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PLATINUM-GROUP MINERALS FROM THE McBRATNEY PGE–Au PROSPECT IN THE FLIN FLON GREENSTONE BELT, MANITOBA, CANADA

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Abstract

The McBratney high-grade PGE–Au occurrence (up to 31 g/t Pd and 9 g/t Pt) is hosted by brecciated mafic–ultramafic volcanic rocks of the Bear Lake mafic unit in the vicinity of pyroxenitic–gabbroic intrusions in the Proterozoic Flin Flon greenstone belt, Manitoba. The occurrence comprises veins of massive sulfide with variable amounts of quartz, carbonate, clinochlore, chamosite, biotite, muscovite and a variety of platinum-group minerals. The sulfides are mainly chalcopyrite, pyrrhotite, pyrite, with minor violarite, pentlandite, nickeloan pyrite, marcasite, sphalerite, galena, millerite and cobaltite–gersdorffite. Magnetite, coloradoite, and Au–Ag alloy occur locally. The platinum-group minerals (PGM) include, in order of abundance: borovskite [$(Pd_{2.6}Ni_{0.35}Fe_{0.12})_{\Sigma 3.07}$ $(Sb_{1.06}Bi_{0.06})_{\Sigma 1.12}$ $Te_{3.81}$)], telluroan sudburyite [$(Pd_{0.97}Ni_{0.01}Fe_{0.02}Hg_{0.01})_{\Sigma 1.01}(Sb_{0.78}Te_{0.21})_{\Sigma 0.99}$], an unknown Pd telluride–antimonide [$(Pd_{1.72}Ni_{0.23}Fe_{0.07})_{\Sigma 2.02}(Te_{1.94}Sb_{1}As_{0.02})_{\Sigma 2.94}$], sudburyite [$(Pd_{0.94}Ni_{0.01}Fe_{0.01}Hg_{0.03})_{\Sigma 0.99}$ $(Sb_{0.95}Te_{0.06})_{\Sigma 1.01}$], sperrylite [$(Pt_{0.94}Ag_{0.01}Ni_{0.01}Fe_{0.09})_{\Sigma 1.05}As_{1.95}$], temagamite [$(Pd_{2.84}Ni_{0.15}Fe_{0.12})_{\Sigma 3.11}Hg_{0.93}(Te_{2.60}Sb_{0.35})_{\Sigma 2.95}$] and merenskyite [$(Pd_{0.97}Ni_{0.01}Co_{0.01}Fe_{0.07})_{\Sigma 1.06}(Te_{1.85}Sb_{0.08}Bi_{0.01})_{\Sigma 1.94}$]. They are commonly found as inclusions in chalcopyrite, pyrite and carbonate, and are partially replaced by cobaltite–gersdorffite. Mineralogical and textural evidence suggests that the mineralization is hydrothermal, and later than the regional metamorphic event. The PGM precipitated coevally with the Ni–Fe–Cu sulfides, chlorite–chamosite, biotite, carbonate and quartz at temperatures below 500°–550°C.

Keywords: McBratney prospect, platinum-group elements, platinum-group minerals, Ni–Fe–Cu sulfides, hydrothermal, mafic–ultramafic volcanic and intrusive rocks, Flin Flon greenstone belt, Bear Lake Block, Manitoba.

Sommaire

L'indice minéralisé en Au et en éléments du groupe du platine de McBratney (jusqu'à 31 g/t Pd et 9 g/t Pt) est situé dans des roches mafiques et ultramafiques bréchifiées de l'unité mafique de Bear Lake, près des massifs intrusifs de pyroxénite et de gabbro de la ceinture de roches vertes protérozoïques de Flin Flon, au Manitoba. A l'indice McBratney, des veines de sulfures massifs contiennent des proportions variables de quartz, carbonate, clinochlore, chamosite, biotite, muscovite, et une variété de minéraux du groupe du platine. Les sulfures principaux sont chalcopyrite, pyrrhotite, et pyrite, avec violarite, pentlandite, pyrite nickelifère, marcasite, sphalérite, galène, millerite et cobaltite–gersdorffite. Magnétite, coloradoïte, et un alliage Au–Ag sont d'importance locale. Les minéraux du groupe du platine comprennent, en ordre d'importance, borovskite [$(Pd_{2.6}Ni_{0.35}Fe_{0.12})_{\Sigma 3.07}$ $(Sb_{1.06}Bi_{0.06})_{\Sigma 1.12}Te_{3.81}$)], sudburyite tellurifère [$(Pd_{0.97}Ni_{0.01}Fe_{0.02}Hg_{0.01})_{\Sigma 1.01}(Sb_{0.78}Te_{0.21})_{\Sigma 0.99}$], un tellurure–antimoniure de Pd méconnu [$(Pd_{1.72}Ni_{0.23}Fe_{0.07})_{\Sigma 2.02}(Te_{1.94}Sb_{1}As_{0.02})_{\Sigma 2.94}$], sudburyite [$(Pd_{0.94}Ni_{0.01}Fe_{0.01}Hg_{0.03})_{\Sigma 0.99}(Sb_{0.95}Te_{0.06})_{\Sigma 1.01}$], sperrylite [$(Pt_{0.94}Ag_{0.01}Ni_{0.01}Fe_{0.09})_{\Sigma 1.05}As_{1.95}$], temagamite [$(Pd_{2.84}Ni_{0.15}Fe_{0.12})_{\Sigma 3.11}Hg_{0.93}(Te_{2.60}Sb_{0.35})_{\Sigma 2.95}$] et merenskyite [$(Pd_{0.97}Ni_{0.01}Co_{0.01}Fe_{0.07})_{\Sigma 1.06}(Te_{1.85}Sb_{0.08}Bi_{0.01})_{\Sigma 1.94}$]. On les trouve généralement en inclusions dans la chalcopyrite, la pyrite et le carbonate, et ils sont partiellement remplacés par cobaltite–gersdorffite. D'après les assemblages de minéraux et les textures, la minéralisation serait hydrothermale, et tardive par rapport à l'événement de métamorphisme régional. Les minéraux du groupe du platine ont été formés en même temps que leurs hôtes, les sulfures Ni–Fe–Cu, chlorite–chamosite, biotite, carbonate et quartz à une température inférieure à 500°–550°C.

(Traduit par la Rédaction)

Mots-clés: indice minéralisé de McBratney, éléments du groupe du platine, minéraux du groupe du platine, sulfures Ni–Fe–Cu, hydrothermal, roches mafiques–ultramafiques, roches intrusives, ceinture de roches vertes de Flin Flon, socle de Bear Lake, Manitoba.

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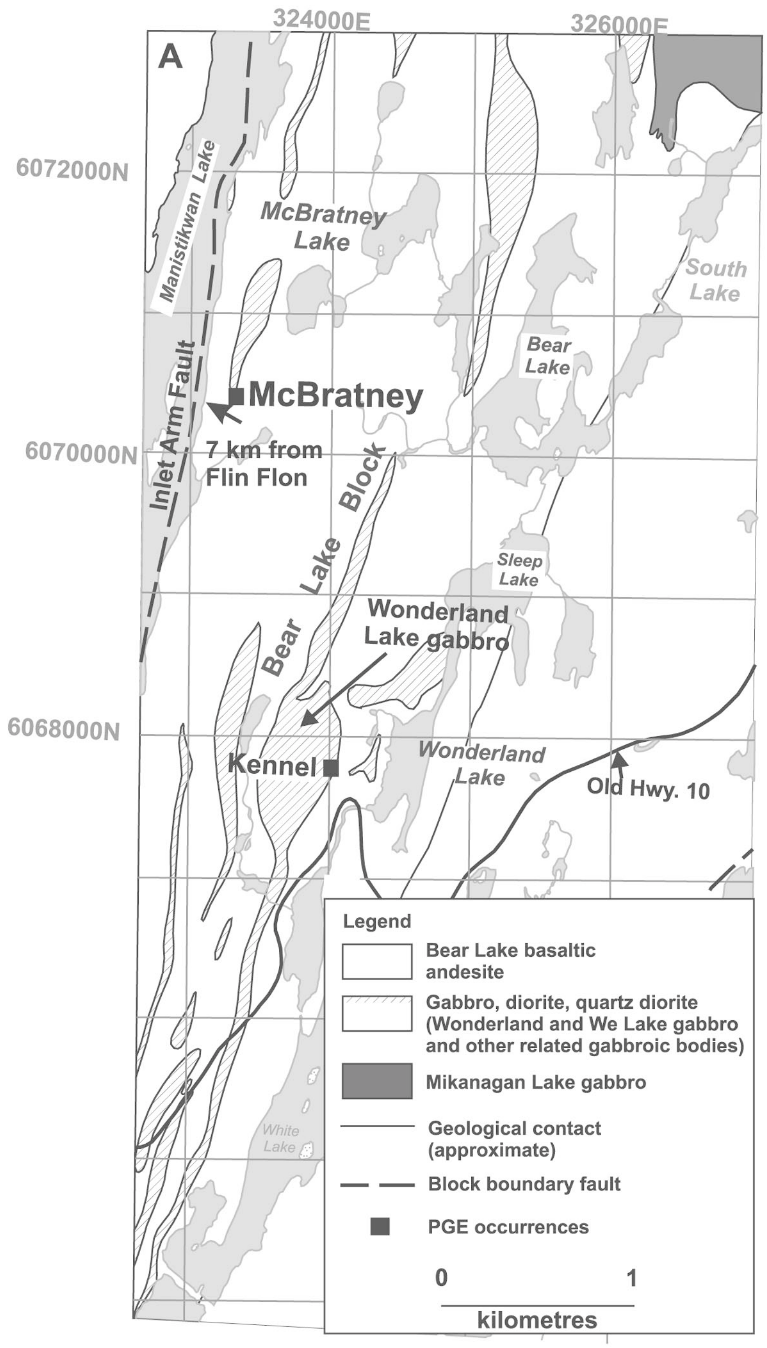
Introduction

The Flin Flon greenstone belt is recognized as the largest Paleoproterozoic volcanic-rock-hosted massive sulfide (VMS) district in the world, with production and reserves exceeding 180 million tonnes (Mt) of Zn–Cu–Au–Ag sulfide ore (Syme *et al*. 1999), exploited at the Flin Flon, Callinan, Cuprus, Trout Lake, North Star and White Lake mines. Recently, occurrences of platinum-group elements (PGE) have been discovered in the belt



(*e.g.*, McBratney and Kennel; Theyer 2001, Olivo *et al.* 2002, Theyer & Heine 2002) (Fig. 1), preferentially distributed along the contact between Proterozoic pyroxenitic and gabbroic rocks with mafic–ultramafic volcanic units. Mainly on the basis of field observations, Theyer (2001) interpreted these occurrences as "contact-type" PGE and highlighted the potential of this greenstone belt for this type of PGE deposit. In the summer of 2001, the exploration team of Fort Knox Gold stripped the high-grade PGE–Au zone on the McBratney property, found high grades up to 31 g/t Pd and 9 g/t Pt. Channel sampling was followed by detailed petrographic study and investigation of mineral compositions. Our study revealed that the high-grade samples contains a variety of palladium-bearing minerals, sperrylite and Au–Ag alloy hosted by intensively hydrothermally altered volcanic units. Our objective here is to report the textural relationship and mineral compositions of the platinum-group minerals (PGM) of the McBratney high-grade mineralization in order to further our understanding of the origin of this type of PGE–Au deposit.

Geological Setting

The McBratney PGE–Au occurrence, located approximately 7 km east of the town of Flin Flon, is hosted by the Bear Lake metamorphosed basaltic rocks in proximity of a pyroxenitic–gabbroic intrusive body interpreted to be related to the Wonderland gabbro (Theyer

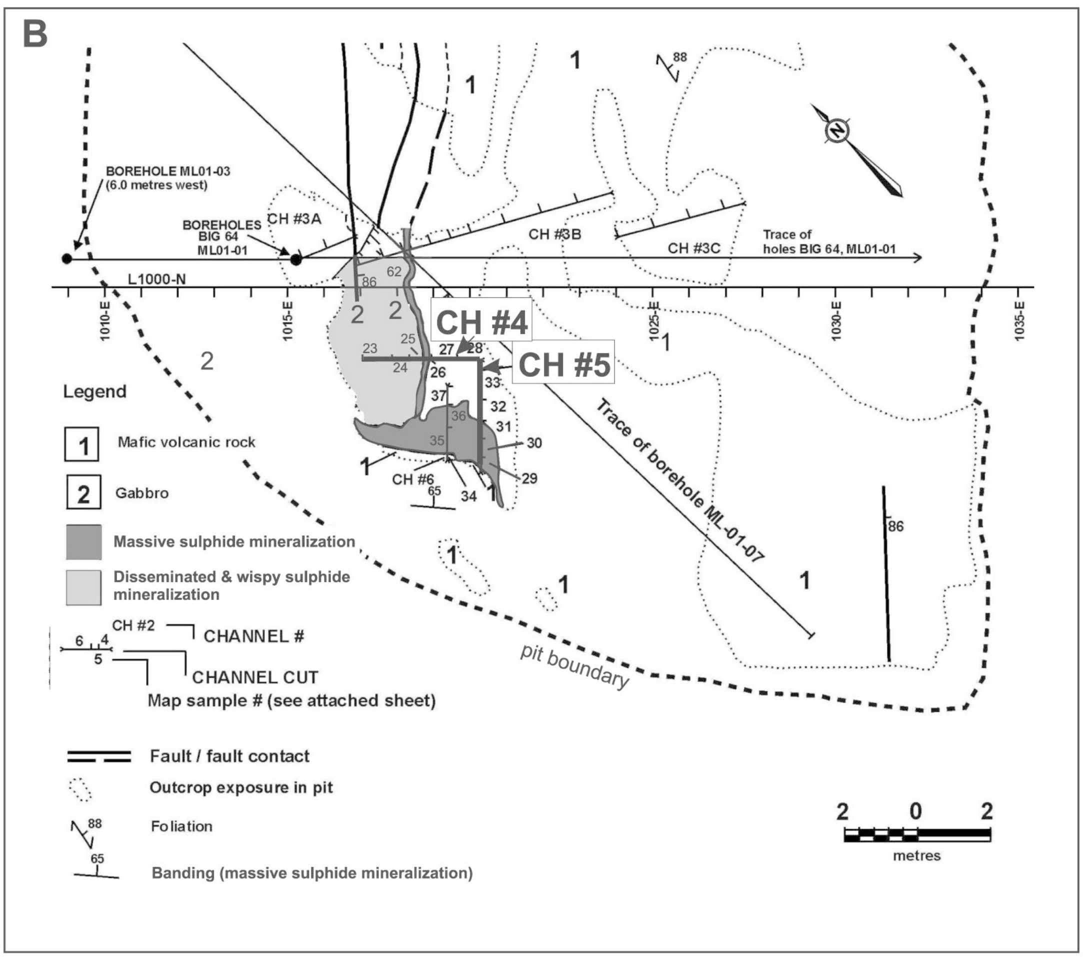


FIG. 1. A. Simplified geological map of the west part of the Bear Lake Block, showing the location of the McBratney PGE–Au occurrence, modified after Bailes & Syme (1989) and Theyer (2001). B. Simplified geological map of the southern part of the McBratney pit showing location of the samples studied (modified after Theyer 2001).

2001). These units are part of the Bear Lake Block of the Flin Flon greenstone belt (Fig. 1A; Syme *et al.* 1987, Bailes & Syme 1989, Gordon *et al*. 1989). The Flin Flon greenstone belt comprises 1.92–1.87 Ga juvenile arc and back-arc rocks and minor oceanic plateau, oceanic island-basalt and evolved plutonic rocks of arc type (Syme *et al.*1999). The Bear Lake Block is composed of juvenile arc-related rocks (Syme *et al*. 1999) grouped in eleven units (Bailes & Syme 1989), which from the base to the top are: Bear Lake basaltic andesite (3300 m thick), heterolithic breccia (150 m), Solodiuk Lake rhyolite (250 m), White Lake dacitic tuff (300 m), Little Spruce Lake andesitic lapilli tuff (350 m), mudstone and massive sulfides (25 m), Two Portage Lake ferrobasalt and rhyolite crystal tuff (200 m), Vick Lake andesitic tuff (900 m), dacite tuff (100 m) and intermediate tuff and breccia (30 m). These units form an east-facing homoclinal structure and are bounded to the west by the Inlet Arm Fault and to the east by the Northeast Arm Fault. In addition to the PGE–Au occurrences, this tectonic block hosts two Cu–Zn massive sulfide deposits (Cuprus and White Lake mines), and an Au-rich Zn massive sulfide deposit (Westfield deposit, not exploited). A total of 1.3 million tonnes of ore were produced in the Cuprus and White Lake deposits between 1948 and 1954 and between 1972 and 1980, respectively.

The Bear Lake metamorphosed ultramafic–basaltic unit, which hosts the McBratney PGE–Au occurrence (Fig. 1), consists of aphyric to pyroxene- and plagioclase-phyric lava flows, breccias with pillow fragments associated with abundant synvolcanic dikes and sills and very minor interflow tuff (Bailes & Syme 1989). In the summer of 2002, we conducted a geological survey in the vicinity of the McBratney occurrence and focused on drill cores that intercept the mineralized zones. Five distinct zones in the metamorphosed Bear Lake basaltic units were documented; they are: (1) pillow basalt, with intense epidote alteration, (2) amygdaloidal basalt with epidote alteration, (3) breccia composed mainly of pillows fragments, (4) medium-grained, mafic volcaniclastic rocks with fragments of plagioclase crystals in a clinochlore- and epidote-rich matrix, and (5) fine-grained mafic–ultramafic volcanic rocks with remnants of plagioclase and hornblende in a chamosite- and actinolite–tremolite-rich matrix. These rocks are deformed and, in the vicinity of the mineralization, they are intensely foliated and locally brecciated. Their contacts with metamorphosed pyroxenitic–gabbroic dikes and sills are tectonic and characterized by deformation zones locally with intense quartz–carbonate veining (Fig. 2A). The metamorphosed pyroxenitic–gabbroic intrusions were tentatively correlated with the Wonderland Lake gabbro unit (Fig. 1) by Bailes & Syme (1989), and are composed dominantly of actinolite–tremolite, plagioclase, with minor hornblende and chlorite. They are cut by fine-grained mafic dikes (Fig. 2B).

Sampling and Analytical Methods

Seven high-grade PGE samples from channels #4 and #5 of the McBratney pit were selected for detailed petrographic and mineralogical investigations (for location, see Fig. 1B). The compositions of the various PGM and Au–Ag alloy were determined using a JEOL JXA–8900L automated wavelength-dispersion electron microprobe (EMP) at McGill University. Calibration for analyses was done using Pd_3HgTe_3 (Pd, Hg, Te), $PtAs_2$ (Pt, As), CANMET tetrahedrite (Sb), CANMET chalcopyrite (Cu), $AgBiSe_2$ (Ag), CANMET CoNiAs (Ni, Co), $AgBiSe_2$ (Bi), CANMET pyrite (Fe, S), and pure gold (Au). The operation conditions were: accelerating voltage 20 kV, and beam current 3×10^8 A. All analyzed PGM are from channel #5. The Au and Hg peaks overlap, but the Au content in the PGM was negligible and did not cause a problem for the analysis. The peak overlap between Sb and As was corrected for during the analysis by using the $L\beta$ line for As.

Modes of Occurrence and Compositions of the Platinum-Group Minerals

The McBratney occurrence comprises veins of massive sulfide and minor veinlets with variable amounts of quartz, carbonate, chlorite, chamosite, biotite and muscovite, hosted by extensively altered, brecciated mafic volcanic rock (Figs. 2C–D, 3A–F, 4A–H). In the host fragments (Fig. 3A), the metamorphosed igneous assemblage, which is composed of tremolite–actinolite, plagioclase, and hornblende, is extensively replaced by clinochlore, chamosite, biotite, and carbonate (mainly ferroan dolomite), sulfides and minor quartz. Rutile and titanite are disseminated in the altered fragments. In addition to the veins of massive sulfide, there are also deformed quartz – chlorite – epidote veinlets cut by veins composed mainly of alternating layers of clinochlore and carbonate. There have thus been various episodes of open space-filling. Biotite laths in the veins are associated with carbonate, included in sulfides (Fig. 3B) or mantled by PGM (Fig. 4G). Muscovite fills embayments in chlorite either in the veins or in the host fragments, but also occurs included in sulfides. Locally, biotite-, clinochlore-, chamosite- and carbonate-filled veinlets are cut by veins dominated by sulfide – chlorite – carbonate and by chamosite-rich veinlets (Fig. 3C).

The PGM occur mainly in the sulfide veins, which comprise pyrrhotite–pentlandite, violarite, pyrite, nickeloan pyrite, chalcopyrite, marcasite, sphalerite, galena, cobaltite–gersdorffite, coloradoite, magnetite and Au–Ag alloy (Figs. 3A–F, 4A–H). The large masses of pentlandite–pyrrhotite were partially or completed replaced by violarite and locally altered to millerite (Fig. 4F) along margins and fractures. In the most weathered samples, pentlandite and its alteration minerals were partially leached out, forming boxworks (Fig. 3D).

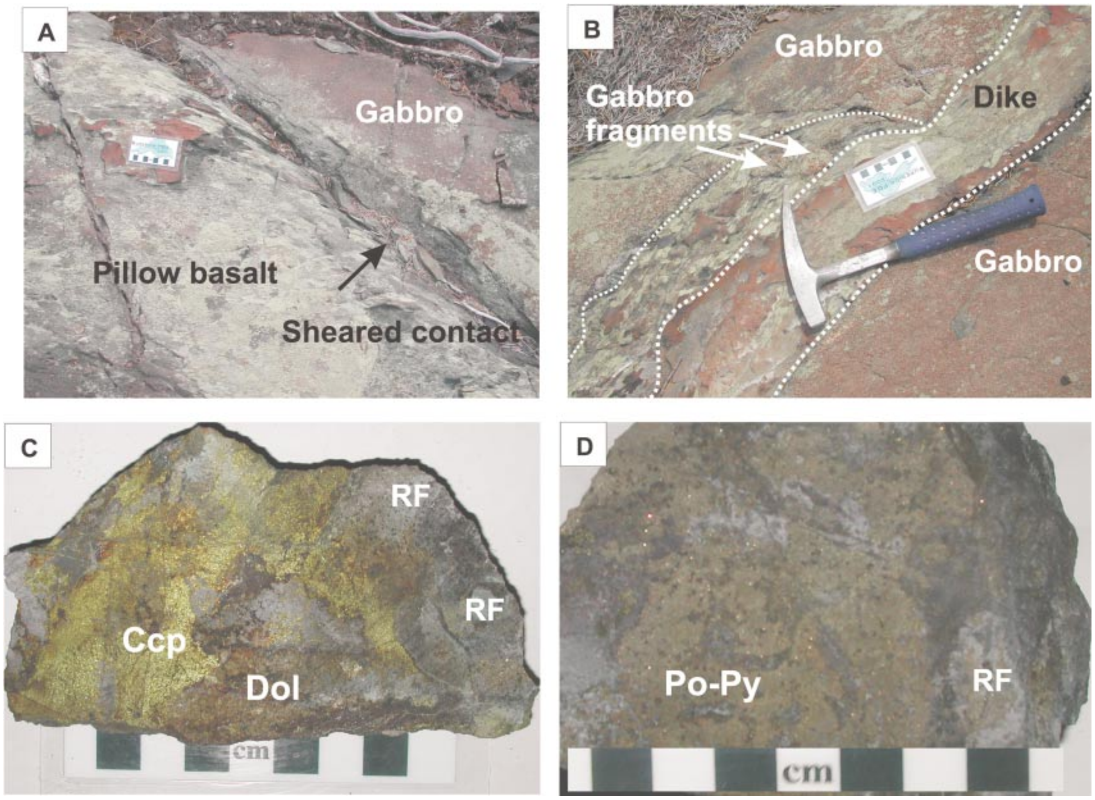


FIG. 2. A. Contact between pyroxenitic–gabbroic dike, interpreted as part of the Wonderland Lake Gabbro suite, and pillow basalt from the Bear Lake basaltic andesite. B. Fine-grained diabase dike cutting the Wonderland Lake gabbro. Note the brecciated contact between the diabase and pyroxenitic–gabbroic rock. C. PGE-rich breccia containing altered fragments of volcanic rock (RF) cut by massive chalcopyrite–pyrite with minor dolomite – chlorite – chamosite and PGM. D. PGE-bearing breccia containing altered fragments of volcanic rock (RF) cut by massive pyrrhotite–pyrite veins with minor chalcopyrite – dolomite – clinochlore – chamosite and PGM.

Some micrometer-sized composite grains of pentlandite – pyrrhotite – Pd telluride are well preserved as inclusions in magnetite (Fig. 3E). Pyrrhotite also forms irregular masses and is commonly included in pyrite and chalcopyrite. Pyrite occurs in fractured aggregates of cubic euhedra or irregular grains and is locally intergrown with nickeloan pyrite (Fig. 3D) and replaced by chalcopyrite, marcasite and cobaltite–gersdorffite. Chalcopyrite forms irregular patches and commonly fills embayments in the margins and fractures of pyrite and pyrrhotite (Fig. 3D) and is commonly associated with violarite. Pyrite and chalcopyrite contain inclusions of carbonate, clinochlore–chamosite, biotite, muscovite and quartz, and are cut by veinlets containing these minerals. Sphalerite is rare and occurs included in chalcopyrite, where it is spatially associated with Au–Ag alloy (Fig. 3F) and locally with PGM. Galena forms irregular grains and is commonly found in late carbonate veinlets (Fig. 3D). Partially corroded euhedra of magnetite occur within chalcopyrite and locally contain inclusions of pentlandite–pyrrhotite and palladium telluride that was too small to be quantitatively analyzed by the EMP. Au–Ag alloy (20–30 wt% Ag) euhedra are included in chalcopyrite, where they are locally in sharp contact with sphalerite, and are commonly found in proximity of fractures. Despite the abundance of PGM, gold is alloyed with silver, and its PGE content is lower than the detection limit on the electron microprobe used. Coloradoite (HgTe) is rare and forms composite grains with PGM (Fig. 4D). Cobaltite–gersdorffite commonly occupies corroded margins and fractures in the Ni-, Fe- and Cu-bearing sulfides (Fig. 4E), Au–Ag alloy and PGM (Fig. 4F) and locally occurs included in sudburyite. Cobaltite–gersdorffite composition varies from (in mol.%), 62–35 CoAsS, 35–43 NiAsS and 21–15 FeAsS, indicating that it formed at temperatures below 550°C (Klemm 1965).

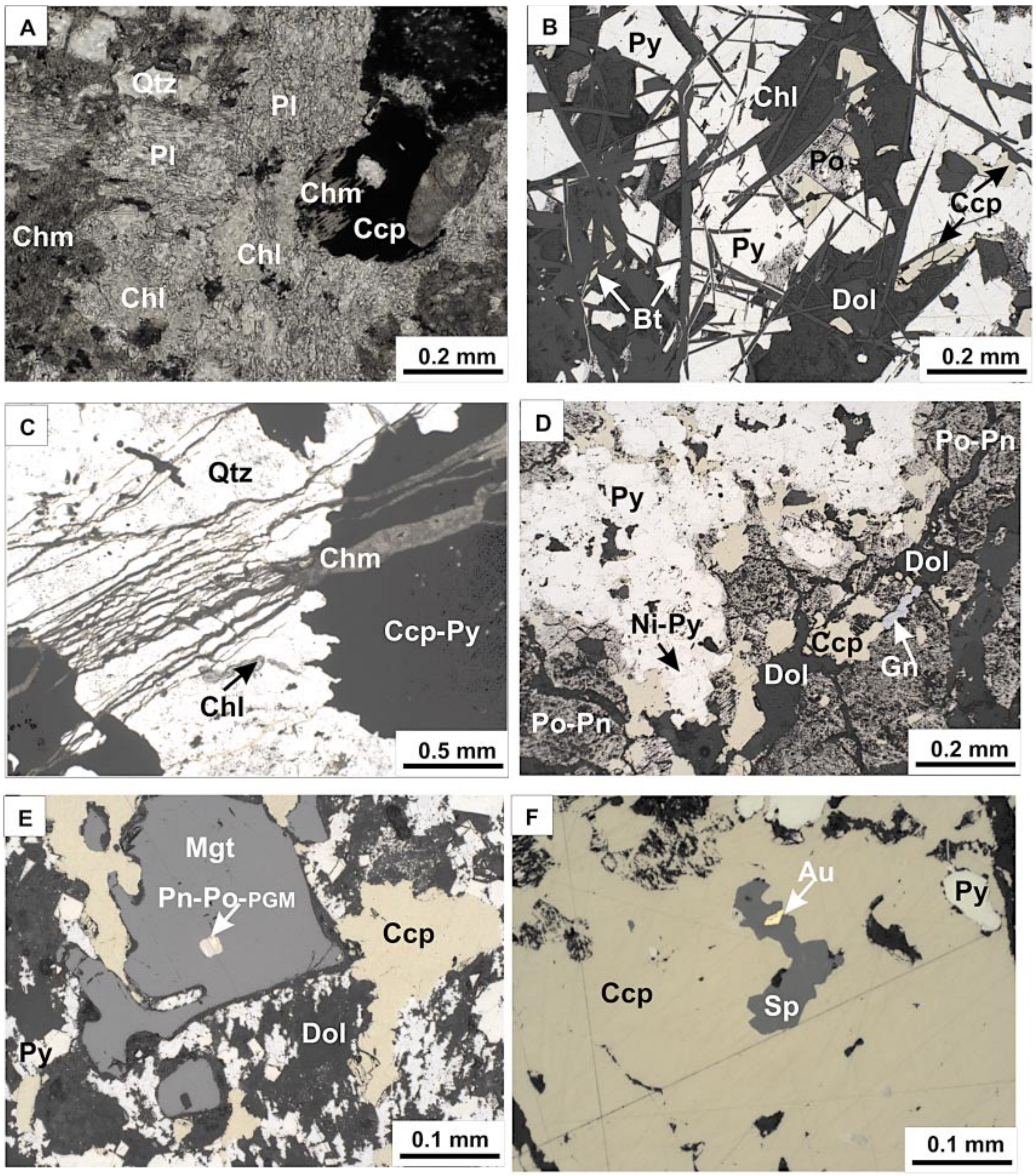


FIG. 3. Photomicrographs of the McBratney mineralized samples. A. Fragments of the mafic volcanic rock in the mineralized breccia. Plagioclase is partially replaced by clinochlore and quartz, and the mafic phases, by chamosite and chalcopyrite (transmitted light). B. Vein with biotite laths included and surrounded by pyrite, chalcopyrite, pyrrhotite and dolomite (incident light). C. Quartz–chlorite and sulfide veins cut by chamosite-rich veinlets (transmitted light). D. Massive sulfide vein containing pyrite – nickeloan pyrite, chalcopyrite, altered pyrrhotite–pentlandite and cut by late dolomite veinlets with galena (incident light) E. Corroded crystal of magnetite with an inclusion of pentlandite – pyrrhotite – Pd telluride as a composite grain. Pyrite, chalcopyrite and dolomite fill the corroded zones in the magnetite crystal (incident light). F. Au–Ag alloy included in sphalerite that is within chalcopyrite (incident light). Au: Au–Ag alloy, Ni–Py: nickeloan pyrite, Ccp: chalcopyrite, Chl: clinochlore, Chm: chamosite, Dol: dolomite, Gn: galena, Pl: plagioclase, Pn: pentlandite, Po: pyrrhotite, Py: pyrite, Qtz: quartz, Sp: sphalerite.

The most common PGM, inferred from results of the wavelength- and energy-dispersion EMP analyses, are: borovskite, sudburyite, telluroan sudburyite, and one unknown PGM. Sperrylite, temagamite and merenskyite are rare and generally form composite grains with the most common PGM. The mode of occurrence and composition of the various PGM are presented in Figures 4 and 5 and Tables 1 to 7, respectively, and described in detail below.

Borovskite

Borovskite, ideally Pd_3SbTe_4 (Figs. 4A–D), is the most abundant PGM and occurs as euhedral, creamy white grains (up to 0.2 mm in diameter). It is anomalously anisotropic (red to brown). It is commonly included in chalcopyrite and pyrite, and locally forms composite grains with merenskyite, sperrylite, temagamite and coloradoite. It contains minor amounts of Ni, Fe and Bi. On the basis of its average composition and a total of 8 atoms per formula unit, its formula is $[(Pd_{2.6}Ni_{0.35}Fe_{0.12})_{\Sigma 3.07}(Sb_{1.06}Bi_{0.06})_{\Sigma 1.12}Te_{3.81})]$ (Table 1).

Sudburyite

Sudburyite, ideally (Pd,Ni)Sb, occurs as (a) euhedral grains (up to 0.2 mm) included in chalcopyrite (Fig. 4E) and chlorite, (b) irregular grains with embayed margins mantled by cobaltite–gersdorffite (Fig. 4F), and (c) locally, as composite grains with temagamite (Fig. 4G). It contains minor amounts of Ni, Fe, Hg, Bi and Te. Its formula, based on its average composition (Table 2) and two atoms per formula unit, is $[(Pd_{0.94}Ni_{0.01}Fe_{0.01}Hg_{0.03})_{\Sigma 0.99}(Sb_{0.95}Te_{0.06})_{\Sigma 1.01}]$.

A telluroan variety of sudburyite is found included in pyrite, chalcopyrite, in the margins of weathered aggregates of pyrrhotite–pentlandite and locally forms complex composite grains with temagamite (Figs. 4G, 5). It contains between 10 to 15 wt% Te, and minor amounts of Hg, Fe, Bi and Ni (Table 3). Its formula is $[(Pd_{0.97}Ni_{0.01}Fe_{0.02}Hg_{0.01})_{\Sigma 1.01}(Sb_{0.78}Te_{0.21})_{\Sigma 0.99}]$. The telluroan sudburyite composition is similar to the sudburyite noted at the Wellgreen Ni–Cu–PGE deposit (Barkov *et al.* 2002).

Temagamite

Temagamite, ideally Pd_3HgTe_3, was found in composite grains (up to 50 μm across) with borovskite–merenskyite (Fig. 4B), sudburyite and telluroan sudburyite (Fig. 4G), commonly included in chalcopyrite or at the contact of this sulfide with biotite and altered pyrrhotite–pentlandite. Temagamite contains minor amounts of Ni, Fe and Sb (Table 4). On the basis of its average composition and seven atoms per formula unit, its formula is $[(Pd_{2.84}Ni_{0.15}Fe_{0.12})_{\Sigma 3.11}Hg_{0.93}(Te_{2.60}Sb_{0.35})_{\Sigma 2.95}]$.

Merenskyite

Merenskyite, ideally $(Pd,Pt)(Te,Bi)_2$, occurs in composite grains with borovskite–temagamite (up to 50 μm; Fig. 4B) and telluroan sudburyite (Fig. 4G), included in chalcopyrite, as well as small grains (6 μm) in the embayed contact between chalcopyrite and cobaltite–gersdorffite, and mantling biotite laths (Fig. 4G). Merenskyite was analyzed in only two locations owing to its small grain-size. It contains minor amounts of Ni, Co, Fe, Sb and Bi (Table 5). Its calculated formula based on three atoms per formula unit is $[(Pd_{0.97}Ni_{0.01}Co_{0.01}Fe_{0.07})_{\Sigma 1.06}(Te_{1.85}Sb_{0.08}Bi_{0.01})_{\Sigma 1.94}]$.

Sperrylite

Sperrylite, ideally $PtAs_2$, forms composite grains (up to 30 μm) with borovskite (Fig. 4C) and an unknown PGM (Pd telluride–antimonide; Fig. 4H) or occurs as isolated, irregular grains included in chalcopyrite, pyrite or carbonate. It contains minor amounts of Ag, Ni and Fe (Table 6). Its calculated formula, based on three atoms per formula unit, is $[(Pt_{0.94}Ag_{0.01}Ni_{0.01}Fe_{0.09})_{\Sigma 1.05}As_{1.95}]$.

Unknown Pd telluride–antimonide

An unknown telluride–antimonide of palladium was found in the samples studied. It commonly forms euhedral grains, which are creamy white and strongly anisotropic, from greenish grey, pink to brownish orange. This unknown PGM occurs mostly included in pyrite, but locally also is found in carbonate (Fig. 4H) or at the contact between pyrite and chalcopyrite. A few grains are composite with sperrylite. Eleven grains were analyzed; they exhibit a consistent composition (Table 7), which differs from the known palladium telluride–antimonides reported in the literature (Cabri 2002, and references therein). Its formula is $(Pd_{1.72}Ni_{0.23}Fe_{0.07})_{\Sigma 2.02}(Te_{1.94}Sb_{1}As_{0.02})_{\Sigma 2.94}$, calculated based on five atoms per formula unit, which corresponds to the best cations:anions ratio obtained from the mineral composition determined.

DISCUSSION AND CONCLUSIONS

Paragenetic sequence

On the basis of the textural relationships described above, the following paragenetic sequence is proposed for the high-grade PGE–Au mineralization in the McBratney prospect (Fig. 6). In the fragments of volcanic rock in the mineralized breccia, the earliest-preserved phases are plagioclase, hornblende and actinolite–tremolite, interpreted to represent the regional metamorphic assemblage, which was almost completely replaced by biotite, clinochlore–chamosite and carbonate, and cut by various generations of clinochlore –

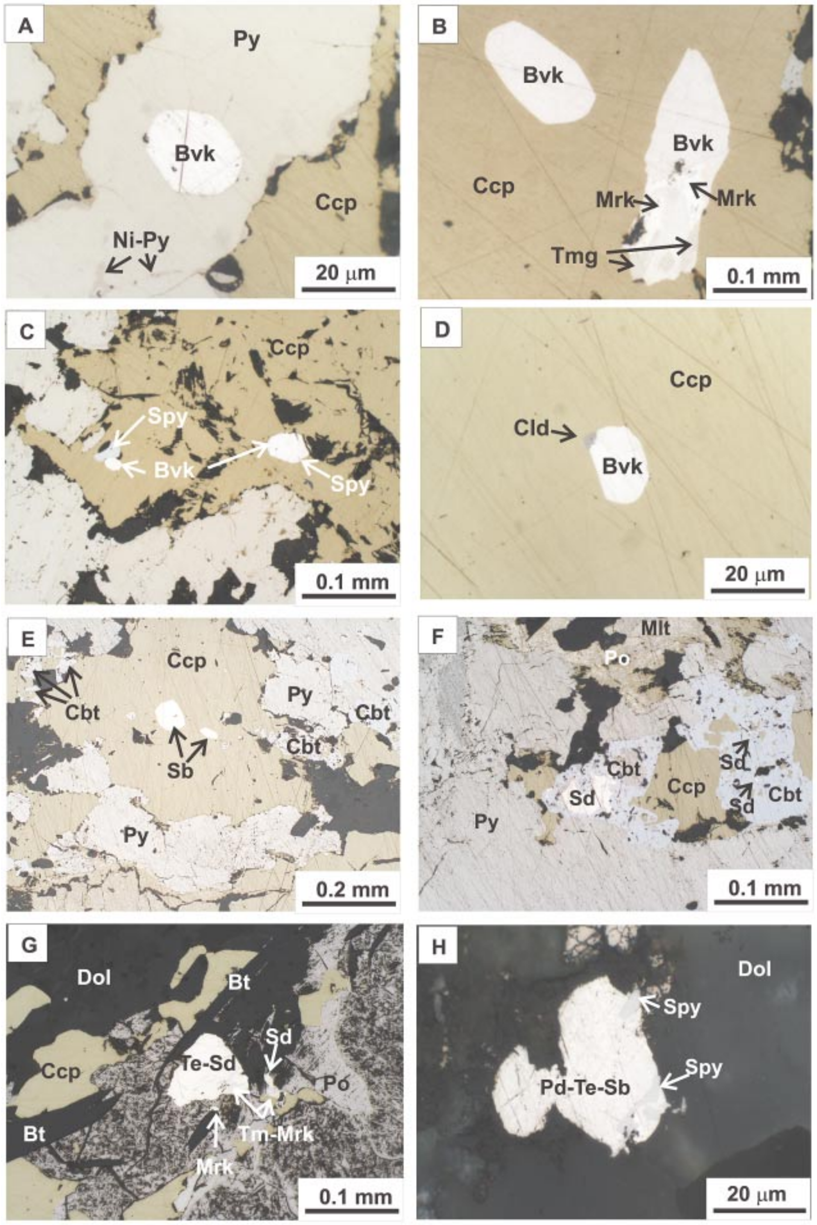


FIG. 4. Photomicrographs of the PGM from the McBratney occurrence (incident light). A. Borovskite euhedral crystal included in pyrite, which is surrounded by chalcopyrite. B. Borovskite – temagamite – merenskyite composite grain included in chalcopyrite. C. Borovskite–sperrylite composite grains include in chalcopyrite. D. Borovskite–coloradoite composite grain included in chalcopyrite. E. Sudburyite included in chalcopyrite. Note that chalcopyrite also contains inclusions of pyrite and nickeloan pyrite and is replaced by cobaltite–gersdorffite. F. Corroded grain of sudburyite included in cobaltite–gersdorffite; The latter fills corroded zones in pyrite, pyrrhotite and chalcopyrite. Note that in the upper part, millerite has replaced pyrrhotite. G. Composite grain of telluroan sudburyite – merenkyite – temagamite in contact with biotite, chalcopyrite and altered pyrrhotite. Note the presence of a small grain of merenskyite mantling a lath of biotite. H. Composite grain of unknown PGE with sperrylite included in dolomite. Bt: biotite, Bvk: borovskite, Cbt: cobaltite–gersdorffite, Ccp: chalcopyrite, Cld: coloradoite, Dol: dolomite, Mlt: millerite, Mrk: merenskyite, Ni–Py: nickeloan pyrite, Pd–Te–Sb: unknown Pd telluride–antimonide, Pn: pentlandite, Po: pyrrhotite, Py: pyrite, Sd: subburyite, Spy: sperrylite, Te–Sd: telluroan sudburyite, Tmg: temagamite.

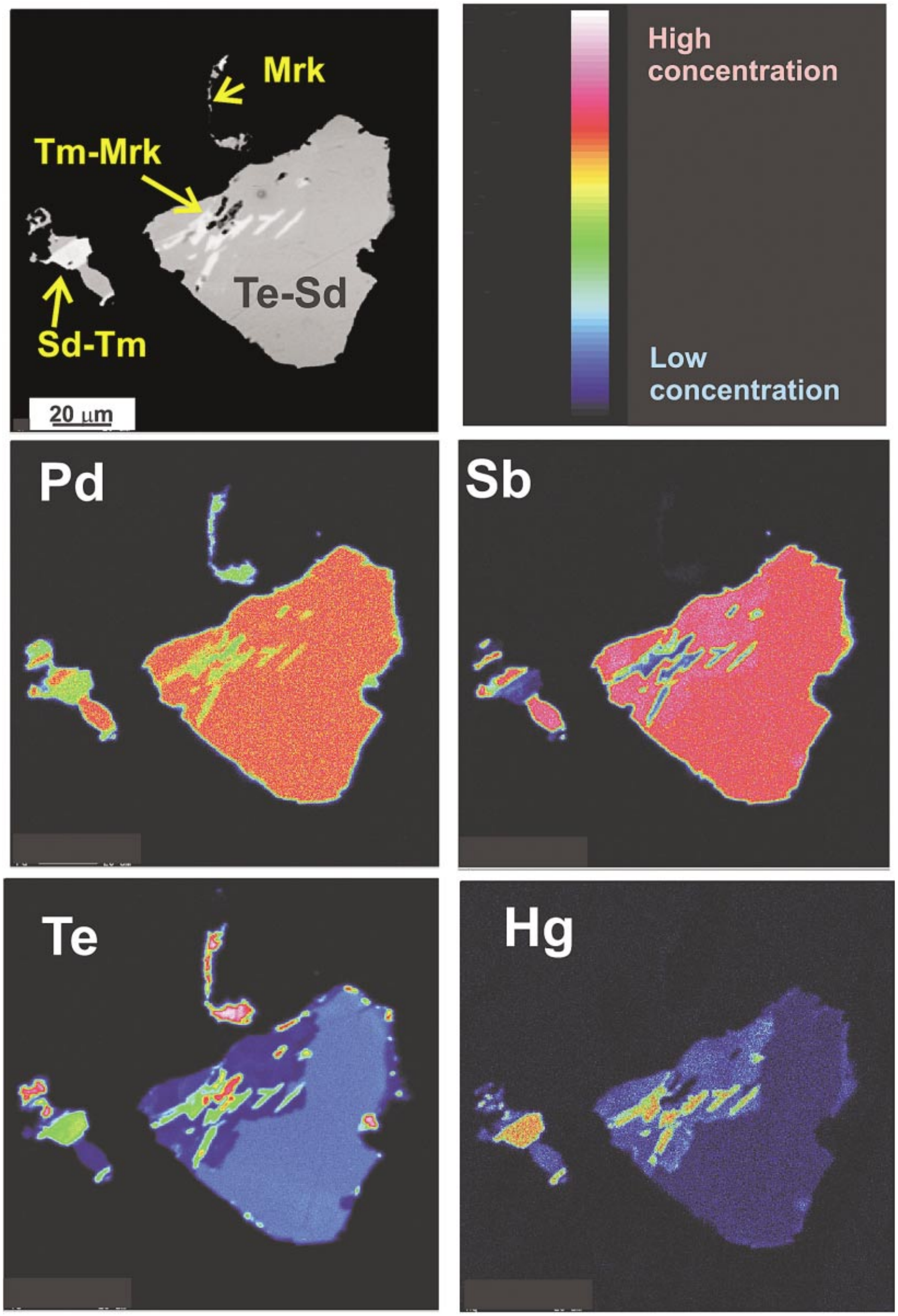

Mrk
Tm-Mrk
Te-Sd
Sd-Tm
20 μm
High concentration
Low concentration
Pd
Sb
Te
Hg

TABLE 1. THE COMPOSITION OF BOROVSKITE FROM THE McBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

No.	Pd	Ni	Fe	Bi	Sb	Te	Total		Pd	Ni	Fe	ΣMe	Bi	Sb	ΣBi+Sb	Te
1 wt%	29.59	2.19	0.29	1.39	13.80	52.40	99.66	1 *apfu*	2.61	0.35	0.05	3.01	0.06	1.07	1.13	3.86
2	29.85	2.21	0.42	1.51	13.70	52.43	100.12	2	2.62	0.35	0.07	3.04	0.07	1.05	1.12	3.84
3	30.10	2.18	0.33	1.35	14.03	52.19	100.18	3	2.64	0.35	0.06	3.05	0.06	1.08	1.14	3.82
4	29.42	2.20	0.53	1.34	13.85	52.60	99.94	4	2.58	0.35	0.09	3.02	0.06	1.06	1.12	3.85
5	30.30	1.64	0.68	1.54	14.22	51.18	99.56	5	2.68	0.26	0.11	3.05	0.07	1.10	1.17	3.77
6	29.92	2.36	0.40	1.59	13.76	52.29	100.32	6	2.62	0.37	0.07	3.06	0.07	1.05	1.12	3.82
7	29.98	2.08	0.42	1.40	13.66	52.06	99.60	7	2.65	0.33	0.07	3.05	0.06	1.05	1.12	3.83
8	29.83	2.15	0.12	1.50	13.96	52.09	99.65	8	2.64	0.35	0.02	3.01	0.07	1.08	1.15	3.85
9	29.28	2.61	0.99	1.29	13.79	52.58	100.54	9	2.53	0.41	0.16	3.10	0.06	1.04	1.10	3.80
10	29.83	2.30	1.44	1.31	13.64	51.93	100.45	10	2.58	0.36	0.24	3.18	0.06	1.03	1.09	3.74
11	29.56	2.22	0.53	1.32	13.88	52.18	99.69	11	2.60	0.35	0.09	3.04	0.06	1.07	1.13	3.83
12	29.36	2.25	0.38	1.41	13.84	52.19	99.43	12	2.60	0.36	0.06	3.02	0.06	1.07	1.13	3.85
13	29.49	2.23	0.70	1.35	13.72	52.39	99.88	13	2.59	0.35	0.12	3.06	0.06	1.05	1.11	3.83
14	29.50	2.16	0.75	1.41	13.66	52.25	99.73	14	2.59	0.34	0.13	3.06	0.06	1.05	1.11	3.83
15	29.18	2.23	0.70	1.49	13.79	51.69	99.08	15	2.58	0.36	0.12	3.06	0.07	1.07	1.13	3.81
16	28.68	2.81	0.47	1.26	13.99	52.46	99.67	16	2.51	0.45	0.08	3.04	0.06	1.07	1.13	3.83
17	29.15	2.45	0.22	1.46	13.88	52.40	99.56	17	2.57	0.39	0.04	3.00	0.07	1.07	1.14	3.86
18	29.21	2.55	1.19	1.69	14.01	52.01	100.66	18	2.52	0.40	0.20	3.12	0.07	1.06	1.13	3.75
18	29.74	2.15	1.42	1.25	13.95	52.02	100.53	19	2.57	0.34	0.23	3.14	0.05	1.05	1.11	3.75
20	27.94	3.19	1.16	1.25	13.91	52.36	99.81	20	2.42	0.50	0.19	3.11	0.06	1.05	1.11	3.78
21	30.44	1.83	0.86	1.29	13.84	52.27	100.53	21	2.66	0.29	0.14	3.09	0.06	1.05	1.11	3.81
22	30.49	1.87	0.61	1.20	13.70	51.85	99.72	22	2.68	0.30	0.10	3.08	0.05	1.05	1.11	3.81
23	30.05	1.78	0.91	1.16	13.66	52.06	99.62	23	2.64	0.28	0.15	3.07	0.05	1.05	1.10	3.82
24	31.63	1.12	1.72	1.42	13.47	51.86	101.22	24	2.73	0.18	0.28	3.19	0.06	1.02	1.08	3.73

Results of WDS electron-microprobe analyses. Pt, Cu, Co, Hg, As, Ag and Au were sought, but found to be less than 0.2 wt% or not detected. The atomic proportions are based on eight atoms per formula unit (*apfu*).

chamosite – carbonate – quartz – biotite veins and veinlets. The diverse sulfides and PGM are associated with these hydrated silicates and carbonate, indicating that they are contemporaneous. The earliest sulfide phases to precipitate were pentlandite and pyrrhotite, which are included in the other sulfides and in magnetite. Subsequently, magnetite, borovskite, sperrylite, merenskyite, telluroan sudburyite, temagamite, the unknown PdTeSb phase and pyrite – nickeloan pyrite started to precipitate, followed by the assemblage of cobaltite–gersdorffite, sudburyite, chalcopyrite, sphalerite and Au–Ag alloy. Galena was probably one of the latest sulfides to precipitate, as it is commonly found in late carbonate veinlets. The Fe-, Cu- and Ni-bearing sulfides, Au–Ag alloy and PGM were later replaced by a second generation of cobaltite–gersdorffite. Marcasite, millerite and violarite were the late products of alteration of the Fe, Cu and Ni sulfides.

FIG. 5. A. Secondary electron image of composite grains of telluroan sudburyite with temagamite and merenskyite (large grain in the center), sudburyite with temagamite (on the left side) and a grain of merenskyite (mantling a biotite lath; in the upper center). B. Scale of relative concentrations of the elements. C–F. Element-distribution maps for Pd, Sb, Te and Hg: note the enrichment in Hg and depletion in Sb and Te in telluroan sudburyite close to the temagamite grains. These minerals are shown under incident light in Figure 4G. Symbols: Mrk: merenskyite, Sd: subburyite, Te–Sd: telluroan sudburyite, Tmg: temagamite).

TABLE 2. THE COMPOSITION OF SUDBURYITE FROM THE McBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

No.	Pd	Ni	Fe	Hg		Bi	Sb	Te	Total
1 wt%	45.94	0.01	0.54	2.09		0.20	45.28	5.91	99.98
2	45.33	0.04	1.15	1.43		0.14	43.99	7.75	99.83
3	41.61	0.26	0.20	3.55		0.25	44.32	6.23	96.42
4	44.87	0.68	0.65	3.87		0.33	44.80	4.68	99.88
5	45.41	0.22	0.06	0.63		0.23	50.69	1.93	99.17
6	45.53	0.18	0.36	0.79		0.17	50.32	1.93	99.27
7	46.05	0.09	0.17	0.82		0.16	50.26	1.84	99.38
8	45.80	0.25	0.00	0.43		0.31	52.36	0.39	99.54
9	45.60	0.22	0.07	0.77		0.30	51.59	0.39	98.95
10	44.79	0.24	0.08	0.62		0.12	52.10	0.50	98.45
	Pd	Ni	Fe	Hg	ΣMe	Bi	Sb	Te	ΣBi+Sb+Te
1 *apfu*	0.92	<0.01	0.01	0.04	0.93	<0.01	0.91	0.12	1.07
2	0.91	<0.01	0.02	0.03	0.93	<0.01	0.88	0.16	1.07
3	0.86	0.01	<0.01	0.07	0.87	0.01	0.92	0.13	1.13
4	0.90	0.01	0.01	0.08	0.93	0.01	0.90	0.09	1.07
5	0.92	<0.01	<0.01	0.01	0.92	<0.01	1.02	0.04	1.08
6	0.98	0.01	0.01	0.01	1.00	<0.01	0.95	0.03	1.00
7	1.00	<0.01	0.01	0.01	1.01	<0.01	0.95	0.03	0.99
8	0.99	0.01	<0.01	<0.01	1.00	<0.01	0.99	0.01	1.00
9	0.99	0.01	<0.01	0.01	1.00	<0.01	0.98	0.01	1.00
10	0.98	0.01	<0.01	0.01	0.99	<0.01	0.99	0.01	1.01

Results of WDS electron-microprobe analyses. Pt, Cu, Co, As, Ag and Au were sought, but found to be less than 0.2 wt% or not detected. The atomic proportions are based on two atoms per formula unit (*apfu*). Composition 8 (core), 9 and 10 (margins) are from the same grain.

There is compelling evidence that the PGE–Au mineralization described above is hydrothermal. The unquestionable evidence is the occurrence of the PGM and Au in veins and veinlets associated with hydrothermal phases, such as chlorite–chamosite, biotite, carbonate and quartz, that replace the metamorphosed magmatic assemblage of the host rock, indicating that the mineralization postdated the regional metamorphic event. This assemblage of hydrothermal minerals formed at

TABLE 3. THE COMPOSITION OF TELLUROAN SUDBURYITE FROM THE McBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

	Pd	Ni	Fe	Hg	Bi	Sb	Te	Total
1 wt%	45.10	0.18	0.74	0.85	0.47	41.47	11.12	99.93
2	45.09	0.07	0.76	1.18	0.47	41.49	11.07	100.13
3	43.60	0.29	1.12	1.01	0.55	39.38	14.81	100.75
4	41.75	0.57	0.62	1.20	0.43	39.69	15.21	99.47
5	45.25	0.05	0.66	0.96	0.43	40.92	11.84	100.11
6	44.53	0.56	0.38	1.55	0.56	40.68	11.93	100.19
7	45.60	0.07	0.98	1.21	0.43	41.12	11.01	100.42
8	45.24	0.05	0.02	1.12	0.33	42.04	10.03	98.83
9	45.28	0.07	0.07	1.29	0.39	42.14	10.38	99.62
10	45.47	0.23	0.28	1.49	0.43	41.61	10.32	99.83
11	44.58	0.15	0.07	1.31	0.20	41.84	10.81	98.95
12	44.56	0.35	0.19	1.35	0.28	41.45	11.14	99.32
13	44.41	0.05	0.10	1.56	0.39	40.21	13.09	99.80
14	44.57	0.24	0.15	1.54	0.33	40.76	12.25	99.83
15	45.54	0.09	0.12	1.26	0.32	41.88	10.75	99.95
16	45.16	0.08	0.45	1.37	0.46	41.38	10.98	99.88
17	45.30	0.06	0.09	1.20	0.43	41.65	10.65	99.37
18	44.91	0.07	0.43	1.59	0.37	41.10	11.09	99.57
19	44.03	0.10	0.33	1.69	0.29	40.95	11.65	99.03
20	44.05	0.02	0.69	1.66	0.36	41.59	11.60	99.97
21	45.39	0.09	0.08	0.56	0.43	42.44	10.37	99.36
22	45.10	0.09	0.16	1.18	0.23	42.12	10.34	99.22
23	45.37	0.01	0.16	1.20	0.43	40.30	12.07	99.54

	Pd	Ni	Fe	Hg	Σ*Me*	Bi	Sb	Te	Σ
1 *apfu*	0.97	0.01	0.03	0.01	1.01	0.01	0.78	0.20	0.99
2	0.97	<0.01	0.03	0.01	1.00	0.01	0.78	0.20	1.00
3	0.93	0.01	0.05	0.01	0.99	0.01	0.73	0.26	1.01
4	0.91	0.02	0.03	0.01	0.95	<0.01	0.75	0.28	1.05
5	0.97	<0.01	0.03	0.01	1.00	<0.01	0.77	0.21	1.00
6	0.96	0.02	0.02	0.02	1.00	0.01	0.77	0.21	1.00
7	0.97	<0.01	0.04	0.01	1.02	<0.01	0.77	0.20	0.98
8	0.99	<0.01	<0.01	0.01	0.99	<0.01	0.81	0.18	1.01
9	0.99	<0.01	<0.01	0.01	0.99	<0.01	0.80	0.19	1.01
10	0.98	0.01	0.01	0.02	1.00	<0.01	0.79	0.19	1.00
11	0.98	0.01	<0.01	0.02	0.98	<0.01	0.80	0.20	1.02
12	0.97	0.01	0.01	0.02	0.99	<0.01	0.79	0.20	1.01
13	0.97	<0.01	<0.01	0.02	0.97	<0.01	0.77	0.24	1.03
14	0.97	0.01	0.01	0.02	0.98	<0.01	0.77	0.22	1.02
15	0.99	<0.01	<0.01	0.01	1.00	<0.01	0.79	0.19	1.00
16	0.98	<0.01	0.02	0.02	1.00	0.01	0.78	0.20	1.00
17	0.99	<0.01	<0.01	0.01	0.99	<0.01	0.79	0.19	1.01
18	0.98	<0.01	0.02	0.02	1.00	<0.01	0.78	0.20	1.00
19	0.96	<0.01	0.01	0.02	0.98	<0.01	0.78	0.21	1.02
20	0.95	<0.01	0.03	0.02	0.98	<0.01	0.79	0.21	1.02
21	0.99	<0.01	<0.01	0.01	0.99	<0.01	0.81	0.19	1.01
22	0.98	<0.01	0.01	0.01	0.99	<0.01	0.80	0.19	1.01
23	0.99	<0.01	0.01	0.01	1.00	<0.01	0.77	0.22	1.00

Results of WDS electron-microprobe analyses. Pt, Co, As, Ag and Au were sought, but found to be less than 0.2 wt% or not detected. The atomic proportions are based on two atoms per formula unit (*apfu*).

TABLE 4. THE COMPOSITION OF TEMAGAMITE FROM THE McBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

No	Pd	Ni	Fe	Hg	Sb	Te	Total
1 wt%	33.97	1.23	0.57	21.87	5.12	37.40	100.16
2	33.08	1.45	0.81	21.49	3.10	40.67	100.60
3	35.67	0.30	0.85	20.30	6.37	34.70	98.19

	Pd	Ni	Fe	Σ*Me*	Hg	Sb	Te	ΣSb+Te
1 *apfu*	2.72	0.22	0.13	3.06	0.94	0.22	2.78	3.01
2	2.81	0.19	0.09	3.09	0.96	0.37	2.58	2.95
3	3.00	0.05	0.14	3.19	0.91	0.47	2.44	2.91

Results of WDS electron-microprobe analyses. Pt, Cu, Bi, Co, As, Ag and Au were sought but were found to be less than 0.1 wt% or not detected. The atomic proportions are based on seven atoms per formula unit (*apfu*).

temperatures lower than 500°C (Slaughter *et al.* 1975). Significantly, the occurrence of sudburyite both included in and with inclusions of cobaltite–gersdorffite also indicates that at least in this instance, PGE–Au mineralization formed at temperatures lower than 550°C (Klemm 1965).

Composition of PGM and the Pd–Sb–Te system

Palladium from the McBratney prospect forms mainly tellurides–antimonides (*i.e.*, borovskite, merenskyite, temagamite, sudburyite, telluroan sudburyite); platinum forms an arsenide (sperrylite). Fe is found in minor amounts in all PGM (up to 2.2 wt%). Ni was incorporated mainly in borovskite (1.2–3.2 wt%), temagamite (0.3–1.5 wt%) and unknown PGM (1.2–2.9 wt%) and is lower than 0.7 wt% in the other PGM. Besides temagamite, Hg was detected only in sudburyite (0.4–3.9 wt%) and telluroan sudburyite (0.9–1.7 wt%).

Figure 7 shows the distribution of the tellurides–antimonides in terms of Pd Sb and Te (in atomic concentrations). The diagram shows that sudburyite and telluroan sudburyite forms a "continuous" solid-solution with kotulskite (PdTe). However, the compositions of borovskite and the unknown PGM plots in very specific fields, and no grain with a composition intermediate to them was found, suggesting that they probably do not form a solid solution. The phase diagram for the system Pd–Sb–Te is not well established (Makovicky 2002), in particular at low temperatures. On the basis of experimental data from Kim & Chao (1991), PdTe (kotulskite) and PdSb (sudburyite) form a complete solid-solution at 600°C. This solid solution extends toward Te-rich zones, forming a non-quenchable solid solution, PdTe (kotulskite) – $PdTe_2$ (merenskyite). In association with Sb-bearing $PdTe_2$, $PdSb_2$ attains the composition Pd $(Sb_{0.32}Te_{0.68})_2$. El Boragy & Schubert (1971) found similar results for the Pd-rich phases at 400°C. However, the composition of the unknown Pd telluride–antimonide reported here falls outside of the solid-solution fields defined by El Boragy & Schubert (1971) and Kim & Chao (1991), indicating that the phase diagram for the system Pd–Sb–Te needs revision.

Comparison with other Ni–Cu(–Co) PGE deposits

PGE deposits and occurrences associated with Ni–Cu(–Co) ore hosted in mafic and ultramafic rocks are common and include the world-class Pd-rich Noril'sk–

Talnakh deposits (Naldrett *et al.* 1996), Jinchuan, China (Chai & Naldrett 1992), PGE-rich Sudbury deposits (Farrow & Lightfoot 2002, and references therein), and PGE-rich komatiite-hosted deposits (*e.g.*, Raglan, Kambalda and Fortaleza de Minas, Lesher & Keays 2002, Almeida 2003, and references therein). Other PGE deposits and occurrences associated with Ni–Cu sulfides in mafic–ultramafic rocks, mainly intrusions, are: Lac des Iles, New Rambler, Rathbun Lake, Thierry, Coldwell, Salt Chuck, Fox River, and Wellgreen (Watkinson & Melling 1992, Barkov *et al.* 2002, Peck *et al.* 2002, Watkinson *et al.* 2002). The PGM commonly described in these deposits are PGE antimonides, tellurides, bismuthides, arsenides and sulfides. The origin of the PGE-rich orebodies and showings is controversial, and the mineralization has been interpreted to be either magmatic (*e.g.*, Mulja & Mitchell 1990, 1991, Naldrett *et al.* 1994, Komarova *et al.* 2002), or hydrothermal (*e.g.*, McCallum *et al.* 1976, Rowell & Edgar 1986, Farrow & Watkinson 1992, 1997, Watkinson & Ohnenstetter 1992, Li & Naldrett 1993, Watkinson & Jones 1996, Molnár *et al.* 1997, Wood 2002, Almeida 2003).

In all of these deposits but Fortaleza de Minas, hydrothermal activity associated with the remobilization of PGE is commonly related to the late stages of the magmatic event. In the Fortaleza de Minas, a structurally controlled PGE-rich Ni–Cu orebody formed during a late hydrothermal event (at 600 Ma), that remobilized the metals from a 2.7-Ga-old komatiite-hosted magmatic Ni–Cu ore (Almeida 2003). The McBratney PGE–Au occurrence exhibits some similarities with the Fortaleza de Minas PGE-rich Ni–Cu orebodies: (a) the PGE-rich mineralization is spatially associated with mafic–ultramafic rocks and postdate the regional metamorphism and deformation, (b) the PGE minerals are associated with hydrothermal Fe–Ni sulfides, chlorite and carbonate in discordant veins and veinlets, and (c) the PGE-bearing minerals are mainly tellurides, antimonides and arsenides.

However, despite their similarities, no magmatic Ni–Cu sulfide deposits were reported in the McBratney area, and the Fortaleza de Minas deposit contains a variety of Ru-, Rh and Ir-bearing minerals that were not found at McBratney. For both deposits, the source of fluids is unknown, and the source of metals for the McBratney occurrence has not yet been identified. These issues are the object of ongoing research.

TABLE 5. THE COMPOSITION OF MERENSKYITE FROM THE McBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

No.	Pd	Ni	Co	Fe		Te	Sb	Bi	Total
1 wt%	27.01	0.15	0.17	1.88		64.94	0.80	0.81	95.75
2	29.41	0.10	0.02	0.38		63.76	4.62	0.48	98.77
	Pd	Ni	Co	Fe	Σ*Me*	Te	Sb	Bi	ΣTe+Sb+Bi
1 *apfu*	0.94	0.01	0.01	0.12	1.08	1.88	0.02	0.01	1.92
2	1.01	0.01	0.00	0.02	1.04	1.82	0.14	0.01	1.96

Results of WDS electron-microprobe analyses. Pt, Cu, Hg, As, Ag, and Au were sought but were less than 0.1wt% or not detected. The atomic proportions are based on three atoms per formula unit (apfu).

TABLE 6. THE COMPOSITION OF SPERRYLITE FROM THE McBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

	Pt	Pd	Ag	Ni	Fe	As	Total
1 wt%	54.71	0.06	0.35	0.01	0.51	43.66	99.30
2	55.08	0.01	0.41	0.02	1.72	43.90	101.13
3	54.62	0.04	0.17	0.69	1.24	43.73	100.49
4	54.31	0.14	0.39	0.01	1.53	43.62	100.00
5	54.80	0.10	0.35	0.12	1.65	44.33	101.35
6	55.60	0.06	0.30	0.29	1.25	44.55	102.06
7	55.12	0.17	0.33	0.11	1.67	44.06	101.47
8	54.92	0.05	0.35	0.23	2.19	44.51	102.24
	Pt	Pd	Ag	Ni	Fe	Σ*Me*	As
1 *apfu*	0.96	0.00	0.01	0.00	0.03	1.00	2.00
2	0.94	0.00	0.01	0.00	0.10	1.05	1.95
3	0.93	0.00	0.01	0.04	0.07	1.05	1.95
4	0.94	0.00	0.01	0.00	0.09	1.04	1.96
5	0.93	0.00	0.01	0.01	0.10	1.05	1.95
6	0.94	0.00	0.01	0.02	0.07	1.04	1.96
7	0.93	0.01	0.01	0.01	0.10	1.06	1.94
8	0.92	0.00	0.01	0.01	0.13	1.07	1.93

Results of WDS electron-microprobe analyses. Hg, Sb, Te, Cu, Bi, Co and Au were sought but found to be less than 0.1 wt% or not detected. The atomic proportions are based on three atoms per formula unit (*apfu*).

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TABLE 7. THE COMPOSITION OF THE UNKNOWN Pd TELLURIDE-ANTIMONIDE FROM THE MCBRATNEY PROSPECT, FLIN FLON BELT, MANITOBA

	Pd	Ni	Fe		Bi	As	Sb	Te	Total
1 wt%	31.93	2.40	0.38		0.36	0.23	21.38	43.48	100.15
2	33.36	1.70	0.77		0.29	0.24	20.88	42.50	99.74
3	33.02	1.83	1.24		0.40	0.22	21.38	43.23	101.32
4	32.45	2.31	1.33		0.35	0.21	21.35	43.48	101.48
5	32.08	2.77	0.10		0.17	0.31	21.47	43.73	100.63
6	32.28	2.16	0.93		0.27	0.29	21.22	43.14	100.29
7	31.98	2.48	0.89		0.37	0.19	21.49	43.17	100.56
8	31.44	2.68	0.38		0.45	0.19	21.35	43.57	100.06
9	31.13	2.84	0.62		0.39	0.19	21.57	43.74	100.48
10	31.41	2.93	0.93		0.31	0.19	21.48	43.67	100.93
11	32.17	2.28	0.16		0.34	0.29	21.33	43.29	99.85
	Pd	Ni	Fe	Σ	Bi	As	Sb	Te	Σ
1 *apfu*	1.73	0.24	0.04	2.00	0.01	0.02	1.01	1.96	2.97
2	1.81	0.17	0.08	2.06	0.01	0.02	0.99	1.92	2.92
3	1.76	0.18	0.13	2.06	0.01	0.02	0.99	1.92	2.91
4	1.72	0.22	0.13	2.07	0.01	0.02	0.99	1.92	2.90
5	1.72	0.27	0.01	2.00	0.00	0.02	1.01	1.96	2.97
6	1.73	0.21	0.10	2.04	0.01	0.02	1.00	1.93	2.93
7	1.71	0.24	0.09	2.04	0.01	0.01	1.00	1.93	2.93
8	1.70	0.26	0.04	2.00	0.01	0.01	1.01	1.96	2.97
9	1.67	0.28	0.06	2.01	0.01	0.01	1.01	1.96	2.97
10	1.67	0.28	0.09	2.04	0.01	0.01	1.00	1.93	2.93
11	1.75	0.22	0.02	1.99	0.01	0.02	1.01	1.96	2.98

Results of WDS electron-microprobe analyses. Pt, Cu, Co, Hg, Ag and Au were sought, but found to be less than 0.2 wt% or not detected. The atomic proportions are based on five atoms per formula unit (*apfu*).

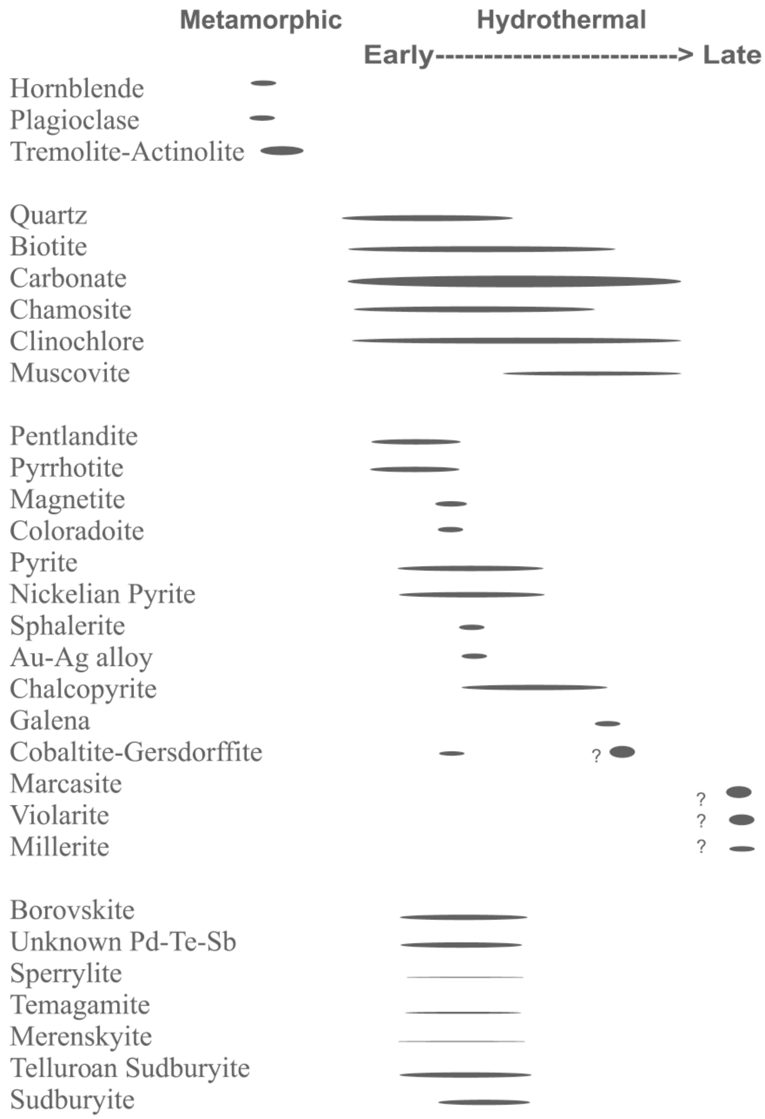

FIG. 6. Paragenetic sequence for the PGE-bearing mineralized breccias from the McBratney occurrence.

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REFERENCES

ALMEIDA, C.M. (2003): *Gênese dos corpos de sulfeto maciço hydrothermal e platinóides associados no Depósito de Fortaleza de Minas*. M.Sc. thesis, Universidade Estadual Paulista, Brazil.

BAILES, A.H. & SYME, E.C. (1989): Geology of the Flin Flon – White Lake area. *Manitoba Energy and Mines Geological Services, Geol. Rep.* **GR 87-1**.

BARKOV, A.Y., LAFLAMME, J.H.G., CABRI, L.J. & MARTIN, R.F. (2002): Platinum-group minerals from the Wellgreen Cu–Ni–PGE deposit. *Can. Mineral*. **40**, 651-670.

CABRI, L.J. (2002): The platinum-group minerals. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall. Petroleum, Spec. Vol.* **54**, 13-129.

CHAI, GANG & NALDRETT, A.J. (1992): Characteristics of Ni–Cu–PGE mineralization and genesis of the Jinchuan deposit, northwest China. *Econ. Geol*. **87**, 1475-1495.

EL BORAGY, M. & SCHUBERT, K. (1971): On some variants of the NiAs family in mixtures of palladium with B-elements. *Z. Metallkunde* **62**, 314-323.

FARROW, C.E.G & LIGHTFOOT, P.C. (2002): Sudbury PGE revisited: toward an integrated model. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 273-297.

________ & WATKINSON, D.H. (1992): Alteration and role of fluids in Ni, Cu and platinum-group element deposition, Sudbury Igneous Complex contact, Onaping–Levack area, Ontario. *Mineral. Petrol.* **46**, 67-83.

________ & ________ (1997): Diversity of precious-metal mineralization in footwall Cu–Ni–PGE deposits, Sudbury, Ontario: implication for hydrothermal models of formation. *Can. Mineral*. **35**, 817-839.

GORDON, T.M., HUNT, P.A., BAILES, A. & SYME, E. (1989): U–Pb zircon ages from the Flin Flon and Kisseynew belts, Manitoba: chronology of crust formation at an Early Proterozoic accretionary margin. *In* The Early Proterozoic Trans-Hudson Orogen of North America: Lithotectonic Correlations and Evolution (J.F. Lewry & M.R. Stauffer, eds.). *Geol. Assoc. Can., Spec. Pap*. **37**, 177-199.

KIM, WON-SA & CHAO, G.Y. (1991). Phase relations in the system Pd–Sb–Te. *Can. Mineral.* **29**, 401-409.

KLEMM, D.D. (1965): Synthesen und Analyse in den Dreieckdiagrammen FeAsS–CoAsS–NiAsS und FeS_2–CoS_2–NiS_2. *Neues Jahrb. Mineral., Abh.* **103**, 205-255.

KOMAROVA, M.Z., KOZYREV, S.M., SIMONOV, O.N. & LULKO, V.A. (2002): The PGE mineralization of disseminated sulphide ores of the Noril'sk–Taimyr region. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 547-567.

LESHER, C.M. & KEAYS, R.R (2002): Komatiite-associated Ni–Cu–PGE deposits: geology, mineralogy, geochemistry, and genesis. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 579-617.

LI, CHUSI & NALDRETT, A.J. (1993): High chlorine alteration minerals and calcium-rich brines in fluid inclusions from

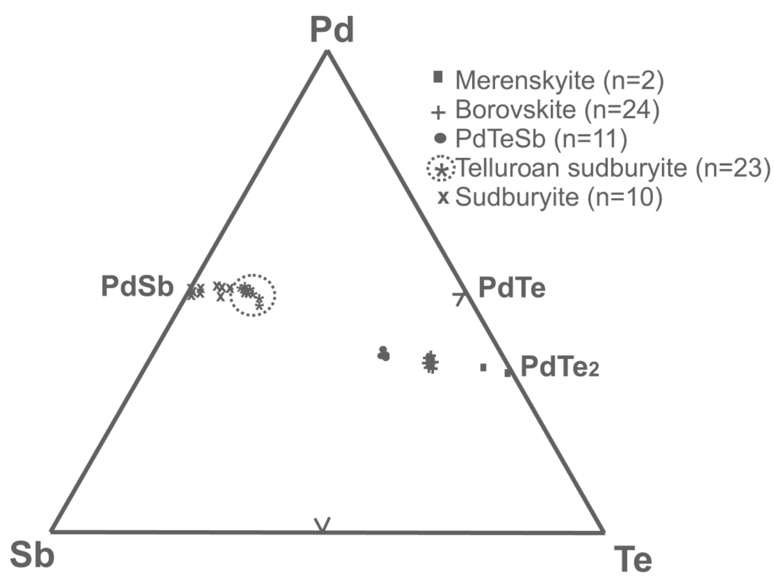

FIG. 7. Compositional variation of the Pd antimonides–tellurides in the McBratney occurrence projected in terms of the system Sb–Pd–Te (atomic proportions); n: number of analyses made of each mineral.

the Strathcona Deep Copper Zone, Sudbury, Ontario. *Econ. Geol.* **88**, 1780-1796.

MAKOVICKY, E. (2002): Ternary and quaternary phase systems with PGE. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 131-175.

MCCALLUM, M.E., LOUCKS, R.R., CARLSON, R.R., COOLEY, E.F. & DOERGE, T.A. (1976): Platinum metals associated with hydrothermal copper ores of the New Rambler mine, Medicine Bow Mountains, Wyoming. *Econ. Geol*. **71**, 1429-1450.

MOLNÁR, F., WATKINSON, D.H., JONES, P.C. & GATTER, I. (1997): Fluid inclusion evidence for hydrothermal enrichment of magmatic ore at the Contact Zone of the Ni – Cu – platinum-group element 4b deposit, Lindsley mine, Sudbury, Canada. *Econ. Geol*. **92**, 674-685.

MULJA, T. & MITCHELL, R.H. (1990): Platinum-group minerals and tellurides from the Geordie Lake Intrusion, Coldwell Complex, northwestern Ontario. *Can. Mineral.* **28**, 489-501.

________ & ________ (1991): The Geordie Lake intrusion, Coldwell Complex, Ontario: a palladium- and tellurium-rich disseminated sulphide occurrence derived from evolved tholeiitic magma. *Econ. Geol.* **86**, 1050-1069.

NALDRETT, A.J., ASIF, M., GORBACHEV, N.S., KUNILOV, V.YE., STEKHIN, A.I., FEDORENKO, V.A. & LIGHTFOOT, P.C. (1994): The composition of the Ni–Cu ores of the Oktyabr'sky deposit, Noril'sk region. *In* Proc., Sudbury–Noril'sk Symposium (P.C. Lightfoot & A.J. Naldrett, eds.). *Ont. Geol. Surv., Spec. Vol.* **5**, 357-371.

________, FEDERENKO, V.A., ASIF, M., LIN SHUSHEN, KUNILOV, V.E., STEKHIN, A.I., LIGHTFOOT, P.C. & GORBACHEV, N.S. (1996): Controls in the composition of Ni–Cu sulfide deposits as illustrated by those at Noril'sk, Siberia. *Econ. Geol.* **91**, 751-773.

OLIVO, G.R., THEYER, P. & BURSZTYN, N. (2002): Platinum group element investigations in the Flin Flon greenstone belt: petrography and mineralogy of the McBratney PGE–Au occurrence. *Report of Activities 2002, Manitoba Industry, Trade and Mines, Manitoba Geol. Surv.,* 94-99.

PECK, D.C., SCOATES, R.F.J., THEYER, P., DESHARNAIS, G., HULBERT, L.J. & HUMINICKI, M.A.E. (2002): Stratiform and contact-type PGE–Cu–Ni mineralization in the Fox River Sill and the Bird River Belt, Manitoba. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 367-387.

ROWELL, W.F. & EDGAR, A.D. (1986): Platinum-group element mineralization in a hydrothermal Cu–Ni sulfide occurrence, Rathbun Lake, northeastern Ontario. *Econ. Geol.* **81**, 1272-1277.

SLAUGHTER, J., KERRICH, D.M. & WALL, V.J. (1975): Experimental and thermodynamic study of equilibria in the system $CaO–MgO–SiO_2–H_2O–CO_2$. *Am. J. Sci.* **275**, 143-162.

SYME, E.C., BAILES, A.H., GORDON, T.M. & HUNT, P.A. (1987): U–Pb zircon geochronology in the Flin Flon: age of the Amisk volcanism. *Report of Field Activities 1987, Manitoba Energy and Mines,* 105-107.

________, LUCAS, S.B., BAILES, A.H. & STERN, R.A (1999): Contrasting arc and MORB-like assemblages in the Paleoproterozoic Flin Flon Belt, Manitoba, and the role of intra-arc extension in localizing volcanic-hosted massive sulphide deposits. *Can. J. Earth Sci.* **36**, 1767-1788.

THEYER, P. (2001): Platinum-group element investigations in the Flin Flon greenstone belt: McBratney Lake occurrence and Josland Lake intrusion (parts of NTS 63K/9,/13). *Report of Activities, 2001, Manitoba Industry, Trade and Mines, Manitoba Geol. Surv*., 33-39.

________ & HEINE, T. (2002): Platinum group element investigations in the Flin Flon Greenstone Belt: regional geology of the McBratney Lake PGE–Au occurrence and part of the Mikanagan Lake Sill (NTS 63k13), Manitoba. *Report of Activities 2002, Manitoba Industry, Trade and Mines, Manitoba Geol. Surv.,* 87-93.

WATKINSON, D.H. & JONES, P.C. (1996): Platinum-group minerals in fluid inclusions from the Marathon deposit, Coldwell Complex, Canada. *Mineral. Petrol*. **57**, 91-96.

________, LAVIGNE, M.J. & FOX, P.E. (2002): Magmatic–hydrothermal Cu- and Pd-rich deposits in gabbroic rocks from North America. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 299-319.

________ & MELLING, D.R. (1992): Hydrothermal origin of platinum-group mineralization in low temperature copper sulfide-rich assemblages, Salt Chuck intrusion, Alaska. *Econ. Geol*. **87**, 175-184.

________ & OHNENSTETTER, D. (1992): Hydrothermal origin of platinum-group mineralization in the Two Duck Lake intrusion, Coldwell Complex, northwestern Ontario. *Can. Mineral*. **30**, 121-136.

WOOD, S.A. (2002): The aqueous geochemistry of the platinum-group elements with applications to ore deposits. *In* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements (L.J. Cabri, ed.). *Can. Inst. Mining, Metall., Petroleum, Spec. Vol.* **54**, 211-249.

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