

Seminar on Platinum Group Elements

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Introduction

In Toronto, on 13 November 1986, the Toronto Geological Discussion Group presented a seminar entitled "What Canadian exploration geologists should know about platinum" (and, by implication, other platinum-group elements, or "PGE"). Terry Bottrill was in the chair. The seminar highlighted two important questions: the first one related to *what* exploration geologists in search of platinum should be looking for and the second one related to *how* they should find such deposits.

John McGoran posed the first of these questions. Rather than looking for another deposit like the Merensky Reef, which requires selective, expensive mining methods, should we instead concentrate our efforts on finding large, relatively low-grade deposits amenable to low-cost extraction techniques? John McGoran's and Richard Sutcliffe's descriptions of two large, relatively low-grade deposits, and Louis Cabri's review of mineralogical considerations, all underlined the point that the biggest gap in our ability to evaluate such deposits is in assessing how well and how cheaply the contained PGEs could be recovered by mineral dressing.

The second question, posed by David Watkinson, and echoed by others was: "can hydrothermal processes be an important mechanism for concentrating platinum-group elements?" Jon Scoates and Bob Mann gave superb accounts of programs of assessment and exploration based largely on the classic magmatic model established at the Merensky Reef. However, if the answer to Watkinson's question is "yes", we must broaden the range of geological features to be recorded during a program of exploration for platinum.

McGoran's question and Watkinson's question are related. Hydrothermal processes are probably capable of forming ore-bodies whose shapes could be more amenable to low-cost mining than are Merensky Reef-type deposits.

After the seminar, some of the speakers helped me to prepare summaries of their talks. These summaries follow. They have been updated and are current as of June 1987.

We acknowledge the dedication of James Macdonald, who transcribed the entire session from tapes, and Elizabeth Beckstead and Lily Ann Powis, word processors!

Platinum Markets

contribution by John McGoran (Fleck Resources, Vancouver)

Eighty-five percent of the world's platinum comes from Southern Africa and 8% from the USSR. (The supply from the USSR has been reduced over the past few years, due to that country's own internal industrial requirements.) Canada, which from the 1920s to around 1950, produced most of the world's platinum, today accounts for about 5.5% of world production.

The greatest demand for platinum is in automobile catalysts (31%). Jewellery demand (29%) is growing very rapidly in the Orient. Hoarding — the accumulation of coins and bars — is growing at a faster rate than any of the other types of demand. Other uses include the chemical, electrical, petroleum and glass industries.

Over the past 10 years, the price of platinum has usually been at a premium to that of gold. The price of palladium has been roughly one-third that of platinum.

Fleck Resources' PGE Property, Coldwell Complex, Marathon, Ontario

contribution by John McGoran (Fleck Resources, Vancouver)

Fleck Resources' Marathon property is a near-surface deposit which is a potential producer of PGE and other metals. Reserve estimates range from 10 to 50 million tons, depending upon the depth of the pit and the cut-off grade. Grade is 0.007-0.015 oz/t Pt, 0.03-0.05 oz/t Pd, 0.01 oz/t Rh, 0.35-0.50% Cu, 0.04% Ni and a little Co.

Fleck acquired the Marathon property (and a lot of others) through the acquisition of Anaconda Canada in 1985. The Marathon property is on the north shore of Lake Superior, 20 miles west of Hemlo, and covers the eastern edge of the Coldwell Complex. The Coldwell Complex (age roughly 1100 Ma) intrudes an anticline in Archean rocks. Within the core of this anticline, there are pyritiferous, felsic pyroclastic rocks. There is a very well-defined band of a magnetite in the gabbro, and, in the vicinity of the sulphide deposit, its magnetic response weakens. A coarse-grained gabbro generally hosts the sulphide zone, which is composed of chalcopyrite, pyrrhotite and cubanite. The sulphur in this zone may have been derived from the adjacent Archean rocks. Fleck Resources took a forty-ton bulk sample from the deposit and sent it to Lakefield for pilot plant tests. Flotation recoveries were: 87.6%

for palladium; 84% for platinum; 79% for gold; 85% for copper. Thirty-eight tons of feed would be required to make one ton of concentrate. The refining charge for this concentrate will be variable, depending upon the refinery and the percentage of platinum in the concentrate. If most of the platinum reports to a copper concentrate, a ball-park figure is that the producer of that concentrate is paid for 90% of the contained platinum, less 0.04 c_z per ton of concentrate and 95% of the contained copper; and is charged \$25.00 (CDN) per ounce for marketing and handling the platinum and 20-25 cents per pound for smelting and refining the copper.

Fifty years ago most of the world's copper came from underground mines. Thirty years later, the largest percentage of the world's copper was coming from bulk tonnage, open-pit deposits. Twenty-five years ago, nearly all the world's gold and silver was mined by underground methods. Every year a larger proportion of the world's gold and silver is produced from low grade deposits by open-pit methods. PGE mines today are in narrow and high-grade reefs, and are mined by high-cost, underground methods. I predict that in the near future there will be several bulk-tonnage PGE deposits. Some of these deposits will be located here in Canada, which is politically secure, and where we have the appropriate expertise.

PGE Geology of the Lac des Iles Complex, Ontario

contribution by Richard Sutcliffe (Ontario Geological Survey, Toronto)

My work has been in collaboration with Mike Sweeny of the University of Western Ontario.

The Lac des Iles Complex (Figure 1) is situated about 100 km northwest of Thunder Bay, Ontario. The complex is part of a circular structure, approximately 30 km in diameter, which consists of several tholeiitic mafic and ultramafic intrusions of late Archean age. Subtle layering within the Lac des Iles Complex demonstrates that it is composed of several upright, conical to basin-like structures. The most fractionated, gabbroic rocks were emplaced first, the more primitive, ultramafic rocks were emplaced later.

The best-known occurrence of PGEs in the Lac des Iles Complex is Boston Bay Mines Limited's Roby Zone which occurs in gabbroic rocks. Boston Bay resumed exploration on the property in 1986 with drilling, trenching and bulk sampling. Indicated reserves are 22.5 million tonnes with an average grade of 6.25 g/t of PGE, with a platinum:palladium ratio of 1:7. We, and other people, have recently found a number of other PGE occurrences associated with ultramafic rocks of the Lac des Iles Complex. These occurrences are generally in websterites (orthopyroxene-clinopyroxene cumulates), which are the most fractionated of the ultramafic rocks. Grades of grab samples are in the range of 1-3 g/t PGE.

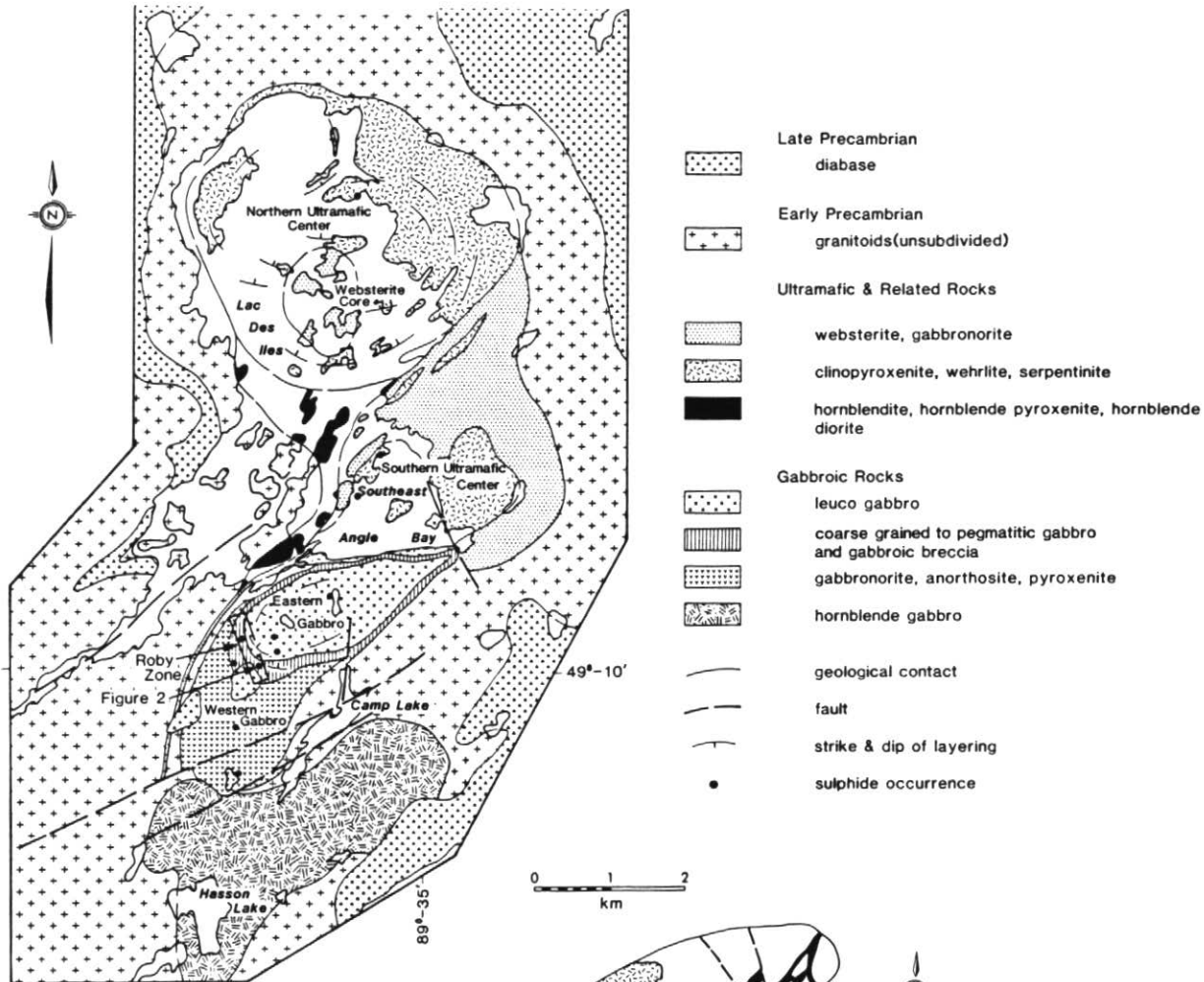
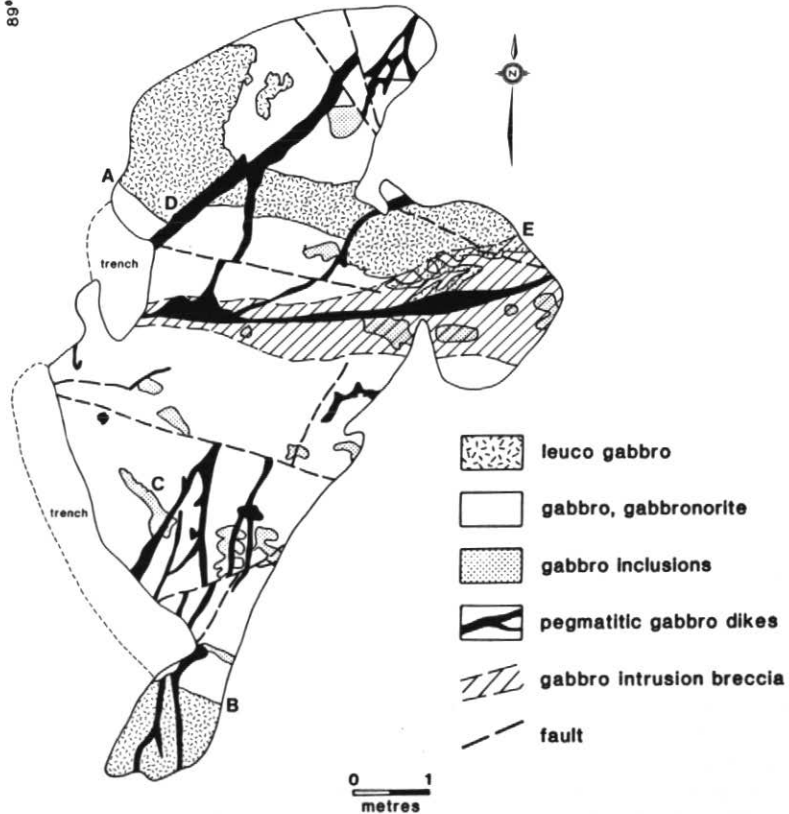


Figure 1 (above) Generalized geology of the Lac des Iles Complex. Simplified from Ontario Geological Survey Map P.3047.

Figure 2 (right) Outcrop map showing details of mineralized breccia zone and pegmatitic gabbro. Located approximately 200 m southeast of the Roby Zone at the "C-Zone". Phase contacts at A and B are interpreted to be primary igneous layers. Leucogabbro inclusions at C have crenulate surfaces suggesting the inclusion was not solid at the time of incorporation. An intrusion breccia zone indicated by the diagonal pattern cross-cuts igneous layering. Pegmatitic gabbro dikes occur in the core of the breccia and also disrupt the layering as at location D. A channel sample at E indicates that the highest PGE values occur in the pegmatitic gabbro in the core of the breccia and that intermediate values occur in the breccia adjacent to the pegmatitic gabbro.



The Roby Zone mineralization occurs along the contact between two units, the Western Gabbro and the Eastern Gabbro. The Western Gabbro is complex, but is dominated by gabbro-norite. The Eastern Gabbro is an anorthositic leucogabbro with higher Fe/(Fe+Mg) than the Western Gabbro. Along the contact, there are many textures which indicate magma mixing. In the Roby Zone, one pod of high-grade mineralization is associated with altered pyroxenitic to melagabbroic rocks right at the contact between the Eastern and Western Gabbros.

Another important feature of the mineralized zone is the presence of discordant pegmatites and breccia zones (Figure 2). The breccia zones are 1-2 m wide, and often have pegmatitic gabbro at their cores. The pegmatites and breccia both contain PGE mineralization.

Chalcopyrite, pyrite, pyrrhotite and pentlandite comprise 1-2% of the Roby Zone, and are most abundant in pegmatitic phases. The PGEs are associated with these sulphides both as a discrete palladium sulphide phase, and in solid solution with other sulphides.

In the Roby Zone, therefore, we have PGE concentrations associated with sulphides: (1) in gabbroic rocks in a zone where magmas mixed; (2) in altered pyroxenitic rock; and (3) where the presence of discordant breccia zones and of pegmatitic gabbro phases indicate the activity of a volatile phase.

The PGEs at Lac des Iles are highly fractionated, relative to chondrites, with a high ratio of palladium to platinum. Background concentration of PGEs at Lac des Iles are

elevated with respect to those of typical mafic and ultramafic rocks.

Differing mineralogies and crystallization sequences suggest to me that the Western Gabbro and Eastern Gabbro might have formed from separate phases of magma. Furthermore, rare earth element chemistry suggests that the pyroxenites of the Roby Zone are distinct from both the Eastern and the Western gabbros and may, in fact, be related to the ultramafic intrusion northeast of the Roby Zone (Figure 1). There appear to be, therefore, at least three different mafic phases in the mineralized zone.

I hypothesize that the source of PGEs at Lac des Iles is the fractionated magma of the ultramafic intrusion. In the Roby Zone, this magma is represented by the altered pyroxenite and possibly by the Western Gabbro. The sulphides in the Roby Zone were apparently precipitated by magma mixing and PGEs were probably co-precipitated with the sulphides. Magmatic, aqueous fluids (perhaps released during mixing) produced pegmatoid dikes and breccia zones, and were involved in the final redistribution of PGE.

The Bird River and Fox River Sills, Manitoba

contributed by Jon Scoates (Geological Survey of Canada, Ottawa, Ontario)

Although anomalous concentrations of platinum-group elements occur in the Bird River and Fox River Sills (1-2 ppm combined PGE), ore grade concentrations have not yet been discovered. However, I view these two intrusions as laboratories where we can investigate the processes that concentrate PGE.

The Fox River Sill, a predominantly ultramafic layered intrusion of Proterozoic age (1883 Ma, U-Pb zircon age) is one of Canada's largest layered intrusions (Figure 3). It forms segments which each have a strike length of about 270 km and which range in thickness from 2 to 2.5 km. The highest concentrations of PGE occur within the Main Layered Series at the contact between the Lower Central Layered Zone and the Upper Central Layered Zone. Across this contact, both the scale and the mineralogy of the cyclic units change dramatically. Disseminated sulphides (typically 3-4% of the rocks in which they occur) are found at the contact and in intervals up to 500 m above the contact. These sulphide-bearing intervals contain PGE concentrations of up to 1200 ppb.

Statistical studies of chemical analyses (of samples of hand-specimen size) suggest that one single factor can account for the variation in abundances of Ir, Th, Pt, Pd and possibly Au. The association noted in the previous paragraph suggests that this factor is related to the presence of sulphides. Variations in Ru content, however, are related to some other factor (possibly the crystallization of laurite and the association of laurite with chromite and/or olivine).

A tentative explanation for the anomalous PGE concentrations in the Fox River Sill involves the possible interaction between successive introductions of fresh, hot magma into the chamber, which eventually produced Upper Central Layered Zone cyclic units, and the evolved, residual magma in the chamber. Mixing of these magmas may have caused sulphur saturation, and the sulphur may have scavenged PGE from the evolved, residual magma.

The Bird River Sill (Figure 4), a layered ultramafic/mafic intrusion of Archean age (2745 Ma, U-Pb zircon age) contains well-known resources of chromite. The intrusion consists of a lower Ultramafic Series (200 m thick) and an upper Mafic Series (400 m thick). In the upper 60 m of the Ultramafic Series, there are six groups of chromitite layers called the Chromitiferous Zone. At the base of this Zone is a 1-3 m thick interval of anomalous PGE mineralization (up to 2500 ppb combined PGE). The PGE-bearing rocks commonly consist of harrisitic peridotites which invade and disrupt chromitite layers. (The harrisitic texture is defined by the presence of olivine crystals, up to several centimetres in size, with skeletal habits.)

Statistical analysis of PGE, Au, base metals, S and Cr concentrations (in samples of hand-specimen size) indicate two distinct associations. In the first association, the concentration of PGE are strongly correlated with those of Cr (+V +Zn), illustrating a clear affiliation between PGE and chromite. In the second, Ni (+Cu+Co) concentrations are correlated with S and Se (±Au) implying a nickel sulphide factor. There is no association between PGE concentrations and concentrations of Ni,

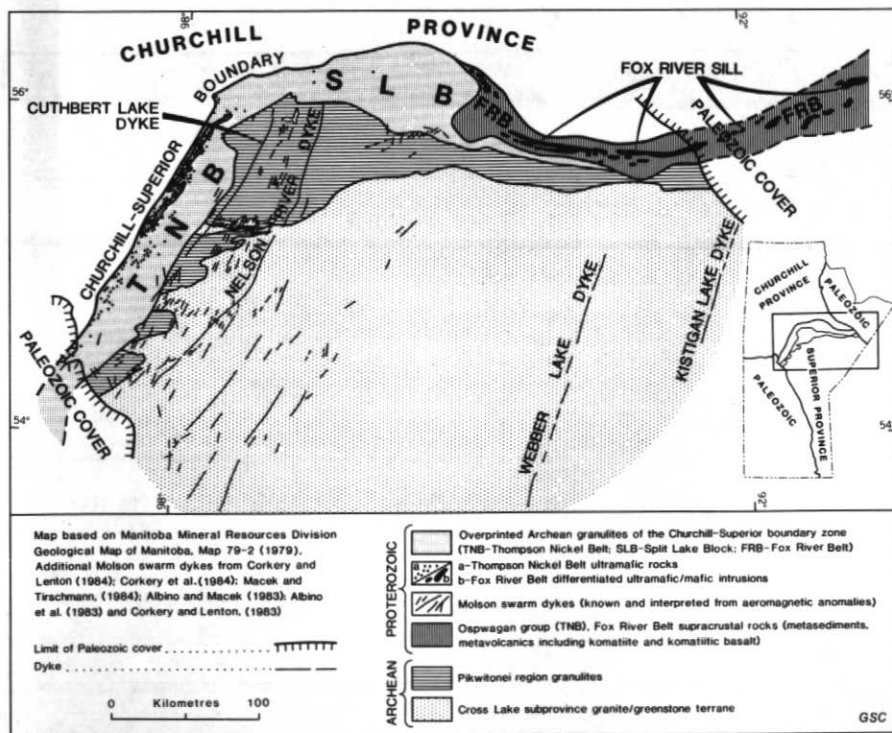


Figure 3 Generalized geological setting of the Fox River Sill.

S and Au. There are two separate statistical associations within the PGE: Ru, Os and Ir (probably related to the occurrence of laurite (Ru, Os, Ir) S₂ in the Chromitiferous Zone); and Rh, Pt and Pd (an incompletely understood association).

All six PGE occur in discrete platinum-group minerals (PGM); laurite, sperrylite, kotulskite, merenskyite, hollingworthite, irarsite and mertieite II. The PGM are usually associated with silicates, and only rarely with chromite or sulphides. Thus, we have a puzzle. The concentrations of PGE are correlated with those of Cr in samples of hand-specimen size, yet PGM show little association with chromite on a microscopic scale. Perhaps the PGE have undergone small-scale remobilization. Such remobilization could have occurred either during late-stage ponding of intercumulus magma and/or during serpentinization. Textural evidence also suggests that the PGM were redistributed, on a microscopic scale, during recrystallization related to upper greenschist- to lower amphibolite-grade metamorphism.

The Role of Manville Corporation in the Exploration for Platinum in the Stillwater Complex, Montana, USA

contributed by E.L. (Bob) Mann (Manville Corp., Denver, Colorado)

Manville Corporation (formerly Johns-Manville ("J-M")) and two partners are bringing into production Manville's discovery of PGE deposit in the Stillwater Complex of southern Montana. The Stillwater Complex is 45 km long by 7.2 km wide. The Complex generally dips 40° to 65° to the NNE except in the main Stillwater Valley where the dips are vertical to overturned.

The succession at Stillwater is listed in Table 1. There are two major fault sets: north-south cross-faults; and younger (Laramide) longitudinal ramp and thrust faults. The complex has undergone low-grade regional metamorphism accompanied by serpentinization.

J-M began an exploration program at Stillwater in 1967. This program was prompted by observations made, by J-M's Exploration Manager, of the Merensky Reef at Rustenburg; by previous records of platinum at Stillwater; and by J-M's expertise in ultramafic rocks.

In 1969-70, J-M and Bondar-Clegg and Co. Ltd. developed a technique for relatively inexpensive analysis of Pt and Pd. By 1971, stream and soil geochemistry and study of glacial boulder trains had led to the discovery of the Janet 50 zone, a small, low-grade occurrence of PGE associated with graphite near the Norite I/Upper Bronzitite contact (see Table 1).

In 1972-73, detailed geochemistry, induced polarization and ground magnetometer surveys indicated several anomalies. Areas of superimposed anomalies were trenched. One such trench led to the discovery of the Camp Zone, where PGE are associated with olivine cumulates and plagioclase-olivine cumulates. However, faulting and deep

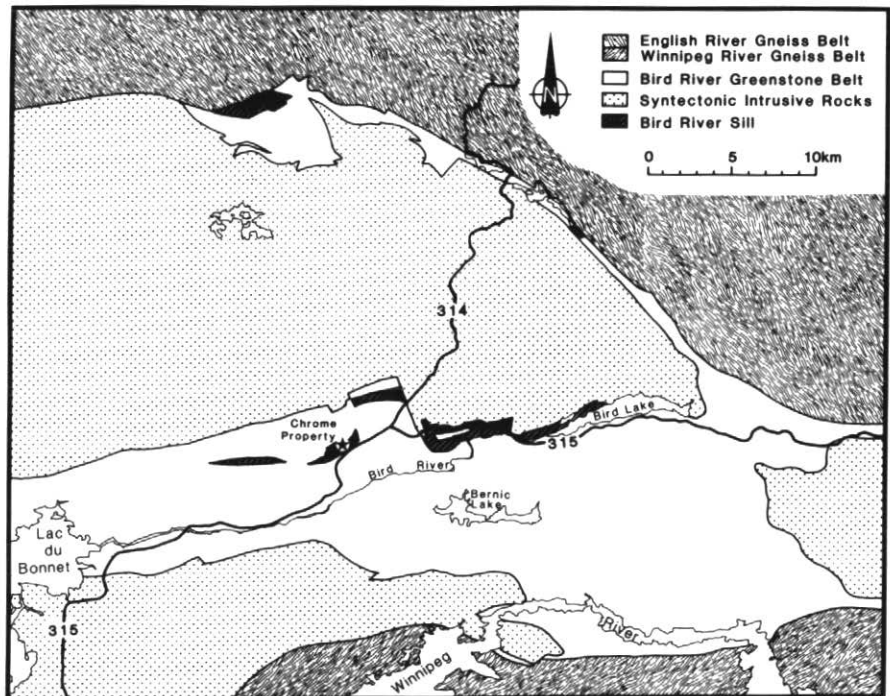


Figure 4 Generalized geological setting of the Bird River Sill.

Table 1 Stillwater Complex succession.

TOP: Paleozoic and Mesozoic sediments

STILLWATER COMPLEX(2.7 Ga):

Upper Banded Series	Gabbronorite III Troctolite V	
Middle Banded Series	Anorthosite II Troctolite IV Troctolite III Anorthosite I	
Lower Banded Series	Troctolite II Gabbronorite II Norite II Troctolite-Anorthosite I Gabbronorite I Norite I	J-M Reef; PGE Mineralization
Ultramafic Series	Upper Bronzitite Periodotite	Chromite
Basal Series	Basal Norite	Cu-Ni

FLOOR: Quartz Monzonite (2.65 to 2.76 Ga)
Metasediments (3.1 to 3.4 Ga)

weathering precluded using this materials for a bulk metallurgical sample.

Contour geochemical sampling, followed by bedrock sampling, trenching and drilling during the summer of 1974 led to the discovery of the J-M Reef where it straddles the West Fork of the Stillwater River Valley. Late in 1974, J-M drove the West Fork Exploration Adit into this occurrence, but this was abandoned early in 1976 due to technical difficulties and low PGE prices. J-M then decided to concentrate its efforts along the western portion of the complex in the hope of locating areas of richer mineralization.

Between 1976 and 1978, Winkie drilling in the Boulder River Valley outlined a sector of the J-M Reef which was 5.5 km long and averaged 2.1 m thick with a grade of 22.3 g/t of Pt + Pd.

In 1979, Manville formed a 50%:50% joint venture with Chevron Resources. The partners explored the Frog Pond sector by driving a decline during the summers of 1981 and 1982. However, in 1983, they ceased work in this area when they had the opportunity to join forces with Anaconda. The three companies then agreed to form the Stillwater Mining Company (SMC) which would explore the Stillwater Valley sector through Anaconda's Minneapolis Adit. In 1985, LAC Minerals bought out Anaconda's interest. Today, each partner owns a one-third share of Stillwater Mining Company.

In 1986, Stillwater Mining decided to develop a mine in the Stillwater Valley, twelve years after the discovery of mineralization in this portion of the complex. The mine is scheduled to produce at an initial rate of 500 short tons per day with a plan to expand to 1000 tons as soon as possible. The mill started in March 1987. It is producing a flotation concentrate which is being shipped to Belgium for further processing. There is a delay of approximately 5 to 6 months between the shipping of concentrate and the delivery of saleable refined metal.

Looking for platinum in the Stillwater Complex is like looking for the proverbial needle in a haystack! It is difficult even when exposure is good: mineralized zones are only 1-2 m thick, the content of sulphides is small (1-3%) and, in a 7000 m succession, only one of the twelve identified sulphide horizons is known to contain PGE of any significance.

The following is a review of the usefulness of different exploration techniques.

The Stillwater Complex is exposed along the glaciated edge of the Beartooth Plateau (elevation 3000 m). *Mapping and prospecting* are hampered on the plateau by sparse exposure (<2%), but better exposures do occur along the steep valley sides.

Subtle variations in mineral composition are important to identify one's whereabouts in the stratigraphy of the Complex (for example, the colour and shape of pyroxenes permit one to distinguish between gabbro and norite). The presence of limonite, however, is of little help in tracing zones of sulphides

because crystals of bronzite and, sometimes olivine, have rusty weathered surfaces.

Geochemistry worked well in Montana: in particular, panned stream sediments, talus fines, soils and rock chips. However, there is an extremely fine line between the analytical limits for Pt and Pd (<10, and <25 ppb, respectively), and the anomalous threshold at Stillwater (25 and 45-50 ppb, respectively). Manville has used enhancement techniques to improve the chances of finding an anomaly. Examples include the use of associated anomalous Cu and Ni concentrations, and anomalous ratios of Cu and Ni to PGEs.

The most useful *geophysical* technique was magnetometry, which was used to trace individual stratigraphic units. This may be useful elsewhere. However, in the Bushveld Complex, the rocks are generally deficient in olivine and the degree of serpentinization is so slight that the magnetic response may be insignificant.

The Bushveld Complex has vast reserves of PGE both in the Merensky Reef and the UG2 horizon below. The Stillwater Complex is much smaller, but the grade is higher — approximately equal amounts of Pt and up to 7 times the quantity of Pd in a zone averaging more than twice the thickness of the mineralized portion of the Merensky Reef.

Canada probably contains more than its rightful share of layered igneous complexes. Any one of these might turn out to be another Bushveld or Stillwater!

Factors Affecting the Recovery of PGEs contributed by Dr. Louis J. Cabri (Canada Centre for Mineral and Energy Technology, Ottawa, Ontario)

The major factors affecting the recovery of PGEs are: company specialization; secrecy; cash flow; mineralogy; and, mineral processing. Note that company specialization and secrecy can be more important than generally recognized!

The importance of cash flow is that, as Bob Mann pointed out, many months can pass between producing a concentrate and getting paid for it. It is possible, therefore, that a company could choose a less efficient extraction process if that process happened to facilitate refining of the ensuing concentrates, for that would also facilitate the receipt of revenues.

The following are comments on how the mineralogy of a deposit affects our ability to extract the PGE which it contains. The mineralogical factors affecting beneficiation are: mode of occurrence, grain size, textures, magnetic properties, cleavage, brittleness and density.

The modes of occurrence of PGE are as separate PGE minerals or as minor components of some of the ore minerals. PGE minerals are rare, fine-grained, and are still incompletely characterized. (For example, in spite of all the work done at the Merensky Reef, no one has ever completely characterized the minerals which carry the rhodium).

In discussing other mineralogical factors affecting beneficiation, I shall employ my own three-fold classification of PGE deposits: sulphide associations, the oxide-silicate association, and miscellaneous associations. I'll discuss only Sudbury-type, Merensky-type, Kambalda-type and Platreef mineralization (all are examples of sulphide associations); and an example of an oxide-silicate association.

In Sudbury-type mineralization, there are only a few principal PGE minerals: sperrylite (PtAs₂), michenerite (PdBiTe), moncheite (PtTe₂), and merenskyite (PdTe₂). Platinum, palladium and rhodium also occur in arsenides and sulpharsenides. However, we have made a detailed investigation of solid solution of PGE in the major sulphides and, with the exception of palladium-rich pentlandite at Stillwater and Lac des Iles (see below), we have not yet been able to detect any by analyses of minerals *in situ*.

At Sudbury, sperrylite accounts for the bulk of the platinum. A small amount is in solid solution as sulpharsenides, and the amount unaccounted for is minimal. The situation for palladium is quite different. The principal carrier of palladium is michenerite. But michenerite and other known palladium minerals account for only 40% of the palladium which shows up in bulk analyses. Where is the rest? It is in small inclusions in the silicates? We don't know.

At INCO Metals' Sudbury operations, the main losses of PGE occur in a circuit which rejects a pyrrhotite concentrate, and in tails from the primary and secondary mills. Much of the lost platinum is in the form of tiny, fragmented sperrylite crystals. Sperrylite is very brittle, so a process which finely grinds ore, to better separate copper and nickel, will shatter that sperrylite. The shattered grains are not efficiently recovered by flotation. We don't know why they are not recovered, because we don't know enough about the surface properties of minerals such as sperrylite.

The J-M Reef at Stillwater is an example of Merensky-type mineralization. The principal minerals are platinum-palladium sulphides: for example, braggite (Pt₆Pd₂NiS₁₀) and cooperite (PtS). Sperrylite is ubiquitous. Pt-Fe alloys are also important and will not necessarily be recovered with sulphides. Merenskyite also occurs. We don't know whether merenskyite will be easily recovered in processing because we don't know anything about its flotation properties. Furthermore, merenskyite often occurs as tiny inclusions in silicate, and these will not be easy to recover. Kotulskite (PdTe) and laurite (RuS₂) are also fairly important constituents of Merensky-type mineralization.

At Stillwater, palladium constitutes up to 3% of the pentlandite. Trace amounts of rhodium and ruthenium also occur in the pentlandite. This means that an operator can recover palladium, rhodium and ruthenium by floating off the sulphides.

The Donaldson West deposit, in the Ungava district of Quebec, represents Kamalalda-type mineralization. Sperrylite is again very important, as are two minerals which are relatively rare elsewhere: sudburyite (PdSb) and testibiopalladite (PdSbTe).

Lac des Iles, in northwestern Ontario, is an example of Platreef-type mineralization. The principal PGE minerals are again platinum-palladium sulphides as in the Merensky-type of deposits, but there are apparently no Pt-Fe alloys. Sperrylite is important again, and isomertieite $Pd_{11}Sb_2As_2$, rare elsewhere, seems to be prominent. A significant quantity of palladium occurs in solid solution in pentlandite.

The Bird River Sill, in Manitoba, provides an example of the oxide-silicate association. As Jon Scoates pointed out, preliminary studies show that most of the PGE minerals (for example, sperrylite) tend to occur in silicates between the chromite grains, and not inside or adjoining the chromite grains. The grain size and association may cause problems in recovery.

The following are general considerations in evaluating the potential recoveries of PGEs.

If PGEs occur as discrete platinum group minerals coarser than about 10 to 40 microns, they can be metallurgically recovered by gravity and/or by flotation. If the PGEs occur as solid solutions in sulphides or as 5 to 10

micron platinum group minerals included in sulphides, they are also recoverable by flotation only, or, sometimes, by magnetic separation. If PGEs occur in solid solution in silicates or oxides, we don't know if they are recoverable. Finally, if the PGEs occur as platinum group minerals, smaller than 5 to 10 microns in diameter and included in oxide or silicates, you will not recover them by present techniques (except magnetic separation in special cases).

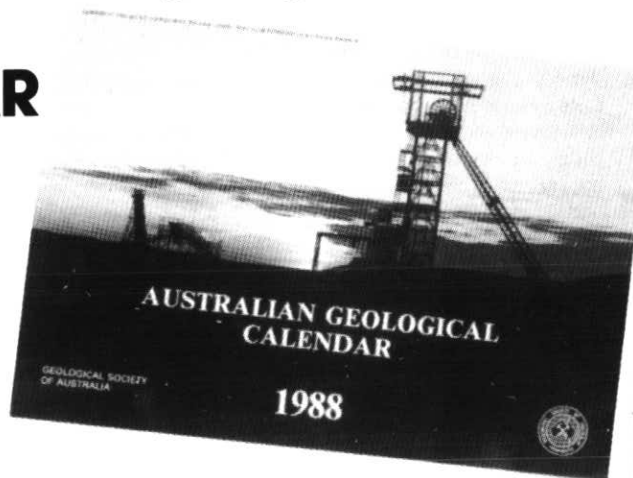
Even today, metallurgical tests are usually done on an empirical basis, without any detailed mineralogical examination. If you are lucky, it works!

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