

Ore Deposit Models #12. The Platinum Group Element Deposits: Classification and Genesis

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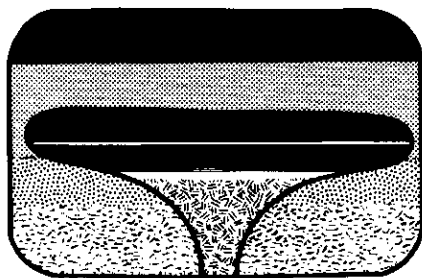
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Résumé de l'article

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Hydrothermal platinum-palladium deposits include those in which a hydrothermal system has been channelled through mafic/ultra-mafic host rocks from which the precious metals may have been leached. Examples include the New Rambler Mine in Wyoming, the Rathbun Lake occurrence in Ontario, and the Nicholson No. 2 uranium ores in the Beaverlodge area of Saskatchewan. The alkaline suite of porphyry copper deposits comprises the second type of hydrothermal mineralization in which platinum and palladium are significantly concentrated. The huge Kupferschiefer Cu-Ag deposits in Central Europe contain locally significant concentrations of platinum and palladium, associated with redox fronts in carbonaceous shales. At the Coronation Hill deposit, in Australia's Northern Territory, PGE are also spatially associated with carbonaceous material, and with uranium and gold mineralization.



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Abstract

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Introduction

The objective of this contribution is to provide a genetic framework in which to consider the several deposit classes of the platinum group of elements (Os, Ir, Ru, Rh, Pt, Pd, or the PGE). A new classification scheme is proposed and the geologic processes responsible for metal concentration in each deposit class are considered in turn. A brief consideration of the geochemistry of the PGE is presented prior to discussion of classification and genetic processes.

Geochemistry of the PGE

The understanding of PGE geochemistry has been constrained until relatively recently by the inability to analyse these elements at levels in which they typically occur in unmineralized rocks, i.e. at the part per billion level. Recent advances, particularly with the aid of radiochemical and instrumental neutron activation analysis, has now removed this obstacle, permitting accurate determination of background PGE contents of most rock types. The most comprehensive survey of PGE geochemistry has been presented by Crocket (1981), from which the bulk of this summary is synthesized.

The most obvious characteristics displayed by the PGE are their siderophile nature and their affinity for sulphides in mafic and ultramafic rocks. Figure 1 gives typical means and ranges of Pt contents in mafic and ultramafic rocks. The average Pt content of carbonaceous chondrites, on the other hand, is approximately 1000 ppb, attesting to the siderophilic character of Pt. Similar data for the other PGE are presented in Naldrett and Duke (1980), Crocket (1981) and Campbell *et al.* (1983).

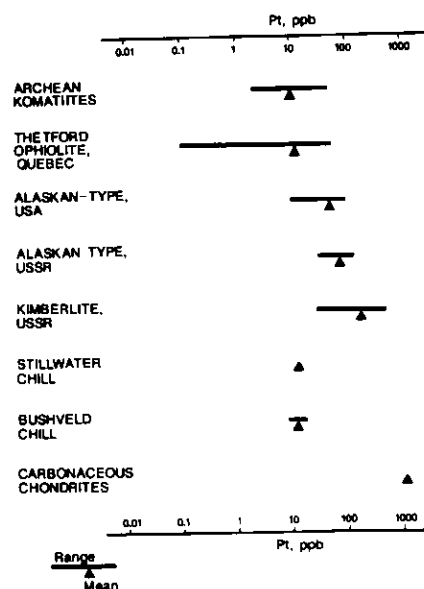


Figure 1 Pt content of some mafic and ultramafic igneous rocks. Bushveld and Stillwater chills may represent magma compositions. Data from Crocket (1981), Campbell *et al.* (1983) and Davies and Tredoux (1985).

al. (1983). PGE contents in intermediate and felsic igneous rocks, and in metamorphic and sedimentary rocks are less well known. Crocket (1981) suggests that typical levels for individual PGE in felsic and intermediate rocks are in the sub-ppb range.

As can be seen from Figure 1, the average Pt content of unmineralized mafic and ultramafic rocks is approximately 10 ppb, with a range from 0.1 ppb to 500 ppb. A typical economic PGE deposit may have a mean platinum grade of between 5 and 10 ppm, which is the same order of magnitude as gold deposits. This suggests that the geologic process(es) which are responsible for formation of a PGE deposit involve enrichment factors of approximately one thousand.

Although the sulphide content of igneous rocks hosting orthomagmatic PGE deposits can be highly variable, the precious metals display a ubiquitous association with sulphides, which has led most researchers to suggest that formation of an economically significant deposit is dependent upon the segregation of immiscible sulphides, into which the PGE preferentially partition (e.g. Naldrett and Duke, 1980). For sulphide to become a discrete phase within a mafic/ultramafic magma, the solubility of sulphur in the magma must be exceeded. The precipitation of an immiscible sulphide phase, which is a critical step in the formation of a PGE deposit, may result from one or more of the following processes:

(1) assimilation of sulphur from an external source; (2) rapid cooling of the magma; (3) assimilation of silica; (4) blending of two or more disparate magmas; (e.g. Irvine, 1975, 1977; Naldrett and Macdonald, 1980; Todd *et al.*, 1982).

Different types of PGE deposit may form as a result of each of these processes, which are discussed in detail in the following section.

Classification of PGE deposits

Classification of mineral deposits can be approached from several perspectives: (a) associated host rock, e.g. shale-hosted Pb-Zn deposits; (b) mineralogical association, e.g. telluride-gold ores; (c) geographic location, e.g. Alpine-type chromite deposits; (d) archetypal, e.g. "Carlin"-type gold deposits; (e) tectonic setting, e.g. rift-related Cu-Ni deposits; (f) mineralization process, e.g. exhalative massive sulphides. The optimal approach to classification of a mineralization type, such as ores of the platinum group of elements, separates radically different classes of mineralization into a manageable number of categories, without permitting duplication of individual deposits within two or more categories. Classification by the sixth approach given above, (f), based upon the process by which the metals are concentrated, avoids potential duplication which can be imposed by classifications reliant upon associated host rocks, mineralogy, geography, archetype, or tectonic setting. The

approach must be flexible enough to permit modification in response to an increased understanding of the processes in question.

A classification of PGE deposit types is given in Table 1, based upon the inferred process by which the PGE were concentrated, and whether the PGE are the primary product, a co-product or a bi-product.

CLASS 1: Orthomagmatic. The orthomagmatic class contains all those deposits that form solely within the magmatic environment. This includes deposits in which the PGE were concentrated during mixing of more than one magma (Subclass 1a), by contamination of a magma with various different types of material from external sources (Subclass 1b) or by deuteric processes, i.e. involving volatile-rich fluids derived from within the magma chamber from which the host rocks crystallized (Subclass 1c). Some PGE deposits may have formed from a combination of one or more of these orthomagmatic processes.

Table 2 gives reserves for a number of the better known PGE deposits. Past production and published reserves for the two other deposit classes in Table 1 are approximately two orders of magnitude less than those for the orthomagmatic class. This does not preclude, of course, significant contributions in the future from deposit types that do not currently constitute a PGE reserve.

SUBCLASS 1a: Magma Mixing. The data in Tables 1 and 2 underscore the pre-eminent position of Subclass 1a, those deposits whose formation is attributed to mixing of more than one magma. The Merensky Reef (sulphide), UG2 Reef (chromitite) and Platreef (sulphide) in the Bushveld Complex, South Africa, together with the J-M Reef (sulphide) in the Stillwater Complex, Montana, USA, and the Great Dyke of Zimbabwe (sulphide) contain over 90% of reserves within the principal PGE deposits (Table 2). This percentage is likely to increase as a result of further exploration in the Stillwater Complex.

Figure 2 (opposite page - upper) Geological map of the Bushveld Igneous Complex, South Africa (from Willemse, 1969).

Figure 3 (opposite page - middle) Geological Map of the Stillwater Igneous Complex, Montana, USA (from Conn, 1979).

Figure 4 (opposite page - lower) Simplified stratigraphy and cumulus phases in the Bushveld and Stillwater Igneous Complexes, modified from Campbell et al. (1983).

Table 1 A classification of PGE Deposits

Deposit Class	Examples
1. ORTHOMAGMATIC	
1a) Magma Mixing	UG2†, Merensky Reef*, Platreef*, BIC J-M Reef *, SIC Great Dyke *, Zimbabwe Lac des Iles *, Canada
1b) Magma Contamination	Noril'sk ‡, USSR Sudbury ‡, Canada Kambalda ‡, Australia Thompson ‡, Canada
1c) Deuteric	Dunite Pipes *, BIC
2. ALLUVIAL	
2a) Placer	Choco *, Colombia Urals *, USSR
2b) Paleoplacer	Witwatersrand ‡, South Africa
3. HYDROTHERMAL	New Rambler ‡, USA Rathbun Lake ‡, Canada Allard Stock ‡, USA Kupferschiefer ‡, Poland Coronation Hill ‡, Australia

BIC - Bushveld Igneous Complex, South Africa

SIC - Stillwater Igneous Complex, USA

* Primary Product

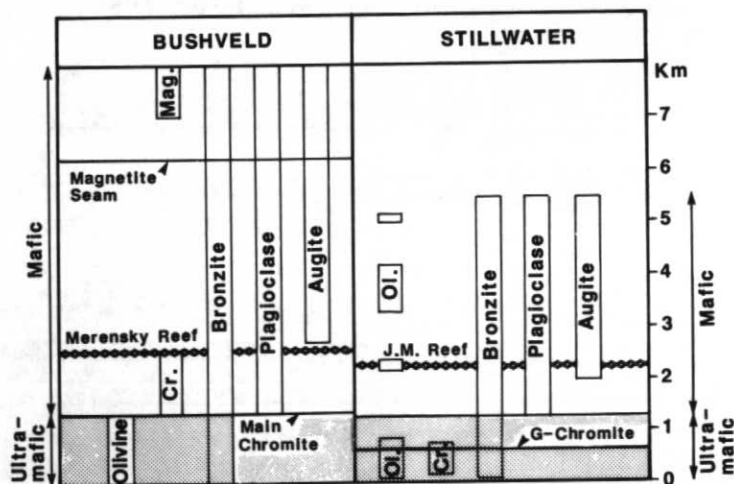
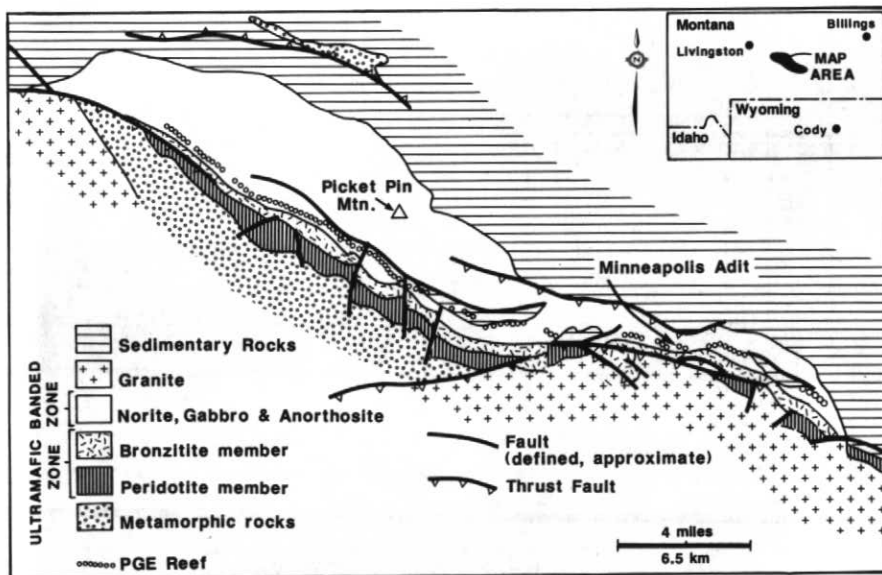
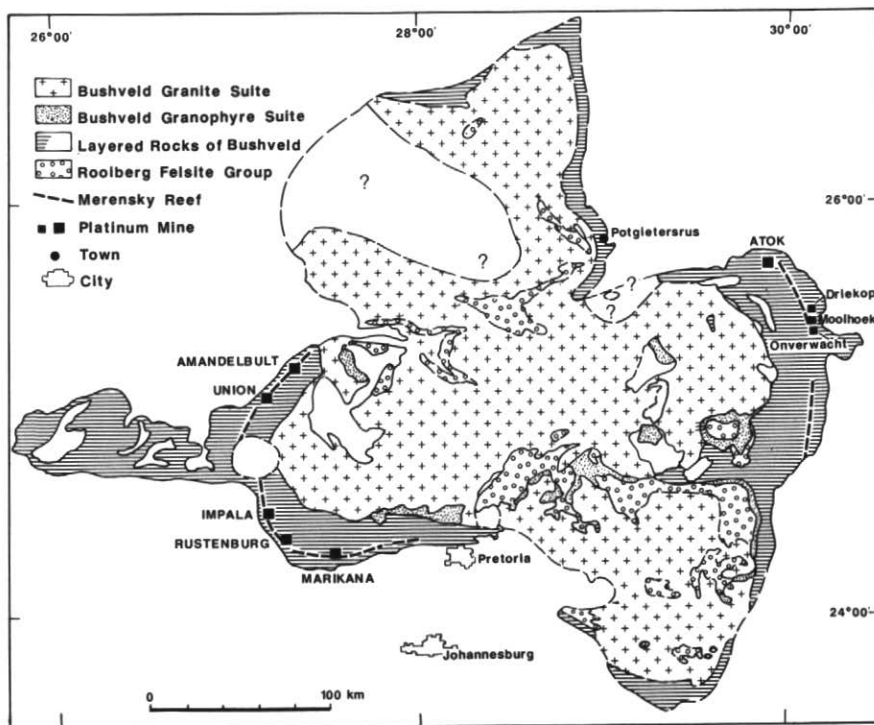
† Co-product

‡ Bi-product

Table 2 PGE Reserves in some Deposits (Data from Buchanan (1979), Naldrett (1981), Robson (1985) and Naldrett et al. (1987))

	Bushveld Complex			Great Dyke *	Sudbury	Noril'sk	Stillwater J-M Reef *
	Merensky Reef *	UG2 *	Platreef *				
Million Tonnes	2160	3700	1700	1679	310	1640	49
Grade (Total PGE + Au, g/t)	8.1	8.71	7.27	4.7	0.9	3.8	22.3
Contained PGE + Au (tonnes)	17496	32227	11900	7890	279	6232	1093
Percentage of total	26.8	49.4	18.2	12.1	0.4	9.6	1.7

* Primary Product



The Bushveld and Stillwater Complexes exhibit considerable morphological, lithological, mineralogical and chemical similarities. The mafic and ultramafic Bushveld Igneous Complex (BIC) is 2.1 Ga, 240 x 400 km in areal extent and approximately 8 km thick (Figure 2), and intrudes 2.26 Ga sediments and lavas (Hamilton, 1977). The mafic and ultramafic Stillwater Igneous Complex (SIC, Figure 3), at 2.7 Ga (DePaolo and Wasserburg, 1979), intrudes 3.14 Ga sedimentary rocks, which are hornfelsed (Page, 1977; Page and Zientek, 1985), and is overlain unconformably by Phanerozoic sedimentary rocks. The SIC has a strike length of 48 km (Figure 3), and the portion of the complex remaining after erosion is 5.7 km thick. The extent of erosion, and hence original thickness, is unknown. Both intrusions contain prominent lithological layering, permitting the establishment of a simplified stratigraphy, consisting of lower ultramafic zones and upper mafic zones in each complex (Figure 4).

In detail, the BIC has been subdivided into four zones; a Lower Zone of harzburgites, bronzitites and dunites (1200 m), the Critical Zone of bronzitites, norites, anorthosites and chromitites (1400 m), the Main Zone of gabbro, norite and anorthosite (3600 m) and an Upper Zone of magnetite-bearing gabbros, troctolites, olivine diorites and magnetitites (2000 m). Detailed descriptions of BIC geology are given in Von Gruenewaldt (1979) and Von Gruenewaldt *et al.* (1985).

The SIC comprises a Basal Zone (Page and Zientek, 1985), an Ultramafic Zone, and a Banded Zone (McCallum *et al.*, 1980). The Basal Zone (60 m), contains inclusions of hornfelsed sediments within noritic rocks and also includes dykes and sills related to the SIC (Page, 1979). The Ultramafic Zone consists of a lower peridotite (915 m), overlain by a bronzite (305 m), with at least 13 chromite groups associated with peridotite. (N.B. - chromitites occur above the ultramafic rocks in the BIC). The Banded Zone of the SIC (4.5 km) contains layers of norite, gabbro, norite, anorthosite and minor troctolite and gabbro. The geology of the SIC is described in detail by McCallum *et al.* (1980) and Czamanske and Zientek (1985).

The Merensky Reef, BIC, is a coarse grained to pegmatoidal, feldspathic pyroxenite (e.g. Vermaak, 1976) that stratigraphically overlies an anorthositic/leuconoritic unit, and underlies a finer grained pyroxenite or melanorite (Figure 5). Two chromite seams are usually associated with the Merensky Reef, separated by less than 1 m of pegmatoidal pyroxenite, although the exact stratigraphy may vary from locale to locale (e.g. refer to sections in Naldrett, 1981). PGE grade correlates with sulphide abundance, which is typically less than 2 wt.%, and highest PGE grades are associated with the chromite seams (Campbell *et al.*, 1983). The thickness of the mineralized unit is variable, but is of the order of 1 m. The reef is

exposed around the perimeter of the eastern and western lobes of the BIC (Figure 2), over a strike length of approximately 250 km. The most common PGE-bearing minerals are braggite, cooperite, laurite and Pt-Fe alloy, the latter being intergrown with base metal sulphides (Vermaak and Hendriks, 1976).

The J-M Reef, SIC, is approximately 2 m thick and has been traced along strike for approximately 40 km, although only a portion, in the vicinity of the Minneapolis Adit, is included within published mining reserves of the Stillwater Mining Company.

Stratigraphic control on mineralization in the J-M Reef is less well constrained than that of the Merensky Reef. Although the J-M Reef is localized generally within the vicinity of the lowest olivine-bearing rock within the Banded Series, known as olivine-bearing Zone 1 (OB1), (McCallum *et al.*, 1980), PGE and sulphides may be found at four different stratigraphic levels in the Minneapolis Adit area (Figure 6, Raedeke and Vian, 1986): (a) in gabbro-norite, 10 m below OB1; (b) across the basal contact of OB1; (c) within 3 m of the basal contact, but totally within OB1; (d) within OB1, but well above the basal contact. In the last three zones sulphides are usually disseminated over 1 to 3 metres. Most commonly, mineralization in any specific area occurs only at one stratigraphic level, although locally mineralization may be found at up to three discrete levels. Sixty to seventy percent of the higher grade mineralization is found at levels (b) and (c), as described by Raedeke and Vian (1986).

In a comparison of the Merensky and J-M Reefs, Campbell *et al.* (1983) point out a number of features common to both which must be accounted for by any genetic model: (1) the PGE are in sulphides; (2) the sulphides are at or near the base of cyclic (macrorhythmic) units, marked by the re-appearance of high temperature cumulus phases (chromite + olivine), and reversals in mineral fractionation trends; (3) local discordances in the footwall rocks, known as "pot-holes", are present below both reefs; (4) development of coarse-grained, pegmatoidal rocks; (5) stratigraphic level; both reefs occur about 500 m above the level at which plagioclase first becomes a cumulus phase (*i.e.* above the level at which the stratigraphy is first dominated by gabbroic, rather than ultramafic, rocks) - Figure 4.

Campbell *et al.* (1983) contend that any model for the origin of these deposits must account for these similarities.

The UG2 chromitite layer, which averages over 0.8 m thick (Naldrett, 1981) is as little as 30 m below the Merensky Reef in the northern sector of the BIC, and as much as 400 m below in the northeastern sector (Figure 2). As seen in Table 2, the PGE resource contained in the UG2 is greater than that of the Merensky Reef. The UG2 is also noteworthy for its higher Rh grades, not only a more valuable metal but also an asset for the manufacture of three-way

autocatalysts, which utilize Rh to reduce oxides of nitrogen (Robson, 1985, 1986). The UG2 mineralogy, with a low sulphide, and high chromite content, caused initial metallurgical difficulties which rendered the ore difficult to treat. By 1985 these problems were resolved and at least two of South Africa's principal PGE mining houses, Rustenburg and Western Platinum, now derive a significant proportion of their production from the UG2 Reef (Robson, 1986).

The UG2 Reef is also associated with a 0.5 m thick pegmatoidal, feldspathic bronzite cumulate (*cf.* Merensky and J-M Reefs).

PGE in the UG2 Reef are present as sulphides and alloys within the chromitite, principally laurite, cooperite, braggite and Pt-Fe alloy (Gain, 1980). Recently Naldrett *et al.* (1987) have proposed that while sulphides, with associated PGE and oxides, were deposited synchronously with the host rocks, PGE, Ni and Cu tenors were upgraded as a result of the subsolidus loss of FeS.

Much evidence is accumulating to indicate that the PGE-rich reefs in the BIC and SIC are spatially associated with mixing zones of magmas with two distinct compositions. For example, Todd *et al.* (1982) described two

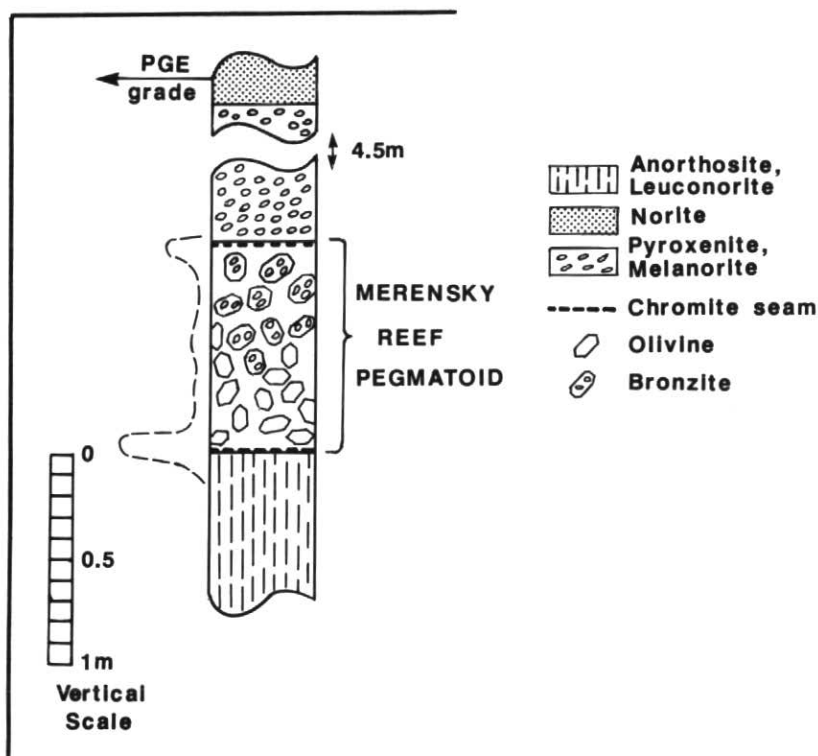


Figure 5 Stratigraphy in the vicinity of the Merensky Reef, Bushveld Igneous Complex (Naldrett, 1981).

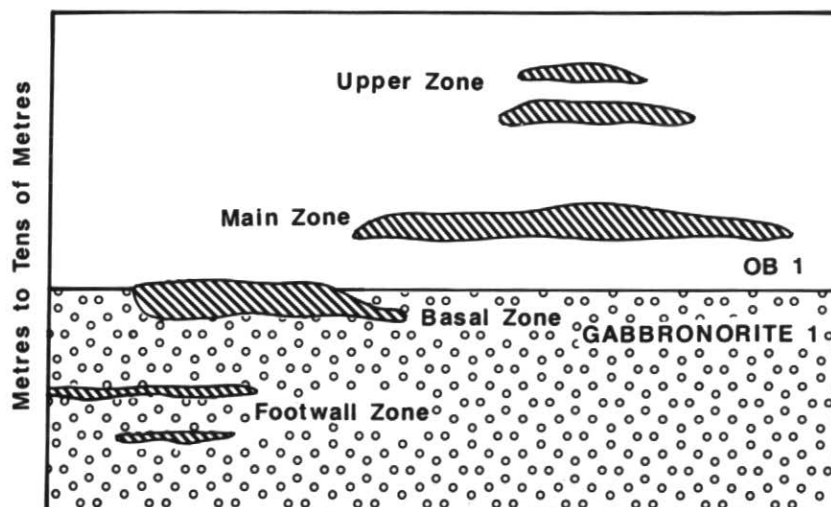


Figure 6 Zones of mineralization and stratigraphy, J-M Reef, Stillwater Igneous Complex (Raedeke and Vian, 1986).

igneous suites within the SIC: rocks with an ultramafic (U) affinity, which exhibit a crystallization order olivine, bronzite, plagioclase, augite; the second magma has an anorthositic (A) affinity with crystallization from plagioclase, to olivine, augite and finally bronzite. Todd *et al.* (1982) proposed that the J-M Reef sulphides formed during mixing of the two magma types.

In the same year, Sharpe (1982) described two magma suites in chilled margins of the BIC, one with pyroxenitic affinity, the other gabbroic. Sharpe also suggested that mixing of the two magma types may have given rise to host rocks for the UG2 and Merensky Reefs.

Irvine *et al.* (1983) refined the magma mixing hypothesis in terms of double-diffusive convection of the two magmas (U and A) for both the Bushveld and Stillwater Complexes. Their principal conclusions are that the J-M, Merensky and UG2 Reefs owe their existence to the extraordinary composition of the Stillwater and Bushveld U-type magmas, which display an olivine-boninitic affinity, i.e. rich in SiO_2 (52-56%), MgO (12-16%), Cr (800-2000 ppm) and incompatible elements (e.g., 20-50 ppm Rb, 150-400 ppm Zr), and, most importantly, exceptionally rich in the PGE (up to 100 ppb total PGE + Au). The A-type magmas are closer to tholeiitic basalt in composition (SiO_2 48-50%, MgO 8-10%), with low Cr and incompatible elements. Note that, interestingly, the specialized magma with ultramafic affinity actually has a higher

silica content than the gabbroic magma. For further discussion of these magmas, refer to the review by Von Gruenewaldt *et al.* (1985).

Irvine *et al.* (1983) also point out that perhaps one of the most significant characteristics of the U-type liquids is their low sulphur content. The ore reefs mark the first occurrence within the stratigraphy of the BIC and SIC, with the exception of basal zones in contact with country rock, that prominent sulphide precipitation — or, sulphide liquation, to emphasize that initial sulphide formation is as liquid droplets, rather than solid crystals — occurred on a sustained basis, permitting scavenging of available PGE by sulphides. The scavenging is a function of the strong partitioning of the PGE in favour of sulphide relative to silicate phases (Naldrett and Duke, 1980). If sulphide liquation had occurred earlier in the development of the U-type liquids, then magmatic enrichment of the PGE to the observed levels would not be possible.

Sulphide precipitation in the magmatic environment, whilst being perhaps the single most important phenomenon in localizing and concentrating PGE, is a poorly understood process. A number of schemes have been proposed to account for the formation of sulphide droplets in a silicate magma: (1) simple cooling of the magma (Haughton *et al.*, 1974); (2) mixing of two magmas, one primitive, the other more evolved (Irvine, 1977); (3) addition of silica by contamination (Irvine, 1975; Naldrett and Macdonald, 1980), discussed further under Subclass 1b.

As much of the gross lithological, mineralogical and chemical data for the Merensky and J-M Reefs, outlined above, are suggestive of mixing two disparate magmas, much effort has been undertaken to relate sulphide-bearing PGE mineralization directly to the hypothesized magma mixing event. Campbell *et al.* (1983) presented an elegant model to relate efficiency of mixing of two

magmas with stratigraphic level in the BIC and SIC. Their fluid dynamic model emphasizes the control on mixing exerted by density contrasts between the magma that is resident in the chamber and the incoming, new magma pulse. Density of the resident magma will vary in sympathy with fractionation, temperature and composition. If a new pulse is more dense, it will spread along the floor of the chamber, with minimal mixing (Figure 7a). A dense magma jet with considerable momentum will spurt into the chamber before falling back to the floor, with only minor mixing (Figure 7b). If the magma pulse is lighter, it will rise through the resident magma to the roof of the chamber (Figure 7c), again with little mixing. If the new magma pulse has the same density as some portion of the magma chamber, it will spread across the chamber at the level in question, mixing with the resident magma (Figure 7d). Campbell *et al.* (1983) demonstrate that in magma chambers which are crystallizing plagioclase — a low density mineral — the density of the remaining magma increases with fractionation. The gradual density increase of the resident magma eventually attains and exceeds that of a new magma pulse (Figure 8). This density crossover point is suggested by Campbell *et al.* (1983) to occur at the approximate stratigraphic levels of the Merensky and J-M Reefs.

Irvine (1977) and Irvine and Sharpe (1986) have also proposed that magma mixing is responsible for the formation of chromitite horizons, with attendant PGE, in layered igneous intrusions. The magma mixing model alone is capable of accounting for formation of both sulphide and oxide phases, but may also involve components of the other two hypotheses mentioned above (cooling and silica contamination): the jet of hot, incoming magma (Figure 7d), upon mixing with the cooler, resident magma, will itself

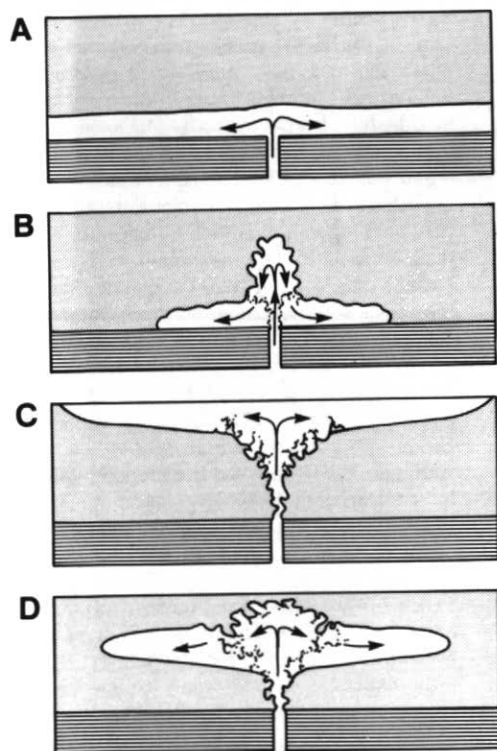


Figure 7 Magma injection plumes into resident magma, with the effect of varying density difference. See text for details (after Campbell *et al.*, 1983).

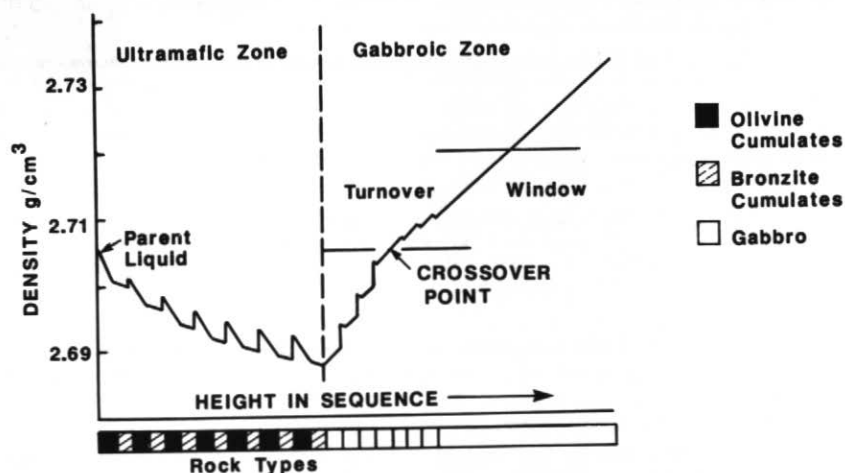


Figure 8 Density variation of magma during sequential injection of primitive melts. Each cyclic unit is assumed to mark the introduction of a new pulse of magma into the chamber equal to 25% of the volume of the magma in the chamber. The turnover window is the density range in the fractionated magma for which magma turnover is possible (after Campbell *et al.*, 1983).

cool, perhaps sufficiently to promote sulphide liquation. In addition, the mixing of two magmas with disparate chemical compositions can also cause sulphide to precipitate, if one has a greater silica content than the other (Irvine, 1975). The chemistry of this process is described more fully in the discussion of the next Subclass, 1b.

While the points of similarity between PGE mineralization in the BIC and SIC are best explained by orthomagmatic processes, with evidence from detailed petrography, geochemistry and radiogenic isotopes (see, for example, Von Gruenewaldt *et al.*, 1985), the same data, when combined with additional observations, suggest that some modifications to the magma-mixing model may be required. These observations include: (a) the close spatial association between PGE and pegmatoidal rocks; (b) the locally transgressive nature of the reef mineralization, often associated with "potholes" (e.g., Viljoen and Hieber, 1986; Turner *et al.*, 1985); (c) the co-existence of hydrous silicates, such as amphiboles, micas, talc and serpentine, often Cl-rich (e.g., Johan and Watkinson, 1985; Mathez *et al.*, 1985); (d) graphite, present in "stockworks" beneath the J-M Reef (Volborth and Housley, 1984) or within potholes in the Merensky Reef (Ballhaus and Stumpfl, 1985, 1986); (e) CO_2 - CH_4 - H_2O -bearing and chloride-rich fluid inclusions in quartz from pegmatoids in the Merensky Reef (Ballhaus and Stumpfl, 1986).

At least four, fundamentally different hypotheses have been proposed to account for the pothole features which form depressions up to several hundred metres in length and 25 m deep into the footwall stratigraphy below both the Merensky and J-M Reefs. The PGE mineralization also sympathetically drapes down into the pothole depressions (Stumpfl and Ballhaus, 1986). The potholes are proposed to be slump structures over voids in the footwall (Cousins, 1964; Leeb-du Toit, 1986). On the other hand, Campbell (1986) suggests that during magma mixing (e.g., Figure 7d) plumes of convecting magma pass downward towards the accreting crystal pile, and induce partial erosion where the down-convecting jet intersects the crystal pile.

A third proposed origin for potholes is based upon the "de-watering" hypothesis, where volatile-bearing, intercumulus liquid is displaced upward during compaction of the lower stratigraphic pile. The upward percolation of fluids could have discharged into the magma as a fumarole. Perhaps the potholes represent the egress zones of this fumarolic activity, and it has been suggested that the Merensky Reef sulphides were up-graded by PGE carried by the upward percolating fluids (Vermaak, 1976; Von Gruenewaldt, 1979). Instead of the fluids being derived through compaction of the lower portions of the magma chamber, Ulmer *et al.* (1981) propose that the fluids were released through

dewatering of the underlying Transvaal sediments.

Stumpfl and Ballhaus (1986), in proposing a fourth hypothesis, reject both the magmatic erosion (e.g., Campbell, 1986) and fumarolic models (e.g., Ulmer *et al.*, 1981) and emphasize the presence of stratigraphically-controlled mineralization and alteration that is present within the stratigraphy around the margins of the potholes in the BIC. Turner *et al.* (1985) have noted similar features in the Minneapolis Adit sector of the J-M Reef, SIC. Turner *et al.* describe "pothole margin mineralization ... concentrated in layered footwall gabbro rocks on pothole margins adjacent to the contact with the Reef package and along favourable layers marginal to pothole depressions". The PGE mineralization has replaced certain horizons, with fluids passing from the J-M Reef at the floor of the pothole into the marginal rocks by a diffusion mechanism. Stumpfl and Ballhaus (1986) suggest that pothole morphology and mineralogy reflect localized, elevated volatile contents during crystallization of the magma that gave rise to the lithological units that define the potholes.

Previous understanding of the complex geometry of the Merensky Reef had been hampered by aspects of confidentiality surrounding the platinum mining industry in South Africa (Viljoen and Hieber, 1986). Recently, however, a number of articles (e.g., Viljoen and Hieber, 1986; Farquar, 1986; Mossom, 1986) have described the widespread, ubiquitous presence of complex pothole (depression) and koppie (elevation) morphologies of the Merensky Reef, with transgressive geometries of both lithological units and mineralization, much as seen in the J-M Reef, SIC (cf. Raedeke and Vian, 1986; Turner *et al.*, 1985). The recent Bushveld descriptions emphasize an interesting association between the locations of potholes, their associated replacement pegmatites and large-scale fracture trends, possibly reflecting a regional tectonic control on these features.

A third style of PGE mineralization in the BIC is located in the Potgietersrus Limb (Figure 2). The Platreef mineralization is found at the basal contact of the Bushveld Complex, and is hosted by rocks generally considered to be part of the Critical Zone (Van der Merwe, 1976), the same general stratigraphic level within the BIC at which the Merensky Reef is located. Disseminated sulphides are present sporadically within a feldspathic pyroxenite and harzburgite over a strike length of 60 km, with a thickness of up to 200 m. Less is known about this style of mineralization than the Merensky Reef, as mining commenced on the Platreef in 1926 and terminated shortly thereafter. Recently the area has seen renewed interest, re-evaluation and detailed study. Wagner (1929) gave the original geological description, providing the basis for further work by Van der Merwe (1976), Mostert (1982), Gain and

Mostert (1982), Buchanan *et al.* (1981), Cawthorn *et al.* (1985) and Barton *et al.* (1986). Until the work of Cawthorn *et al.* (1985), most authors related mineralization to contamination or hybridization of the Platreef host rocks by wallrock, mainly dolostone from the adjacent Transvaal sediments. On the basis of geochemical and isotopic constraints, however, Cawthorn *et al.* (1985) and Barton *et al.* (1986) developed an hypothesis for contamination of the mafic magma by rheomorphic influx of a felsic magma, probably generated by partial melting of the immediate floor rocks, banded tonalite gneisses; these felsic fluids mixed with the BIC magma, and may have promoted sulphide liquation and PGE scavenging. Barton *et al.* (1986) point out, however, that formation of an immiscible sulphide liquid predated contamination of the BIC magma by rheomorphic felsic magmas, and suggest that initial sulphide liquation was in response to a new influx of BIC magma, a process similar to that described for the Merensky Reef. It appears possible, therefore, that the mineralization was modified subsequently by processes related to influx of a felsic magma. As understanding of the Platreef mineralization evolves, the popularity of the sediment-contamination theory is waning, with the bulk of the new evidence indicating that blending of ultramafic, mafic and felsic magmas appears to have been responsible for the observed features. Mixing in the Potgietersrus limb is, therefore, a more complicated process than that invoked for the Merensky and J-M Reef mineralization. In the latter, specialized magmas of ultramafic and mafic affinities — possibly differentiates from the same parent magma, in a master chamber at depth — have mixed. In the Platreef, however, an additional magmatic component of melted country rock gave rise to felsic magmas which entered the Bushveld magma chamber, to mix with the mafic/ultramafic magmas therein.

Cabri and Naldrett (1984) suggested that the Lac des Iles deposit in Northern Ontario, Canada, is a Platreef-type of PGE deposit, based upon mineralogy and metal contents. Recent geological data support this hypothesis (Macdonald, 1987). Several sulphide zones with anomalous PGE grades (up to 1000 ppb total PGE + Au) are found in gabbroic rocks contaminated by felsic magmas, which formed by rheomorphic melting of country rock. Higher grades of PGE mineralization at Lac des Iles, up to 15,000 ppb PGE + Au, are related to intrusion of an ultramafic liquid into, and blending with, a more evolved, iron-rich, anorthositic gabbro. The orthomagmatic mineralization experienced considerable remobilization due to influx of deuteric fluids, locally concentrating the noble metals into transgressive gabbro pegmatites, which may carry up to 37,000 ppb PGE + Au.

The Great Dyke in Zimbabwe represents a

highly significant PGE resource, estimated to contain at least approximately 8000 tonnes of PGE (as reported in Naldrett *et al.*, 1987), or approximately 50% of the estimated Merensky Reef reserve (Table 2). Worst (1960), Wilson and Wilson (1981), Wilson (1982) and Prendergast (1987a,b) described the geology of the Great Dyke, which is a complex of four, sub-parallel, narrow, layered mafic-ultramafic intrusions. The lower ultramafic series consists of chromitite, dunite, harzburgite, olivine-bronzitite, bronzitite and websterite, with at least fourteen cycles of magma replenishment. The overlying mafic sequence consists of olivine gabbro, norite and gabbro-norite in three cycles. Little is available in the literature on the stratiform Main Sulphide Zone (MSZ) of the Great Dyke, although it has been known and explored for over 60 years. The MSZ, unlike the Merensky and J-M Reefs, is hosted by ultramafic rocks, just below the contact between the Main Websterite of the ultramafic series and the lowermost olivine gabbro of the mafic series (Prendergast, 1987a,b). The MSZ is hosted by bronzitite, several metres stratigraphically below the Main Websterite, and exhibits three principal features: (1) considerable stratigraphic continuity; (2) characteristic vertical metal profiles; (3) systematic lateral variations in width of mineralization, sulphide content, inter-metallic ratios and PGE content when normalized to 100% sulphide (Prendergast, 1987a,b). Prendergast (1987b) considers that the MSZ mineralization of the Great Dyke resulted from a combination of magma replenishment, convective overturn, and magma cooling.

With the resurgence of interest in the PGEs during the latter half of this decade, much new information on the MSZ is anticipated, as a result of not only academic research possibilities offered by the recent availability of diamond drill core that penetrated the MSZ, but also by aggressive exploration and development by the many mining companies with interests in Zimbabwe.

SUBCLASS 1a: Summary. While various competing hypotheses continue to support, on the one hand, magma mixing and, on the other, deuteric concentration of PGE to form the Merensky/UG2/J-M Reefs, the following observations are generally accepted: (a) Mixing of two discretely different magmas (U and A) occurred at the stratigraphic levels occupied by the Reefs; (b) Effects of a conspicuous deuteric component within the magma are manifest in the Reefs' host rocks as hydrous silicates, pegmatoidal layers and cross-cutting pegmatite dykes, locally abundant graphite in potholes and complex fluid inclusions trapped in quartz.

It is also generally agreed (dissenters include Ulmer *et al.*, 1981) that the fluids responsible for the variable textures and compositions in the Reefs' host rocks are deuteric in origin; that is, the fluids are derived from within the parent magma, retaining the integrity of the orthomagmatic hypothesis (Table 1). Until conclusive evidence is available to the contrary, the optimal working hypothesis for the origin of the UG2, Merensky and J-M Reef mineralization invokes magma mixing of two specialized magmas, with some degree of deuteric effect upon (a) silicate crystallization, and (b) subsequent, local redistribution of the PGE-bearing sulphides.

In other deposit types whose formation is attributed to mixing of magmas, such as the Platreef and Lac des Iles, contamination by rheomorphic, felsic melts appears to have modified both magma chemistry and the geometry of mineralized zones. Mineralization containing higher grades of PGE are, however, related to blending of mafic and ultramafic magmas; simple mixing of felsic and gabbroic magmas does not appear to be a critical factor in the formation of economically significant PGE mineralization in this deposit type.

SUBCLASS 1b: Magma Contamination. The second subclass of orthomagmatic, PGE-bearing sulphide deposits are found within mafic/ultramafic intrusions and extrusions in which sulphur saturation has been achieved by addition to the magma of external material, i.e. wallrock contamination.

In 1959, Sullivan suggested that Ni deposits in the Manitoba Nickel Belt, Canada, formed by "sulphurization", the reaction of sulphur, from an external source, with metals (e.g., Fe, Ni) in the magma. Naldrett (1966) proposed a similar process for Fe-Ni sulphides in the Porcupine District of Ontario.

Irvine (1975) described an elegant model for the origin of stratiform chromite and sulphide layers in large, layered igneous intrusions, where addition of silica from an external source can initiate precipitation of chromite and/or liquation of sulphide. In 1977, however, Irvine also demonstrated how the same phenomena may result from the mixing of two magmas, discussed in the previous section.

The Sudbury deposit in Ontario is Canada's principal PGE resource (Table 1). For a recent synthesis of Sudbury geology, see Pye *et al.* (1984). A number of features of the Sudbury ores and host rocks led Naldrett and Macdonald (1980) to propose that contamination of the mafic magma by relatively silica-rich wallrock was the cause of sulphide liquation. These features include (a) the high percentage of normative quartz, co-existing with pyroxenes and plagioclase whose composition is relatively primitive, reflecting little differentiation; (b) numerous, partially digested inclusions in the host rocks (Stevenson and Colgrove, 1968); (c) the relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.706 for the noritic host rock (Gibbins and McNutt, 1975); (d) the relative lack of cyclical units and modal layering, when compared with mafic intrusions of similar size, suggesting a viscous magma, which is consistent with elevated silica content. The silica-contamination model is demonstrated in Figure 9. The FeO-SiO₂ side of the ternary is equivalent to silicate melts and the FeS corner is equivalent to sulphide magmas. A magma at a composition indicated by Point A is a one phase, homogeneous FeO-SiO₂-FeS liquid. If SiO₂ is added such that the composition changes to that of, for example, Point B, the magma now consists of a two-phase, silicate-rich liquid (Y) and co-existing sulphide liquid (X).

The Noril'sk-Talnakh-Kharaulakh Ni-Cu-PGE camp in Siberia, is the Soviet Union's premier source of the PGEs (Table 1). The geology of the Noril'sk area is described by Smirnov (1966), Bazunov (1976), Glaskovsky *et al.* (1977), and is summarized by Naldrett and Macdonald (1980). The Ni-Cu-PGE mineralization has been described recently by Godlevsky and Likhachev (1986). Sulphur isotopic data for the Noril'sk area ($\delta^{34}\text{S} = +7$ to $+10\text{‰}$) are consistent with sulphur assimilation from sulphate-bearing, Devonian evaporites that were intruded by the Permian and Triassic gabbro-dolerite host rocks for the mineralization (Godlevsky and Grinenko, 1963; Kovalenko *et al.*, 1975).

Komatiite-associated Ni-Cu sulphide deposits, such as at Kambalda, Australia, and Thompson, Manitoba, are important hosts for sulphide deposits with significant PGE

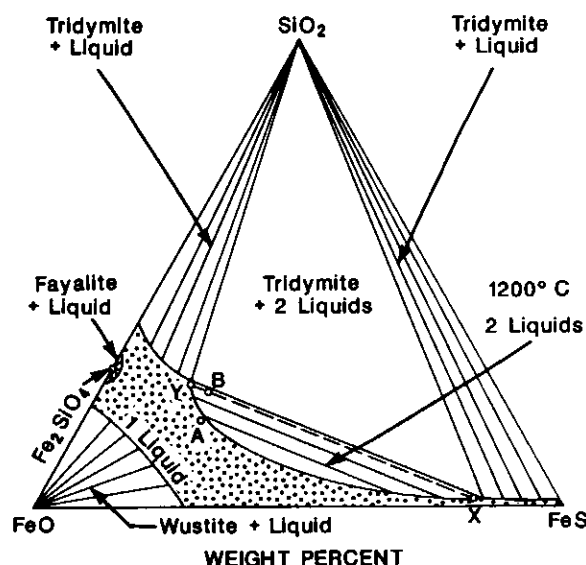


Figure 9 The effect of silica contamination upon an FeO-FeS melt. See text for details (after Naldrett and Macdonald, 1980)

contents. At Kambalda, for example, the ores contain 2.96% Ni, 0.22% Cu, 0.07% Co, 8.09% S, 1141 ppb PGE, 339 ppb Au and 1170 ppb Ag (Hudson and Donaldson, 1984). Until recently, all components of these ores were generally considered to be solely magmatic in origin, modified by metamorphism and deformation (e.g., Groves *et al.*, 1979; Barrett *et al.*, 1977; Marston and Kay, 1980). Leshner and Groves (1986), on the other hand, suggest that the sulphur is externally derived and present arguments that the sulphide ores exsolved from komatiitic magmas *in situ*, in response to assimilation of country rocks during emplacement. They point out that the sulphide deposits show a marked spatial association with sulphidic sediments.

SUBCLASS 1b: Summary. Contamination by wallrock is an effective process for initiating sulphide liquation, whether the contaminant be sulphur itself, silica in the form of assimilated sediments, or as a granitic melt. Sulphide deposits may be expected, therefore, at contacts between mafic/ultramafic bodies and their country rocks, where chemical interaction between the two has occurred. The PGE tenor of this type of sulphide deposit is a function of (a) the amount of magma available for PGE scavenging by sulphide, and (b) the PGE content of the magma.

SUBCLASS 1c: Deuteric Processes. While the deuteric component of mineralization in the Merensky, UG2 and J-M Reefs is still controversial, some PGE deposits are contained within features that demonstrably transect stratigraphy within the layered intrusions. Perhaps the most well-known of these are the dunite, or hortonolite (olivine with 50-70% fayalite) pipes. The pipes are commonly contained within envelopes of olivine dunite and olivine-bronzite-plagioclase pegmatoid (Wagner, 1929). These bodies have not provided large tonnages: the largest is the Driekop Pipe, up to 25 m in diameter, and mined through a vertical depth of 200 m (Schiffries, 1982). Grades, on the other hand can be spectacularly high, up to 2000 ppm total PGE, although average mining grades are substantially less: the Onverwacht Pipe averaged approximately 10 ppm, the Driekop Pipe contained 6 ppm total PGE (Wagner, 1929).

Where a dunite pipe cuts across an easily identifiable stratigraphic marker, such as a chromitite layer at the Onverwacht Pipe (Wagner, 1929) disrupted blocks of chromitite are found within the pipe, more or less at their projected stratigraphic level (Figure 10). The layered rocks around a pipe locally form collapse structures, with layering becoming sub-vertical at the pipe contact (Schiffries, 1982).

The dunite pipes do not reflect intrusion of an olivine-rich magma; rather, the presence of chromitite slabs within pipes suggests an infiltration metasomatism, or replacement phenomenon (Stumpff and Rucklidge, 1982; Schiffries, 1982). Schiffries (1982) proposes that a channelled, high-temperature chloride

solution is responsible for reacting with the noritic host rock, resulting in a dunite. The replacement process involves desilication of pyroxene, and production of an iron-rich olivine (Schiffries, 1982).

Wagner (1929) noted that not all dunite pipes are mineralized. Stumpff and Rucklidge (1982) draw attention to the presence of graphite and pegmatoidal textures, seen also in the Merensky Reef, implying that there may be some relation between pipe and reef formation.

Desilication of pyroxene may be a common phenomenon in other intrusions. An example may be the classic "pillowed troctolite" exposure in the Stillwater Complex, described by Hess (1960), containing elliptical masses of plagioclase-olivine rock (troctolite) in an anorthositic matrix. According to a model proposed by McCallum *et al.* (1977), the troctolite "clumps" are the vestiges of original gabbro (cumulus plagioclase and augite) included within anorthosite; the original augite has been replaced by olivine. Boudreau and McCallum (1986) describe transgressive sulphide zones on Picket Pin Mountain in Anorthosite Subzone II, the thickest anorthosite member (600 m) of the Stillwater Complex, approximately 3 km stratigraphically higher than the J-M Reef. The cross-cutting sulphide zones pass upward into conformable sulphide-bearing zones (1% pyrrhotite, pentlandite and chalcopyrite), that contain approximately 800 ppb total PGE + Au. Boudreau and McCallum (1986) infer that the transgressive sulphide zone reflects a fluid conduit for upward percolating fluids to feed a stratabound sulphide deposit. Perhaps the Picket Pin mineralization can be considered to be an intra-magma chamber, exhalative deposit!

SUBCLASS 1c: Summary. Deuteric and sub-solidus phenomena may be significant processes, especially in large magma chambers, causing considerable modification to original magmatic mineralogy, chemistry, and morphology of lithologies and mineralization. Alteration and replacement features are beginning to receive considerable attention within mafic and ultramafic intrusions, such as the Bushveld and Stillwater complexes. PGE-bearing sulphide mineralization can, it appears, form within this deuteric, late-stage period in the development of a mafic/ultramafic magma body. To date, however, only relatively small mineralized bodies, such as the dunite pipes, are considered to owe their genesis to solely deuteric processes. An understanding of the effects of late-magmatic fluids is, however, crucial to explain fully all features

observed in the much more voluminous "reef"-style of mineralization.

CLASS 2: Alluvial Deposits

SUBCLASS 2a: Placer Deposits.

Platinum was "discovered" by Spanish Conquistadors in Colombia in the mid-16th Century. A detachment of troops moving along a drainage system in northwest Colombia, found gold and grains of an unknown, heavy, silvery mineral in the banks of a river that, subsequently, became known as the Rio Platino del Pinto. As the unknown metal had an extremely high melting point, it was regarded as useless and a hinderance to the refining of gold, and was contemptuously dubbed "platino", meaning silver of poor quality. The Choco district of Colombia has been a source of alluvial PGE since this time, although has long since ceased to be significant, contributing approximately 0.5% of supply to the Western world (Robson, 1985).

The Goodnews Bay alluvial deposits in Alaska yielded just over 3 tonnes of PGE between 1927 and 1982, and is currently under re-evaluation (Robson, 1986). This deposit, like many other alluvial placer deposits such as those in Colombia, is associated with "Alaskan-type" ultramafic complexes (Naldrett, 1981). Similar placers are present down stream from the Tulameen ultramafic/mafic complex in British Columbia (Racevic and Cabri, 1976). The weathering process enriched the Pt/(Pt + Pd) ratio in the placer, with respect to the source, as palladium is more easily dissolved and removed in the weathering environment (Naldrett, 1981). "Alpine-type" ultramafic bodies are also commonly the source for placer PGE, such as in the Ural Mountains of the USSR (Mertie, 1969). Interestingly, placer PGE in the Urals are also associated with "Alaskan-type" zoned mafic/ultramafic complexes (Naldrett, 1981).

SUBCLASS 2b: Paleoplacers. The Witwatersrand paleoplacer in South Africa, dis-

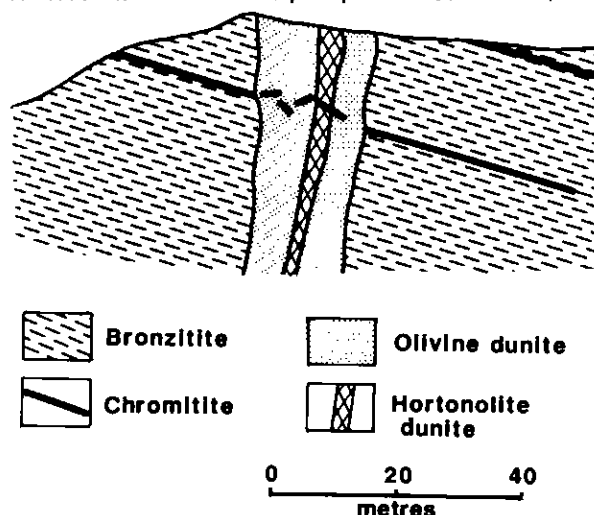


Figure 10 Dunite pipe transecting stratigraphy, Onverwacht, Bushveld Igneous Complex. Note rafts of chromitite within pipe at approximately same stratigraphic level as chromitite seam outside pipe (after Stumpff and Rucklidge, 1982).

covered in 1892, comprises PGE-bearing auriferous-uraniferous conglomerates within the Witwatersrand Supergroup. Pretorius (1975) presents a comprehensive summary of the geological environment of mineralization in the Witwatersrand conglomerate.

Although the PGE are only a trace constituent of the Witwatersrand (less than 10 ppb) the PGE are collected as a bonus during extraction of gold from crushed ore. Annual production of the PGE, since 1921, was in the range of 150-210 kg until 1965, after which time production figures were not released, for security reasons (Reimer, 1979). It is estimated, however, that annual production of the PGE in recent years has risen to 350 kg, giving a total of about 12 tonnes from this one deposit, or 10% of the PGE produced from conventional placer sources (Reimer, 1979).

CLASS 2: Summary. Placer deposits of the PGE are spatially associated with mafic/ultramafic complexes, most commonly of the "Alaskan-" or "Alpine-type" of mafic/ultramafic intrusions. The only known paleoplacer PGE deposit of economic significance, the Witwatersrand, may have resulted from greenstone belt erosion, although arguments still rage as to the origin of other constituents, such as gold (cf. Skinner and Merewether, 1986).

CLASS 3: Hydrothermal PGE Deposits. Hydrothermal PGE deposits form from epigenetic fluids, whose compositions are, as yet, not well constrained, in a wide variety of geological environments; including: (1) associated with shear zones cutting mafic/ultramafic host rocks; (2) associated with alkaline porphyry copper-precious metal deposits; (3) in late diagenetic flow of metal-bearing brines in carbonaceous sediments. This deposit type is generally rich in platinum and palladium, with respect to the other PGE (Naldrett, 1981). Hydrothermal PGE deposits have yet to contribute significantly to global PGE production, although this may be a function of lack of exploration for this deposit type.

SUBCLASS 3a: Shear Zone-related. The Rathbun Lake PGE-bearing Cu-Ni sulphide deposit is located within the Wanapitei gabbro-norite intrusion in Central Ontario (Dressler, 1982). Fluids focussed in sheared rocks are inferred to have been formed a secondary silicate assemblage of chlorite, sericite, quartz, epidote and biotite (Rowell and Edgar, 1986). Massive and disseminated chalcopyrite and pyrite are the principal base metal sulphides. Grab samples average 9% Cu, 0.2% Ni, 20.8 ppm Pd, 9.7 ppm Pt and 3.1 ppm Au. The ratio $(Pt + Pd)/(Os + Ir + Ru)$ of > 1000, much higher than for the orthomagmatic J-M Reef (250) and Merensky Reef (12.5) (cf. Naldrett, 1981), is taken as supportive evidence for a hydrothermal origin (Rowell and Edgar, 1986). The massive sulphide body at Rathbun Lake is, however, of insignificant size, measuring 14 m x 0.3 m to 0.6 m wide. Unfortunately, the occurrence is no longer exposed and its association with a fault can only be inferred (Rowell and Edgar, 1986). This

leaves open the possibility that the deposit may be the result of orthomagmatic, deuteric activity, as suggested by Dressler (1982).

The New Rambler PGE-bearing Cu deposit is located within Precambrian rocks of the Medicine Bow Mountains, Southern Wyoming (McCallum and Orback, 1968). The host rocks are metagabbroic; other spatially associated lithologies include upper amphibolite metamorphic grade leucogneiss, and medium-grained, equigranular granite, with associated quartz monzonite, apite and pegmatite, and a large luxullianite (tourmaline-rich) body exposed on the northern margin of the stock. Major minerals in the granite are albite, quartz, microcline, shorl, muscovite and garnet (McCallum *et al.*, 1976).

Mineralization at New Rambler is associated with both quartz-carbonate-sulphide fissure veins and large sulphide "pods", up to 20 m in horizontal diameter and 15 m in depth. The pods contain little quartz and carbonate, but considerable, finely banded, cryptocrystalline, jasperoid, or more correctly, chrysocolla. The pods are considered to be, at least in part, of supergene origin; the copper sulphide-bearing veins, on the other hand, are probably primary, hypogene features (McCallum and Orback, 1968).

The copper ores contain high Pd and Pt grades (average 75 ppm and 4 ppm, respectively), contrastingly low grades of the other PGE (< 50 ppb in total), and are considered by McCallum *et al.* (1976) to be of solely hydrothermal origin, there being no evidence for remobilization of a magmatic sulphide protore. They consider that faults and shear zones, related to the Mullen Creek-Nash Fork Shear Zone (Houston *et al.*, 1968) may have acted as fluid conduits for the hydrothermal solutions. Again, as at Rathbun Lake, geological investigation of this deposit is hampered by the fact that exposure of the mineralization is not available as mining terminated after a fire in 1918. Investigation of the few outcrops on the property, and study of material from the dump by this author and B.O. Dressler (Ontario Geological Survey) in 1985, reveals intensely hydrothermally altered gabbroic rocks, which are not, however, highly strained. The abundance of felsic dykes, pegmatites and veins cutting gabbroic rock, may indicate that a hydrothermal system related to the felsic intrusion was responsible for hypogene mineralization. High Pt and Pd tenors may either reflect an original hydrothermal fluid content, or, alternatively, be a function of hypogene and/or supergene leaching from the mafic host rocks.

Recently, Hulbert (1986) has described PGE-bearing, uraniferous veins in the Beaverlodge area of Northern Saskatchewan. Veins at, for example, the Nicholson Number 2 deposit, are spatially associated with a mafic intrusion. Hulbert (1986) reports that PGE grades appear to decrease with increasing distance from the mafic rocks, which may

therefore, have been the source from which hydrothermal fluids leached PGE.

SUBCLASS 3b: Alkaline Porphyry Deposits. The alkaline suite of porphyry copper deposits has been known for some time to be enriched in precious metals. Kesler (1973), for example, proposed a porphyry copper-gold subclass of the porphyry copper family and Finch *et al.* (1983) noted, in addition, a significant enrichment of PGE. Werle *et al.* (1984) described the syenitic Allard Stock, an epizonal Laramide intrusion at the southwestern end of the Colorado Mineral Belt, 25 km northwest of Durango, Colo. A porphyry copper/precious metals deposit is hosted within the Allard Stock, containing typically 0.6% Cu, 2-20 ppm Ag, 10-200 ppb Au, 3 ppm Mo and 100-170 ppb total PGE. Werle *et al.* (1984) conclude that fractionation of magma and volatiles in the parent magma chamber of the Allard Stock concentrated H₂O, CO₂ (up to 10% CO₂ is present in the syenitic rocks, and CO₂-bearing fluid inclusions are present in both host rocks and veins), F and S. The volatile, base and precious metal-bearing fluid phase was responsible for breccia and vein mineralization, precipitating metallic minerals, calcite, fluorite and quartz.

SUBCLASS 3c: Late Diagenetic/Epithermal. In contrast to Subclasses 3a and 3b, the hydrothermal Kupferschiefer stratabound Cu-Ag (Pb-Zn) deposits show no spatial nor temporal relationship with igneous activity. Kupferschiefer mineralization is at the contact between Lower Permian volcanic rocks and rift-filling red beds, and Upper Permian marine carbonates, evaporites and red beds, with the largest and richest deposits being found in Southwest Poland. Most recent studies have indicated that the Kupferschiefer mineralization is epigenetic, deposited from late diagenetic, convecting fluids (Jowett, 1986).

At the Lubin and Polkowice Mines in Poland, Kucha (1982) described Pt-rich (> 10 ppm) shales that were mapped along strike lengths in excess of 1.5 km. Maximum values of > 200 ppm Pt have been found over 50 m strike lengths, associated with the contact zone between white, oxidized sandstone, and black, reduced shale, containing thucholite, ketones, kerogen, phenols, tertiary alcohols and aromatic hydrocarbons. Kucha (1982) suggests that the precious metals are concentrated in the shale, during late diagenetic fluid flow, by a process of auto-oxidation and desulphurization of the organic matter. Kucha (1982) further suggests that the PGE may act as catalysts in this reaction.

A second interesting polymetallic, PGE-bearing deposit, not obviously related to felsic intrusions, has been described recently at Coronation Hill, in the Northern Territory of Australia (Needham and Stewart-Smith, 1987). The Coronation Hill Mine is one of a suite discovered in the South Alligator Valley district, mined for uranium in the mid-1950s to 1960s. The uranium deposit is hosted by

highly faulted conglomerate, altered volcanic rocks and carbonaceous schist. Needham and Stewart-Smith (1987) interpret the deposit to be allied to the class of epigenetic, sandstone-hosted uranium deposits, with uranium-enriched felsic volcanic rocks as the metal source, sandstone beds as fluid conduit, and carbonaceous schist acting as reductant. The precious metal mineralization (PGE + Au) is finely disseminated in felsic volcanic rocks, altered to quartz, sericite and chlorite, immediately to the east of the open cut from which uranium was produced. The gold is very fine grained, not visible to the naked eye, and also not associated with any prominent quartz veining. Only minor uranium mineralization is found directly associated with the precious metals. Felsic dikes locally intrude the host rocks. A joint venture between BHP Minerals Limited, Noranda Pacific Limited and EZ Industries Limited discovered the precious metal mineralization in 1985 and report that of 177 two-metre core assays, 163 gave gold values greater than 1 g/t, averaging 0.61 g/t Pt, 1.15 g/t Pd and 772 g/t Au (Noranda Pacific Limited, Quarterly Report, December 31, 1985). It is presently unclear whether the spatial association between precious metal and uranium mineralization is purely fortuitous. The exploration companies believe that the precious metal mineralization is epithermal in nature, related to sub-aerial, acid volcanism.

CLASS 3: Summary. While hydrothermal PGE deposits are less well understood than the more extensively described orthomagmatic deposits, at least three distinct categories are currently identified: (a) those associated with epigenetic fluid flow in mafic/ultramafic rocks, (b) precious metal-enriched (PGE, Au, Ag), porphyry copper deposits, of alkaline affinity, (c) carbonaceous, shale-hosted deposits, related to diagenetic fluid flow. As research progresses, other subclasses of the hydrothermal PGE deposit type will undoubtedly be identified.

Implications For Exploration

The current domination of global PGE markets by deposits of the orthomagmatic class, suggests that, based upon "track record", this deposit type remains the optimal exploration target. Subclass 1a is currently the most desirable target within the orthomagmatic deposit class, as the PGE are a primary product, rather than a byproduct of less economic, base-metal mining. Utilizing an understanding of Bushveld and Stillwater mineralization, the following criteria can be regarded as positive indicators for mineralization: (1) large, compositionally stratified, mixed mafic and ultramafic, layered intrusive complex; (2) zones of mixing between liquids of different U- and A-type affinities (Todd *et al.*, 1982; Irvine *et al.*, 1983), within the mafic portions of the intrusive complex, rather than the lower ultramafic zone. *Nota bene* the MSZ in the Great Dyke is an exception,

located within ultramafic host rocks, several metres below the contact with the mafic series; (3) sulphides, typically only 1-2%, in zone of mixing.

Magma mixing in the BIC and SIC has been documented in the context of chemical and isotopic signatures (e.g., Irvine *et al.*, 1983; Sharpe *et al.*, 1986). Field expressions of the proposed mixing phenomena are complex (e.g., Turner *et al.*, 1985) inasmuch as the geology within the zones of mixing can be highly variable on all scales, contrasting with the relative uniformity of layered rocks stratigraphically above and below the mineralized units. Detailed mapping of the Minneapolis Adit in the Stillwater Complex (Figure 3) reveals such complexity on a small scale that certain packages of rocks are mapped collectively as "Mixed Rock" (Bow *et al.*, 1982). Mixed Rock is an complex igneous breccia, with a matrix of plagioclase cumulate gabbro, containing 20-40% amoeboidal olivine, associated with clusters of pegmatoidal, poikilitic crystals of bronzite and augite. The rock also contains boulders of olivine cumulate, plagioclase-olivine cumulate (troctolite) and plagioclase cumulate.

Macdonald (1985, 1987) has mapped rocks of similar complexity hosting PGE mineralization at Lac des Iles, Canada. In contrast with the relatively monotonous gabbroic rocks that comprise the bulk of the intrusive complex hosting significant PGE at Lac des Iles, the immediate host rocks are highly complex: a wide (500 m) zone of texturally and compositionally variable lithologies — from fine grained to pegmatoidal, pyroxenite, norite, gabbro, quartz gabbro to anorthosite — is cored by an igneous breccia, up 100 m wide that is spatially associated with the higher grades of PGE + Au. The breccia has a gabbroic matrix, with clasts, up to in excess of 3 m in long dimension, of gabbro, pegmatoidal gabbro, anorthosite and pyroxenite. The breccia is cut by gabbro pegmatite dikes, locally containing up to 37,000 ppb total PGE + Au. Mineralization at Lac des Iles is spatially, and probably genetically, related to a pyroxenite that has intruded and locally blended with the anorthositic gabbro host (Macdonald, 1987).

While deposits that formed in response to magma mixing exhibit evidence of at least a partial role played by deuteric fluids, it is by no means certain that this is an essential component of the mineralization process; suffice to say that deuteric effects are not considered deleterious to economic potential.

The renewed interest in PGE mineralization, driven by political and market forces, may result in the discovery of potentially economic concentrations of the PGE in unconventional geologic settings. For example, the Kupferschiefer-style mineralization was not widely recognized until 1982. The PGE-black shale connection is worthy of further investigation in, for example, the Central African Copper Belt and the shale-hosted copper

deposits of Oklahoma, etc. The relatively recent (1985) discoveries of PGE mineralization associated with apparently epithermal gold mineralization at Coronation Hill, in Australia's Northern Territory, suggests that the numerous deposits of this type, in a similar geological environment, warrant a closer inspection for PGE content.

The association of PGE deposits with CO₂-rich, alkaline igneous intrusions is also in need of further description. The deposit type may have to be expanded or redefined to include carbonatite bodies: the pyroxenite-syenite-carbonatite complex at Phalaborwa, in northeastern South Africa, for example, in addition to supporting apatite and vermiculite mines, contains one of the most efficient open pit copper mines in the world, producing 100MT of ore per annum, grading 0.48-0.57% Cu. The composition of recoverable precious metals is dependent largely upon copper content (typical concentrate contains 45% ± 15 Cu). The following composition of anode slimes is typical: 3.5 kg/t Au, 85 kg/t Ag, 0.45 kg/t Pt, 0.55 kg/t Pd and 0.025 kg/t Rh (Verwoerd, 1986).

Conclusions

Deposits of the platinum group of elements form in three fundamental environments: (a) as an integral component of orthomagmatic processes, including mixing of magmas, wallrock contamination of magmas and by deuteric processes; (b) by alluvial concentration of degraded source material — most modern placers being derived from mafic/ultramafic complexes of the "Alaskan-" or "Alpine-type"; (c) by hydrothermal transport, related either to leaching of PGE from mafic/ultramafic host rocks, or to alkaline porphyry copper and/or epithermal precious metal mineralization, or to late-diagenetic fluid flow in sedimentary basins.

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