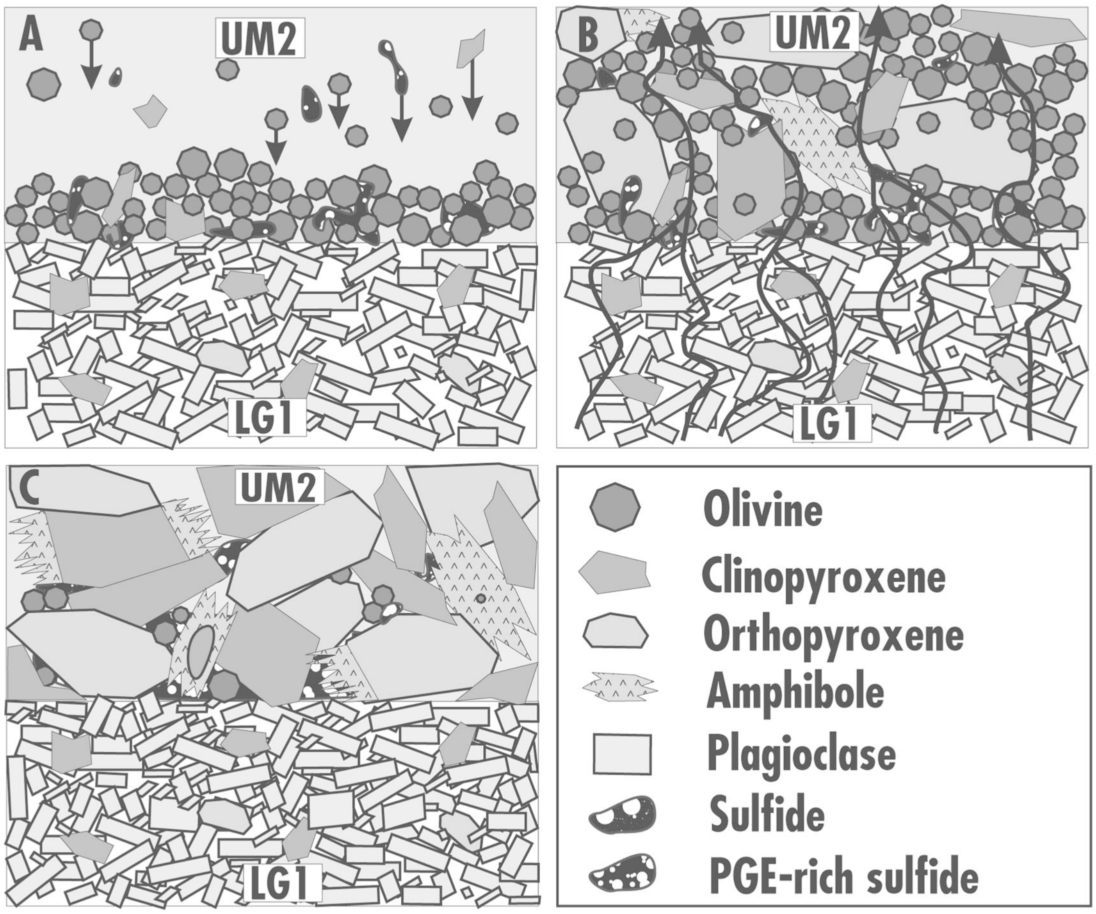

FIG. 8. Model showing the evolution of the base of the KO Zone. A. A crystal mush of leucogabbroic composition forms the top of LG1. The second pulse of magma is sulfide-oversaturated and crystallizes olivine and pyroxene on top of LG1. B. Intercumulus melt enriched in PGE and volatile components migrates upward through the crystal pile. The melt enriches the sulfides it encounters in Cu and PGE and recrystallizes olivine and pyroxene to amphibole. C. The base of the KO Zone is the most highly replaced and has the coarsest grain-size.

rated to dissolve the sulfides at the contact and reprecipitate them within the pods. Alternatively, the sulfides could have been physically transported upward by the percolating melt.

DISCUSSION

The model described above is similar to that proposed by Vermaak (1976) and von Gruenewaldt (1979) for the mineralization of the Merensky Reef in the Bushveld Complex. There are a few problems with this model, as applied to the Merensky Reef (Naldrett 1989). Firstly, there is a mass-balance problem in the case of the Merensky Reef. Assuming 20% interstitial liquid containing 15 ppb Pt, 1667 meters of underlying cumulate material would be necessary to account for the enrichment in the reef. Secondly, the intercumulus liquid would have percolated through several sulfide-rich layers, including the Pseudoreef and "tarentaal" during its ascent. These horizons should have scavenged the PGE; however, they contain low concentrations of the PGE. These inconsistencies are not valid for the KO Zone. Unlike the Merensky Reef, which has PGE grades that are very consistent along its entire length (Cawthorn *et al.* 2002), the mineralization in the KO Zone is discontinuous along strike. The mineralized areas could represent areas of high flux of liquid (*i.e.,* sections of the contact with permeability properties that caused funneling of the intercumulus melt). As well, the KO Zone is the first significant accumulation of sulfides occurring above the base of the Fox River Sill (*i.e.,* there are no horizons of barren sulfides below the KO Zone).

Conclusions

The KO Zone is a PGE-rich unit that appears to have developed through a two-stage process of immiscible sulfide accumulation and zone refining. Evidence supporting this model includes: a) the sulfides have a distribution and texture suggesting that they were deposited from the magma column onto the crystal pile of Cyclic Unit 1, b) the coarse grain-size and degree of recrystallization of the KO Zone decrease away from the basal contact with LG1, resembling a reaction zone, c) gabbroic material is present at the base of the KO Zone and the pods of varitextured gabbro a few meters above LG1, d) a high Cu:Ni ratio in the sulfides normally corresponds to compositionally more evolved magmas (*i.e.,* gabbroic as opposed to ultramafic), e) an undulatory and scalloped contact strongly resembles features produced by dewatering of sediments, or mechanical erosion, f) sulfide occurrences in the KO Zone associated with the above-noted features, which are characteristic of a high flux of melt, are enriched in PGE, and g) sulfides having a high tenor in PGE do not appear to occur in segments of the KO Zone that lack these features.

Assays obtained from grab samples of the KO Zone confirm that the sulfide mineralization is prospective for PGE, Cu and Ni. These findings, coupled with previous investigations of stratiform sulfide mineralization in the lower part of the Upper Central Layered Zone, demonstrate the significant potential for PGE deposits in the Fox River Sill. The mineralization in the KO Zone of the Great Falls area appears to lack significant lateral continuity and thickness, but the character of the Zone at more distal locations is not yet known.

The following criteria for exploration of this type of PGE–Cu–Ni mineralization can be applied to other layered intrusions. a) Identify sulfides at the contact between major cyclic units. b) Look for evidence of sulfide undersaturation in the underlying units, as well as lower-than-average (although not necessarily depleted) values. c) Determine whether evidence exists of flow of evolved liquids across the contact and through the sulfide-bearing unit (coarse grain-size, varitextured gabbro, and irregular contact relationships).

Acknowledgements

We thank Falconbridge Limited, Manitoba Industry Trade and Mines and the Natural Sciences and Engineering Research Council, for funding. Kevin Olshefsky, Michelle Huminicki and Lucy Potter provided essential geological expertise during the field programs. The authors are also very grateful to Peter Theyer, William Meurer, Anthony Beswick, and Robert F. Martin, whose constructive criticism contributed to a considerably improved final version of this paper.

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Received December 16, 2002, revised manuscript accepted August 9, 2003.