Exploration for Platinum-Group Element (PGE) Deposits in Mafic and Ultramafic Rocks

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Most economic PGE deposits belong to a continuum of Ni-Cu-PGE sulfide mineralization styles from those that tend to be sulfide-poor and mined mainly for their PGE contents, through to those that are sulfide-rich and are mined mainly for their Ni and Cu contents. These sulfide deposits occur in association with mafic and ultramafic rocks in a variety of settings:

- Narrow "reefs" with low sulfide content within layered mafic/ultramafic intrusions (e.g., the Merensky Reef, South Africa; the J-M Reef of the Stillwater Complex, USA; and the Great Dyke, Zimbabwe).
- Wider zones of PGE sulfide enrichment within mafic/ultramafic intrusions (e.g., Munni Munni, Australia; River Valley and East Bull Lake Intrusions, Canada).
- Stratiform lenses of massive to disseminated Ni-Cu (PGE) sulfides at the base of komatiitic flow units (e.g., Kambalda, Australia; Cape Smith Fold Belt, Canada).
- In association with the outer contact phase of the Sudbury Igneous Complex, Canada, and concentrated in early-formed Offset dykes and the proximal country rocks.
- Stratabound zones of disseminated Ni-(Cu-PGE) sulfides within komatiitic rocks (e.g., Mount Keith, Australia).
- Within feeder zones of magmatic systems (e.g., Voisey's Bay, Canada).
- Within subvolcanic sills which acted as feeders to continental mafic volcanic sequences (e.g., Noril'sk, Russia; and possibly the Thompson Nickel Belt, Canada).

Many Ni-Cu sulfide deposits contain appreciable amounts of the PGEs, although the PGE tenor (calculated in 100% sulfide) varies enormously. Most of the mineralization was formed from magmas that were initially S-under-saturated but became S-saturated either by assimilation of S-bearing crustal rocks (e.g., komatiite-associated Ni sulfide deposits) or by magma mixing (e.g., Bushveld). During the fractionation of S-under-saturated mafic magmas, incompatible elements such as Cu, S, Se, Pd, and Pt accumulate in the residual silicate melt, whereas compatible elements such as Ni, Ir, Ru and Os are removed with the early silicate and/or oxide phases (Keays, 1995). Once a magma achieves S-saturation and fractionates even small quantities of immiscible magmatic sulfides, it will become strongly depleted in the PGE because of their very high Nernst partition coefficients (i.e. concentration element in sulfide melt/concentration element in silicate melt). The depletion in the PGE will be much more pronounced than the depletion in the other chalcophile elements such as Cu, S, and Se because the PGE have partition coefficients 1-3 orders of magnitude higher than these siderophile and chalcophile elements. A good example of this is provided by the Ni-Cu-PGE sulfide ores of the Sudbury camp; the noritic rocks of the Main Mass of the Sudbury Igneous Complex overlying the Sudbury ores are depleted in Cu and Ni, and, they are extremely depleted in PGE (Keays and Lightfoot, 1999).

In the case of layered intrusions, the ratios of the PGE to elements such as S, Cu and Se are much more useful exploration tools than absolute PGE concentrations. We show that data sets from the Munni Munni Complex, Great Dyke, Stillwater Complex, and the Bushveld Complex exhibit cross-overs in PGE/chalcophile metal ratios proximal to mineralized horizons. This is illustrated for the Merensky Reef of the Bushveld Complex (Fig. 1). The Pd/Cu and Pt/Cu ratios of rocks occurring above the mineralized horizons are all significantly lower than for rocks occurring below the mineralized horizons in these intrusions. The reason for this is that prior to ore formation, the magmas below the mineralized horizons were S-under-saturated whereas those from above it were S-saturated. The advantage of this approach to exploration for PGE deposits is that stratigraphically controlled analyses of ordinary, non-mineralized rocks will provide valuable clues

as to the probable presence and location of PGE mineralization within an intrusion.

A feature of all of these mineralized layered intrusions is that the S-under-saturated magmas, which formed the rocks underlying the mineralized horizons, were high Pd- and high Pt-bearing Siliceous High Magnesian Basaltic Magmas (SHMB). In all but the Munni Munni Complex, the ultramafic rocks are dominated by orthopyroxene, and so they crystallized from Si-rich melts. It is unclear whether these SHMB magmas were boninites or crustally contaminated komatiites. However, it appears that these magmas were initially S-under-saturated, a feature that we suggest is critical to the formation of important magmatic PGE deposits.

The Bushveld magmas appear to have contained more than an order of magnitude higher concentrations of the PGE than "normal" S-under-saturated magmas, such as komatiites that contain about 10 ppb Pd. The UG-2 and the Merensky Reef lie at the bases of cyclic units of rocks, termed the UG-2 Cycle and the Merensky Cycle that are both located in the Upper Critical Zone (Figure 1). They formed from discrete units of magma and possibly within double diffusion convection cells. All of the PGE decline in abundance from the base to the top of each cycle (Figures 1 and 2). In the UG-2 cycle, Pd drops off from 3100 ppb Pd at the base to 0.7 ppb Pd at the top. These variations indicate that the magma that formed the UG-2 was initially S-under-saturated but became S-saturated as it cooled; the first sulfides to segregate from the magma were Pd-rich reflecting the high partition coefficient. Sulfides that formed at the top of the UG-2 cycle have very low Pd contents; by the time they formed, the bulk of the Pd had been removed from the magma. Mass balance considerations suggest that the magma that formed the UG-2 contained 57 ppb Pd and 73 ppb Pt, while the Merensky Reef magma contained 106 Pd and 266 Pt.

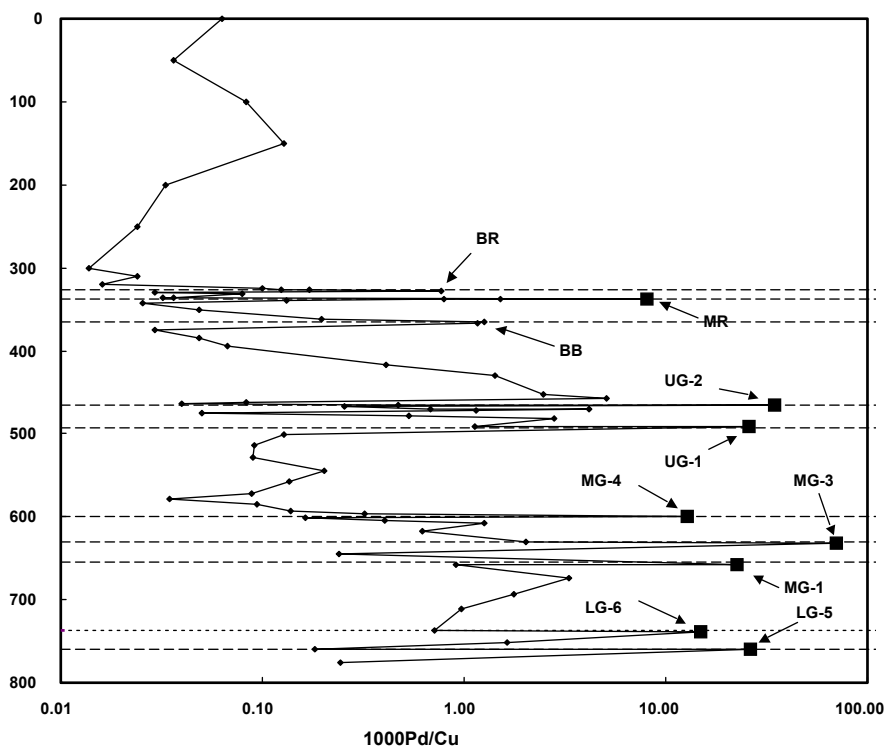

Figure 1. *Variation in Pd/Cu ratios of rocks from a drill hole traverse across the Rustenberg Mine (Bushveld Complex). Note that the Pd/Cu ratios decrease upwards from the chromitite seams (solid black squares) located at the base of each package of rocks. Except for the low Pd/Cu values at the top of these packages, Pd/Cu ratios in rocks below the Merensky Reef are higher than those of rocks above. Copper and Pd data for the chromite samples are from Hiemstra (1986) and Lee & Parry (1988)). Symbols: BR-Bastard Reef, MR-Merensky Reef, BB-Boulder Bed, UG-1 & UG-2 are Upper Group chromitite seams, MG-1, -3 and –4 are Middle Group chromitite seams and LG-5 and –6 are Lower Group Chromitites.*

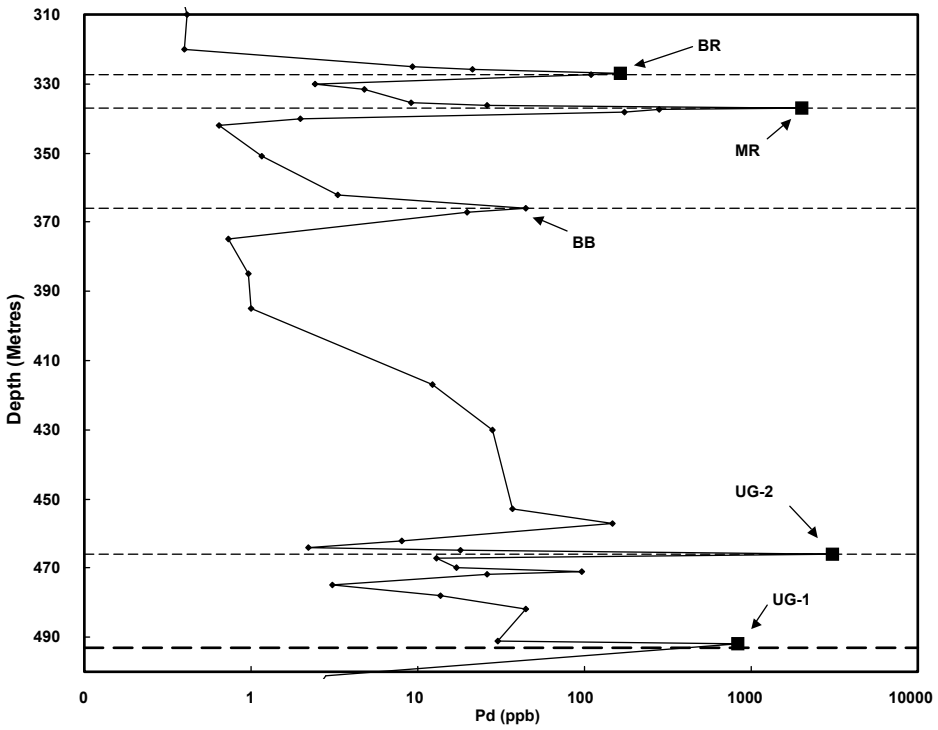

Figure 2. *Variation in Pd contents of samples from the base of the UG-1 to the top of the Bastard Reef in samples from a traverse across the Upper Critical Zone of the Bushveld Complex in the Rustenberg Mine. Note that Pd contents in the UG-2 cycle decrease from 3100 ppb Pd at the base of the cycle (in the UG-2) to 0.7 ppb Pd at the top of the cycle (immediately below the Boulder Bed). See Figure 1 for symbols.*

A mechanism is required to explain the very high PGE content of the Bushveld magmas. It is suggested that PGE-rich sulfides were initially deposited in a magma chamber at a deeper level than that of the present Bushveld Complex, as a result of interaction between a mantle-derived magma and the crust. Evidence for such interaction is provided by the strongly radiogenic Os-isotope signature of samples from the UG-2 and the Merensky Reef (Schoenberg et al., 1999). At some later stage, these PGE-rich sulfides were dissolved by a second, strongly S-under-saturated magma, such as a SHMB, and introduced into the Bushveld magma chamber where they eventually became S-saturated due to cooling and consequently precipitated the PGE-rich sulfides in the UG-2 and the Merensky Reef.

Many other Ni-Cu-(PGE) sulfide deposits (e.g. Noril'sk, Voisey's Bay) are probably products of two-stage processes initially involving deposition of Ni-Cu-PGE sulfides at depth due to interaction of mantle-derived magmas with crustal materials and subsequent transport of these sulfides to higher levels in the crust. However, unlike the Bushveld, instead of dissolving the PGE-rich sulfides, the second "carrier" magma simply transported these as immiscible sulfide droplets into the higher-level magma chambers.

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