

HYDROTHERMAL ORIGIN OF PLATINUM-GROUP MINERALIZATION IN THE TWO DUCK LAKE INTRUSION, COLDWELL COMPLEX, NORTHWESTERN ONTARIO

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ABSTRACT

Platinum-group minerals (*PGM*) occur in chalcopyrite-rich sulfide assemblages [$\text{Cu}/(\text{Cu} + \text{Ni}) = 0.94$, $\text{Pt}/(\text{Pt} + \text{Pd}) = 0.22$] from very coarse-grained to pegmatitic gabbroic rocks of the Two Duck Lake intrusion at the eastern contact of the Coldwell alkaline rock complex with Archean metavolcanic rocks, in northwestern Ontario. The *PGM* occur: 1) in sulfides or at their contacts, 2) in postcumulus chalcopyrite, 3) in the rim of plagioclase grains with chalcopyrite, 4) in veins along the contacts of chalcopyrite and other minerals, and 5) in veins and areas of alteration of the primary silicate and oxide assemblage. Some *PGM* are strikingly zoned (hollingworthite and atokite-zvyagintsevite); others are single homogeneous grains (sperrylite, bismuth-rich kotulskite, Pd_5As_2), and some occur in complex aggregates (such as mertieite II with $\text{Pd}_2(\text{Sb}, \text{As})$, palladium-bearing nickeline, majakite, sperrylite and gold; atokite with zvyagintsevite and lead-rich kotulskite). The relationship of the platinum-group minerals to: 1) interstitial areas in pegmatitic gabbro, 2) F- and Cl-bearing biotite and apatite, 3) chloritic and calcitic veins at mineral contacts, 4) assemblages of iron-rich chlorite, epidote, amphibole, sericite, calcite, especially after magnetite, and 5) chalcopyrite - cubanite replacing primary pyrrhotite, are compatible with enrichment of sulfides by Cu and platinum-group elements where hydrous fluid has interacted with primary igneous minerals at low temperature.

Keywords: hydrothermal, alteration, chalcopyrite, electron microprobe, fluid, platinum-group minerals, Coldwell Complex, Ontario.

SOMMAIRE

Les minéraux du groupe du platine (*MGP*) sont associés aux paragenèses sulfurées, riches en chalcopyrite [$\text{Cu}/(\text{Cu} + \text{Ni}) = 0.94$, $\text{Pt}/(\text{Pt} + \text{Pd}) = 0.22$], des gabbros et des ferrogabbros à texture grenue et pegmatitique de l'intrusion de Two Duck Lake du complexe alcalin de Coldwell, située au contact oriental des roches métavolcaniques archéennes, dans le nord-ouest de l'Ontario. Les *MGP* apparaissent: 1) dans les sulfures ou à leur contact, 2) dans la chalcopyrite postcumulus, 3) en bordure des

grains de plagioclase au contact de la chalcopyrite, 4) dans les filonets séparant la chalcopyrite des autres minéraux, et 5) dans les zones d'altération des paragenèses primaires de silicates et d'oxydes. Certains *MPG* sont fortement zonés, en particulier la hollingworthite et la série atokite-zvyagintsevite, d'autres ont des compositions homogènes (sperrylite, kotulskite riche en Bi, Pd_5As_2); enfin, certains *MGP* se présentent en agrégats complexes comme la mertieite II associée à $\text{Pd}_2(\text{Sb}, \text{As})$, la nickeline palladifère, la majakite, la sperrylite et l'or, et l'atokite associée à la zvyagintsevite et à la kotulskite enrichie en plomb. Les relations des *MGP* avec: 1) les plages interstitielles des gabbros pegmatitiques, 2) du mica et de l'apatite riches en fluor et chlore, 3) la calcite et la chlorite dans les zones d'altération, 4) les assemblages de chlorite ferrière, d'épidote, d'amphibole, de séricite, de calcite qui remplacent préférentiellement la magnétite, et 5) chalcopyrite - cubanite qui remplacent la pyrrhotite, sont compatibles avec l'enrichissement en cuivre et en éléments du groupe du platine des sulfures lors de l'interaction des fluides hydrothermaux de basse température avec les minéraux magmatiques.

Mots-clés: hydrothermale, altération, analyses à la microsonde, chalcopyrite, fluides, minéraux du groupe du platine, complexe de Coldwell, Ontario.

INTRODUCTION

The Coldwell Complex, in northwestern Ontario (Fig. 1), is an unmetamorphosed, undeformed, alkaline plutonic complex emplaced at 1.1 Ga (Heaman & Machado 1987, unpubl. manuscript) into Archean metavolcanic, metasedimentary and granitic plutonic rocks (Puskas 1967, Dahl *et al.* 1986). The ultramafic to felsic, silica-saturated to silica-undersaturated suites of rocks were interpreted to group around three intrusive centers (Currie 1980, Mitchell & Platt 1982). The first center consists of an arcuate, massive to layered succession of gabbroic (Eastern gabbro, host to most of the sulfide-rich rocks) and syenitic rocks (Wilkinson 1983, Watkinson 1987).

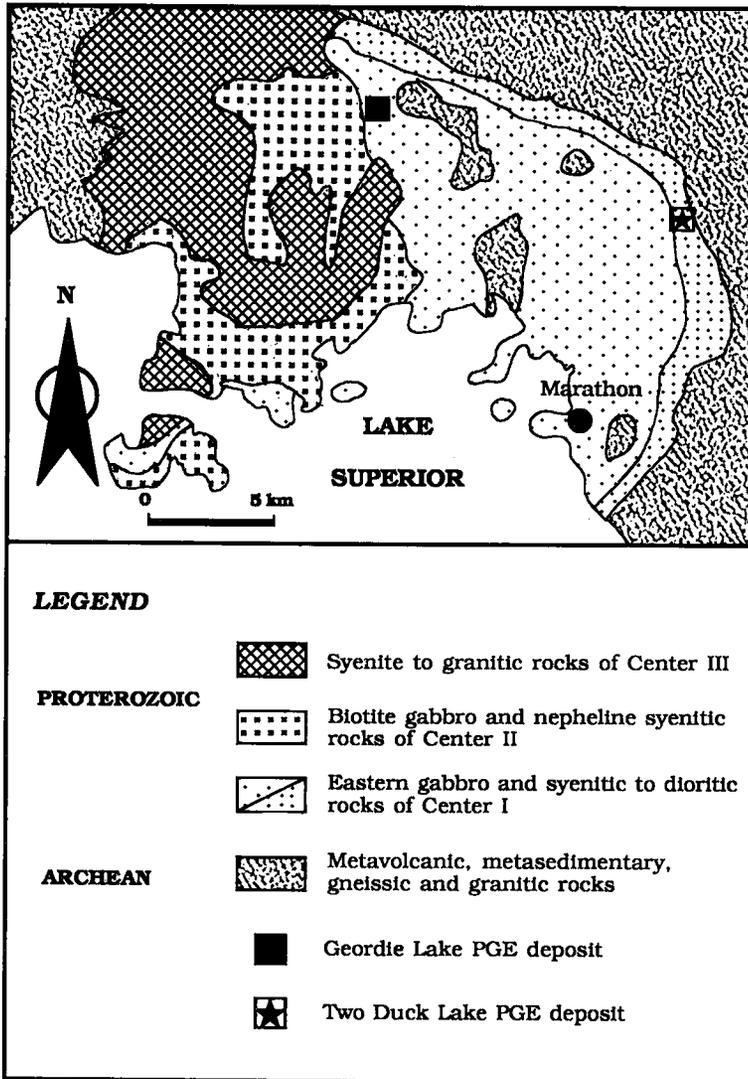


FIG. 1. Geological map of the Coldwell Complex showing the locations of the Two Duck Lake deposit (star) and Geordie Lake deposit (square); map after Puskas (1967) and Mitchell & Platt (1982).

Dahl *et al.* (1986, unpubl. manuscript) have shown that the rocks enriched in the platinum-group elements (*PGE*) and Cu near the contact of the complex with Archean metavolcanic rocks are not a facies of the Eastern gabbro, but are part of a later intrusive complex, the Two Duck Lake intrusion (Fig. 2). This is a coarse-grained to pegmatitic, zoned intrusion with a central magnetite-bearing unit underlain and overlain by sulfide-rich rocks. Fleck Resources Ltd. has

outlined a 30 Mt deposit grading 0.43% Cu, 0.69 g/t Pt and 1.85 g/t Pd; Cu/(Cu+Ni) and Pt/(Pt+Pd) are about 0.94 and 0.22, respectively (Watkinson 1987). Based on detailed mapping (Dahl *et al.* 1986, Watkinson 1987), samples relatively enriched in sulfides and *PGE*, as well as rocks with pegmatitic and other coarse-grained textures, were investigated to establish the mineralogy and petrology of the *PGE*- and sulfide-rich assemblages.

GEOLOGY OF THE EASTERN COLDWELL COMPLEX

The Eastern gabbro of the Coldwell Complex is a massive to layered intrusion ranging from wehrlite to diorite, and locally to anorthosite; these units are generally unaltered. Marginal units are massive to weakly layered, but the main layered series consists of laminated cumulates, mainly of magnetite, olivine, plagioclase, clinopyroxene and minor orthopyroxene. The Eastern gabbro has variable concentrations of magmatic sulfides (Wilkinson 1983, Watkinson 1987) and locally abundant, partially digested xenoliths; there appears to be a positive correlation in the occurrences of sulfides and xenoliths of country rocks.

Detailed mapping (Dahl *et al.* 1986, unpubl. manuscript) of the (Cu + PGE)-rich sulfide units has revealed that most of the sulfide-bearing rocks near the eastern contact, on the Marathon property of Fleck Resources Ltd., are part of a cross-cutting suite of sill-like intrusions that comprise the Two Duck Lake intrusion (Fig. 2). This complex unit was subdivided from bottom to top into: 1) a fine- to medium-grained hornblende gabbro to monzodiorite, 2) a coarse-grained to pegmatitic olivine ferrogabbro to ferrodiorite, and 3) a coarse- to very coarse-grained olivine gabbro to diorite. All these units contain abundant xenoliths of Archean volcanic rocks and Coldwell Complex (Eastern gabbro), partial digestion of which has modified the composition of the Two Duck Lake magma or magmas and has resulted in pods of granophyric material (Watkinson & Dahl 1988).

PETROLOGY OF PGM-BEARING ASSEMBLAGES

The sulfide assemblage in rocks of the Coldwell Complex is predominantly pyrrhotite + chalcopyrite + pentlandite. The fourth major mineral is either pyrite or cubanite, but some specimens contain mackinawite or other Fe sulfide minerals that are interpreted to be secondary after chalcopyrite or pyrrhotite. The assemblage of primary sulfides and their textures (massive and disseminated in gabbroic rocks) were justifiably interpreted to be of magmatic origin (Puskas 1967). However, as pointed out by Wilkinson (1983) and Watkinson (1987), the PGE-enriched sulfides are found in the

Watkinson, & J. McGoran); sulfide- and xenolith-bearing unit (mainly gabbro): intensely dotted pattern; ferrogabbroic rocks: sparsely dotted pattern.

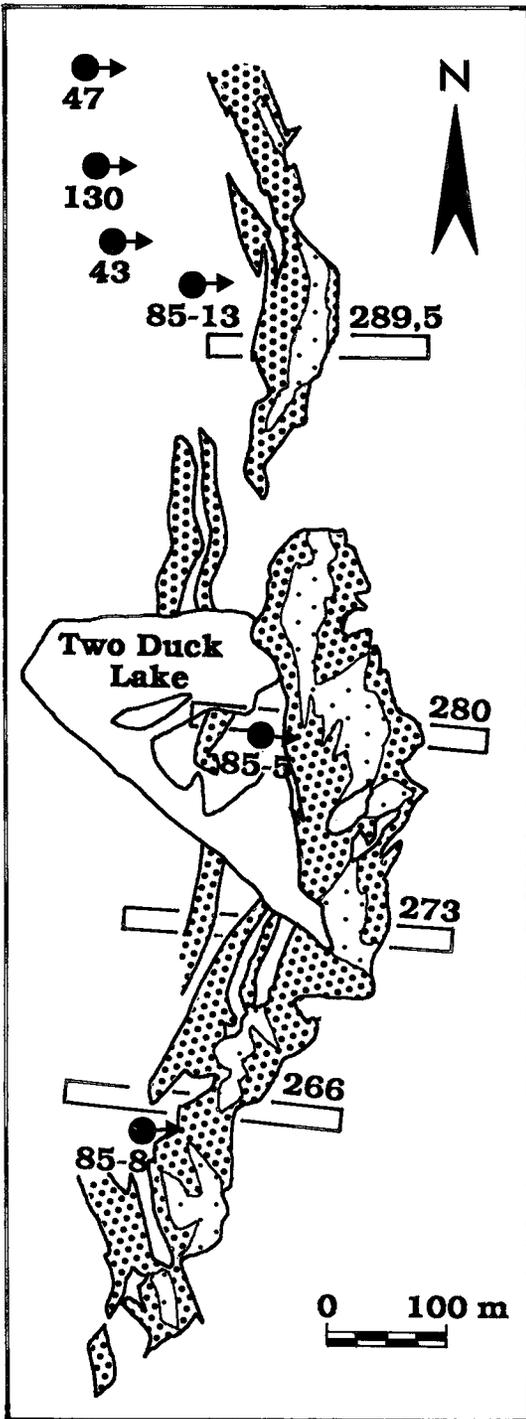


FIG. 2. Geological map of the Two Duck Lake intrusion showing the location of drill holes and trenches (simplified from unpublished map of R. Dahl, D.H.

most Cu-rich rocks, and the platinum-group minerals (*PGM*) (Figs. 3–5) are associated with pyrrhotite-poor assemblages of chalcopyrite and cubanite, with minor bornite, digenite and chalcocite (Watkinson 1990). There is a positive correlation of the *PGE*-rich sulfides with biotite, apatite and granophyric intergrowths in coarse-

grained to pegmatitic gabbro. Most rocks in the Two Duck Lake intrusion are unaltered, but the *PGE*- and Cu-rich assemblages are partly altered to an assemblage of actinolite + chlorite + epidote + sericite + calcite (Watkinson & Dahl 1988). *PGE* contents are generally low in fine-grained rocks; the highest contents occur in coarse-grained to pegmatitic rocks, but contents are slightly lower in pegmatites with the coarsest grain-size.

The *PGM* have been found in the following settings in the Two Duck Lake rocks: 1) included in or adjacent to postcumulus sulfides, mainly chalcopyrite and cubanite, 2) in chalcopyrite or pentlandite along sulfide-oxide grain boundaries, 3) in the rim of plagioclase grains with chalcopyrite, and 4) in veinlets along the contacts of chalcopyrite with other minerals, or 5) in veins cutting magnetite (with ilmenite lamellae) that is partly altered, and in other areas of altered primary magmatic minerals.

Some of the petrographic relationships are illustrated in Figures 3–5 for the largest and most complex assemblages of *PGM*. However, most *PGM* occur as isolated grains in chalcopyrite with cubanite lamellae, commonly related spatially to galena and altaite. In only one case was a *PGM* (Bi-rich kotulskite) found within pyrrhotite (Fig. 5D). There is a close spatial relationship of the *PGM* with mica and apatite; the mica contains as much as 0.35 wt.% Cl and 1.1 wt.% F, whereas apatite has as much as 1.07 wt.% Cl and 4.15 wt.% F. The *PGM* are even more closely associated with minerals of the alteration assemblage chlorite + actinolite + epidote + sericite + calcite. In addition, some of the *PGM* occur in veins and within or at contacts where the primary Fe minerals, such as pyrrhotite and magnetite (Figs. 4A, B), have been partly replaced. Magnetite is replaced by Fe-rich chlorite, epidote and siderite-calcite, whereas the ilmenite lamellae are fresh or

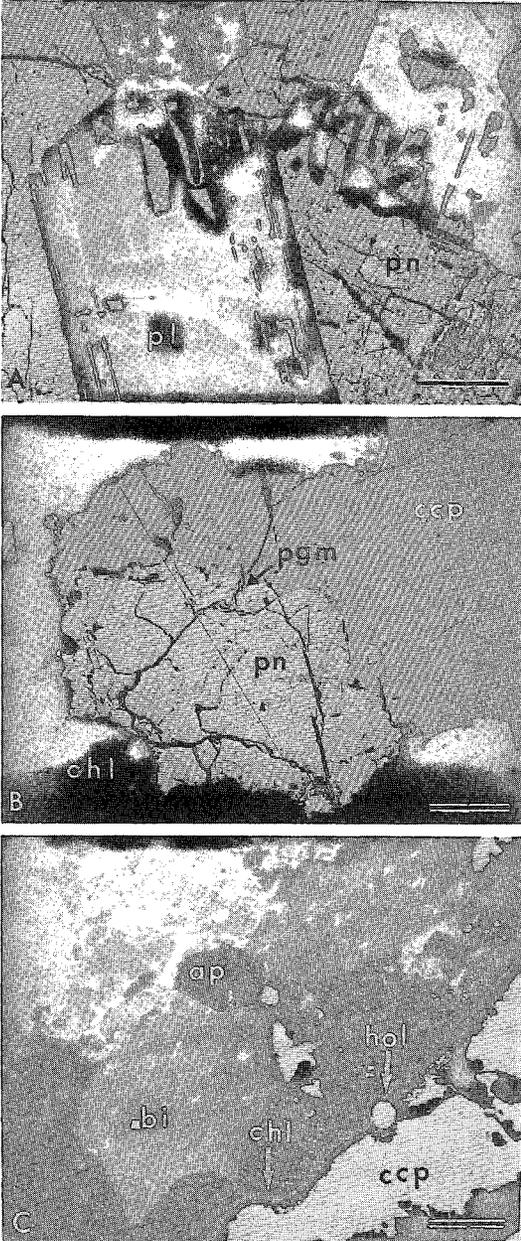


FIG. 3. Petrographic relationship of *PGM* to the silicate, sulfide and oxide minerals. A) Pb-rich kotulskite, zvyagintsevitse and atokite with chalcopyrite with abundant cubanite lamellae, enclosed in margin of plagioclase (pl) in contact with pentlandite (pn) and altered pyrrhotite: trench 289.5. Scale bar: 0.60 mm. B) Complex assemblage of platinum-group minerals (pgm) enclosed by pentlandite adjacent to chalcopyrite (ccp) and enclosed by chlorite (chl) after plagioclase: drill hole 43–320. Scale bar: 0.67 mm. C) Zoned hollingworthite (hol) along chlorite + calcite vein adjacent to chalcopyrite + biotite (bi) + apatite (ap) + plagioclase assemblage; vein also contains argentic pentlandite: drill hole 43–290. Scale bar: 0.1 mm.

less strongly altered to titanite and rutile. Some PGM with chalcopyrite occur in veins that cut magnetite with ilmenite lamellae that have undergone penecontemporaneous alteration (Figs. 5A, B). Pyrrhotite is commonly rimmed by chalcopyrite (commonly with cubanite lamellae), with re-

entrants into pyrrhotite indicative of replacement of early pyrrhotite. In some specimens, there are pyrrhotite grains where replacement by siderite is evident because the pentlandite flames in pyrrhotite protrude into siderite.

THE PLATINUM-GROUP MINERALS

The PGM in sulfide-rich rocks of the Coldwell Complex have been described by Wilkinson (1983), Watkinson (1987), Mulja (1989), Mulja & Mitchell (1990, 1991), Watkinson (1990), Ohnenstetter *et al.* (1991) and Ohnenstetter & Watkinson (1991). Mulja's study concerned the MacRae occurrence, Geordie Lake area, in the central part of the Coldwell Complex (Fig. 1), whereas the other data are from the eastern part. PGM discovered to date from the Two Duck Lake rocks are hollingworthite (ideally RhAsS; Ohnenstetter *et al.* 1991), merenskyite (PdTe₂; Wilkinson 1983), moncheite (PtTe₂), sperrylite (PtAs₂), kotulskite (PdTe, including Bi- and Pb-bearing varieties), atokite (Pd₃Sn), zvyagintsevite (Pd₃Pb), guanglinite (Pd₃As), mertieite II (Pd₈Sb₃), sopcheite (Pd₃Ag₄Te₄), unnamed minerals [Pd₅As₂ and Pd₂(Sb,As)], majakite (NiPdAs) and Pd-bearing nickeline. Other precious-metal minerals are argentic gold (Au/Ag ratio near 1), hessite and argentic pentlandite. Kotulskite is the most abundant PGM, and sperrylite, hollingworthite and the atokite-zvyagintsevite solid-solution group also are relatively abundant.

The minerals found during routine petrography were examined by scanning electron microscopy using energy-dispersion spectrometry (SEM-EDS; see Figs. 4, 5) in laboratories at Carleton University, Geological Survey of Canada, and Bureau de Recherches Géologiques et Minières (BRGM). Quantitative analyses were performed at BRGM by wavelength-dispersion spectrometry using the X-ray lines TeL α , AuL α , AsL α , SK α , SbL α , PtL α , BiM α , AgL β , NiK α , PbM α , SnL α , HgM α , PdL α , FeK α , IrK α , CuK α , RhL α ; stand-

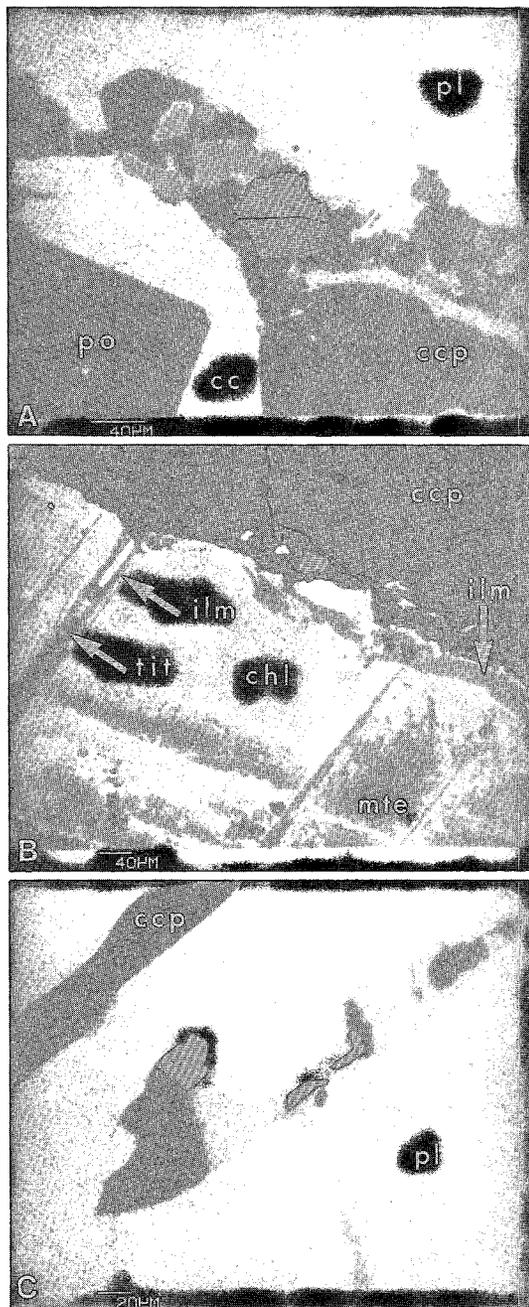


FIG. 4. Scanning electron micrographs of platinum-group minerals. A) Complexly zoned hollingworthite (Ohnenstetter *et al.* 1991) in chalcopyrite adjacent to plagioclase, ilmenite, calcite (cc) and pyrrhotite (po): drill hole 85-13-109.5. B) Kotulskite (white) in chalcopyrite along contact of partially altered magnetite (mte) and ilmenite (ilm). Alteration assemblage is chlorite + epidote + titanite (tit) + calcite: drill hole 43-319.5. C) Atokite + zvyagintsevite + Pb-bearing kotulskite assemblage adjacent to chalcopyrite, enclosed by plagioclase (see Fig. 3A).

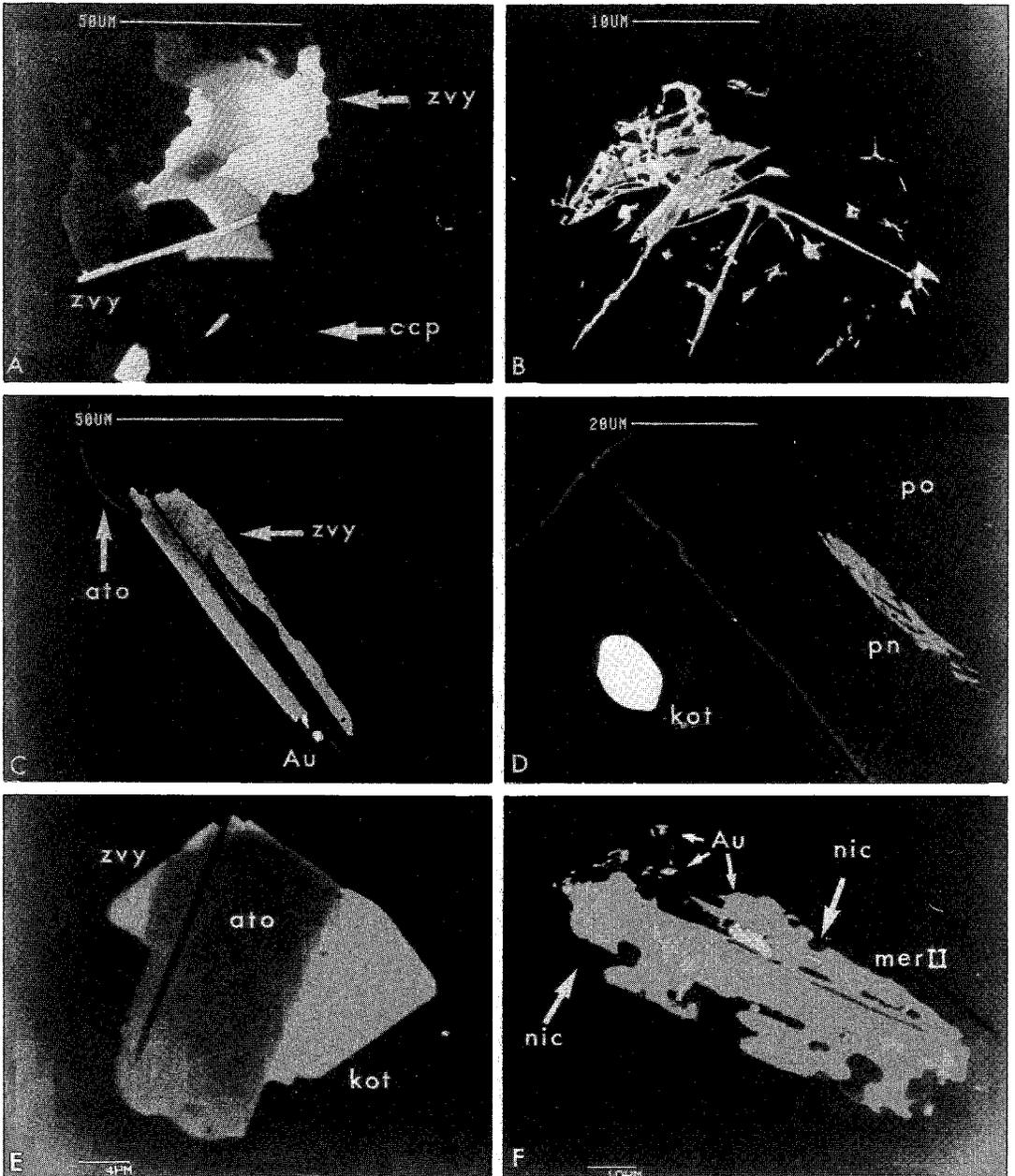


FIG. 5. Scanning electron micrographs of platinum-group minerals. A) Zoned zvyagintsevite (zvy) adjacent to chalcopyrite along vein in magnetite + ilmenite, the latter altered to chlorite + epidote + calcite + titanite; differing shades of grey result from complex zoning of Pd, Pt, Pb, Ag, Te, Sn, As; drill hole 47-404. B) Delicate habit of atokite with Pd and Pt zonation, about 1 mm from 5A; drill hole 47-404. C) Atokite (ato) + zvyagintsevite + gold (Au) assemblage adjacent to chalcopyrite in vein cutting pyroxene; trench 266. D) Bismuth-rich kotulskite (kot) in pyrrhotite with pentlandite flames; some pyrrhotite partly replaced by siderite, and very small amount of pentlandite altered to argentic pentlandite; drill hole 85-5-160. E) Atokite + zvyagintsevite + Pb-bearing kotulskite enclosed by plagioclase and chalcopyrite (see Fig. 4C). F) Complex assemblage of mertieite II (mer II) + sperrylite + majakite + argentic gold (white) + $\text{Pd}_2(\text{Sb,As})$ + palladian nickeline (nic) enclosed by pentlandite (see Fig. 3B). Note various shades of grey in nickeline and mertieite II, indicating variable Pd/Ni and Sb/As, respectively.

ards were pure metals, and pyrite for S, galena for Pb, sperrylite for As, stibnite for Sb, cinnabar for Hg and synthetic SnO₂ for Sn. Analytical conditions were: accelerating voltage 25 kV, reference current 30 nA, counting time 10 s, data reduction by MBXCOR-ZAF (Henoc & Tong 1978).

Representative compositions of the PGM are presented in Tables 1-8; all other PGM data and compositions of coexisting sulfides and silicates are presented by Ohnenstetter (1990). Cu, Fe and S contents of the PGM are mainly the result of analysis of small grains enclosed in chalcopyrite.

The composition of most minerals varies only slightly; however, hollingworthite from Two Duck Lake (Ohnenstetter *et al.* 1991) and atokite-zvyagintsevite are intricately zoned. Atokite and rustenburgite (Pt₃Sn) may form a complete solid-solution (Mihálik *et al.* 1975, Malevskiy *et al.* 1978), and a complete solid-solution exists from atokite to zvyagintsevite (Genkin *et al.* 1966, Mihálik *et al.* 1975). Chemical compositions of atokite - zvyagintsevite from Two Duck Lake specimens are illustrated in Figure 6; there appears to be complete solid-solution between the two intermetallic compounds. Pt/(Pt+Pd) versus Sn/(Sn+Pb) data define a line $y = 0.2x$; variance about the line is 0.77 ($n = 45$). The subtle variation in compositions is revealed in some SEM-EDS photographs (Figs. 5 A, B,); however, sharp contacts (Figs. 5C, E) may result from low-temperature exsolution that produced coexisting Pt-rich and Pt-poor compositions (Fig. 5C). This proposed exsolution is compatible with the Au contents of some phases with intermediate compositions (as much as 1.84 wt. %: Table 1), as compared with Au-free compositions in the grains coexisting

with argentian gold (Fig. 5C). Gold-bearing zvyagintsevite associated with an Ag-Au alloy from Noril'sk was described by Cabri & Traill (1966). Zvyagintsevite (Fig. 5A) also tends to As-rich compositions, and one composition is closer to guanglinite (Pd₃As) than to Pd₃Pb. Te contents (atomic) nearly attain those of Pb, Sn and As; details of these solid solutions are discussed by Ohnenstetter & Watkinson (1991).

Three groups of kotulskite compositions are apparent in Figure 7; similar compositions of kotulskite were reviewed by Cabri (1981). The most Bi-rich cluster of compositions (Table 3) is similar to those described by Beaudoin *et al.* (1990) and Mulja & Mitchell (1990). This may indicate that solid solution exists toward sobolevskite (PdBi). Kotulskite with Pb contents as high as 9.5 wt. % Pb (Table 4) is significantly more Pb-rich than those compositions described by Kovalenker *et al.* (1973) from Noril'sk and by Cabri *et al.* (1979) from Stillwater.

Sperrylite (Table 5) occurs as isolated grains, with an overgrowth of zoned hollingworthite, or as inclusions in mertieite II (Table 6, Fig. 5F). Unnamed Pd₅As₂ (Table 7) occurs with chalcopyrite; the association of Pd₅As₂ with palladoarsenide, sperrylite, chalcopyrite and stillwaterite also has been described by Cabri *et al.* (1975).

The complex association of mertieite II with palladium-antimony arsenide (Table 7), majakite and nickeline (Fig. 8, Table 8) plus argentian gold is shown in Figure 5f. This mertieite II is relatively rich in As compared to examples from Noril'sk (Kovalenker *et al.* 1978) and similar to those described by Cabri & Chen (1976) from Tweefontein, South Africa. The Pd₂(Sb,As) mineral may

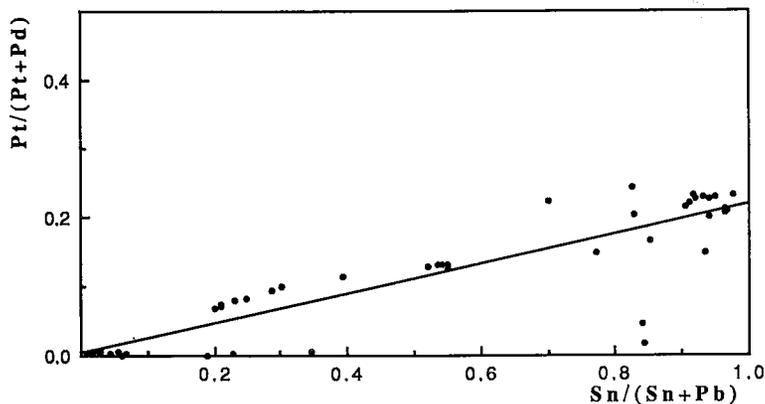


FIG. 6. Linear regression of Pt/(Pt+Pd) versus Sn/(Sn+Pb) for atokite and zvyagintsevite solid-solutions. Points well below line refer mainly to As-rich compositions.

TABLE 1. SELECTED ELECTRON-MICROPROBE DATA ON ATOKITE

	1	2	3	4	5	6
Weight percent						
Pt	23.13	25.68	24.40	22.53	25.56	23.40
As	1.09	0.10	0.01	0.84	0.16	0.00
Pd	48.83	43.78	46.47	48.91	47.17	48.63
Ir	0.13	0.00	0.00	0.00	0.00	0.00
Cu	0.28	0.25	0.23	0.58	0.33	0.19
Ni	0.00	0.00	0.00	0.01	0.00	0.09
Fe	0.35	0.33	0.34	0.38	0.21	0.28
S	0.03	0.12	0.05	0.07	0.05	0.09
Rh	0.00	0.00	0.00	0.00	0.05	0.00
Te	0.00	0.00	0.00	0.00	0.00	0.00
Sn	22.66	21.16	15.40	23.39	23.89	23.88
Bi	0.61	0.11	0.22	0.23	0.05	0.00
Pb	1.43	7.76	11.46	2.61	2.15	1.41
Sb	0.00	0.00	0.00	0.00	0.00	0.00
Hg	0.00	0.00	0.11	0.14	0.17	0.41
Ag	0.00	0.21	0.11	0.00	0.00	0.00
Au	1.84	1.16	1.13	n.d.	n.d.	n.d.
Total	100.38	100.66	99.93	99.69	99.79	98.38
Atomic percent (total: 4 atoms)						
Pt	0.582	0.673	0.653	0.566	0.655	0.600
As	0.071	0.007	0.001	0.055	0.011	0.000
Pd	2.254	2.104	2.279	2.253	2.216	2.287
Ir	0.003	0.000	0.000	0.000	0.000	0.000
Cu	0.022	0.020	0.019	0.045	0.026	0.015
Ni	0.000	0.000	0.000	0.001	0.000	0.008
Fe	0.031	0.030	0.032	0.033	0.019	0.025
S	0.005	0.019	0.008	0.011	0.008	0.014
Rh	0.000	0.000	0.000	0.000	0.002	0.000
Te	0.000	0.000	0.000	0.000	0.000	0.000
Sn	0.938	0.912	0.677	0.966	1.006	1.007
Bi	0.014	0.003	0.005	0.005	0.001	0.000
Pb	0.034	0.192	0.289	0.062	0.052	0.034
Sb	0.000	0.000	0.000	0.000	0.000	0.000
Hg	0.000	0.000	0.003	0.003	0.004	0.010
Ag	0.000	0.010	0.005	0.000	0.000	0.000
Au	0.046	0.030	0.030			

Atokite associated with Pb - bearing kotulskite and zvyaginsevite (n.d. = not determined); trench 289.5.

relate to (Pd,Pt,Ni)₂(Sb,Sn) and Pd₂(Sn,Sb) described by Ren & Huang (1973) and Yakovlev *et al.* (1991), respectively. Majakite (Genkin *et al.* 1976) and Sb-rich majakite, as well as nickeline and Pd-bearing nickeline, also are members of this

TABLE 2. SELECTED ELECTRON-MICROPROBE DATA ON ZVYAGINTSEVITE

	1	2	3	4	5	6	7
Weight percent							
Pt	7.79	13.93	10.04	7.29	8.76	11.00	12.28
As	0.05	0.00	0.01	0.00	0.00	0.11	0.00
Pd	53.86	50.55	53.35	52.30	53.82	53.32	52.17
Ir	0.81	0.00	0.91	1.36	1.16	0.88	0.44
Cu	0.21	0.13	0.19	0.24	0.41	0.28	0.41
Ni	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.40	0.29	0.48	0.37	0.43	0.32	0.00
S	0.05	0.02	0.08	0.11	0.06	0.00	0.00
Sn	4.79	12.51	6.18	4.75	5.56	6.48	9.11
Bi	0.13	0.60	0.18	0.26	0.25	0.11	0.72
Pb	31.63	17.82	26.74	31.37	29.47	26.16	24.39
Sb	0.00	0.00	0.00	0.02	0.00	0.00	0.00
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Au	0.00	1.51	0.00	0.00	0.00	0.00	0.00
Total	99.75	97.36	98.16	98.07	99.92	98.66	99.52
Atomic percent (total: 4 atoms)							
Pt	0.211	0.378	0.273	0.201	0.235	0.299	0.331
As	0.004	0.000	0.001	0.000	0.000	0.008	0.000
Pd	2.674	2.513	2.661	2.648	2.652	2.655	2.581
Ir	0.022	0.000	0.025	0.038	0.032	0.024	0.012
Cu	0.017	0.011	0.016	0.02	0.034	0.023	0.034
Ni	0.003	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.038	0.027	0.046	0.036	0.040	0.030	0.000
S	0.008	0.003	0.013	0.018	0.010	0.000	0.000
Sn	0.213	0.557	0.276	0.216	0.246	0.289	0.404
Bi	0.003	0.015	0.005	0.007	0.006	0.003	0.018
Pb	0.806	0.455	0.685	0.815	0.746	0.669	0.620
Sb	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hg	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ag	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Au	0.000	0.041	0.000	0.000	0.000	0.000	0.000

1-2: isolated grain, 3-7: grain associated with atokite and Pb-bearing kotulskite; trench 289.5.

association; nickeline (Table 8) is either Pd-poor (4–8 wt.%; black in Fig. 5F) or Pd-rich (as high as 30 wt.%; dark grey in Fig. 5F). Their occurrence with mertieite II and the unnamed phase may result from unmixing of a solid solution.

Pb-bearing minerals are common with the PGM. The relative abundance of Pb and Sn compounds with PGE and the observation that galena and altaite are found as very minor constituents of almost all PGE-rich rocks at Two Duck Lake may relate to the interaction of gabbroic magma (probable source of the PGE) and felsic metavolcanic xenoliths (possible source of Pb and Sn). Sn may be held in magnetite and released to form intermetallic compounds when it was altered (Figs. 4, 5).

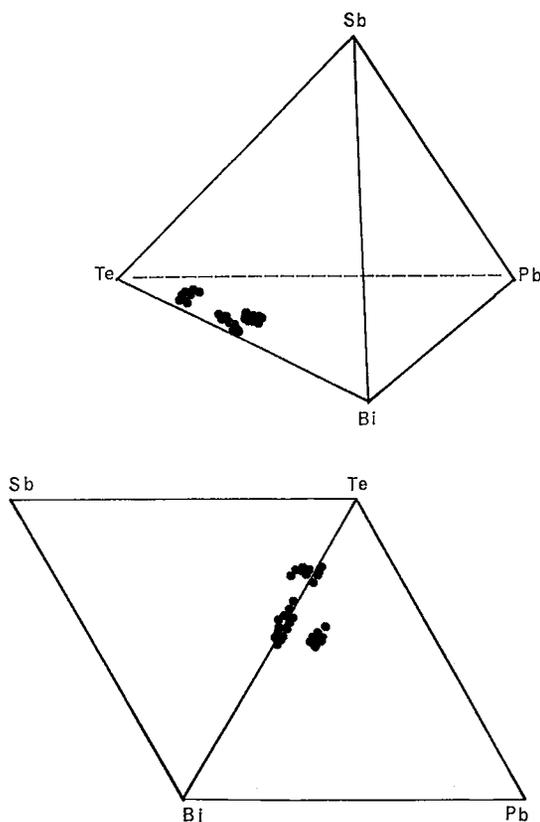


FIG. 7. Clusters of kotulskite compositions projected onto the Te-Bi-Sb-Pb tetrahedron and on two triangular faces.

DISCUSSION

Previous studies of sulfide assemblages in the Two Duck Lake area (Puskas 1967, Wilkinson 1983, Good & Crocket 1989) have led some researchers to interpret that sulfide mineralization was a magmatic process and that the present mineralogy resulted from exsolution from monosulfide solid-solution that had precipitated from gabbroic magma. However, the PGE- and Cu-rich sulfide assemblages are unusual for classic, magmatic assemblages (Naldrett 1989) in that the mineralogy is dominated by chalcopyrite and cubanite. Pyrrhotite and magnetite with ilmenite lamellae (presumably of high-temperature magmatic origin) are partly replaced, and many PGM occur in veinlets, some of which cut partly altered primary magmatic minerals. These types of features, among others, led Watkinson (1990) to conclude that the Two Duck Lake PGE- and

TABLE 3. SELECTED ELECTRON-MICROPROBE DATA ON KOTULSKITE

	1	2	3	4	5	6	7
Weight percent							
Pt	0.79	0.65	0.51	0.81	0.28	1.33	1.12
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pd	38.70	38.85	39.34	38.58	38.75	36.82	39.59
Ir	0.08	0.24	0.13	0.19	0.27	0.06	0.08
Cu	0.03	0.08	0.00	0.02	0.00	0.03	0.57
Ni	0.00	0.00	0.02	0.00	0.00	0.02	0.00
Fe	0.40	0.32	0.42	0.35	0.40	1.62	0.52
S	0.06	0.04	0.05	0.02	0.04	0.27	0.07
Rh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Te	38.76	38.19	37.86	38.58	39.40	28.82	24.96
Sn	0.00	0.00	0.00	0.00	0.07	0.00	0.00
Bi	19.58	20.21	19.79	19.98	19.60	30.28	32.23
Pb	0.15	0.12	0.03	0.21	0.05	0.00	0.02
Sb	1.00	1.03	1.29	1.11	1.27	1.02	0.87
Hg	0.00	0.00	0.00	0.01	0.04	0.10	0.00
Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.55	99.73	99.44	99.86	100.17	100.37	100.03
Atomic percent (total: 2 atoms)							
Pt	0.010	0.009	0.007	0.011	0.004	0.018	0.015
As	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pd	0.928	0.933	0.942	0.926	0.923	0.898	0.985
Ir	0.001	0.003	0.002	0.003	0.004	0.001	0.001
Cu	0.001	0.003	0.000	0.001	0.000	0.001	0.024
Ni	0.000	0.000	0.001	0.000	0.000	0.001	0.000
Fe	0.018	0.015	0.019	0.016	0.018	0.075	0.025
S	0.005	0.003	0.004	0.002	0.003	0.022	0.006
Rh	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Te	0.775	0.764	0.756	0.772	0.782	0.586	0.518
Sn	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Bi	0.239	0.247	0.241	0.244	0.238	0.376	0.408
Pb	0.002	0.001	0.000	0.003	0.001	0.000	0.000
Sb	0.021	0.022	0.027	0.023	0.026	0.022	0.019
Hg	0.000	0.000	0.000	0.000	0.001	0.001	0.000
Ag	0.000	0.000	0.000	0.000	0.000	0.000	0.000

1-6: three different grains from drill hole 85-8-244.08. 7: drill hole 43-319.5.

Cu-rich assemblages were similar in origin to those from other PGE- and Cu-enriched sulfide assemblages, such as at the Salt Chuck mine (Watkinson 1990, Watkinson & Melling 1992), New Rambler mine (Loucks & McCallum 1978), Thierry mine (Patterson & Watkinson 1984), Shebandowan mine (Morton 1982), Messina mine (Mihálik *et al.* 1974), and Murunsky pluton (Dobrovol'skaya *et al.* 1985).

The field, petrographic and mineral-chemical data from the Two Duck Lake intrusion lead us to interpret that the concentrations of the PGE and Cu in the sulfide assemblages result from the interaction of a fluid phase with early-precipitated

TABLE 4. SELECTED ELECTRON-MICROPROBE DATA ON LEAD BEARING KOTULSKITE

	1	2	3	4	5	6	7
Weight percent							
Pt	1.27	1.34	1.33	1.52	1.24	0.79	1.03
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pd	35.4	36.66	36.63	37.94	38.5	38.64	36.87
Ir	0.00	0.00	0.00	0.00	0.81	0.41	0.41
Cu	0.47	0.34	0.47	0.56	0.41	0.79	0.20
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.52	0.31	0.45	0.64	0.54	0.54	0.55
S	0.04	0.04	0.04	0.00	0.08	0.00	0.00
Rh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Te	25.59	24.07	24.48	25.79	25.17	25.43	25.40
Sn	0.00	0.02	0.00	0.01	0.00	0.07	0.00
Bi	27.65	28.19	27.65	26.08	24.77	25.68	26.78
Pb	7.93	8.50	7.36	8.42	7.96	8.36	9.55
Sb	0.00	0.00	0.00	0.00	0.00	0.00	0.07
Hg	0.00	0.00	0.00	0.00	0.00	0.08	0.00
Ag	0.15	0.14	0.01	0.00	0.00	0.00	0.00
Total	99.02	99.61	98.42	100.96	99.48	100.79	100.86
Atomic percent (total: 2 atoms)							
Pt	0.018	0.019	0.019	0.021	0.017	0.011	0.014
As	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pd	0.912	0.945	0.946	0.948	0.971	0.962	0.936
Ir	0.000	0.000	0.000	0.000	0.011	0.006	0.006
Cu	0.020	0.015	0.020	0.023	0.017	0.033	0.008
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.026	0.015	0.022	0.030	0.026	0.026	0.027
S	0.003	0.003	0.003	0.000	0.007	0.000	0.000
Rh	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Te	0.550	0.517	0.527	0.537	0.529	0.528	0.537
Sn	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bi	0.363	0.370	0.364	0.332	0.318	0.326	0.346
Pb	0.105	0.112	0.098	0.108	0.103	0.107	0.124
Sb	0.000	0.000	0.000	0.000	0.000	0.000	0.002
Hg	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Ag	0.004	0.004	0.000	0.000	0.000	0.000	0.000

1-3: grain associated with atokite and zvyagintsevite, 4-6: isolated grain, 7: isolated grain; trench 289.5.

magmatic sulfides, oxides and silicates. The fluid was probably derived from a combination of magmatic fluid, and fluid from the breakdown of xenoliths of metamorphosed Archean rocks. This is compatible with the spatial relationship of *PGM* to rocks of coarse-grained to pegmatitic texture, with partly digested xenoliths and granophyric patches, Cl-bearing mica and apatite, local assemblages of alteration minerals (chlorite, epidote, amphibole, sericite, calcite), and their occurrence in veinlets in marginal units of the Two Duck Lake intrusion. The occurrence of intricately zoned hollingworthite was interpreted by Ohnenstetter *et al.* (1991) to have resulted from precipitation from fluid of changing composition; this process is also

TABLE 5. SELECTED ELECTRON-MICROPROBE DATA ON SPERRYLITE

	1	2	3	4	5	6	7
Weight percent							
Pt	55.01	53.77	53.36	53.85	53.04	53.56	53.23
As	39.58	42.84	42.88	42.93	43.22	43.31	42.21
Pd	0.00	0.00	0.00	0.09	0.00	0.00	0.01
Ir	0.18	0.40	0.65	0.16	0.80	0.69	0.81
Cu	1.37	0.39	0.54	0.50	0.79	0.83	0.85
Ni	0.00	0.00	0.00	0.02	0.00	0.04	0.00
Fe	0.37	0.32	0.36	0.38	0.51	0.51	0.59
S	2.46	0.58	0.58	0.52	0.48	0.54	0.49
Rh	0.39	0.53	0.39	0.35	0.39	0.37	0.34
Te	0.06	0.04	0.00	0.00	0.00	0.00	0.00
Sn	0.00	0.01	0.00	0.00	0.07	0.00	0.00
Bi	0.00	0.01	0.26	0.00	0.00	0.00	0.06
Pb	0.31	0.29	0.45	0.51	0.76	0.36	0.48
Sb	0.00	0.02	0.00	0.01	0.00	0.00	0.19
Total	99.73	99.20	99.47	99.32	100.06	100.21	99.26
Atomic percent (total: 3 atoms)							
Pt	0.918	0.933	0.923	0.933	0.909	0.915	0.923
As	1.719	1.935	1.93	1.936	1.928	1.924	1.905
Pd	0.000	0.000	0.000	0.003	0.000	0.000	0.000
Ir	0.003	0.007	0.011	0.003	0.014	0.012	0.014
Cu	0.070	0.021	0.029	0.027	0.042	0.044	0.045
Ni	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Fe	0.022	0.019	0.022	0.023	0.031	0.030	0.036
S	0.250	0.061	0.061	0.055	0.05	0.056	0.052
Rh	0.012	0.017	0.013	0.011	0.013	0.012	0.011
Te	0.002	0.001	0.000	0.000	0.000	0.000	0.000
Sn	0.000	0.000	0.000	0.000	0.002	0.000	0.000
Bi	0.000	0.000	0.004	0.000	0.000	0.000	0.001
Pb	0.005	0.005	0.007	0.008	0.012	0.006	0.008
Sb	0.000	0.001	0.000	0.000	0.000	0.000	0.005

Specimen from trench 266

the probable explanation of the atokite-zvyagintsevite compositions, especially in light of the occurrence of these Pb- and Sn-bearing minerals in veins and alteration assemblages that cut primary magmatic minerals.

Watkinson (1990) concluded that the enrichment in Cu, *PGE* and other precious metals in some pegmatitic and vein-like deposits is directly related to the occurrence of an alteration assemblage composed of calcic amphibole + epidote + chlorite, commonly with sericite, calcite and quartz. Furthermore, there are very saline fluid inclusions in some quartz and epidote grains from the host rocks to some Cu- and *PGE*-enriched sulfides from the Coldwell Complex and other deposits (Watkinson 1990, unpubl. data); these are interpreted to represent trapped fluid that reacted with primary minerals to produce the hydrated (and somewhat oxidized) phases such as Fe-rich epidote, and

TABLE 6. SELECTED ELECTRON-MICROPROBE DATA ON MERTIETTE II

	1	2	3	4	5	6	7
Weight percent							
Pt	0.61	0.17	0.10	0.23	0.10	0.64	0.62
As	4.32	3.63	3.06	1.81	2.91	3.00	2.53
Pd	69.93	71.08	70.00	67.77	68.81	69.29	68.13
Ir	0.20	0.18	0.31	0.00	0.00	0.17	0.00
Cu	0.03	0.04	0.00	0.11	0.00	0.12	0.37
Ni	0.39	0.23	0.58	1.01	0.83	0.64	0.24
Fe	0.20	0.10	0.38	0.80	0.70	0.30	0.36
S	0.09	0.03	0.10	0.22	0.12	0.13	0.16
Rh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Te	0.13	0.00	0.09	0.00	0.02	0.01	0.16
Sn	0.09	0.02	0.05	0.12	0.18	0.17	0.19
Bi	0.10	0.04	0.00	0.37	0.00	0.00	0.10
Pb	0.03	0.18	0.14	0.00	0.23	0.02	0.00
Sb	24.19	24.80	25.44	28.00	26.74	26.27	27.45
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Total	100.31	100.50	100.25	100.44	100.64	100.76	100.36
Atomic percent (total: 11 atoms)							
Pt	0.037	0.010	0.006	0.014	0.006	0.039	0.038
As	0.679	0.573	0.482	0.284	0.455	0.471	0.400
Pd	7.743	7.897	7.769	7.491	7.576	7.661	7.592
Ir	0.012	0.011	0.019	0.000	0.000	0.010	0.000
Cu	0.006	0.007	0.000	0.020	0.000	0.022	0.069
Ni	0.078	0.046	0.117	0.202	0.166	0.128	0.048
Fe	0.042	0.021	0.080	0.168	0.147	0.063	0.076
S	0.033	0.011	0.037	0.081	0.044	0.048	0.059
Rh	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Te	0.012	0.000	0.008	0.000	0.002	0.001	0.015
Sn	0.009	0.002	0.005	0.012	0.018	0.017	0.019
Bi	0.006	0.002	0.000	0.021	0.000	0.000	0.006
Pb	0.002	0.010	0.008	0.000	0.013	0.001	0.000
Sb	2.342	2.409	2.468	2.706	2.574	2.539	2.674
Hg	0.000	0.000	0.000	0.000	0.000	0.000	0.003

Specimen from drill hole 43-320.

TABLE 7. SELECTED ELECTRON-MICROPROBE DATA ON UNNAMED PALLADIUM ARSENIDE AND PALLADIUM ANTIMONIDE MINERALS

	1	2	3	4	5	6
Weight percent						
Pt	0.00	0.11	0.00	0.53	0.89	0.43
As	22.28	21.68	22.14	9.36	11.02	10.92
Pd	73.00	72.36	71.33	64.30	59.90	64.32
Ir	0.00	0.23	0.04	0.76	0.61	0.33
Cu	3.17	3.71	2.98	0.02	0.35	0.13
Ni	0.08	0.14	0.10	0.38	4.36	0.47
Fe	0.90	1.17	0.96	0.35	0.30	0.28
S	0.02	0.11	0.02	0.07	0.18	0.07
Rh	0.00	0.00	0.00	n.d.	n.d.	n.d.
Te	0.00	0.00	0.00	0.01	0.01	0.02
Sn	0.21	0.28	0.36	0.06	0.11	0.16
Bi	0.00	0.11	0.00	0.00	0.00	0.05
Pb	0.00	0.26	0.12	0.00	0.33	0.33
Sb	n.d.	n.d.	n.d.	23.32	22.32	22.78
Hg	0.00	0.33	0.29	0.00	0.00	0.00
Total	99.66	100.49	98.34	99.16	100.38	100.29
Atomic percent						
Pt	0.000	0.004	0.000	0.009	0.014	0.007
As	1.976	1.907	1.994	0.397	0.444	0.455
Pd	4.560	4.482	4.523	1.922	1.698	1.885
Ir	0.000	0.008	0.001	0.013	0.010	0.005
Cu	0.332	0.385	0.316	0.001	0.017	0.006
Ni	0.009	0.016	0.011	0.021	0.224	0.025
Fe	0.107	0.138	0.116	0.020	0.016	0.016
S	0.004	0.023	0.004	0.007	0.017	0.007
Rh	0.000	0.000	0.000			
Te	0.000	0.000	0.000	0.000	0.000	0.000
Sn	0.012	0.016	0.020	0.002	0.003	0.004
Bi	0.000	0.003	0.000	0.000	0.000	0.001
Pb	0.000	0.008	0.004	0.000	0.005	0.005
Sb				0.609	0.553	0.584
Hg	0.000	0.011	0.010	0.000	0.000	0.000

1-3: unnamed palladium arsenide from drill hole 43-404,
 4-6: unnamed palladium antimonide from drill hole 43-320.
 The structural formulae are calculated on the basis of 7
 and 3 atoms for the arsenide and antimonide, respectively
 (n.d.: not determined).

precipitated Cu-rich and precious-metal (especially Pd-bearing) minerals. Fluid inclusions have been documented in PGE-bearing rocks from Bushveld (Ballhaus & Stumpfl 1986, Johan & Watkinson 1987), Sudbury (Farrow & Watkinson 1992) and New Rambler (Nyman *et al.* 1990).

PGE- and Cu-rich sulfides in troctolite-gabbro of the Georgie Lake intrusion, a northerly striking unit intruded into Coldwell Complex rocks, were described by Good & Crocket (1989) and Mulja & Mitchell (1990). Cu/(Cu + Ni) and Pt/(Pt + Pd) are about 0.92 and 0.05, respectively. Mulja (1989) described sperrylite, kotulskite, merenskyite, michenerite, sopcheite, polovite, guanlingite, and other palladian arsenides, antimonides and bismuth

tellurides. He ascribed a late magmatic origin to the PGM and concluded that crystallization of sulfide-rich magma was induced by magnetite precipitation and cyclic deposition of Cu-rich

TABLE 8. SELECTED ELECTRON-MICROPROBE DATA ON MAJAKITE AND NICKELINE

	1	2	3	4	5	6
Weight percent						
Pt	0.76	0.40	0.51	0.00	0.00	0.34
As	31.08	33.01	53.92	52.81	48.33	34.54
Pd	49.02	37.04	4.18	7.44	12.35	30.55
Ir	0.16	0.21	0.25	0.18	n.d.	n.d.
Cu	0.81	0.02	0.57	0.56	0.59	4.26
Ni	16.69	23.25	38.27	36.28	33.71	18.29
Fe	1.04	0.17	0.76	0.80	0.75	4.77
S	0.50	0.26	0.41	0.38	0.37	6.07
Rh	n.d.	0.00	0.13	0.04	0.00	0.10
Te	0.18	0.19	0.39	0.29	0.26	0.17
Sn	0.00	0.02	0.00	0.00	n.d.	n.d.
Bi	0.15	0.00	0.00	0.02	0.00	0.02
Pb	0.25	0.00	0.31	0.36	0.00	0.00
Sb	0.04	7.88	0.72	1.38	2.69	0.00
Hg	n.d.	n.d.	0.33	0.00	n.d.	n.d.
Total	100.68	102.43	100.75	100.54	99.05	99.11
Atomic percent						
Pt	0.010	0.005	0.004	0.000	0.000	0.002
As	1.024	1.044	0.983	0.976	0.926	0.656
Pd	1.137	0.825	0.054	0.097	0.167	0.409
Ir	0.002	0.003	0.002	0.001		
Cu	0.031	0.001	0.012	0.012	0.013	0.095
Ni	0.702	0.939	0.891	0.856	0.824	0.443
Fe	0.046	0.007	0.019	0.020	0.019	0.122
S	0.039	0.019	0.017	0.016	0.017	0.269
Rh		0.000	0.002	0.001	0.000	0.001
Te	0.003	0.004	0.004	0.003	0.003	0.002
Sn	0.000	0.000	0.000	0.000		
Bi	0.002	0.000	0.000	0.000	0.000	0.000
Pb	0.003	0.000	0.002	0.002	0.000	0.000
Sb	0.001	0.153	0.008	0.016	0.032	0.000
Hg			0.002	0.000		

1: majakite, 2: Sb-bearing majakite, 3 and 4: nickeline, 5 and 6: Pd-bearing nickeline from drill hole 43 - 320. The structural formulae are calculated on the basis of 3 atoms for majakite, and 2 atoms for nickeline (n.d.: not determined).

sulfide and magnetite. However, Mulja noted that whereas sulfides are concentrated near the base of the intrusion, they do extend into the enclosing syenite. He also stated that the abundance of sulfide is correlated with the amount of amphibole

and biotite. Watkinson (1990) noted the similarity of some assemblages from Geordie Lake that he had examined, to those from the Salt Chuck and New Rambler mines, and interpreted the Cu sulfides (chalcopyrite + bornite + digenite + chalcocite) and PGM to have resulted from replacement of magmatic sulfides (essentially pyrrhotite + chalcopyrite + pentlandite) by fluid enriched in Cu + Pd + Pb + Ag + Au after consolidation of the silicate + sulfide assemblage. Mihálik *et al.* (1974) described PGM in association with similar alteration assemblages from a hydrothermal environment at Messina, South Africa.

Johan & Watkinson (1987) proposed that the chlorine that could have complexed PGE in fluids of the Upper Critical Zone, Bushveld Complex, could originate from the breakdown of magmatic Cl-bearing mica and apatite; the same mechanism was proposed independently by Boudreau *et al.* (1986) for PGE enrichment in the Bushveld and Stillwater complexes. The results of fluid-inclusion studies on host minerals to PGE deposits (Ballhaus & Stumpfl 1986, Johan & Watkinson 1987, Nyman *et al.* 1990) provide confirmation that a fluid phase may well be a necessary part of some PGE-enrichment processes. Wood's (1987) calculations revealed that the transport of PGE as chloride complexes in supercritical solutions is one but not the sole such possibility, because of the appreciable solubility of other metals under these conditions. Mountain & Wood (1987) concluded that the PGE may be transported as chloride complexes in very acidic and oxidized fluids, although other complexing agents under different conditions could not be ruled out. Sassani & Shock (1990) confirmed that Pd was sufficiently soluble in fluids under appropriate conditions of $f(\text{O}_2)$, pH, Cl activity, P and T to account for the petrographic features in PGE deposits; such petrographic features are similar to those outlined in this study and to those described by Ballhaus & Stumpfl (1986) and as reviewed by Mathez (1990) for the Stillwater and Bushveld complexes.

We contend that the PGM of the Two Duck Lake intrusion may have precipitated from a chloride-bearing solution, probably under reducing conditions (Johan & Watkinson 1987), when it interacted with magnetite (and pyrrhotite) to produce chlorite, epidote, carbonates, cubanite and chalcopyrite. The occurrence of some PGM with argentian gold in fractures in altered magnetite or at magnetite-chalcopyrite contacts at Two Duck Lake is compatible with this mechanism. This reaction would not be unlike that proposed for Au deposition in some Fe-rich rocks (Phillips *et al.* 1984), in which case oxygen is released to the ore fluid during magnetite replacement.

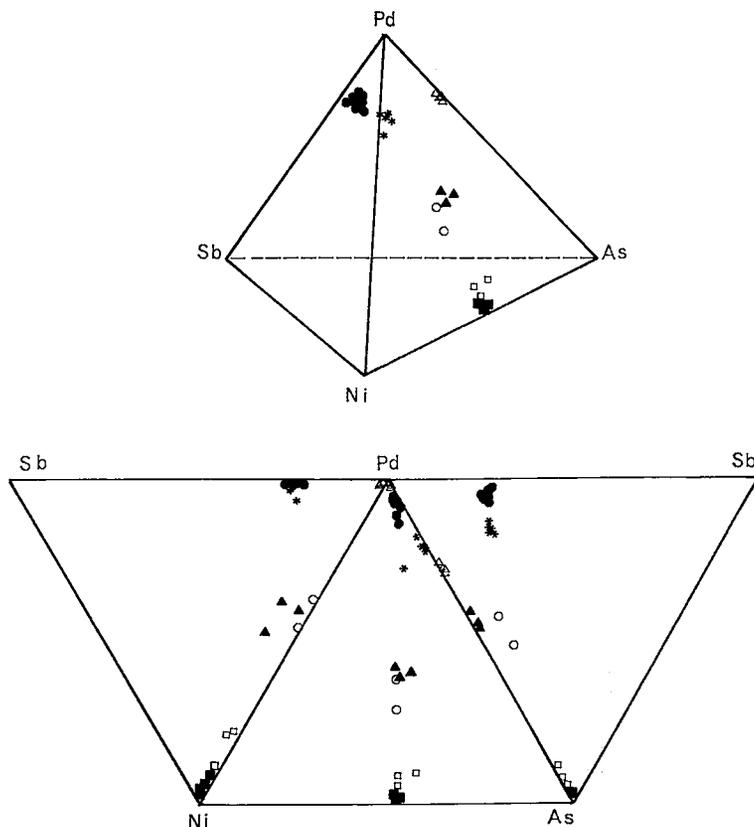


FIG. 8. Tetrahedron Pd-Ni-As-Sb and triangular faces showing variation in mineral compositions. Filled circles: mertieite II, open circle: Sb-bearing majakite, asterisk: unnamed $\text{Pd}_2(\text{Sb}, \text{As})$, filled square: nickeline, open square: Pd-bearing nickeline, open triangle: unnamed Pd_3As_2 , filled triangle: majakite.

CONCLUSIONS

The platinum-group elements in the eastern part of the Coldwell Complex are not concentrated in assemblages of typical magmatic sulfides at the contact of the complex with Archean rocks, but are located in Cu-rich sulfide assemblages in the separate Two Duck Lake intrusion (Dahl *et al.* 1986, unpubl. manuscript). Only one example of *PGM* enclosed with pentlandite flames in pyrrhotite, a probable magmatic association (Cabri 1981, Naldrett 1989), was found in the specimens examined. Enrichment in Cu and *PGE* (predominantly Pd) occurs in coarse-grained to pegmatitic gabbroic rocks that contain abundant mica and apatite (both Cl- and F-bearing), and partially digested xenoliths and granophyric patches derived from assimilation. The mineral assemblage adjacent to *PGE*-enriched Cu-sulfides

in the otherwise fresh and unmetamorphosed gabbroic rocks is epidote + actinolite + chlorite + sericite + calcite. Some *PGM* occur in veins within or at contacts with minerals of the alteration assemblage.

The *PGM* are a diverse assemblage of homogeneous to intricately zoned minerals, mainly of Pd, Pt and Rh as intermetallic compounds with Sn, Pb, and as arsenides, antimonides and tellurides; they may be found in small veins, cutting altered, primary igneous minerals. Primary magmatic Fe minerals (pyrrhotite and magnetite) were partly replaced, and most of the *PGM* were precipitated where this replacement occurred.

The field, petrographic and mineral-chemical data are interpreted as the result of the interaction of magmatic mineral assemblages with a solution, probably a mixture of magmatic (deuteric) fluid and volatile species generated by the breakdown of

the abundant xenoliths, mainly felsic metavolcanic rocks. This interaction coincided with local replacement of plagioclase by chlorite, albite and epidote, and of pyroxene by amphibole. The fluid was capable of transporting *PGE* (especially Pd), Cu and other metals, probably as chloride complexes, of refining the sulfides to give higher contents of Cu and precious metals, and of precipitating *PGM* (as well as galena, altaite, argentian pentlandite, calcite, and other minerals) when the composition of the fluid was modified during replacement of magnetite by chlorite and carbonate, and of pyrrhotite by chalcopyrite and cubanite.

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