

PLATINUM-GROUP MINERALS IN THE LAC SHEEN Cu–Ni–PGE PROSPECT, QUEBEC

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ABSTRACT

Moncheite [Pt(Te>Bi)₂] and michenerite (PdBiTe) were identified within samples from the small Cu–Ni–PGE prospect at Lac Sheen, Abitibi–Témiscamingue, Quebec. Moncheite, the more common platinum-group mineral (PGM) identified, has a wide compositional range (from 5 to 21 wt.% Bi). The PGM are associated with coexisting pyrrhotite, chalcopyrite and pentlandite within strongly deformed lenses of amphibolite. The PGM typically occur either at grain boundaries between the sulfide and neighboring amphibole or are totally enclosed within the amphibole. Textural and other criteria suggest synmetamorphic hydrothermal remobilization, redistribution and recrystallization of a pre-existing PGE-enriched sulfide deposit, although a hydrothermal origin for the PGE mineralization, in which the PGE are derived from external sources, cannot be ruled out. Within nearby boulders, which may be genetically unrelated to the deposit itself, an unnamed Pt-mineral with the proposed stoichiometry PtBi₂PbS·2Bi₂(S,Se)₃ has been found as 5–15 µm flakes within an amphibole matrix. Microanalytical and reflectance data are presented for this unnamed Pt-mineral.

Keywords: platinum-group minerals, moncheite, michenerite, Lac Sheen, Quebec.

SOMMAIRE

Nous avons identifié la monchéite [Pt(Te>Bi)₂] et la michenerite (PdBiTe) dans un indice minéralisé en Cu, Ni et en éléments du groupe du platine au lac Sheen, en Abitibi – Témiscamingue, Québec. La monchéite, plus répandue, varie largement en composition (entre 5 et 21% de Bi, par poids). Les minéraux du groupe du platine sont associés à pyrrhotite, chalcopyrite et pentlandite dans des lentilles d'amphibolite fortement déformées. Ils sont localisés le long des bordures de grains de sulfures, au contact avec l'amphibole, ou sont englobés dans celle-ci. Selon les critères texturaux, parmi d'autres, il semble y avoir eu remobilisation hydrothermale synmétamorphique, redistribution et recristallisation d'un amas de sulfures pré-existant déjà enrichi en éléments du groupe du platine, quoiqu'une origine complètement hydrothermale de la minéralisation en métaux précieux, dérivés d'une source externe, ne peut être exclue. Dans des blocs non *in situ*, et qui pourraient donc ne pas être affiliés au gisement lui-même, nous avons découvert ce qui semble être une nouvelle espèce minérale, qui aurait une stoechiométrie PtBi₂PbS·2Bi₂(S,Se)₃, sous forme de paillettes de 5 à 15 µm dans l'amphibole. Nous en présentons des données sur la composition et la réflectance.

(Traduit par la Rédaction)

Mots-clés: minéraux du groupe du platine, monchéite, michenerite, lac Sheen, Québec.

INTRODUCTION

Earlier studies of the Lac Sheen Cu–Ni–PGE prospect, in the Belleterre area of Quebec (Wood & Vlassopoulos 1990, Cook *et al.* 1992) have demonstrated anomalous concentrations of Pt, Pd and Au in soils, lakewater, groundwater and lake sediments sampled close to the prospect. In those studies, the behavior of Pt and Pd in the weathering environment was related to the known behavior of the PGE in solu-

tion. Lesser attention was given in these initial studies to the characterization of the Cu–Ni sulfide and PGE mineralization. This paper describes the platinum-group minerals (PGM) present in the mineralized rocks and their paragenetic relationships.

GEOLOGY

The Lac Sheen prospect is located in the southeastern corner of Guillet Township, Abitibi–

Témiscamingue, Quebec (Long. 78° 20' W, Lat. 47° 30' N), immediately north of the contact between the Grenville and Superior tectonic provinces (Fig. 1). The geological context was described by Wood & Vlassoupoulos (1990) and by Cook *et al.* (1992). Extensive exploration over the past thirty years has shown that the mineralization is too localized and too low in grade to be of economic importance.

Field relationships can only be clearly seen in two exploration trenches. A series of small lenticular bodies of metagabbro were intruded parallel to the regional SW–NE schistosity of the Archean metasedimentary rocks of the Pontiac Group. Sulfide mineralization and significant concentrations of the PGE occur within these lenses, which are 1–10 m in thickness and some tens of meters in length. The lenses are bounded at some contacts with the metasedimentary rocks by albite – microcline – quartz – biotite pegmatites, considered to result from the anatexis of the host metasedimentary rocks. Several lenses of amphibolite also are cross-cut by granitic pegmatite. Although all

amphibolite samples investigated contain sulfides, concentrations of sulfide are highest in amphibolites lying close to the pegmatites. Away from the pegmatites, samples of amphibolite also have lower PGE contents. The entire sequence is intensely deformed and cut by abundant quartz veins. Concentrations of sulfides, particularly chalcopyrite, are common within the quartz veins, and may have been remobilized into their present position. Microfractures within the rock fabric are filled with quartz, minor sulfides (chalcopyrite and pyrrhotite) and also oxides, which possibly replace the sulfides. Quartz veining and the associated microfracturing are most intense in the sulfide-bearing amphibolites around the pegmatite bodies. On a hand-specimen scale, there seems to be a strong correlation among the amount of sulfides, PGE content, quartz veins and extent of microfracturing.

The mineralogy of the metagabbroic rocks is dominated by 50–60% amphibole, with lesser amounts of chlorite (10–25%), quartz (5–20%), epidote (5–10%) plagioclase (<5%), oxides, and sulfides. Sulfides only

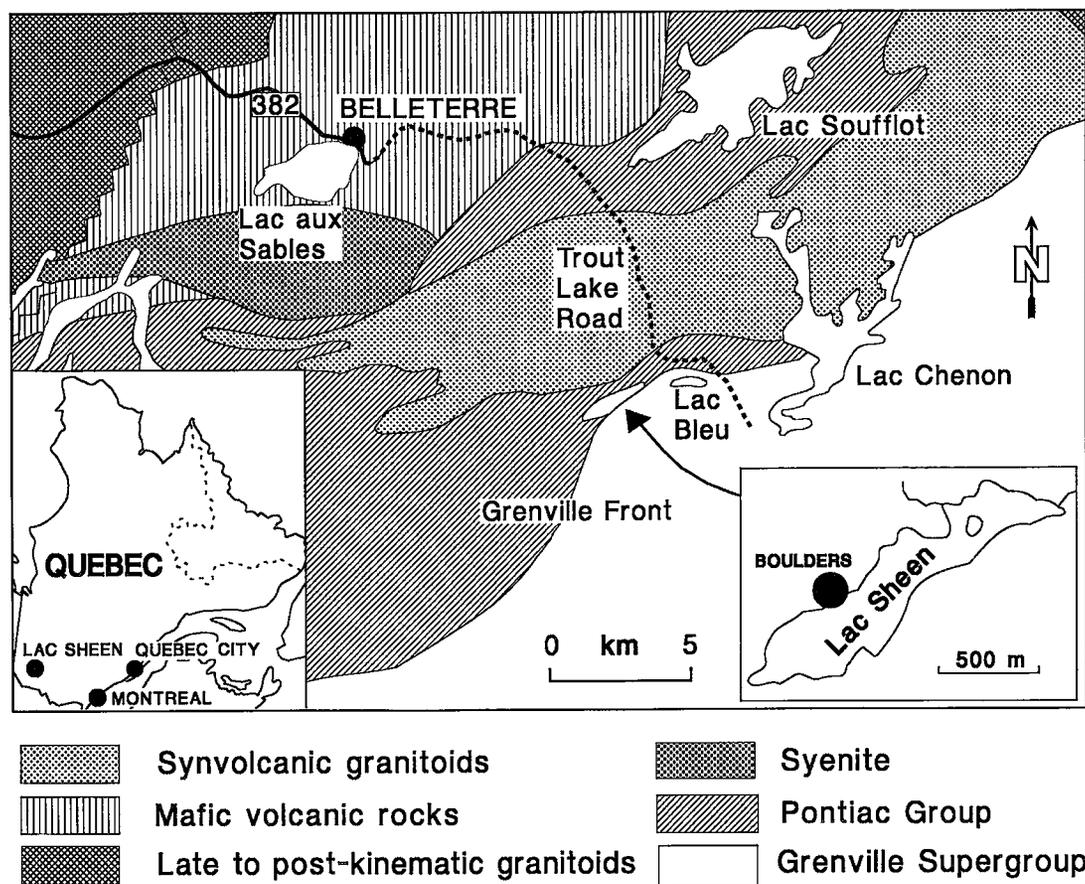


FIG. 1. Geological sketch map of the Belleterre area of Quebec, indicating the location of the Lac Sheen prospect.

rarely exceed 2 vol.% of these amphibolites, and are, in order of decreasing abundance, chalcopyrite, pyrrhotite, pentlandite, and pyrite.

Mineralogical data presented here pertain to samples collected from the exploration trenches that expose the mineralized amphibolites, and from PGE-bearing boulders found on the shore of Lac Sheen. The relationship between the boulders and the mineralization in the trenches is uncertain because the boulders have significantly different Au/(Au+Pt+Pd) values (Cook *et al.* 1992). The boulders were glacially transported into their present position and may be unrelated to the Lac Sheen deposit.

GEOCHEMISTRY

Up to 5 500 ppb Pt and 4 700 ppb Pd were found in bulk samples (>5 kg) of amphibolite containing sulfides. Pt/Pd values are generally close to 1. Concentrations in the host metasedimentary rocks are more than three orders of magnitude lower (<5 ppb Pt, Pd, Au). Concentrations of Au are generally an order of magnitude lower than for Pt and Pd, and the other PGE also are low (Rh 12–55 ppb, Ru 6–11 ppb, Os <5 ppb, Ir 4–31 ppb). Concentrations of sulfur, Cu and Ni in the amphibolite attain 5 wt.%, 0.68% and 0.64%, respectively. Cu/Ni values are typically close to 1. In general, there is a significant correlation between concentrations of the PGE and those of Cu, Ni and S in the amphibolites.

METHODOLOGY

All electron-probe microanalyses (EPMA) were obtained using the CAMECA SX-50 instrument at the Mineralogical Institute in Würzburg. The analyses were obtained using an accelerating voltage of 15 kV and a specimen current of 10 μ A. Natural pure metal standards were used. Data-reduction procedures were carried out using the PAP program supplied by CAMECA.

Reflectance spectra on an unnamed Pt-bearing phase were measured in air and in oil at the Ruhr-Universität Bochum. A Leitz Orthoplan microscope and Hamamatsu R1477 photomultiplier system were used. A Zeiss WTiC standard was employed in air and immersion oil (DIN 58.884). Effective numerical apertures of 0.20 were used in both media. The sections were polished using diamond paste, and final buffing prior to measurement of reflectivity was carried out using a 0.25 μ m diamond-oil mixture.

MINERALOGY AND PETROGRAPHY

The amphibole in these rocks is a tremolite (Table 1, anal. A), with a Mg/(Mg+Fe) value in the range 0.95–0.98. Chlorite overgrows the tremolite and also is highly magnesian (Table 1, anal. B). The textural

TABLE 1. RESULTS OF ELECTRON-PROBE MICRO-ANALYSIS OF AMPHIBOLE (A), CHLORITE (B) AND ILMENITE (C)

SAMPLE /GRAIN	A	B	C
	R1b 2	R1b C2	R1a A/2
SiO ₂ Wt.%	55.00	33.25	0.07
TiO ₂	0.23	0.05	53.12
Al ₂ O ₃	2.89	14.54	<0.05
Fe ₂ O ₃	0.09	0.84	<0.05
Cr ₂ O ₃	0.37	<0.05	0.24
MgO	22.21	34.52	1.11
CaO	13.30	0.08	<0.05
MnO	0.14	0.06	4.57
FeO	1.60	3.58	40.88
Na ₂ O	0.69	0.04	<0.05
K ₂ O	0.24	<0.05	<0.05
Total	96.77	87.04	99.91

relationship of the two minerals suggests chlorite growth during a late metamorphic (retrograde) overprint on the prograde amphibole-plagioclase-dominated assemblage. Peak metamorphic conditions can be estimated on the basis of the mineral assemblage as being close to the greenschist-amphibolite transition. Round grains of magnetite and ilmenite (Table 1, anal. C) are common inclusions within the grains of amphibole, suggesting possible formation from titaniferous augite.

The sulfide assemblage in the amphibolites is dominated by chalcopyrite (40% of sulfides) and pyrrhotite (30%). Pentlandite (about 10%) is present as small idiomorphic grains and as exsolution lamellae within pyrrhotite. Small grains of violarite also are associated with pentlandite, probably as a product of its alteration. Pyrite (5%) is restricted to small euhedral porphyroblasts within chalcopyrite and pyrrhotite. Trace amounts of accessory pyrite also are present in the host metasedimentary rocks and in the pegmatites. Coarse-grained chalcopyrite and pyrrhotite occur as anhedral granular aggregates within a mixture of amphibole and quartz (Fig. 2). Both chalcopyrite and pyrrhotite show extensive deformation-induced twinning as well as annealing textures. Fractures within pyrite are commonly filled with oxides, chiefly magnetite, and chalcopyrite or pyrrhotite, of which the latter may be replaced by secondary marcasite. Galena and sphalerite are present as small (<100 μ m) anhedral

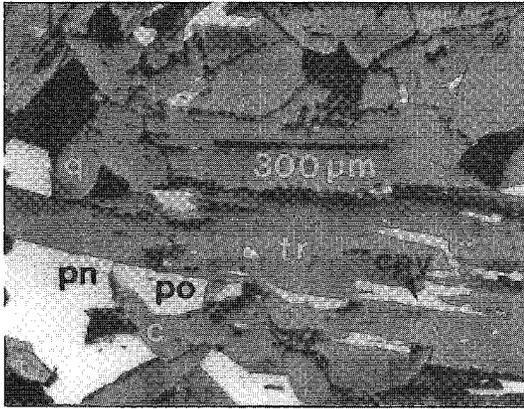


FIG. 2. Photomicrograph of sulfide-bearing amphibolite showing the rock's typical texture. Symbols: tr: tremolite, c: chlorite, po: pyrrhotite, pn: pentlandite, cpy: chalcopyrite, q: quartz.

grains within chalcopyrite, pyrrhotite or along chalcopyrite-pyrrhotite grain boundaries. Trace amounts of arsenopyrite, tetrahedrite, altaite (PbTe), Se-bearing joseite-B [$\text{Bi}_{4-x}(\text{Te,Se})_{2-x}\text{S}$], native bismuth and tellurobismuthite (Bi_2Te_3) also were observed, all associated with galena. Ilmenite is the main oxide present, chiefly enclosed within the amphibole grains. Lesser quantities of rutile and secondary goethite were also noted.

The chemical composition of typical pyrrhotite (A), pentlandite (B), and violarite (C) are given in Table 2. We noted no detectable difference in pyrrhotite compositions among the various samples. Fine-grained

TABLE 2. RESULTS OF ELECTRON-PROBE MICROANALYSIS OF PYRRHOTITE (A), PENTLANDITE (B), VIOLARITE (C) AND PYRITE (D)

SAMPLE /GRAIN	A	B	C	D
	101 3/H2	101 H6/3	106 C1/5	106/2C
Fe	58.49	27.85	22.72	43.68
Ni	0.62	38.47	34.04	1.15
Co	<0.05	1.33	0.74	<0.05
Cu	<0.05	<0.05	0.74	1.14
S	39.97	31.87	41.05	53.58
Total	99.08	99.52	98.55	99.55

Formulae:

A. ($\text{Fe}_{0.840}$ $\text{Ni}_{0.009}$) $\Sigma 0.849\text{S}$
B. ($\text{Fe}_{0.502}$ $\text{Ni}_{0.659}$ $\text{Co}_{0.023}$) $\Sigma 1.184\text{S}$
C. ($\text{Fe}_{1.271}$ $\text{Ni}_{1.812}$ $\text{Co}_{0.039}$ $\text{Cu}_{0.036}$) $\Sigma 3.158\text{S}_2$
D. ($\text{Fe}_{0.937}$ $\text{Ni}_{0.023}$ $\text{Cu}_{0.021}$) $\Sigma 0.981\text{S}_4$

pyrite within pyrrhotite contains appreciable Ni and Co (Table 2, D). Coarse pyrite and marcasite, the latter commonly replacing pyrrhotite, do not contain detectable concentrations of Co and Ni. We suggest that the fine-grained pyrite is a distinct type and has formed from Ni- and Co-bearing pyrrhotite.

Four <10- μm grains of electrum were observed within chalcopyrite in the boulder samples. In the trench samples, only one grain of electrum was noted, intergrown with moncheite and tellurobismuthite. The compositions of the electrum fall within a narrow range (76.2 to 78.2 wt.% Au). Cu, Hg, the PGE, Pb, Bi, Fe, Co, Ni, As, Sb and Zn were not detected in the electrum.

THE PLATINUM-GROUP MINERALS

The platinum-group minerals (PGM) were identified only in samples of amphibolite. Examination of twelve rock-chip samples from the trenches revealed eleven grains of moncheite [$\text{Pt}(\text{Bi,Te})_2$], and four grains of michenerite (PdBiTe). Samples in which PGM were found are characterized by high contents of sulfide (10–20%) and abundant quartz-filled microfractures. This is consistent with the assay data on bulk rock, in that PGE concentrations are higher where the amphibolites display microfracturing. However, we note no correlation between the distribution of microfractures and concentrations of sulfides on the scale of a polished section. No PGM were identified within the quartz-filled microfractures. In addition to the amphibolite samples, rock chips from the boulders contain significant quantities of an apparently unknown Pt-bearing mineral (see below).

The grains of moncheite and michenerite occur at the grain boundaries between chalcopyrite and pentlandite, between chalcopyrite and amphibole (Fig. 3),

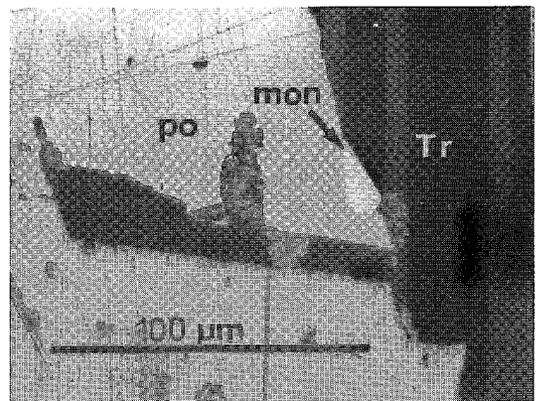


FIG. 3. Photomicrograph of moncheite grain (mon) at pyrrhotite (po) - tremolite (tr) grain boundary.

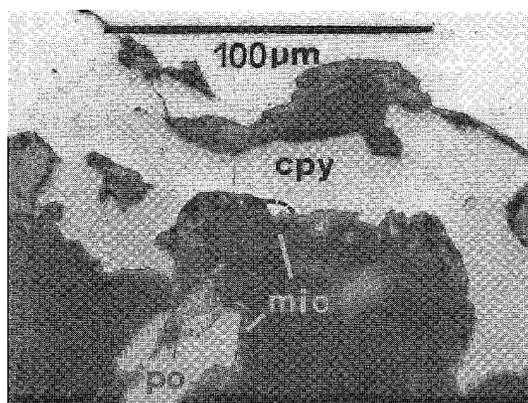


FIG. 4. Photomicrograph of michenerite (mic) grains coexisting with chalcopyrite (cpy) and pyrrhotite (po) in silicate matrix (black).

between pyrrhotite and amphibole (Fig. 4), or are totally enclosed, with minor pyrrhotite within the amphibole (Fig. 5). None of the grains is totally enclosed within sulfide. Two grains of PGM also were found within microcracks in the sulfides. Grain size rarely exceeds 10 μm in diameter. The largest grain (michenerite, Fig. 5) measures $75 \times 16 \mu\text{m}$. The significance of the textural relationships is discussed in a later section.

Compositions of selected grains of moncheite and michenerite are given in Table 3 and plotted in terms of Pd-Te-Bi, Pt-Te-Bi and Pd-Pt-(Te+Bi) in Figure 6. The compositions of michenerite are close to the ideal stoichiometry (PdBiTe); the Pd (+ Pt + Ni) content ranges from 33.0 to 33.2 wt.%, Bi, from 33.1 to 33.9%, and Te, from 32.1 to 33.1%. Moncheite

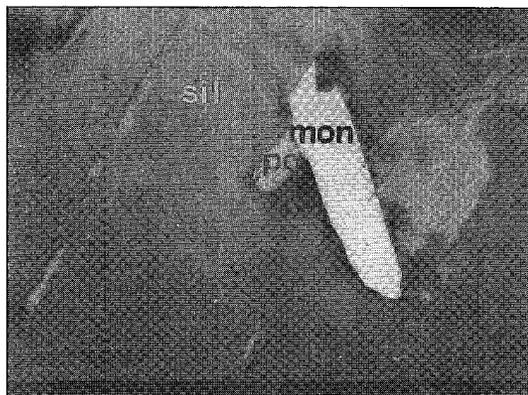


FIG. 5. Photomicrograph of moncheite (mon) grain combined with pyrrhotite (po) in silicate (sil) matrix. Scale as for Fig. 3.

TABLE 3. RESULTS OF ELECTRON-PROBE MICROANALYSIS OF MICHENERITE (A) AND MONCHEITE (B - D)

SAMPLE /GRAIN	A	B	C	D
	101 FA6	R1b 2	R1b210	R1a/HB3
Pd	22.12	0.78	0.44	0.23
Pt	2.85	37.85	37.58	39.78
Ni	<0.05	0.30	0.10	<0.05
Te	28.46	53.56	43.03	40.38
Bi	46.61	5.75	17.26	20.38
Pb	<0.05	<0.05	<0.05	<0.05
Fe	0.24	0.08	0.42	0.87
Total	100.28	98.32	98.83	101.64

Formulae:

A.	(Pd _{0.917} Pt _{0.064} Fe _{0.019})	Bi _{0.983} Te _{0.983}
B.	(Pd _{0.032} Pt _{0.935} Fe _{0.007} Ni _{0.025})	Bi _{0.132} Te _{2.019}
C.	(Pd _{0.021} Pt _{0.935} Fe _{0.036} Ni _{0.008})	Bi _{0.401} Te _{1.638}
D.	(Pd _{0.010} Pt _{0.920} Fe _{0.070} Ni ₀)	Bi _{0.440} Te _{1.428}

compositions vary between near-end-member PtTe₂, with 5 wt.% Bi, to compositions with up to 21 wt.% Bi, consistent with the partial solid-solution series that is known to exist between moncheite and insizwaite, PtBi₂ (Tarkian 1987, and references therein). Moncheite contains less than 1 wt.% Pd. A negative correlation is noted between the Pd and Bi content of moncheite, with the Pt/(Pt+Pd) ratio varying from 0.94 in the Bi-poor type to 0.99 in the Bi-rich type. No compositional variations were noted between moncheite grains from different textural associations. The michenerite contains 2.65 to 2.93 wt.% Pt. Both minerals contain detectable Ni (< 0.5 wt.%), which substitutes for Pt and Pd.

The PGM are similar to those reported from other sulfide-rich deposits associated with gabbroic rocks, for which a hydrothermal, rather than magmatic origin has been proposed. In such deposits, compounds with bismuth and tellurium constitute the dominant PGM; for example, Rathbun Lake, Ontario (Edgar *et al.* 1989) or the New Rambler deposit, Wyoming (McCallum *et al.* 1976, Nyman *et al.* 1990). At Lac Sheen, PGE-bearing sulfides, arsenides and metal alloys of the PGE were not observed.

Within the boulder samples, a Pt-bearing mineral was identified, whose composition does not match any named mineral or any phase of uncertain composition for which data have been published (Cabri 1981, Chapters 8 and 9; pers. comm. 1992). Twenty-two small grains (one grain 23 μm in diameter, the rest <15 μm in diameter) were identified in two different polished sections, and all have similar compositions. The mineral has a white-grey color in air, with a slight bluish tint under oil. The phase does not display birefractance, is isotropic, does not give internal reflections, and is clearly softer than chalcopyrite where the two minerals share a grain boundary. Nine grains were observed totally enclosed within amphibole, and thirteen at the contact between amphibole

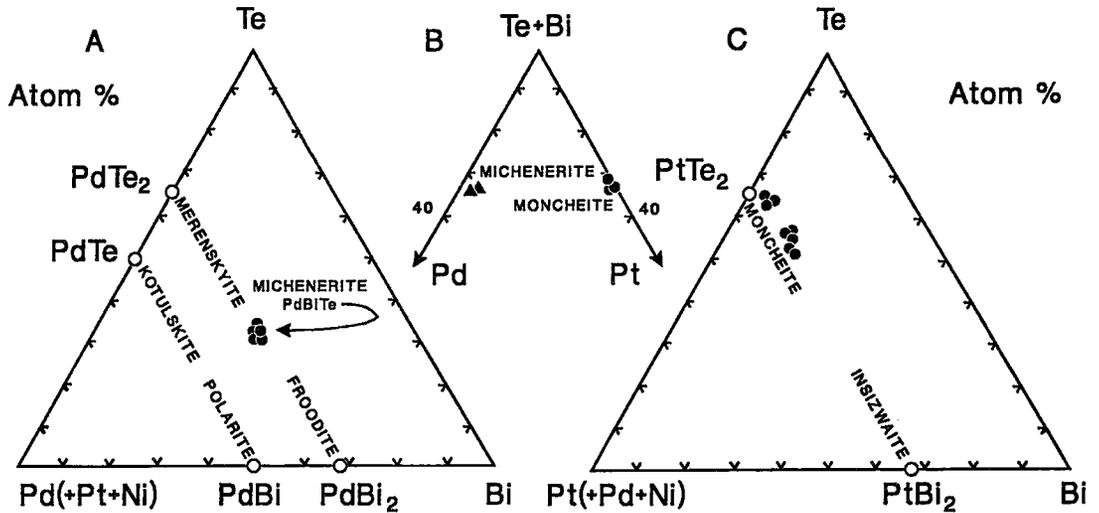


FIG. 6. Composition of PGM from Lac Sheen in terms of A) Pd-Bi-Te, B) Pt-Pd-(Te+Bi), and C) Pt-Bi-Te diagrams.

and chalcopyrite. This mineral was not observed in the *in situ* samples, and neither moncheite nor michenerite was observed in the boulder samples. The boulder samples contain silicate minerals of similar composition to the trench samples, and the textural associations of silicates and sulfides also are comparable.

Representative results of electron-probe microanalysis of the unknown mineral are given in Table 4. All compositions are similar to one another, with only Pb showing any significant variation in concentration among grains; it is inversely correlated with Bi content. Element concentrations fall within the following ranges (all wt.%): 9.74–10.72 Pt; less than the minimum detection limit (<mdl)–0.11 Pd; <mdl–0.14 Ni;

<mdl–0.27 Te; 62.11–67.95 Bi; 9.70–14.48 Pb; 9.70–10.73 S; 1.14–2.09 Se; 0.27–1.28 Fe; <mdl–0.54 Cu. Minimum levels of detection were on the order of 0.05 wt.%. The formula of the mineral conforms closely to: $\text{Pt}(\text{+Pd+Ni})\text{Bi}_2\cdot\text{PbS}\cdot 2\text{Bi}_2\text{S}(\text{+Se})_3$, with the position of the Cu and Fe in the formula uncertain. Inspection of back-scattered electron images indicates that the grains are homogeneous.

Reflectance spectra for the phase were measured in air and in oil (Table 5, Fig. 7). Reflectance data were collected on five grains; no significant difference in shape of curve or absolute values were found.

The extremely small size of the grains makes it difficult to readily obtain full X-ray-diffraction data. Although attempts to drill out grains were successful, the volume has so far been insufficient to produce a powder pattern.

[*Note added in proof:* Since this paper was accepted, we have been able to more completely characterize the unknown mineral. Approval of new mineral status has been granted by the Commission on New Minerals and Mineral Names, IMA (application 94-003). The structural formula is given as $(\text{Pt,Pb})\text{Bi}_3(\text{S,Se})_{4-x}$].

The relative lack of Pd minerals compared to those of Pt suggests that a substantial portion of Pd must be in solid solution in the base-metal sulfides. Various authors (*e.g.*, Cabri & Laflamme 1984) have reported that it is commonly harder to account for Pd than for Pt in a PGE-mineralized rock. Genkin *et al.* (1973) concluded that Pd in some cases is dispersed in sulfides and is not present as mechanical inclusions of Pd minerals. In recent years, sophisticated microbeam analyses have led to the quantitative determination of concentrations of Pd, Pt, Rh and Ru in the common sulfides. These data confirm that some of the PGE, Pd

TABLE 4. RESULTS OF ELECTRON-PROBE MICROANALYSIS OF UNNAMED Pt-BEARING MINERAL.

SAMPLE /GRAIN	A 103 N2	B 103 Q2	C 101 J1	D 101 L2	E 101 G1
Pd	<0.05	<0.05	<0.05	0.09	<0.05
Pt	10.51	10.72	10.21	9.73	9.90
Ni	0.12	<0.05	<0.05	<0.05	0.08
Te	<0.05	0.16	<0.05	0.13	<0.05
Bi	66.11	66.17	63.24	63.31	63.06
Pb	10.18	9.70	13.05	14.16	13.80
S	10.04	10.62	10.21	10.73	10.32
Se	1.79	1.14	1.43	1.34	1.30
Fe	0.87	1.06	1.28	0.59	0.86
Cu	0.30	0.11	0.95	0.26	0.14
Total	99.92	99.68	100.37	100.34	99.46

Atomic proportions:

A.	Pt _{0.054} Ni _{0.002} Bi _{0.316} Pb _{0.046} S _{0.319} Se _{0.022} Fe _{0.019} Cu _{0.035}
B.	Pt _{0.086} Te _{0.001} Bi _{0.317} Pb _{0.047} S _{0.331} Se _{0.014} Fe _{0.016} Cu _{0.002}
C.	Pt _{0.052} Bi _{0.305} Pb _{0.083} S _{0.316} Se _{0.016} Fe _{0.023} Cu _{0.015}
D.	Pd _{0.001} Pt _{0.056} Te _{0.001} Bi _{0.303} Pb _{0.088} S _{0.326} Se _{0.017} Fe _{0.017} Cu _{0.004}
E.	Pt _{0.051} Ni _{0.001} Bi _{0.302} Pb _{0.067} S _{0.322} Se _{0.017} Fe _{0.016} Cu _{0.002}

TABLE 5. REFLECTANCE DATA AND COLOR VALUES FOR UNNAMED MINERAL

Wavelength (nm)	400	420	440	460	480	500	520	540
R (%) in air	53.67	53.75	53.08	52.42	51.60	50.81	50.50	49.93
R (%) in oil	41.15	40.01	39.32	38.41	37.47	36.54	35.87	35.40
Wavelength (nm)	560	580	600	620	640	660	680	700
R (%) in air	49.66	49.43	49.35	49.08	48.89	48.73	48.51	48.49
R (%) in oil	35.11	34.85	34.68	34.31	34.07	33.91	33.82	33.63
Color values in air: $x = .3048$ $y = .3098$ $Y = 49.9$ $\lambda_d = 474.4$ $Pe = 2.1$								
Color values in oil: $x = .3010$ $y = .3051$ $Y = 35.3$ $\lambda_d = 477.8$ $Pe = 3.7$								

in particular, may reach significant concentrations within the common Fe–Ni–Cu sulfides (Paktunc *et al.* 1990, Cabri 1992, Czamanske *et al.* 1992). Cabri (1992) noted that in both sulfide-poor and sulfide-rich deposits, significant concentrations of Pd characterize pentlandite. Further support for a hypothesis of PGE in solid solution within the common sulfides has come from the experimental work by Makovicky *et al.* (1986, 1990), who have shown that several percent Pd may dissolve in Fe–Ni sulfides at magmatic or hydrothermal temperatures; although most of the Pd is expelled on cooling, the sulfides may nevertheless retain considerable Pd.

Although we lack direct evidence in the form of microanalyses of pentlandite, we believe that the relative absence of Pd minerals and the positive correlation between Pd and Ni concentrations among the samples suggest that at least some of the Pd may be in solid solution at the ppm level in pentlandite. If so, this somewhat contradicts the findings of Paktunc *et al.* (1990) who, at least on the basis of their analytical evidence, stated that pentlandite that contains significant Pd is restricted to deposits in which tellurides and bismuthotellurides are not abundant. They concluded that the availability of Bi and Te effectively controls the extent of PGE solution in sulfide hosts, of

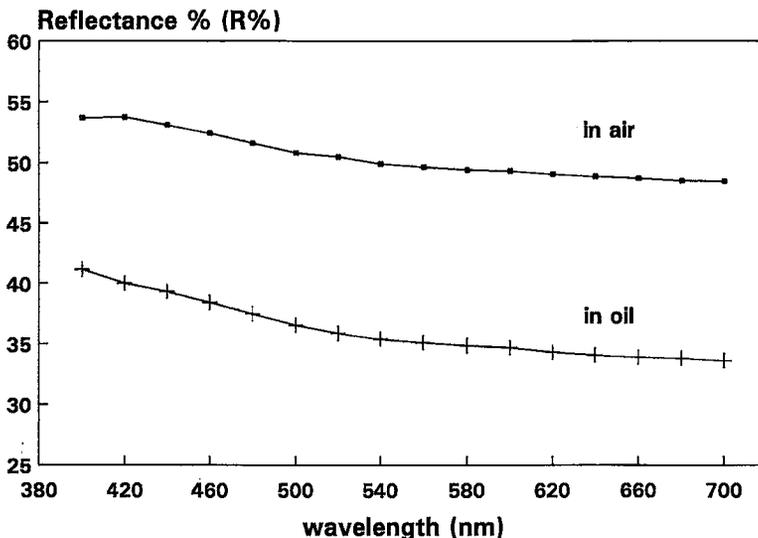


FIG. 7. Reflectance data for unknown mineral in air and oil.

which pentlandite is the most significant.

PARAGENESIS OF THE PGM

Although the PGM at Lac Sheen are restricted to the same rock units as the sulfides, mineral relationships do not suggest a primary magmatic origin for the mineralization, at least not without very extensive reworking at a subsequent stage. The textural evidence presented here clearly indicates that the PGM are not enclosed within sulfide phases and are present either at sulfide-silicate interfaces or entirely within the metamorphic silicates. Furthermore, the PGM are restricted to those parts of the amphibolite units that show the strongest evidence of deformation, quartz veining and abundant retrograde development of chlorite and epidote after amphibole minerals. We therefore suggest that the PGE mineralization at Lac Sheen is a result of substantial local remobilization, redistribution and recrystallization of magmatic PGE-bearing sulfide mineralization under metamorphic or hydrothermal conditions. Alternatively, the deposit could be of hydrothermal origin, with the PGE derived from an external source.

The textures shown both by the Cu-Ni-Fe sulfides and the PGM indicate an origin by metamorphic recrystallization. In addition, the textural development of the PGM strongly suggests remobilization during a syntectonic, metamorphic, fluid-dominated event, possibly during the retrograde metamorphism that has so strongly overprinted the rocks. Conditions of peak metamorphism would probably have been above the maximum thermal stability limit of some of the sulfides, and chalcopyrite in particular has also been extensively remobilized. We note that some of the PGM are combined with chalcopyrite, the sulfide acting as a surface for nucleation during recrystallization.

The phase chemistry of platinum bismuthinides, bismuthotellurides and tellurides (Cabri 1981) suggests that they should decompose at relatively low temperatures, and thus be available for transport, even at conditions of moderately low-grade metamorphism. Stumpfl (1974), Stumpfl & Tarkian (1976) and others have suggested that hydrothermal fluids have played a significant role in redistributing PGE in a number of deposits. In recent years, an increasing number of authors (Mihálik *et al.* 1974, McCallum *et al.* 1976, Rowell & Edgar 1986, Nyman *et al.* 1990, Mogessie *et al.* 1991, Watkinson & Melling 1992, Watkinson & Ohnenstetter 1992) have recorded convincing evidence in support of a hydrothermal origin for a number of PGE deposits, or at least a remobilization of PGE within an existing deposit. At the New Rambler deposit, Wyoming, which like Lac Sheen lies near a major tectonic contact, McCallum *et al.* (1976) recognized ore textures suggestive of PGE mineralization at about 300–335°C. This is supported by fluid-

inclusion data from Nyman *et al.* (1990), who recognized an amphibolite-grade metamorphic assemblage overprinted by propylitic and phyllic alteration. Rowell & Edgar (1986) and Edgar *et al.* (1989) described a series of low-temperature Pd minerals associated with silicate minerals from Rathbun Lake, Ontario, suggested a hydrothermal origin for them, and identified variations in pH, oxygen fugacity and temperature of hydrothermal fluids that can control PGM compositions. Further supporting evidence for significant solubility of PGE in hydrothermal solutions has been given by McKibben *et al.* (1990).

The extremely high (Pt+Pd)/(Ir+Ru+Os) ratios of the Lac Sheen samples (181–376) also lend credence to their origin through hydrothermal remobilization. In contrast to the ease of hydrothermal redistribution of Pt and Pd, Ir, Os and Ru tend to behave as relatively immobile elements (*e.g.*, Barnes *et al.* 1988, Ripley 1990). However, as an alternative, it could be argued that the high ratio resulted from primary fractional crystallization in an immiscible sulfide liquid, leaving Pt, Pd and Cu enriched in the residual liquids relative to Ni, Ir, Ru, Os and Rh.

Recently, a number of theoretical and experimental investigations (Mountain & Wood 1988, Wood *et al.* 1989, Wood 1991, Wood *et al.* 1992, 1994, Gammons *et al.* 1992, 1993, Pan & Wood 1994, Gammons & Bloom 1993) have been conducted in an effort to quantify the solubility of Pd and Pt minerals in hydrothermal solutions and to identify the complexes involved in PGE transport. These studies show that at temperatures up to 300°C, significant concentrations (>10 ppb) of Pd and Pt are attained in hydrothermal solutions as chloride complexes only under extremely oxidizing and acidic conditions. Inasmuch as chlorite and amphibole remained stable during any possible remobilization of the PGE at Lac Sheen, and sulfide minerals predominate over oxide minerals, it is unlikely that significant PGE transport occurred in the form of chloride complexes. On the other hand, the above-mentioned studies strongly suggest that solubilities in the high parts-per-trillion to hundreds of parts per billion range could reasonably be attained as bisulfide complexes under the conditions prevailing during syntectonic hydrothermal alteration at Lac Sheen. Furthermore, the solubility of Au as bisulfide complexes has been shown to be two to three orders of magnitude greater than that of either Pd and Pt under the same conditions. This fact might explain the relatively low Au content of the trench samples, with much of the gold having been lost to the system owing to its greater solubility. Mountain & Wood (1988) have indicated that elements such as Te and Bi will greatly restrict the mobility of Pt and Pd. This finding is consistent with the fact that the remobilization and redistribution of the PGE at Lac Sheen have probably not led to dispersion over a great distance from their original source.

CONCLUSIONS

1. Tellurides and bismuthotellurides of Pt and Pd are the only PGM identified in the *in situ* mineralization at Lac Sheen.
2. Michenerite, PdBiTe, close to ideal stoichiometry, and moncheite, Pt(Te,Bi)₂, with a widely variable Bi:Te ratio, are the main PGM present.
3. An unnamed mineral with a composition close to PtBi₂·PbS·2Bi₂S₃ is present in samples taken from nearby PGE-bearing boulders. Electron-microprobe and reflectivity data suggest that this could be a new mineral species.
4. Appreciably more Pt- than Pd-bearing minerals have been observed, although the bulk Pd/Pt value is close to 1. This is indirect evidence in favor of structural incorporation of some of the Pd in pentlandite or other sulfides.
5. The PGM are generally associated with chalcopyrite, pentlandite and pyrrhotite, as well as with metamorphic silicate phases, chiefly tremolite.
6. Textural and other criteria suggest that the PGE mineralization at Lac Sheen is either the product of synmetamorphic hydrothermal remobilization and redistribution of magmatic PGE-sulfides on a local to intermediate scale, or a hydrothermal deposit in which the PGE derive from an external source. The association between PGM and sulfides and the lack of PGE enrichment in the host metasediments favor the former hypothesis.

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