

A Short Geological Review of the Bushveld Complex

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At present most of the worldwide supply of platinum and palladium and the associated elements is obtained from mines within four major layered igneous intrusions. These are the Bushveld Complex in South Africa, the Stillwater Complex in the U.S.A., the Great Dyke in Zimbabwe, and the Noril'sk/Talnakh Complexes in Russia (1). These layered intrusions consist of rocks which

cooled slowly from molten magma, deep within the earth. Silicate minerals in fixed proportions crystallised and aggregated to form the final igneous rocks. The composition of the minerals changed with the slow drop in temperature in the magma brought about by cooling. The first silicate minerals which crystallised and settled out are rich in magnesium and iron (the 'mafic' parts of the

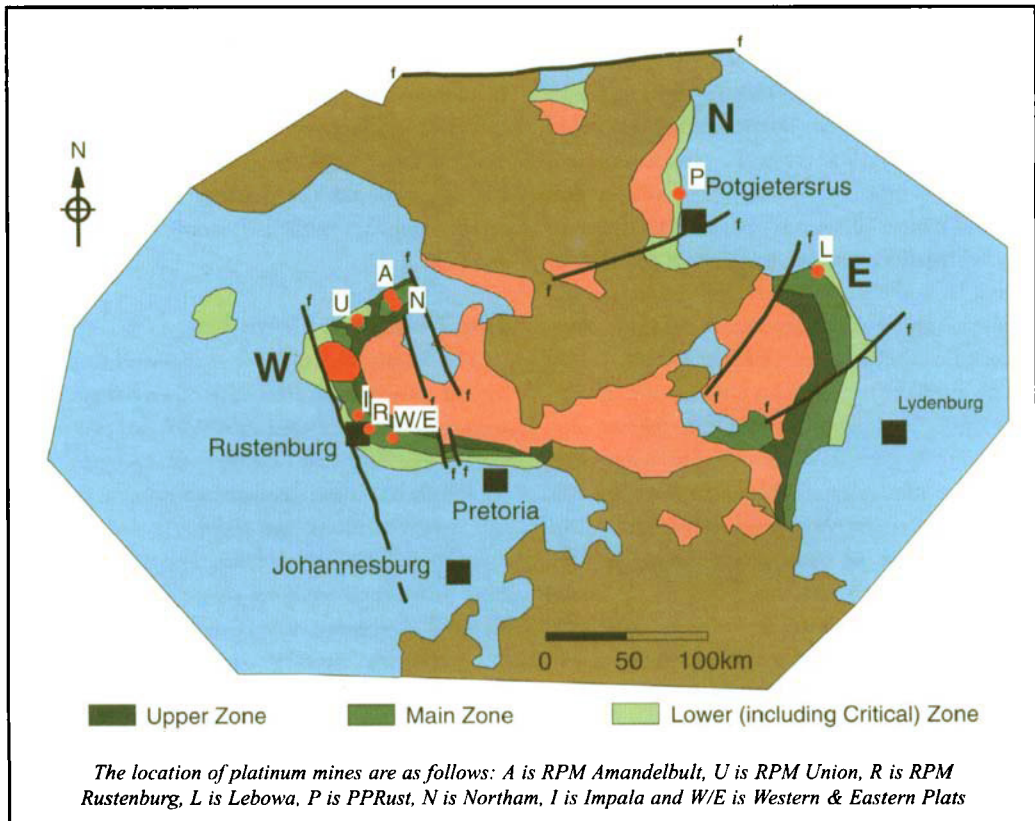


Fig. 1 Simplified geological map of the Bushveld Complex (2). The green shades represent the Bushveld rocks, the rose shades are the granitic cover rocks, the blue and brown shades represent the pre- and post-Bushveld rocks, respectively. The red circular shape near Rustenburg is the Pilanesberg alkali complex. E = eastern limb, W = western limb, N = northern or Potgietersrus limb; f are faults

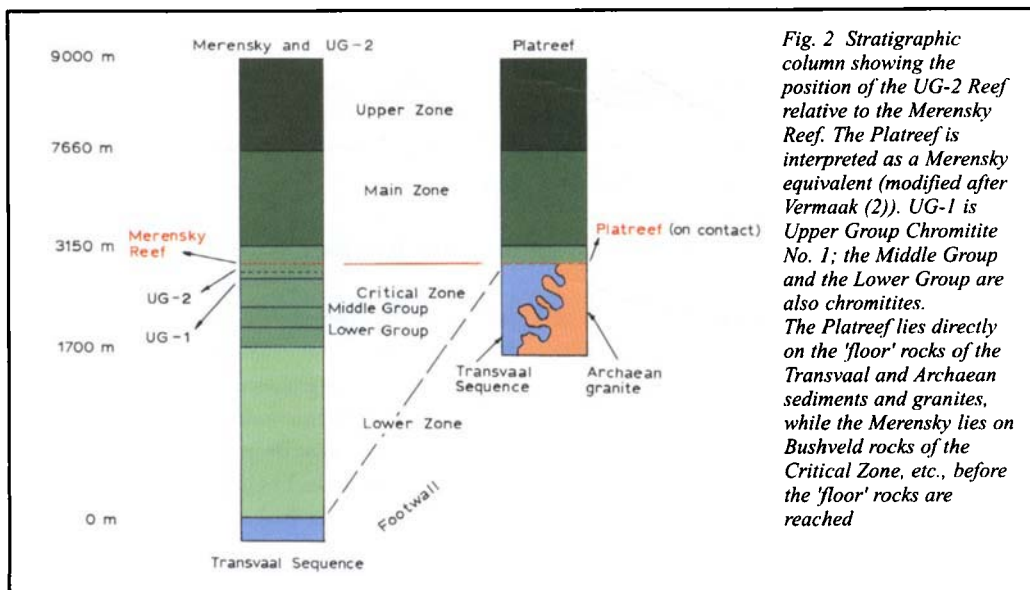


Fig. 2 Stratigraphic column showing the position of the UG-2 Reef relative to the Merensky Reef. The Platreef is interpreted as a Merensky equivalent (modified after Vermaak (2)). UG-1 is Upper Group Chromitite No. 1; the Middle Group and the Lower Group are also chromitites. The Platreef lies directly on the 'floor' rocks of the Transvaal and Archaean sediments and granites, while the Merensky lies on Bushveld rocks of the Critical Zone, etc., before the 'floor' rocks are reached

magma), whereas at the lower temperatures, calcium, aluminum and sodium silicates crystallised (the more 'silicic' facies). This regular change in composition is called fractionation. As more magma is intruded and cools, the cycle is repeated, and this can re-occur many times until several thousand metres of solid rock have been formed. This segregation can be recognised on a scale ranging from the microscopic right through to the complete stratigraphic sequence made up of kilometres-thick accumulations of rock layers.

The resultant layering also controls the distribution of the ore deposits. Chromite (chromium-rich oxide), ilmenite (titanium-rich oxide) and platinum group minerals normally occur in association with the more mafic parts, whereas magnetite (iron oxide), cassiterite (tin oxide), zircon (zirconium silicate), etc., are generally restricted to the more silicic parts. The formation of ore is generally ascribed to the concentration of a specific group of minerals by gravity settling, or is linked to the influx of a magma of a different composition. Reaction of the magma with surrounding rocks, or immiscibility of a melt may also play an important role in the concentration process (3).

From time to time in this process the magma may vary a little in composition and layers of the chromium-rich mineral (chromite) will form, to

give the rock known as chromitite. Layers of chromitite are frequent in these intrusions. Less frequently, the variation in magma composition gives rise to a layer which is rich in the sulfides of iron, nickel, copper, together with the sulfides, arsenides, tellurides and alloys of the platinum group elements (PGE) forming the platinum group minerals.

The Bushveld Complex

The Bushveld Complex is the world's largest layered intrusion, and because of its unique character most other layered intrusions are compared with it. The Bushveld Complex, as exposed at current levels of erosion, consists of eastern, western and northern limbs, see Figure 1, and is some seven to nine kilometres thick. The large scale layering forms the basis for a simple subdivision, see Figure 2. A characteristic is that to a large extent the layers are laterally continuous, except for minor downward magmatic erosional discontinuities known as potholes. This lateral continuity is a help in the exploration, evaluation (of the economic sequences), mine planning and operation.

The upper Critical Zone of the Bushveld Complex, see Figure 1, hosts the largest concentration of PGEs in the world. Apart from the Upper Group Chromitite No. 2 (UG-2) and

Fig. 3 Slab of a typical piece of the Merensky Reef, Rustenburg section (Amplats). Note the thin chromitite layer (black, approximately 1.5 cm thick) outlining the bottom contact of the reef, as well as the coarse-grained (pegmatoidal) nature of the reef. The white rock (norite) consists predominantly of plagioclase feldspar. The bright spots are the sulfides. The footwall is on the left and the hanging wall is on the right



Merensky Reef, the Zone also hosts the Platreef mineralisation of the northern limb of the Bushveld Complex. The stratigraphic column shown in Figure 2 illustrates the relative positioning of the UG-2 in relation to the Merensky Reef, and the position of the Platreef.

The Merensky Reef

Although the Merensky Reef (4–8) is generally regarded as a uniform reef type, large variations occur in reef thickness, reef composition, as well as the position of the mineralisation.

The rock-forming minerals of the Merensky

Reef comprise approximately equal amounts of dark iron-magnesium silicate minerals and lighter calcium-aluminium-sodium silicate minerals (called a feldspathic pyroxenite) under- and overlain by thin (5 to 15 mm) often discontinuous layers of chromite concentrations, see Figure 3. The total thickness of this package is generally less than 30 cm. This zone, commonly known as the Merensky pegmatoid, contains the base metal sulfide grains and associated platinum group minerals. The Merensky Reef has been traced for 300 km around the entire outcrop of the eastern and western limbs of the Bushveld Complex, and to depths of 5 km.

Mineral group	Mineral	Composition
Pyroxene	Enstatite	Mg, Fe silicate
	Augite	Mg, Fe, Ca silicate
Feldspar	Plagioclase	Ca, Na, Al silicate
Mica	Phlogopite	K, Mg, Al silicate
	Biotite	K, Mg, Fe, Al silicate
Chlorite	Chlorite	Hydrated Mg, Fe, Al silicate
Clay	Talc	Hydrated Mg silicate
Serpentine	Serpentine	Hydrated Mg, Fe silicate
Spinel	Chromite	Cr, Fe, Mg oxide
	Pentlandite	Ni, Fe sulfide
Sulfide	Chalcopyrite	Cu, Fe sulfide
	Pyrrhotite	Fe mono-sulfide
	Pyrite	Fe di-sulfide

Table II Regional Distribution of Platinum Group Minerals across the Bushveld Complex						
Discrete platinum group mineral categories	Volume percentage distribution in the Merensky Reef at various localities					
	Rustenburg*	Lebowa*	Amandelbult*	Union*	Boschkoppies*	Western Platinum**
Pt-Fe alloys + intergrowths	9.6	1.2	48.6	82.8	13.1	6.1
Palladium alloys	–	Trace	0.2	0.4	2.3	–
Electrum (AuAg)	3.5	0.7	0.9	0.5	0.7	4.1
Platinum arsenides	6.4	1.3	4.1	0.3	39.9	51.0
Laurite (RuS ₂)	15.4	6.8	11.6	7.0	8.0	–
Platinum-palladium sulfides	31.6	70.9	20.7	2.3	29.4	17.3
Platinum-palladium tellurides	33.5	19.1	13.3	6.7	6.5	21.4
Others	Trace	Trace	0.6	Trace	Trace	Trace
Platinum group mineral associations with:						
Base metal sulfides	56	80	67	89	47	68
Silicates	43	20	31	10	52	42
Chromite	< 1	< 1	2	< 1	< 1	–

*Amplats data ** Data modified after Kinloch, 1982 (10)

The rock-forming silicate minerals of the Merensky Reef consist predominantly of orthopyroxene (~ 60 per cent), plagioclase feldspar (~ 20 per cent), pyroxene (~ 15 per cent), phlogopite (5 per cent), and occasional olivine, see Table I, which lists the composition of some of the common minerals found in the Bushveld-type rocks. Secondary minerals such as talc, serpentine, chlorite and magnetite have widespread occurrence.

The base metal sulfides consist of pyrrhotite (~ 40 per cent), pentlandite (~ 30 per cent), chalcopyrite (~ 15 per cent), and trace amounts of millerite (NiS), troilite (FeS), pyrite (FeS₂), and cubanite (Cu₅FeS₄). The major platinum group minerals are cooperite (PtS), braggite [(Pt,Pd)NiS], sperrylite (PtAs₂) and PGE alloys, although in some areas minerals such as laurite (RuS₂) can be abundant.

The regional distribution and associated data of the platinum group minerals in the Merensky Reef are summarised in Table II.

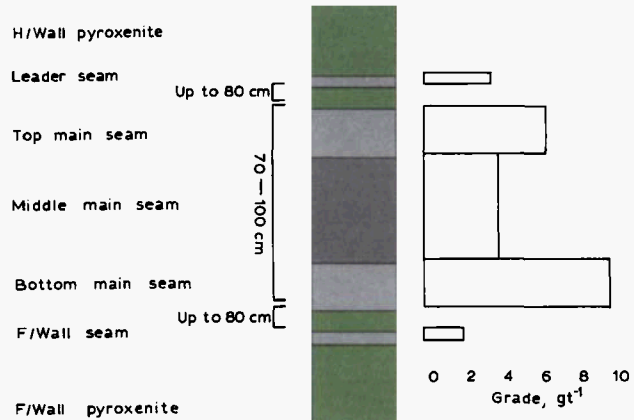
The UG-2 Reef

The UG-2 Reef (2, 9–12) is a platiniferous chromitite layer which, depending on the geographic location within the Complex, is developed

some 20 to 400 metres below the better known Merensky Reef. The chromitite itself is usually 1 m thick but can vary from ~ 0.4 to up to 2.5 m. Thin chromitite seams (generally less than 20 cm in thickness) may be present in both the footwall and, more commonly, in the hanging wall rocks. The UG-2 consists predominantly of chromite (60 to 90 per cent by volume) with lesser silicate minerals (5 to 30 per cent pyroxene, and 1 to 10 per cent plagioclase (2)). Other minerals, present in minor concentrations, can include the silicates: phlogopite and biotite, the oxides: ilmenite, rutile and magnetite, and base metal sulfides. Secondary minerals include quartz, serpentine and talc, see Table I. The Cr₂O₃ content of the UG-2 Reef varies from 30 to 35 per cent (the pure chromite mineral has an average Cr₂O₃ content of 44 per cent (12)).

Total PGE values vary from locality to locality, but on average range between 4 and 7 g ton⁻¹. Figure 4 illustrates a typical distribution of the values in the UG-2 Reef, and Table III summarises the contribution of the individual PGE. The base metal distribution follows a similar trend to that of the PGE, with most of the values occurring in the bottom and top part of the reef. The base metal

Fig. 4 Idealised section through the UG-2 Reef illustrating the distribution of the platinum group elements. The grades, measured in grams per ton, of the platinum group elements are shown for each seam. The bottom main seam is seen to contain a higher proportion of the platinum group elements. H/Wall is hanging wall F/Wall is footwall. The green colour denotes pyroxenite



content of a typical UG-2 Reef is approximately 200 to 300 ppm nickel occurring as nickel sulfide and less than 200 ppm copper occurring as copper iron sulfide.

The platinum group minerals present in the UG-2 Reef are highly variable, but generally the UG-2 is characterised by the presence of abundant PGE sulfides, comprising predominantly laurite (RuOsIr sulfide), cooperite (PtS), braggite (Pt, Pd, NiS), and an unnamed PtRhCuS. The platinum group minerals only reach an average size of approximately 12 μm , with particles larger than 30 μm being extremely rare. Most of the platinum group minerals occur in association with the base metal sulfides and silicates. It is only the mineral laurite which exhibits a preferred association with the chromite grains. Both the grain size and associations are extremely important as these affect the metallurgical behaviour during subsequent processing.

The major base metal sulfides constitute chalcopyrite, pentlandite and pyrrhotite. The base

metal sulfides occur almost entirely within the interstitial silicate and are only very rarely enclosed within the chromite particles. The grain size of the base metal sulfides rarely exceeds 30 μm .

The Platreef

In the northern limb of the Bushveld Complex, the Lower and the Critical Zones of the Bushveld are poorly developed. Where the Bushveld rocks are in contact with the floor rocks (that is the Archaean granite and sediments of the Transvaal Sequence), a unique type of mineralisation has developed, see Figure 2. This reef, known as the Platreef (13, 14) consists of a complex assemblage of pyroxenites, serpentinites and calc-silicates. The different nature of these rocks, compared to normal Merensky Reef, is the result of the hot Bushveld magma reacting with the lime-rich floor rocks. An exchange of heat and material between the magma and the floor rocks resulted in the formation of abundant lime-rich minerals (calc-silicates) as well as the serpentinisation of the overlying pyroxenites.

	Pt	Pd	Ru	Rh	Ir	Os	Pt:Pd
Western Bushveld	52	24	14	8	< 2	< 1	2.2
Eastern Bushveld	41	37	11	7	3	1	1.1

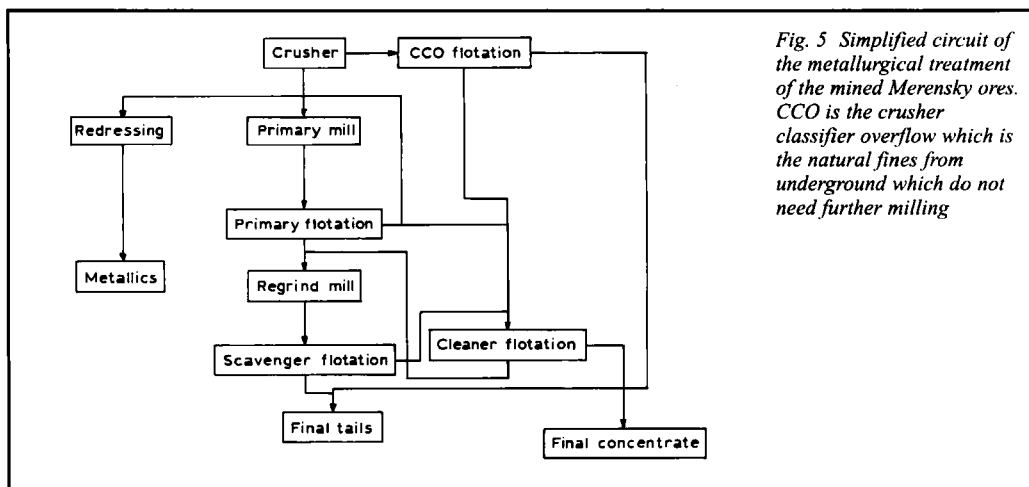


Fig. 5 Simplified circuit of the metallurgical treatment of the mined Merensky ores. CCO is the crusher classifier overflow which is the natural fines from underground which do not need further milling

Base metal mineralisation and PGE concentrations are found to be highly irregular, both in value as well as in distribution. The mineralisation in places reaches a thickness of up to 40 metres. Although the major platinum group minerals consist of PGE tellurides, platinum arsenides and platinum sulfides, there appears to be a link between the rock type and the type of PG-minerals: serpentinites are characterised by a relative enrichment in sperrylite (PtAs₂), whereas the upper pyroxenites are generally characterised by more abundant PGE sulfides and alloy. PGE alloys generally dominate mineralisation closer to the floor rocks.

Common base metal sulfides include pyrrhotite, pentlandite, chalcopyrite and pyrite, and although PG-minerals frequently occur, enclosed in or on grain boundaries of these base metal sulfides, a high association of PG-minerals with silicate minerals is found in some areas.

Metallurgical Treatment

The Anglo American Platinum Corporation (Amplats) mining operations on the three reefs utilise froth flotation for recovery of the value minerals to concentrates. The exceptions are the Rustenburg and Amandelbult Merensky Reef operations of Amplats, where historically, the coarse and dense PG metals (about 30 per cent of the total platinum in the Merensky) are concentrated and removed from the circuit at an early stage

by gravity techniques prior to the main flotation banks. This results in a very high-grade stream, which by-passes the smelter stages and is an early feed to the refinery. The remainder of the PGE are recovered by flotation, followed by electric smelting, converting to produce a nickel-copper-PGE matte which, after slow cooling and extraction of the precious metal alloy phases, is sent to the refinery where platinum, palladium, rhodium, ruthenium, iridium, osmium, gold and silver are produced. The base metal portion of the converter matte is processed separately in the base metal refinery for recovery of nickel, copper and cobalt.

A simplified flowsheet of the mineral processing operations on the Merensky and Platreef ores is shown in Figure 5.

The UG-2 operations, due to the fine grain size of the PG metals and the paucity of base metal sulfides, utilise flotation as the sole method of concentration. Gravity concentration is used on occasion for recovery of a chromite byproduct.

Reserves

Cawthorn (3b) reports the proven and probable reserves of platinum and palladium for the Bushveld Complex to a depth of 1200 m as 204 and 116 million ounces platinum and palladium, respectively. Amplats proven and probable reserves are 95.5 million ounces platinum and 59 million ounces palladium. Inferred resources of platinum and palladium to 2 km depth are estimated

as 939 and 711 million ounces, respectively, for the whole Bushveld. This represents 75 per cent and 50 per cent of the world's platinum and palladium resources, respectively. Cawthorn (3b) estimates that for the Bushveld Complex as a whole, the proven and probable reserves are sufficient for 40 years production at the current rate of production. The Bushveld Complex is truly a world class deposit and unlikely to be duplicated by any new discovery.

On-going Research

The potential for improving current recoveries of value minerals from the ores of the Bushveld Complex is significant and, to this end, research in all fields of geology, mining, mineralogy, minerals processing and in the various refining processes is on-going. Optimisation of these resources, via process technology and other technical measures, is one of the major functions of the continuing research undertaken at the Amplats Research Centre.

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Euan Kinloch retired in March 1999 as Manager of the Amplats Research Centre in Johannesburg; he is currently a consultant for Amplats. His main interests are in the mineralogy of the ores of the Bushveld Complex and the metallurgical products derived from the Amplats mining operations.

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Chris Lee is a Consulting Geologist for Amplats and is a recognised specialist in the field of platinum exploration worldwide. His primary interests are related to the Bushveld Complex.

Submicron Platinum Metals Powders

Uniform platinum and palladium powders of submicron size are important conductor materials for the electronics industry, but their synthesis is difficult. Researchers from the Université de Picardie Jules Verne, France, have now reported a room temperature synthesis of spherical platinum and palladium submicron particles by controlled hydrazine reduction of $PtCl_6^{2-}$ and $Pd(NH_3)_4^{2+}$, respectively, in glycols (K. Tekaia-Elhsissen, F. Bonet, S. Grugeon, S. Lambert and R. Herrera-Urbina, *J. Mater. Res.*, 1999, **14**, (9), 3707–3712).

Platinum powders produced in this way contain particles with a bimodal size distribution which can be narrowed by synthesis at -5°C . Palladium powders are monodisperse, of average particle size 0.1–0.3 μm ; their particle size and distribution can be controlled by modification of the solution chemistry.